The University Of Sheffield.

Small wind turbines for decentralised rural electrification: case studies in Peru, Nicaragua and Scotland

Thesis submitted to the E-Futures Interdisciplinary Centre for Energy Sustainability Studies for the degree of Doctor of Philosophy

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Abstract

This thesis began as an engineering optimisation of Small Wind Turbine (SWT) blades for hand manufacture in developing countries. However, it soon became apparent that many of the SWTs installed in rural communities across the global south were not even in operation, let alone operating efficiently. This thesis reconceptualises SWTs as more than just a piece of technology that exists independent of the people that construct, install, operate and maintain it. The fundamental argument put forward is that in order to truly understand the reasons why so many SWTs are failing to provide the energy services for which they were designed, a holistic viewpoint must be taken that encompasses both social and technical issues.

Case studies in Peru, Nicaragua and Scotland were undertaken to determine the key factors that have led to the success or failure of SWTs in each particular local context. From this evidence, a framework was developed to break down the socio-technical system that exists in each place into its component parts and the interactions between them, facilitating comparison between cases and the identification of the critical factors in wind-based decentralised rural electrification.

The case study evidence has shown that taking this socio-technical perspective is in fact even more important for SWTs than for solar photovoltaics (PV), as almost every stage in the technology life cycle requires more support. Most notably, the wind resource is highly variable in both space and time (making resource assessment particularly difficult and limiting the scalability of the technology) and maintenance requirements are high (making technical support after installation from a service network and the empowerment of community technicians/end-users essential). SWTs have not been as successful as either solar PV or micro-hydro and nor do they have the potential to be. However, they do provide a third option for rural electrification in windy regions where neither solar nor hydro can provide sufficient electrical power throughout the year.

Acknowledgements

Firstly I must thank Anna Caitlyn Sumanik-Leary, who I had the pleasure of marrying half way through this PhD. Despite constantly disappearing off to faraway places to conduct fieldwork, she continued to support me throughout the entire process. In fact, without the support of Caitlyn, my mother Jane, my father Greg and my brother Rowan I would not be sitting here writing this now. From the moment that I even thought about beginning a PhD, they have always been there to help me make this dream reality.

Next I would like to thank my supervisors, Rob Howell & Aidan While. Aidan took me on as an engineer and with much perseverance, transformed me into a social scientist. Rob guided me through the process of scientific enquiry, allowing me to find my own path whilst always making sure I knew where I was going and why I was going there. I can truly say that having the guidance of both these incredible people was a fine example of how the whole can be far greater than the sum of the parts, as neither an engineer nor a social scientist alone would have been properly equipped for the task at hand.

Hugh Piggott has been a third supervisor to me throughout the research in all but official title. In particular, during the technical performance measurements that took place on Scoraig. Not only did Hugh teach me everything I know about measuring the performance of SWTs, but he also welcomed me into his home as if I were part of his family. In fact, I should thank all the people who opened their homes to me during the course of this research: Lilian and Cow in Monkey Point; Rosa Zenayda in Cuajinicuil; Michael in Trujillo; and of course Hugh, Jytte, Catherine and William on Scoraig.

No research assistants were formally employed during this research, however countless individuals have given up their spare time to share their experiences of SWTs with me, to accompany me to remote communities, to review documents, share ideas and to help me in whatever way they could. In no particular order: Milan Delor, Drew Corbyn, Teodoro Sanchez, Gustavo Reyes, Caitlyn Peake, Bryan Ferry, Aran Eales, Tom Dixon, Matt Little, José Chiroque, Cesar Fernando Pinedo Lujan, Bruno Domenech, Matteo Ranaboldo, David Sharman, Pushkar Mandahar, Peter Freere, Kimon Silwal, Jay Hudnall, Esteban Van Dam, Piet Chevalier, Pedro Neves, Cindy Bennet, Laura Ketteringham, Marcia Espinoza and anybody else I have forgotten!

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Glossary of terms

Currencies: Unless otherwise stated, the symbol '$' refers to USD (United States Dollar), which is used as the standard currency throughout this thesis. The following standard exchange rates were used[1]:

- C$, NIO, Nicaragua Cordoba Oro, $1 = C$24.15
- £, GBP, Great Britain Pound, $1 = £0.64

The following technical terms are often used throughout this thesis to describe wind turbine performance:

Power curve: A graph of power (DC power delivered to the batteries) vs. wind speed that indicates how much power the wind turbine will produce over a range of wind conditions. A standard curve produced to international specifications by an independent testing agency should be available for most commercial machines; however, the actual power curve of any particular machine after installation on a real site is likely to be different. For locally manufactured machines, the data is much less reliable as it has usually only been measured by the manufacturer themselves using very basic equipment. Appendix B shows the power curves for each of the Locally Manufactured Small Wind Turbines (LMSWTs) discussed during this thesis.

Efficiency: There are many different ways of defining efficiency in a wind power system (blade efficiency, mechanical efficiency, AC/DC conversion efficiency, etc.), however unless otherwise stated the term efficiency is used throughout this thesis to mean the following:

$$Efficiency = \frac{P_{DC}}{P_{wind}} = \frac{IV}{1/_2\,\rho A V^3} \tag{1}$$

Where: P_{DC} *= DC electrical power delivered to the batteries (W)*

P_{wind} *= power available in the wind (W)*

I = current (A)

V = voltage (V)

P = density of air (kg/m^3*)*

A = swept area of wind turbine (m^2*)*

V = wind velocity (m/s)

Rated power: The power produced by the wind turbine at its rated wind speed, which is arbitrarily defined by the manufacturer. For example, Soluciones Prácticas' 3m diameter SP-500 is rated at 500W, but has almost identical performance (until

[1] Exchange rates obtained from www.xe.com in June 2013

	furling) to the Piggott 3N, which is also 3m in diameter, but rated at 800W. The former is rated at 8m/s, whilst the latter at 13m/s.
Rated Annual Energy Yield (RAEY):	Estimated annual energy yield on a standard site with a 5m/s annual mean wind speed. Produced by multiplying the power produced at each wind speed on the power curve with the corresponding number of hours that this wind speed occurs each year in a Rayleigh wind speed frequency distribution with a mean of 5m/s and summing the products[2]. This is a much more reliable and comparable measure of performance than the rated power, however it relies upon the accuracy of each machine's power curve.
Hybrid:	Power generation system with more than one power source, e.g. PV-wind hybrid.
Capacity factor:	The ratio of actual annual energy production with respect to the amount of energy that would have been produced if the device had been operating at rated power for an entire year.

The following abbreviations are used throughout this thesis:

AFPM	Axial Flux Permanent Magnet
CEDECAP	Centre for Demonstration and Training (Centro de Demonstración y Capacitación, Perú)
CEPAL	Economic Commission for Latin America and the Caribbean (Comisión Económico para America Látina y el Caribe)
COMET-ME	Community Energy Technology in the Middle East
CREE	Regional Centre for Wind Energy (Centro Regional de Energía Eólica, Argentina)
ENEL	Nicaraguan Electricity Company (Empresa Nicaragüense de Electricidad)
ESMAP	Energy Sector Management Assistance Program
EWB	Engineers Without Borders
FOB	Freight on Board
GIS	Geographic Information System
INATEC	National Technological Institute (Instituto Nacional Tecnológico, Nicaragua)

[2] For the power curves shown in Appendix C in which data up to 20m/s was not available, the RAEY calculations were performed using an extrapolation of the last known data point, i.e. drawing a horizontal line of constant power output from the highest available wind speed. Although this is not realistic, the low frequency of high winds means that it is unlikely to introduce an error of more than 10%.

INE	Nicaraguan Institute of Energy (Instituto Nicaragüense de Energía)
INETER	Nicaraguan Institute of Territorial Studies (Instituto Nicaragüense de Estudios Territoriales)
INTI	National Technological Institute (Instituto Nacional de Tecnología Industrial, Argentina)
IRENA	International Renewable Energy Agency
LCoE	Levelised Cost of Energy ($/kWh)
LGC	Levelised Generating Cost ($/kWh)
LMSWT	Locally Manufactured Small Wind Turbine[3]
MEM	Ministry of Energy and Mines (Ministerio de Energía y Minas, Nicaragua and Peru)
NGO	Non-governmental Organisation
NREL	National Renewable Energy Laboratory (US)
NPC	Net Present Cost
O&M	Operation and Maintenance
PV	Photovoltaic
RAAN	Northern Atlantic Autonomous Region (Región Atlántico Autónoma Norte, Nicaragua)
RAAS	Southern Atlantic Autonomous Region (Región Atlántico Autónoma Sur, Nicaragua)
SIEPAC	Interconnected Central American Electricity Grid (Sistema de Interconexión Eléctrica de los Países de América Central)
SWERA	Solar and Wind Energy Resource Assessment Program (of the NREL)
SWT	Small Wind Turbine[4]
UCA	Central American University (Universidad Centro Americana, Nicaragua)
ULSA	La Salle University (Universidad La Salle, Nicaragua)
UNI	National Engineering University (Universidad Nacional de Ingeniería, Nicaragua)

[3] Defined in this thesis as an SWT produced in the country in which it is to be installed.
[4] Rated power of 10 kW or below.

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Chapter 1. Introduction

1.1 Rural electrification

Globally, 1.4 billion people have no access to electricity, 85% of whom live in rural areas (UN AGECC, 2010 and IEA, 2010). Electricity is the most versatile energy carrier and the link between electricity use and human development is clear. Figure 1-1 demonstrates that the first few kilowatt-hours (kWhs) of electricity have the biggest impact on quality of life; this fact alone can justify the increased cost of bringing electricity to remote areas. Among the many benefits of electrification, the most prevalent is electric lighting (Practical Action, 2010). Open flame kerosene lamps are widely used throughout the developing world due to their availability and low initial purchase cost (Foster, Tre et al., 2000), however not only are they dangerous (Peck, Gerebreg et al., 2008), but also costly per unit of light output (Foster, Tre et al., 2000) and inefficient (Practical Action, 2010).

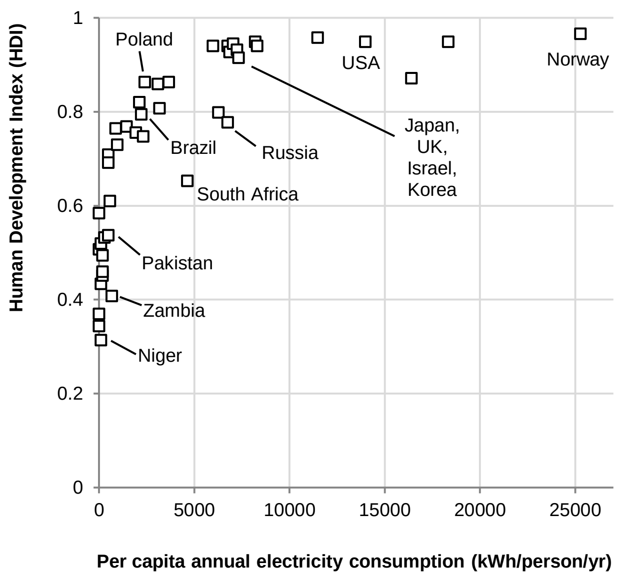

Figure 1-1: Relationship between annual per capita electricity consumption and quality of life, as measured by the Human Development Index (HDI). Source: UNDP (2006).

Whilst centralised electricity supply networks will continue to expand, there is growing interest in improving electricity access in remote regions of the developing world via decentralised renewable energy systems (Wilkins, 2002; GNESD, 2006; Developing Renewables, 2008). Such systems are capable of providing a flexible, locally controllable and consistent supply of electricity that will allow for future expansion in energy use as quality of life increases (GNESD, 2006). On a global scale, the possibility of a low-carbon development pathway adds further weight to the argument. There are a range of different technologies on offer, however the three most widely available renewable energy resources for small scale electricity production are the sun, the wind and flowing rivers. As a result, decentralised solar, wind and hydro power generation technologies can offer many rural communities the potential to produce their own electricity from their own natural resources. Of course, these resources also exist in urban areas, however higher population densities mean that as long as suitable infrastructure exists, the most economical method for urban electricity distribution is generally via a central grid (represented by a 500MW coal-fired power plant in Figure 1-2). This is not the case in remote areas, where it is often impractical for governments and unprofitable for private energy companies to build long, expensive and inefficient transmission lines to connect the many scattered and impoverished communities. Here, decentralised generation is the only practical option.

As a result, diesel generators are often used in stand-alone power systems because of their availability, low initial purchase costs, modularity and ease of installation. However the on-going need for fuel distribution, rising fossil fuel prices, environmental contamination and the associated health risks mean that they are rarely the most economically, socially or ecologically sustainable option (Casillas, 2012). Unfortunately, many people are now 'locked-in' to using this technology in inappropriate circumstances, as significant infrastructure has already been established in their local area to import, distribute, install and maintain diesel generators (as well as the fuel they burn), whilst no equivalent yet exists for renewable technologies. Demand for electricity is inherently linked to supply and as a result, when the only technological option available in a particular place is a costly diesel generator, then electricity use is often severely restricted. Consequently, the value of having access to electricity is dramatically reduced and demand is constrained until a more appropriate alternative becomes available.

The Energy Sector Management Assistance Program (ESMAP, 2007) estimated the Levelised Generating Cost (LGC) for various power generation technologies using a standard methodology that compares the total costs (initial capital, O&M and where applicable, fuel, transmission and distribution) to the total energy generated over the predicted lifetime of the technology[5]. All costs are discounted to the base year, and the resulting figure is the value at which electricity would have to be sold at in order to break even (see section 5.2.2.2). The results of the analysis, seen in Figure 1-2, show that economically, renewables are undoubtedly the best option for small-scale distributed power generation, providing that a suitable resource and supporting infrastructure exit in that location (World Bank, 2008).

[5] Renewable technologies are assumed to have been sited in locations with 'good' renewable resources (modelled by 20-30% capacity factors).

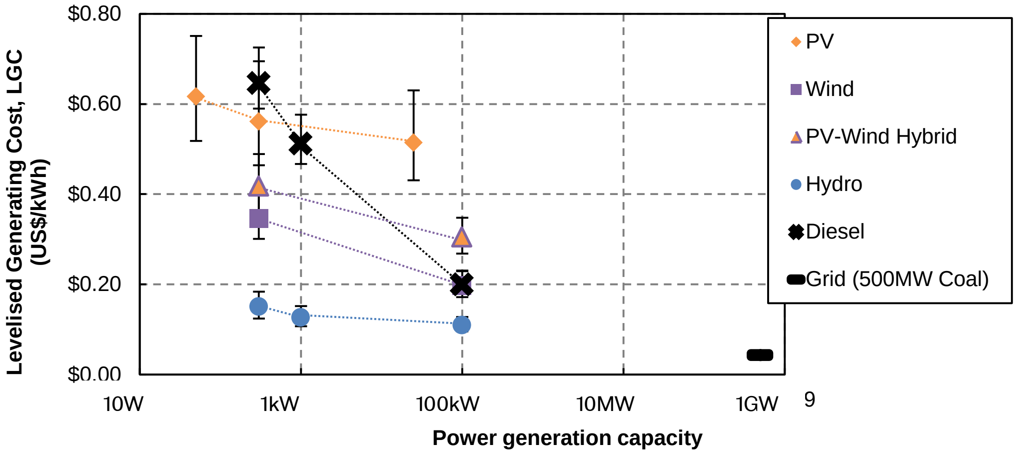

Figure 1-2: Cost comparison of power generation technologies (Source: ESMAP (2007))

The use of micro-hydro and photovoltaics (PV) for rural electrification is already well established (Wilkins, 2002) however these technologies are not appropriate in all local contexts. For example, a suitable watercourse is not always available and although prices continue to fall, PV is often still prohibitively expensive (IEA, 2013). As will be discussed in the subsequent chapter, the successful dissemination of wind power technology in Inner Mongolia has shown that where a reasonable wind resource is available, wind power can provide a cost-effective and reliable solution to rural electrification (Batchelor *et al.*, 1999). Moreover, as will be demonstrated in the subsequent chapter, the option to manufacture Small Wind Turbines (SWTs) locally can offer a number of additional benefits. Figure 1-3 shows the global availability of wind resources, which can be compared to the solar and hydro resources, as well as the global distribution of people without access to electricity in Appendix A.

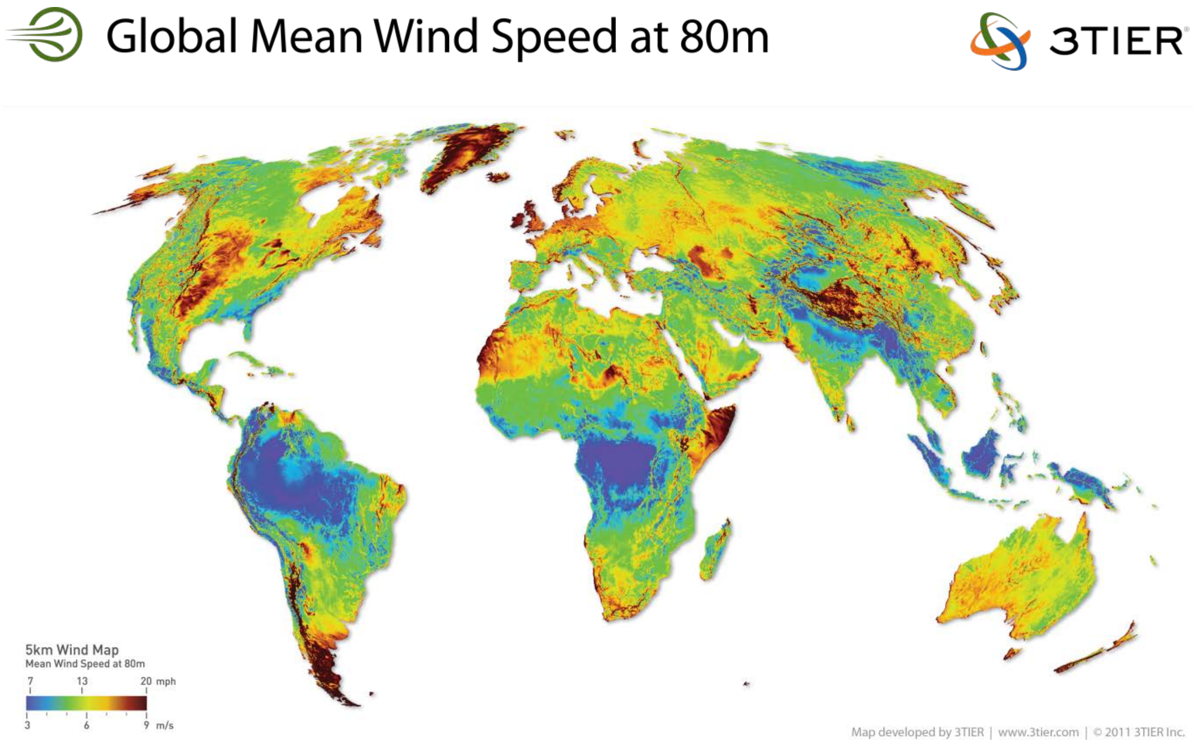

Figure 1-3: Global wind resource map (3TIER, 2011).

Simple statistics stating whether or not a person has access to electricity do not accurately reflect reality. Clearly, carrying a heavy lead-acid battery to and from a charging station and to then only be able to use a limited range of DC appliances does not correspond to the same level of energy access as the instant availability of mains quality AC power. To categorise these discrepancies, Practical Action (2013) have devised an indicative electricity framework with six tiers, each representing an improved quality of access to electricity, bridging the gap between no access at all and mains quality AC power. Figure 1-4 shows this framework with regard to household electricity access; similar frameworks for earning a living and community services are also defined. The framework represents the textured reality of energy access, with each tier defined by the attributes of the electricity supply, such as "*quantity, duration, evening availability, affordability, quality of supply and legality of connection" (Practical Action, 2013: 29)*. The technologies likely to deliver these levels of electricity access are shown on the bottom row of Figure 1-4, with SWTs likely to fall into either tier 2 or 3.

Tier	0	1	2	3	4	5
Electricity services	None	Electric lighting, radio, mobile phone charging	Tier 1 + multi-bulb lighting, air circulation, TV	Tier 2 + water heater, rice cooker	Tier 3 + refrigerator, mechanical loads	Tier 4 + electric cooking, space heating and cooling
Energy supply attributes		**Continuous spectrum of improving energy supply attributes** including: quantity (watts), duration (hrs), evening supply (hrs), affordability, legality, quality (voltage)				
Likely energy supply technology (indicative)	None	Solar lanterns	Stand-alone home systems	Mini-grids with limited supply or poor grid connection	Unreliable grid with limited supply	Reliable grid with 24-hour supply

Figure 1-4: Practical Action's (2013) indicative household electricity framework.

1.2 Extracting power from the wind

1.2.1 A typical wind power system for rural electrification

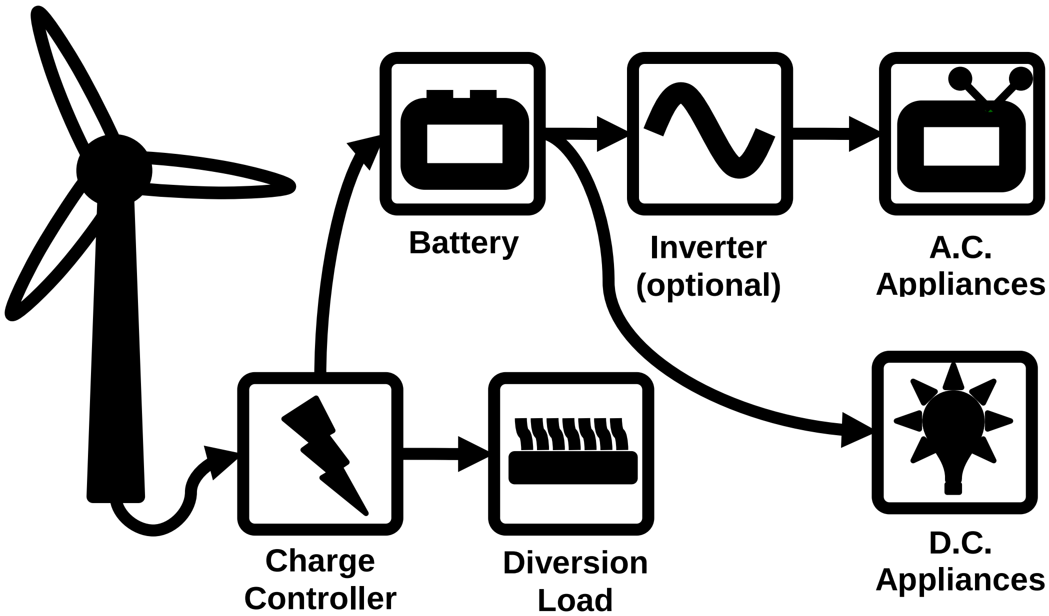

Figure 1-5: Schematic of the power flow in a typical off-grid wind power system

Figure 1-5 shows the key components of a typical off-grid wind power system. The wind turbine converts kinetic energy from the wind into electrical energy, the flow of which is regulated by the charge controller to prevent over-charging of the battery by sending excess power to a diversion load.

The battery provides the energy storage necessary to match the variable power supply from the wind turbine to the variable power demand of the end user. D.C. power can be drawn directly from the battery, whilst the use of A.C. power requires an inverter. Finally, electrical appliances provide the energy services such as lighting to the end user. 110-240V A.C. at 50 or 60Hz is the standard for mains electricity around the world and as a result, any appliance that plugs into the mains will need an inverter to operate on an off-grid system. Batteries use D.C. power and although the range of D.C. appliances is growing, it still lags behind the growth in the market for off-grid electricity, meaning that even appliances such as mobile phones that operate on D.C. often still require an inverter, as they may only be supplied with an A.C. charger (see 2.4.1 for more details).

The performance of a wind turbine is very difficult to predict and is highly dependent on the site on which it is installed. In particular, turbulence and shelter from nearby obstructions, the sensitivity of the furling system designed to protect the machine in high winds, cable length and diameter, tower height, seasonal and inter-annual variation in wind resource and air density changes due to altitude (see Figure 4-15) can have a major influence on energy yields. In fact, Khennas, Dunnett et al (2008: 23) give the following advice to those planning a small wind installation: "*the best approach may be to make an informed guess and then refine this in light of practical experience.*"

The SWTs described in this thesis range in size from 1-5m rotor diameter. Any larger than this and the logistics of transporting the equipment to a remote community (in particular the tall tower and heavy generator), then installing it (digging anchors, lifting the tower/turbine etc.) and performing maintenance (taking it down around once a year) becomes difficult. The rated power of such machines is likely to range from 100W-2.5kW and Figure 1-6 shows that predicted annual energy yields can vary widely, from 2-430kWh, depending on the size of the machine and quality of the wind resource at that particular site. The power available in the wind varies with the cube of the wind speed (see equation (1)), which means that the mean wind speed at the site on which a turbine is installed has a huge influence on power production. Appendix B describes the Beaufort scale, which correlates wind speeds (m/s) with what would typically be observed at that wind speed (e.g. tree leaves rustle and flags wave slightly at 2-3m/s). Appendix C shows the technical specifications of the Locally Manufactured Small Wind Turbines (LMSWTs) described in this thesis.

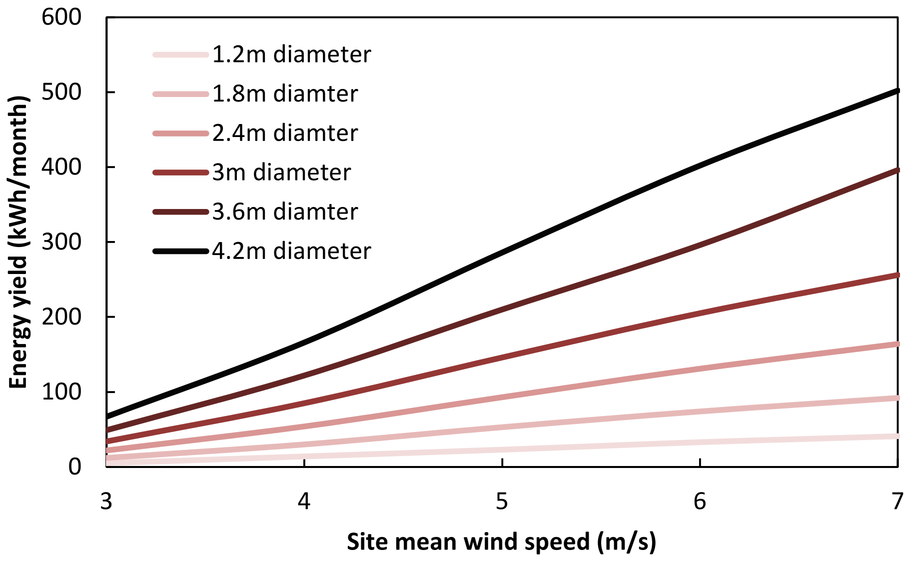

Figure 1-6: Estimated monthly energy yields for SWTs of up to 5m rotor diameter in varying wind conditions. Data source: Khennas et al. (2008).

1.3 Identifying the research problem: going beyond the technical

This research began as an optimisation of SWT blades that could be produced by hand in basic workshops in developing countries. However, during initial background research, a far more relevant research problem was identified. When asked if wind power is working for rural electrification, the original designer of much of the LMSWT technology in use around the world today, Hugh Piggott, replied:

> *"...the answer is no, it is not, but it could in the right context...it needs to be better established at a local level. The big problems are lack of understanding of the technology and also the long distances people have to travel to make repairs etc. It needs to be well supported and marketed, and understood at a local level."* (personal communication, 31st May 2011)

This pessimistic viewpoint was confirmed at the *Simposio Internacional de Energía Eólica de Pequeña Escala 2011*[6], with many practitioners confirming that they were also having significant difficulty keeping the SWTs they had installed in operation (Chiroque, 2011; Neves, 2011; Pinedo Lujan, 2011; Reyes, 2011). Despite investing hundreds of thousands of pounds in the development of their LMSWTs, Practical Action readily admit that they are unsure about the sustainability of the technology (personal communication, Steven Hunt, 15th April 2011) and as a result held a public debate on the subject at their '*Small is... Festival 2011*'[7]. In a recent study of the Kenyan small wind sector, where many locally produced machines are also employed, it was found that "*lack of government incentives and out-of-order turbines are the main factors that inhibit confidence in SWTs*" (Vanheule, 2012: 90). What is

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[6] *International Symposium for Small Scale Wind Energy*, Hotel Boulevard, Lima, Peru, 5th-9th December 2011.

[7] *Small is... Festival 2011*, The Schumacher Centre for Technology and Development, Rugby, UK, 2nd-4th September 2011.

more, blueEnergy, an organisation founded on the basis of providing energy access to impoverished communities on Nicaragua's Caribbean Coast with LMSWTs (Craig, 2007), took the decision to drop wind turbines all together from their rural electrification technology portfolio (Bennett *et al.*, 2011). Major factors in this decision included: corrosion from heavy rainfall, heat and high salinity; lighting strikes; hurricanes; difficulties in building and sustaining communal energy commissions; as well as preoccupation of the communities with more basic issues such as territorial disputes with neighbouring communities.

As a result, the author was faced with the dilemma of whether three years spent improving the efficiency of hand carved blades would be of any relevance if the machines to which they belonged were destined to spend the majority of their lives out of service. Surely even a 20% increase in aerodynamic efficiency becomes completely irrelevant if the blades don't even begin to spin?

Despite the widespread acknowledgement from the field that so many SWT-based rural electrification projects are unsustainable, there has been little academic work done to discover why. Many such studies have been conducted for both solar and micro-hydro based rural electrification initiatives and the findings have greatly improved the sustainability of such projects by providing constructive feedback to guide the development of the technology (Nieuwenhout *et al.*, 2001).

Sustainability in this sense refers not to the global environmental sustainability concerns surrounding carbon emissions that feature so heavily in the discourse surrounding renewable energy technologies, but instead focusses on the ability of the technology to provide the energy services required by the end-users. Technical issues such as corrosion, economic issues such as lack of access to capital to purchase spare parts or social issues such as the lack or technical knowledge to be able to perform repairs all affect this aspect of sustainability,

As a result, the research question was reformulated as follows:

- *Why are so many SWTs out of service and what can be done about it?*

To answer this question, Chapter 2 describes a theoretical framework that was developed to identify the factors that have led to the success or failure of SWTs in any particular local context and provide *'pathways for action'* (Practical Action, 2013: 41) for each specific case. This theoretical framework seeks to reframe SWTs in the context of rural electrification as a socio-technical system. By doing so, social issues such as access to technical knowledge with which to perform repairs are viewed with equal importance as technical issues such as the overheating of generators due to a poorly designed over-speed protection system. The socio-technical system can be seen as an assemblage of these issues that combine in different ways in each local context.

Chapter 3 describes the methodology adopted to build this theory: a multidisciplinary analysis of specific case studies of rural electrification initiatives employing SWTs. Chapters 4, 5 and 6 describe the case study evidence collected from Peru, Nicaragua and Scotland respectively. Chapter 7 cuts across these cases and uses the framework developed in Chapter 2 to determine the generic and place-specific factors that influence the sustainability of SWTs in the context of rural electrification. Chapter 8 pulls together the evidence and concludes the study by making recommendations for policy and further research.

1.3.1 Aim

To identify the factors that critically affect the sustainability of SWT rural electrification initiatives.

1.3.2 Objectives

- To identify the key factors that have affected the sustainability of SWT rural electrification initiatives.
- To determine how and why these factors vary between places.
- To establish the implications of these insights for intervention in support for SWT rural electrification initiatives.

Chapter 2. Small wind turbines as socio-technical systems

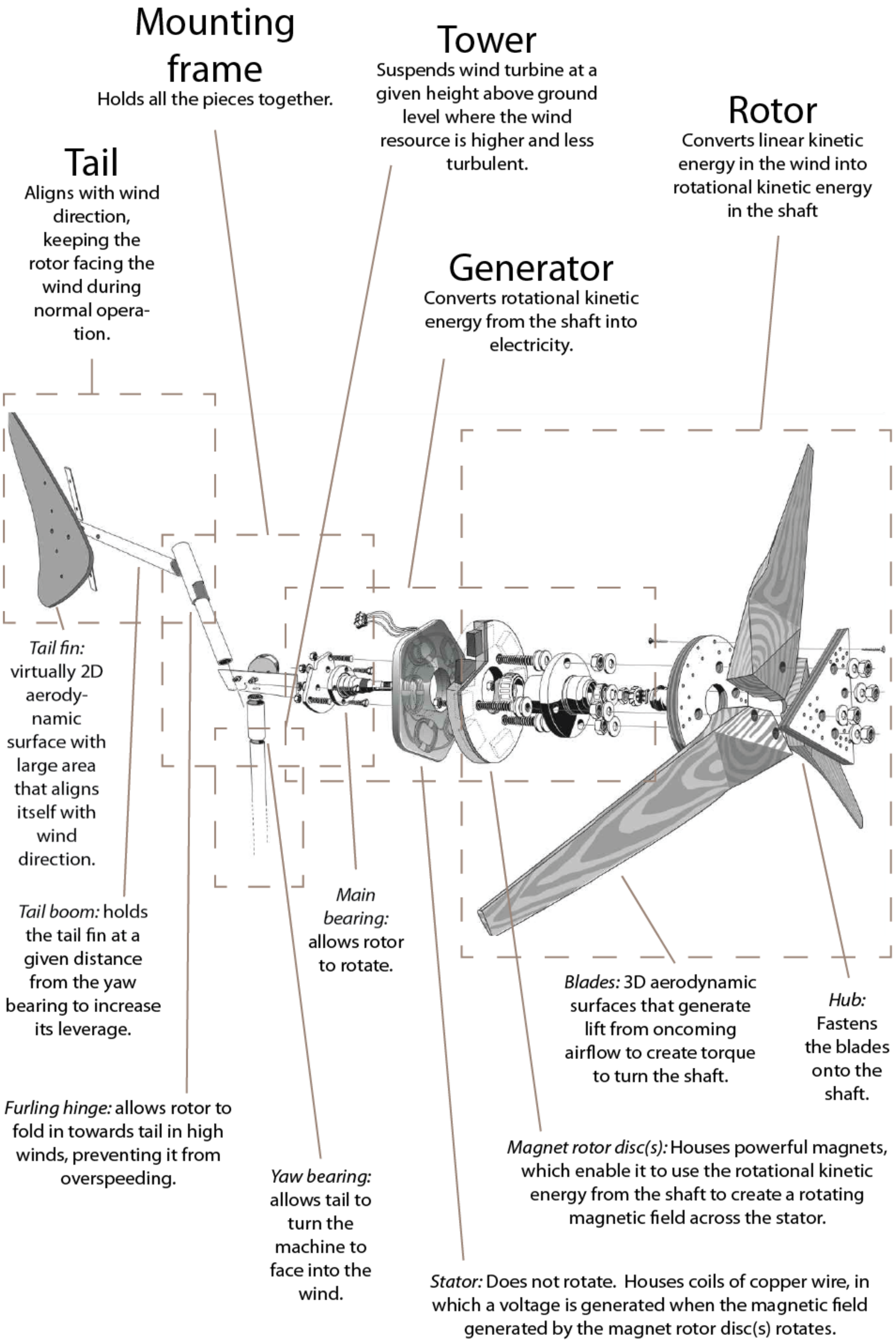


Figure 2-1: Exploded CAD illustration of an LMSWT identifying and classifying the key components and the interactions between them. Image adapted from Roland Beile/Tripalium.

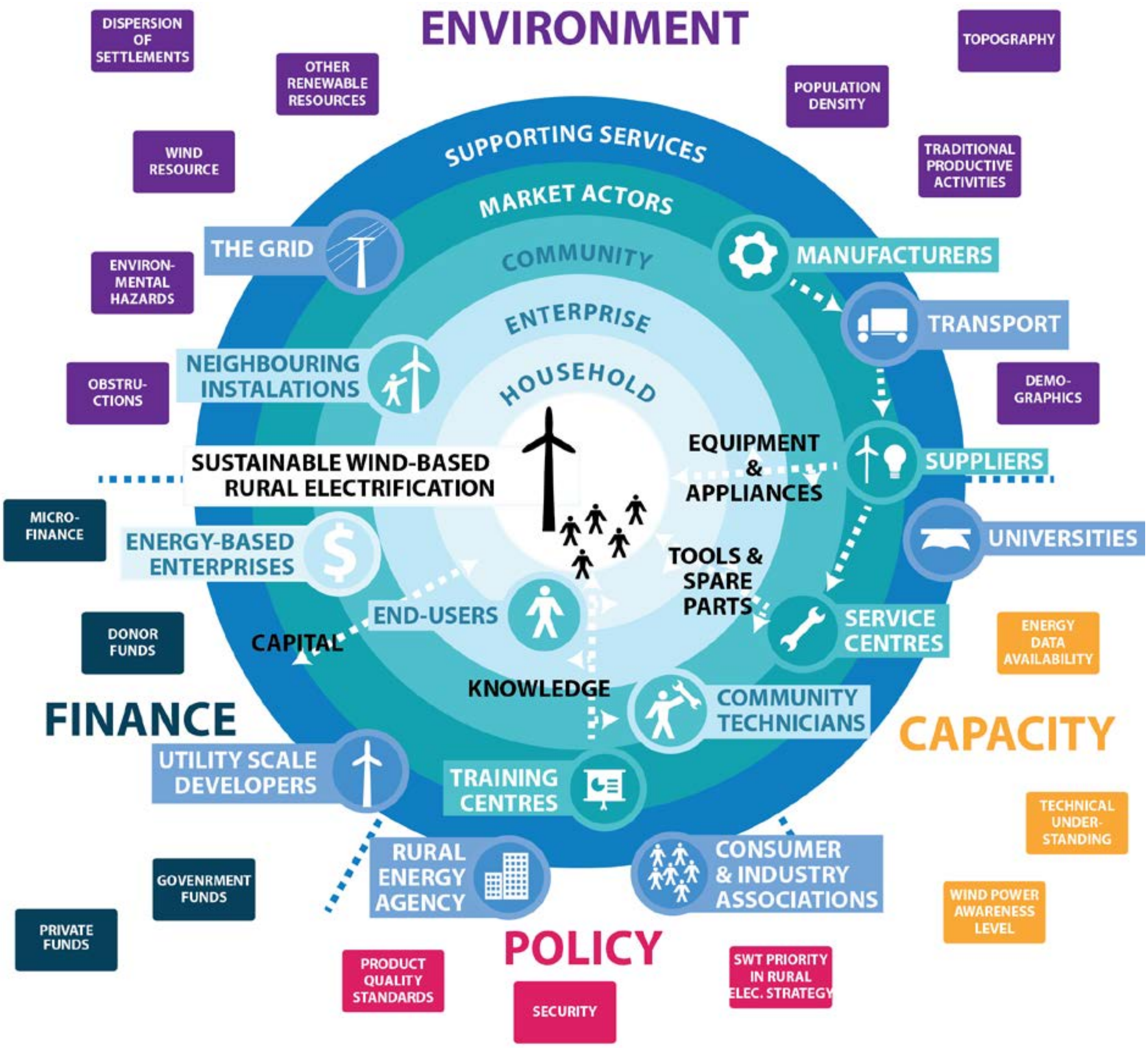


Figure 2-2: Graphical representation of the many elements that make up the socio-technical system in which SWTs exist and the various complex interactions between them. Adapted from (Practical Action, 2012).

2.1 Introduction

In this chapter, the concept of SWTs as socio-technical systems is introduced. As mentioned previously, this PhD research began as a search for an optimal solution to a technical problem, specifically the optimisation of SWT blades for manufacture by hand in developing countries. However, this reductionist approach neglects that fact that what may be optimal in one particular local context may be far from it in another. For example, does carving blades from wood make sense in locations where there are no trees, such as the plains of Inner Mongolia or the high peaks of the Peruvian Andes? If there are no trees, there is also likely to be a lack of carpentry skills with which to carve any wood that may be brought in from elsewhere. The appropriateness of wood as a construction material and consequently the optimisation of a set of blades can therefore be said to be governed by the interaction of the social and the technical. Separating the two is impossible and as a result, in order to understand one, the other must also be understood.

Many of SWTs studied during the course of this research have spent months out of service - sitting idle, awaiting spare parts, a trained technician with the right tools and/or funds to pay for the repair. Some have even spent longer out of service than in, however almost all experience some kind of failure during every year of their life. To discover why, it is therefore necessary to investigate not just the technical factors (such as blown rectifiers and burnt out stators), but instead to consider the entire socio-technical system that surrounds the technology in each particular place. By taking a socio-technical perspective, factors such as the inability of a community to raise funds for a replacement part and the lack of technical knowledge with which to perform repairs are seen as equally important as the technical factors mentioned above.

In this chapter, a theoretical framework is presented that was developed during the course of this research. The framework seeks to frame (or reframe) the 'problem' of SWTs in the context of rural electrification as a socio-technical system by emphasising the relationship between social systems (people) and wind turbine technology (engineering). It is presented at the beginning of the work to give structure to the evidence presented in each case study and guide the reader through the thesis by identifying the key components of the system and the most influential interactions between them. In much the same way that Figure 2-1 identifies the key technical components in an LMSWT, Figure 2-2 illustrates the key generic components in this socio-technical system (Practical Action, 2012). Throughout the course of this research, this generic system is used as a reference when discussing the socio-technical system in each case study, in order to decompose each system into its component parts and the interactions between them. This decomposition allows comparison between the socio-technical systems that exist in different places and the identification of the components/interactions that have been most influential in the success or failure of SWTs in each specific local context. It recognises SWTs as assemblages of the social and the technical that come together (and pull apart) in different ways in different local contexts. Precisely what matters in the assemblage – i.e. what brings it together, helps it stay together and prevents it falling apart – is a contingent matter that varies according to the technology employed and its positioning within wider social and institutional networks.

The framework is divided first into the technical and the social: the technological requirements of SWTs (what needs to be done in order for SWTs to function) and the role of people (who need to perform these functions). This leaves a space in between for the inseparably socio-technical flow of goods, knowledge and capital that is required in order for people to be able to perform these actions. Table 2-1 shows these divisions, which form the structure of this chapter and the analysis conducted in the subsequent chapters. Whilst it may be useful to divide the system up in this way, it is merely a tool designed to aid the discovery of what is important in each local context. As stated previously, it is not possible to completely separate the social from the technical, however this framework allows the grouping of ideas relating to the key technical processes, followed by those relating to the social, thereby facilitating an orderly discussion and providing a basis by which to compare between cases.

Table 2-1: Separating/combining the social and the technical.

Technical	*Socio-technical*	*Social*
What needs to be done?	What is needed to perform these actions?	Who needs to do it?
Identifying the key roles in the socio-technical system.	Identifying the flow of goods, knowledge and capital necessary to make the system work.	Identifying the key actors in socio-technical system.

2.2 What needs to be done – identifying the key roles in SWT-based electrification

Figure 2-3 shows the eight key processes in the technology lifecycle of a SWT. Manufacture, site selection and system design can all occur in parallel to prepare for an installation. After which, a SWT must be operated and maintained and at some point in the future, upgraded. Feedback should be collected from previous installations and used to direct research. Although in practice, this stage is often neglected, the creation of this feedback loop is essential for the improvement of SWT technology that continually evolves to meet the needs of the end-users in each particular place

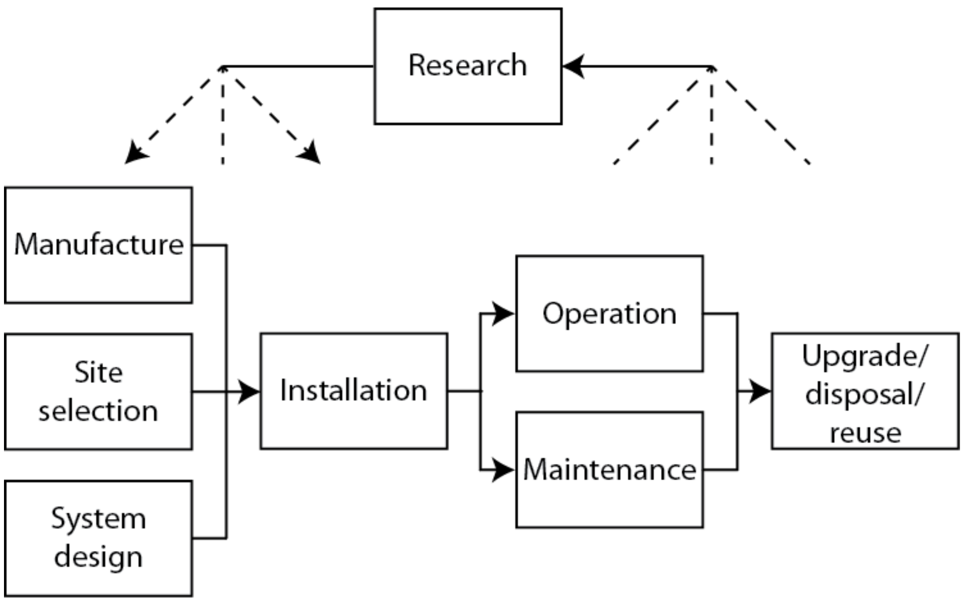


Figure 2-3: The stages of the technology lifecycle, which designate the key roles in SWT-based rural electrification.

2.2.1 Manufacture

Whilst solar PV may have many advantages over SWTs in the field of rural electrification (modularity, simplicity, reliability, a good geographical correlation of resource availability with those living without access to electricity, etc.), the option of local manufacture is simply not available. As a result, Cross (2012: 1) describes how the end-users of the first solar rural electrification projects back in the 1960s and '70s (see Figure 2-4a) were seen as:

> *"…passive beneficiaries whose identity, knowledge and practices were deemed irrelevant…unable to physically interact with or manage the solar array and…entirely dependent on the intervention of specialist engineers should something go wrong."*

Much has changed in the field of solar powered rural electrification since then, with products such as the solar lantern and solar home system (Nieuwenhout *et al.*, 2001; Gurung *et al.*, 2012) that have been designed specifically for people living on less than $2 per day now available and the establishment of bottom-up initiatives such as the Barefooot College (Bhowmick, 2011), which trains illiterate women to assemble solar home systems (see Figure 2-4b), However, the fact remains that the solar panel itself is essentially a 'black box' technology: they can only be manufactured in clean rooms, increasing the dependence of developing countries on foreign imports and entrenching the role of the end-users as *"passive beneficiaries"* (Cross, 2012: 1).

Figure 2-4: a) The first solar PV rural electrification project in Mali (Cross, 2012) and b) Kamla Devi, the first woman to graduate from the Barefoot College in Rajasthan, India, as a solar engineer (Bhowmick, 2011).

It is widely acknowledged that SWTs are much less reliable than solar PV (Chiroque, 2011; Neves, 2011; Marandin *et al.*, 2013) and as a result, many previous rural electrification initiatives that have imported SWT technology from abroad have not been successful due to high uprfront capital costs and a lack of techinical knowledge, tools and spare parts with which to perform repairs (Khennas *et al.*, 2008). One of the biggest decisions to be made after choosing wind power is whether to import a wind turbine or whether to manufacture one locally. In this thesis, the terms '*imported*', '*mass-produced*' and '*commercial*' SWT are used interchangeably to refer to a machine produced in a high-tech factory and sold on the international market. As such manufacturing facilities are usually not available in developing countries; there is normally a choice between importing such technology and starting to manufacture it locally. The implications of choosing either of these two options are investigated throughout the course of this thesis.

Khennas *et al.* (2008) state that manufacturing SWTs locally not only has the potential to boost the local economy and build local capacity, but it can also help create a resilient energy system through the creation of a strong supply chain for spare parts (accompanied by trained local tradesmen to perform repairs). In addition, by involving community members in the construction and installation phases, local manufacture can increase the likelihood of successful knowledge transfer to the end-users by transferring tacit, as well as theoretical knowledge. This technical knowledge is necessary to make productive use of the energy, to ensure reliable operation through the carrying out of proper Operation and Maintenance (O&M) procedures and enable upgrading of the system to meet future increases in demand (Ferrer-Martí *et al.*, 2010). However, the greatest advantage of local manufacture is often the flexibility to adapt the technology to the local context and provide an appropriate energy solution based on factors such as the local availability of skills and materials, the local wind regime and local energy demand.

Unfortunately, the risk with local manufacture is that lack of skills, knowledge and quality standards will result in the production of unreliable, low quality equipment that will fail to meet the expectations of the end user and undermine the reputation of the technology as a whole (Vanheule, 2012). The lack of availability of raw and reclaimed materials of a consistent quality (and quantity) can also significantly weaken the supply chain and hinder both manufacturing and maintenance operations (Ghimire *et al.*, 2010).

2.2.1.1 The manufacturing process

Piggott's (2013) *A Wind Turbine Recipe Book* gives a step by step guide for manufacturing a range of SWTs from 1.2-4.2m rotor diameter using only basic tools, techniques and materials. Figure 2-5 shows the carving of blades from planks of wood and the grinding and welding of a tail and mounting frame from standard lengths of steel using Piggott's (2013) open source design in a basic workshop in Mozambique. The main bearing is from the wheel of a scrap car and much of the steelwork can be made using reclaimed pieces of metal. A specially designed Axial Flux Permanent Magnet (AFPM) generator is built to match the blades by casting powerful neodymium (NdFeB) magnets onto steel rotor discs using resin, which is also used to set specially wound copper coils into a stator. The AFPM generator topology is particularly simple to manufacture due to the fact that it uses only planar components and is ideal for wind power as it can be specifically designed for low speed operation. Piggott designed the machines to provide power for his home community of Scoraig in Scotland and over the last 30 years, he has continually refined the design to improve reliability, lower costs and create a machine that is well respected across the globe for its durability, simplicity & adaptability (Leary *et al.*, 2012). Figure 2-1 describes each of the key components in an LMSWT and shows how they fit together, whilst Appendix B lists the manufacturing techniques adopted by each manufacturer studied during this thesis, along with other key variables with which to make technological comparisons.

Figure 2-5: Manufacture of a SWT using simple tools and techniques in Mozambique. Photo courtesy of The Clean Energy Initiative.

2.2.2 Site selection

Selecting a site for a SWT is a balancing act between: selecting the site with the best wind resource to maximise energy yield; selecting the site with best potential for anchoring; and selecting the site closest to the end-user to minimise power cable length. The most difficult part is assessing the resource, as the wind is exceptionally variable. Its extreme variability in both the time and spatial domains make the wind resource one of the most difficult to estimate. In the time domain, there are gusts acting over seconds, calm periods lasting for days, seasonal patterns across the year and climatic influences leading to inter-annual variation. In the spatial domain, trees cause very localised shelter effects, gentle hills can funnel the wind smoothly around them and continental land masses slow down the winds that whip across the ocean. Consequently, assessing the wind resource is not easy, but is of vital importance as the power available is proportional to the cube of the wind speed, meaning that a doubling of the wind speed yields an eight-fold increase in power:

$$P = {}^{1}/_{2}\,\rho A V^{3} \tag{2}$$

P = wind power (W)

ρ = density of air (kg/m^3)

A = swept area of wind energy conversion device (m^2)

V = wind velocity (m/s)

An accurate assessment of the wind resource at each proposed site is much more difficult, as local micro-climates and shelter effects both affect the wind resource more and are harder to predict than for the solar resource. Yet an accurate resource assessment is much more important for SWTs than for solar (where the power produced is linearly proportional to the resource), as even a relatively small difference in the average wind speed at a given site can make the difference between a viable and unviable project (see Figure 1-6).

Whilst a reasonably accurate resource assessment for solar PV can be conducted by simply accessing an online database of atmospheric conditions (NASA, 2013), doing so for SWTs is simply not possible for anywhere other than flat regions with little vegetation. National and even regional wind maps, such as the extract from the Peruvian wind atlas (MEM, 2008) shown in Figure 4-5 are also often available and offer much higher resolution than the global wind map in Figure 1-3. However, they must be used with caution as wind maps are produced by measuring the wind speed at specific locations using an anemometer, wind vane and datalogger, and joining up the dots by inter- and extrapolating with computer modelling. If the quality of the computer model is poor, the measurements are inaccurate, or there aren't enough of them then the resulting wind map will be wrong (Marandin *et al.*, 2013). A visual inspection of the site and collection of anecdotal evidence from local people can give an indication of a good site; however the only way to accurately measure the wind resource is with an the equipment shown in Figure 2-6 (Gipe, 2004). The highly variable nature of the wind resource means that the instrumentation must be mounted as close to the potential site of the turbine as possible, i.e. on a mast to raise the sensors up to the planned hub height. The equipment required and the other associated costs for the wind resource assessment conducted in the community of Cuajinicuil in Nicaragua totalled $1,712[8] (see Appendix F).

Figure 2-6: The Power Predictor (Better Generation, 2013).

2.2.3 System design

Occurring in parallel with site selection as an iterative process, system design involves selecting the optimal configuration of power generation, storage and distribution equipment to convert the energy resources available in a particular place into sufficient electricity to meet end-user demand for energy services. Due to the difficulty in predicting the wind resource, designing an energy system with a SWT requires a high level of technical knowledge. The most relevant issues are:

- How viable are other renewable resources in that particular place? Hybrid systems can greatly reduce the lifecycle costs of a renewable energy system (Lew *et al.*, 1997).
- How does the spatial distribution of demand points (houses, schools etc.) match up with the spatial distribution of renewable resources in that particular place? If there is only one windy point and the buildings are close together then a mini-grid is a viable option, however if there are many windy places and the buildings are dispersed, then individual SWTs are the only option if wind is the only power source (Ferrer-Martí *et al.*, 2011).
- How big should the system be? Demand must first be quantified so that it can be matched with the available renewable resources via the currently available technological options. In Inner Mongolia (see section 2.6), household demand for lighting, television and radio was estimated at 130kWh/year. As there were few suitable streams for hydro power generation and at the time, PV technology was not sufficiently developed, SWTs of around 1.5m diameter were found to be the most appropriate choice to meet this demand.
- When is the power needed? The irrigation system in the Nicaraguan community of Cuajinicuil (see section 5.2.2) was only designed to be used in the rainy season, whilst domestic lights were to be used all year round.

[8] However this could be reduced to $1,017 per site if the equipment could be reused for a total of 10 resource assessments.

2.2.4 Installation

Transporting the components to the installation site is often very challenging, as many components are bulky and/or heavy. Towers are usually designed to be dismantled into roughly 6m lengths and the tail and individual blades detach from the generator (Piggott, 2013). However the logistics of transporting these components is still challenging, especially as they must often be carried by hand for long distances over difficult terrain. After arriving on site, the base of the tower, four guy anchors and a lifting anchor must then to be secured to the ground (see Figure 2-7). On rocky ground, these points can be bolted to the rock; otherwise an anchor/base must be created using concrete or '*deadmen*' (heavy items buried in the ground).

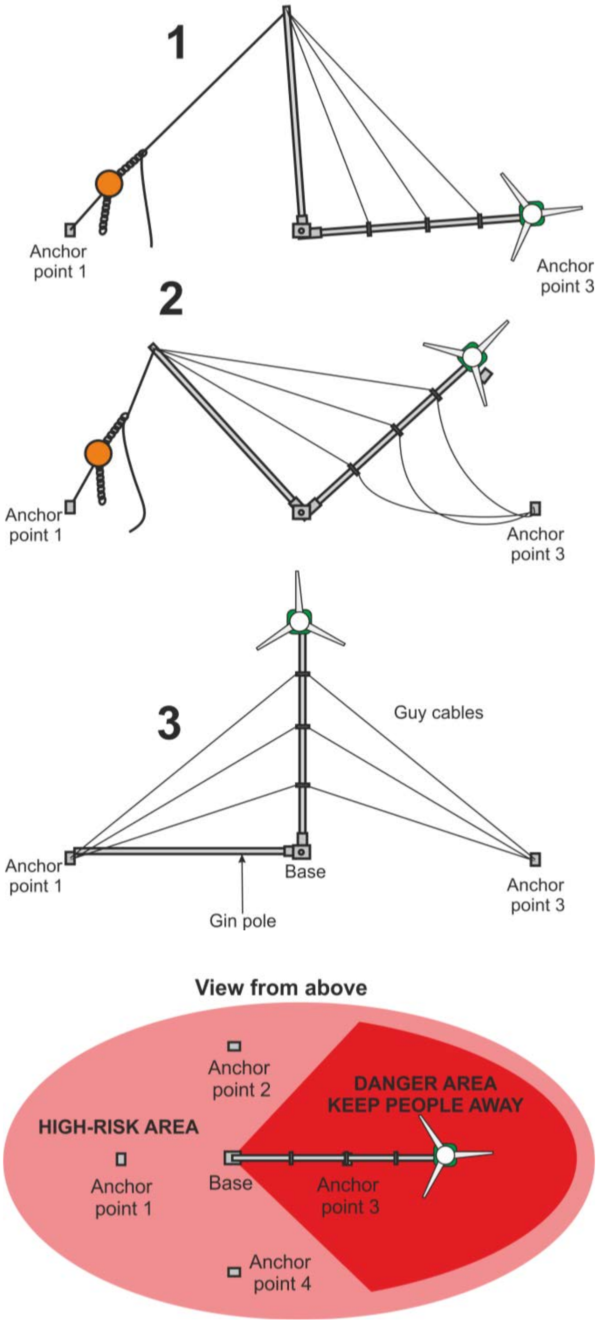


Figure 2-7: Procedure for raising/lowering a SWT on a tilt-up tower (Little and Corbyn, 2008).

Figure 2-8 shows the layout of a typical off-grid wind turbine electrical system. The power cable running from the base of the tower to the battery bank will usually run underground, so a thin trench must be dug from the turbine to the powerhouse. The wind turbine will require a charge controller capable of operating in diversion load control mode to automatic balance power generation with consumption[9] and an electrical brake switch which shorts the power cables and allows the user to manually stop the turbine for raising/lowering the tower (before hurricanes or when a fault has occurred). Finally, the turbine can be assembled and placed on top of the tower, which can then be raised using the procedure shown in Figure 2-7.

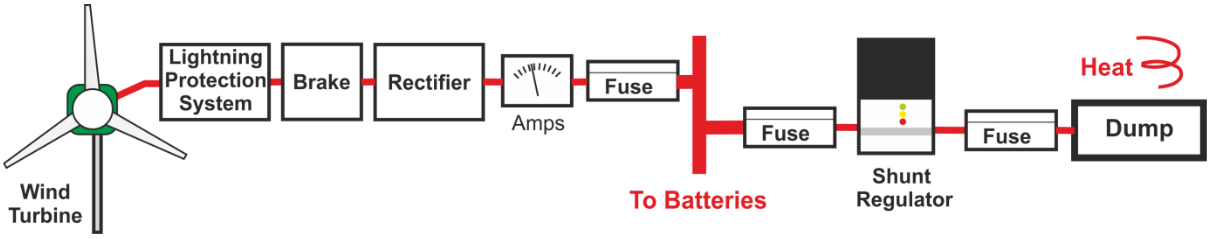


Figure 2-8: Layout of the specific components relating to the wind power component of a typical off-grid power system (Little and Corbyn, 2008). A full system diagram can be found in Appendix D.

2.2.5 Operation

Both condition monitoring and preventative maintenance (see subsequent section) are widely used by wind energy utilities due to their ability to "*reduce maintenance costs and breakdown frequency, increase machine life and productivity, and reduce spare parts inventories*" (US DoE, 2011: 19). Whilst condition monitoring of MW-scale wind turbines generally involves high-tech sensors feeding data into an automated control system, such systems are simply too expensive and too complex for most SWTs, let alone LMSWTs. However, a SWT often has somebody nearby to 'keep an eye' on the machine and protect it from the most dangerous environmental conditions. A daily check-up to verify if the machine is following the wind, whether it is making any rubbing sounds, etc. can flag up any minor problems and allow appropriate action to be taken before a minor problem turns into a major failure. Such a check-up merely consists of watching and listening to the turbine for a few seconds, however the frequency with which these check-ups are conducted depends primarily on the location of the turbine. SWTs situated out the front of a household are likely to have the most frequent check-ups as the users will pass the turbine every time they leave/enter their home. Lightning and extreme winds can both cause serious damage to a SWT, however applying the brake switch or lowering the tower in time can protect the machine (see Table 2-2). The likelihood of either of these environmental hazards affecting any particular system is geographically dependant – for example the 30-40 SWTs installed on the Scoraig peninsula on the Northwest coast of Scotland (Chapter 6) have never been directly struck by lightning in the last 30 years, whilst the single SWT installed in the community of Monkey Point on

[9] When the batteries are full, the turbine must not be left to run free because it would reach dangerously high rotational speeds due to the fact that the energy it is accumulating from the wind has nowhere else to go.

the Caribbean coast of Nicaragua (Chapter 5) has been struck by lightning multiple times in the few years since its installation (see Figure 5-20 for more details).

Table 2-2: Requirements for successful operation of a SWT.

Task	*Description*	*Frequency*	*Time commitment*	*Expertise*	*Tools & consum-ables*
Visual/audial inspection	Watching & listening to the turbine in operation	Daily	<1 minute	Well trained end-user or community technician	None
Protection from extreme winds	Lowering the tower before extreme winds to protect the system	Hurricanes /typhoons/ cyclones	<1 minute to apply brake, 4 hours to lower tower[10]	Well trained end-user or community technician (+10 strong people)[10]	Rope winch/ pulley & rope if lowering
Lightning protection	Apply brake during lightning storms to electrically disconnect turbine from electronics	Lightning storms	<1 minute	Well trained end-user or community technician	None

2.2.6 Maintenance

Wind turbines are notoriously unreliable and Piggott (2013) warns builders of his machines to expect two problems in the first year and one per year thereafter. Maintenance can be divided into two key categories:

- *Preventative maintenance* – a regular maintenance routine significantly reduces the risk of failure and is essential if SWTs are to achieve their expected lifetime. The procedure detailed in Table 2-3 is specific to Piggott turbines, as each SWT will have its own recommended procedures as specified by its manufacturer.

Table 2-3: Preventative maintenance routine to ensure reliable operation of Piggott turbines

Task	*Description*	*Frequency*	*Time commitment*	*Expertise*	*Tools & consumables*
Battery service	Check battery health and top up electrolyte if necessary	Every 2 weeks	10 mins	Well trained end-user or community technician	Multimeter, hydrometer, deionised water
Wind turbine service	Lower tower, inspect turbine & repaint blades/tighten	Every 6-12 months	2 days[10]	Community technician (+10 strong people)[10]	Spanners, screwdrivers, paintbrush, paint, grease,

[10] Based on 4.2m Piggott turbine without rope winch, i.e. using 10 strong people to raise and lower tower using pulleys. The estimate of 4 hours includes the time taken to assemble this many people and coordinate them to lower the tower together.

Task	Description	Frequency	Time commitment	Expertise	Tools & consumables
	bolts/grease bearings etc. as required				rope winch/pulley & rope

- *Corrective maintenance* – even with the most stringent preventative maintenance regime, it is only a matter of time before a failure occurs. Table 2-4 lists the failures that present the highest levels of risk. Although this is specific to Piggott turbines, many of the failures (e.g. blade failure or generator seizing up) are common to all SWTs. Corrective maintenance is classified into advanced and basic, to distinguish what can/cannot reasonably be carried out by a community technician. In general, it is expected that basic corrective maintenance can be carried out by a well-trained community technician, whilst advanced corrective maintenance will require a site visit by an engineer (or for the community technician to disassemble the failed component and send it back to the manufacturer for repair or replacement).

Table 2-4: Common failures of Piggott turbines and their consequences.

Failure	Probable cause	Safety risk	Likelihood[11]	Repair	Spare parts	Tools & consumables[12]
			BASIC CORRECTIVE MAINTENANCE			
Worn bearing	Bearing reaches end of life	None	Medium	Replace bearing[13]	New bearing	Screwdriv-ers, span-ners, jacking screws[14], rope winch/pulley & rope
Pendant cable twisting	Excessive yawing on turbulent sites	None – turbine stuck facing one direction only	High	Untwist cable & repair broken section (if necessary)	None (except in extreme cases)	Wire strip-pers, electri-cal connect-er, electrical tape
Blown rectifier	Overspeed protection system jamming	Small fire risk	Medium	Replace rectifier	New rectifier	Screwdrivers

[11] High probability = likely to occur within the lifetime of each LMSWT.
Medium probability = may occur during the lifetime of some turbines.
Low probability = unlikely to occur.

[12] To install spare part, not to manufacture new spare part.

[13] Unless bearing has become so loose that friction between the stator and rotor has also caused these parts to fail.

[14] Short lengths of threaded bar designed to raise and lower the magnet rotor discs.

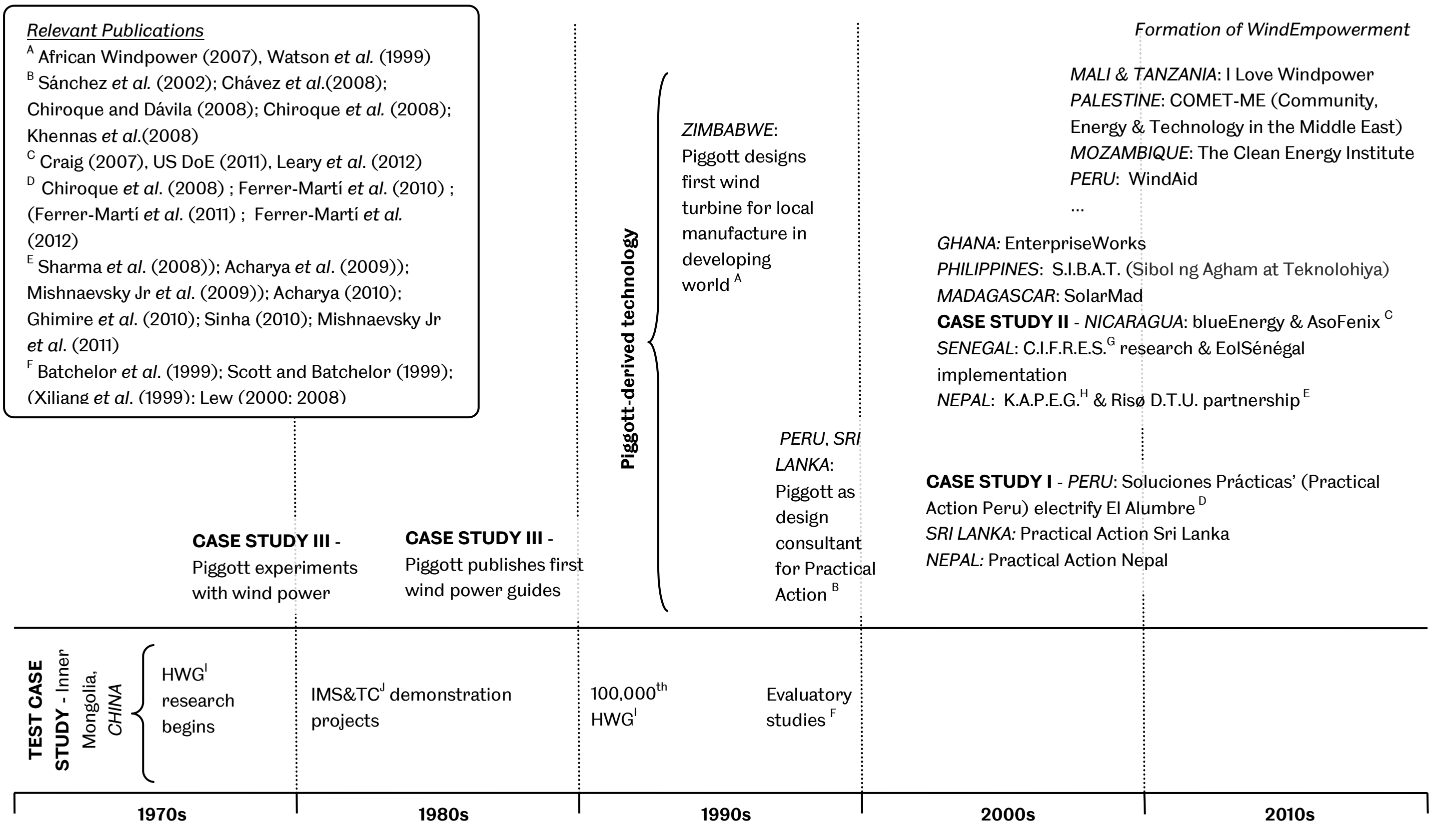
Failure	*Probable cause*	*Safety risk*	*Likelihood*[11]	*Repair*	*Spare parts*	*Tools & consumables*[12]
			ADVANCED CORRECTIVE MAINTENANCE			
Blade failure	Blade hitting tower, blade mounting failure	Flying blade fragments	Medium	Replace or repair blade/s	New set of blades	Screwdriv-ers, span-ners, rope winch/pulley & rope
Tower collapse	Guy rope failure	Falling tower & turbine	Low	Replace or repair broken components	Typically 1 or 2 new blades & a new tower section	As required for installa-tion
Generator seizing up	Magnets corroding & swelling up	None	High	Replacement of magnets	New rotor disc/s (and stator in severe cases)	Screwdriv-ers, span-ners, jacking screws, rope winch/pulley & rope
Burnt out generator	Overspeed protection system jamming	Small fire risk	Medium	Replacement or repair of stator	New stator (and often also rotor discs)	Screwdriv-ers, span-ners, jacking screws, rope winch/pulley & rope
Lightning strike	Lightning storm	Fire	Dependent on location – see Figure 5-20	Replacement of stator/electr onics	Stator/electr onics	Screwdriv-ers, span-ners, jacking screws, rope winch/pulley & rope

2.2.7 Upgrade/disposal/reuse

Demand for electricity often grows rapidly in the years following electrification: new appliances are added to domestic systems, new businesses are established (such as mobile phone charging or workshops with power tools) and new buildings are connected (Ferrer-Martí *et al.*, 2010). The implications of this changing demand are that any proposed energy system must be flexible enough to supply the required quantity of energy in the place where the end-user needs it and at the time that the need it. The addition of new power generation capacity requires in-depth technical knowledge of the entire system, as a suitable site must be selected for the new power generation equipment and the installation may also require the upgrading of other components, such as fuses, charge controllers or the battery bank. Eventually, the equipment will reach the end of its life and will need to be disposed of in a responsible manner, or better: reused.

2.2.8 Research

Research is required first and foremost to develop SWT technology. Piggott's (2013) open-source design for a 3-bladed horizontal axis rotor coupled to an axial flux generator can be built to low tolerances in basic workshops from widely available reclaimed and low-cost materials, yet when looked after carefully, each machine is capable of providing electricity for up to 15 years in harsh, remote environments, such as the Scoraig peninsula (see Chapter 6). Piggott has over 30 years' experience designing, manufacturing, installing, operating and maintaining SWTs and is recognised as a "*trusted independent expert*" by the commercial small wind industry (Sharman, 2009: 41). However the potential of the design is greatly increased by its open-source nature, which enables it to draw on the global pool of expertise, from hobbyists to Non-governmental Organisations (NGOs) to universities (Wind Empowerment, 2013). de Laet and Mol (2000: 251) describe how the success of the Zimbabwe Bush Pump can largely be attributed to its "*fluidity*" - how easily it is adapted to suit the task at hand. It is precisely this "*fluidity*" that has also made the Piggott turbine so successful. Not only can anybody anywhere start from Piggott's basic design and adapt it to their local context (see Figure 2-9), but any successful generic design modifications they may make can then be fed back into the open-source design, thus ensuring its continual development (see Figure 2-10). As a result, the Piggott turbine has become the basis for the majority of recent wind-based rural electrification initiatives that employ locally manufactured technology. This is in contrast to the development of similar technology in Inner Mongolia that occurred in parallel (also shown in Figure 2-9) and will be discussed later on in this chapter.



[G]Centre International de Formation et de Recherche en Energie Solaire, l'Ecole Supérieure Polytechnique de Dakar
[H]Kathmandu Alternative Power and Energy Group
[I]Household Wind Generator
[J]Inner Mongolia Science & Technology Commission

Figure 2-9 – Timeline showing the separate developmental pathways of open-source Piggott derived technology and that of the IMS&TC in Inner Mongolia, China.

Continued research is essential to ensure that the technology continues to evolve. For example, changes in the prices and availability of construction materials (for example the recent volatility in the price of rare earth metals have led many to reconsider the use of neodymium magnets in their AFPM generators in favour of the cheaper, but less powerful ferrite equivalent), the development of new technological options (such as Maximum Power Point Tracking, MPPT) and end-user experiences all need to be fed back into the continuingly evolving design. Social and economic research into delivery models and financing mechanisms are equally essential in ensuring that the technology can reach its full potential.

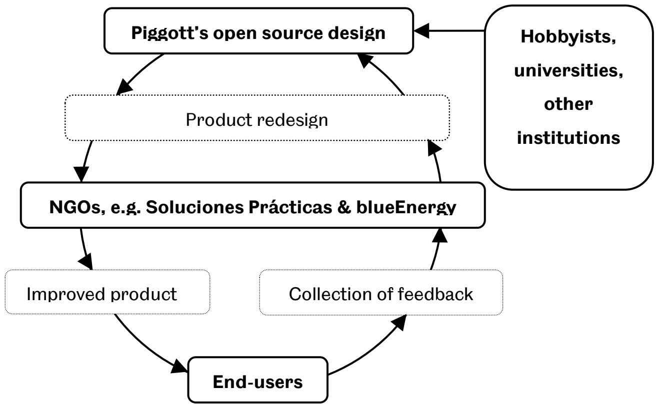


Figure 2-10: The feedback cycle that ensures the continual evolution of Piggott's (2013)open source design.

2.3 Ecosystems and socio-technical systems

In the world of business, management theorists have been comparing markets to natural ecosystems for many years (Iansiti and Levien, 2004). In both natural and business ecosystems, *"co-evolution and collaboration, as well as competition"* are recognised as the drivers of healthy ecosystems (Practical Action, 2013: 41). In the Poor People's Energy Outlook, Practical Action (2012: 71) defined the concept of an energy access ecosystem *"to describe the system conditions which could enable rapid growth in access to the range of energy services"* outlined in their minimum basic standards. The energy access ecosystem analogy identifies the influence of the enabling environment on the dissemination of energy access technologies by identifying a range of factors that can shape market conditions in a particular local context in favour of the market actors and supporting services capable of delivering access to energy. The aim of the framework is to identify "*pathways for action"* (Practical Action, 2013: 41) that can promote rapid growth in the dissemination of technologies required to provide access to energy services. In this thesis, this technology-independent theoretical framework is applied to SWTs, with the goal of identifying the critical factors that influence the long-term success or failure of SWT-based rural electrification in various local contexts.

The aim of this research is not to show that one approach to rural electrification with SWTs is right or wrong, but to determine which approaches can be more or less effective in specific local contexts. Just as the same species can perform different roles depending on the environment it is born into and the other species that also inhabit that particular environment, the roles of each actor in an energy access ecosystem are slightly different in each local context. It is the combination of actors that work well together and are appropriate for a specific local context that create a strong ecosystem and are likely to be successful. This research aims to isolate the generic and place-specific components of these systems with the hope that they can then be applied in other local contexts to identify areas where SWTs are an appropriate technology for rural electrification and to determine the most effective "*pathways for action"* in such places.

The technical processes required to develop, create and maintain SWTs have been described in the previous section (2.2). Next the flow of capital, knowledge and goods that these processes require are discussed and finally, the species within the ecosystem (the actors that make it all happen) are described.

2.4 What is needed to perform these actions?

In a healthy SWT ecosystem, the flow of capital, tools, construction materials/spare parts, equipment/appliances and technical knowledge supports the *'creation and regeneration of the system'* (Practical Action, 2013: 41), facilitating the construction and maintenance of SWT-based energy systems by the various actors using the aforementioned technical processes.

2.4.1 Equipment & appliances

Energy is a derived demand: it is not the wind turbine itself that people want, nor even the energy it produces, but the energy services that it is capable of providing them with (Practical Action, 2010). A total system package from turbine to appliances should therefore be offered, creating an appropriate energy system to deliver the required energy services to the end user. A holistic view of system design is necessary; one that takes into account the local availability of power generation equipment and appliances. If the required components are not available locally, new supply chains must be created; however the additional costs of doing so (not just for the initial installation, but also for spare parts and future upgrades) must be properly evaluated.

The availability of power generation equipment and appliances often dictates the design of off-grid electrical systems. For example, in terms of appliances, 120-240V AC are the most widely available as this is the mains electrical standard. However, in off-grid systems, running DC appliances straight from the battery is more efficient and more cost effective, as the need for an inverter is eliminated. The limiting factor is usually the availability of DC appliances, some of which can be available locally from car scrapyards (cars run on 12V DC), whilst specially manufactured 12V DC lights must usually be imported. In fact, higher voltage systems (24V & 48V DC) are more efficient for larger systems (SWTs above 2m diameter), however DC appliances that operate at these voltages are almost impossible to acquire and the choice of inverters and other electrical system components also becomes restricted.

2.4.2 Construction materials and spare parts

Construction materials are required for the manufacture, installation and maintenance of SWTs[15]. Most of the materials required to build a Piggott turbine (plywood, lengths of steel, planks of wood, etc.) are readily available in markets/hardware stores in most reasonably sized towns in most parts of the world. However, the most troublesome materials to acquire are usually:

[15] Piggott (2013) gives full details of the tools and construction material needed to manufacture a range of LMSWTs.

- Permanent magnets - usually rare earth neodymium (NdFeB), which is almost exclusively produced in China (Bradsher, 2009);
- Reclaimed car wheel bearings – only specific makes and models of car are suitable (Piggott, 2013);
- Steel rotor discs – discs of the correct diameter and thickness normally have to be cut to order using specialist machinery (Piggott, 2013);
- Enamelled copper wire – specific dimensions are required (Piggott, 2013);
- Plywood – must be of sufficient quality for resin casting (Piggott, 2013);
- Tirfor – rope winch required to raise and lower the tilt-up tower (Piggott, 2013).

For corrective maintenance, pre-manufactured spare parts are required (although in some cases if tools and technical knowledge are available, construction materials can be used to manufacture a spare part on site). The supply chain for these spare parts has a huge effect on the resilience of a particular SWT installation (the time it takes for a failure to be repaired); a specialist part that must be sent from overseas can take months to arrive, whilst carving a new set of blades from planks of wood can be done in just a few days if the wood can be sourced locally. The case study work described later in this thesis has shown that stock of spare parts kept locally (in the community or at a service centre) can shorten this supply chain and greatly improve resilience.

2.4.3 Tools

Tools are essential for manufacture, installation, operation, maintenance and upgrading. Piggott turbines are designed to be able to be manufactured using only basic tools[15], such as a chisel, saw, an arc welder, a drill press and an angle grinder. Many of the specialist tools required to manufacture a Piggott turbine can be built using standard hand tools, for example the plywood mould for stator/rotor casting. In addition to the tools required for manufacture, the following tools are required for installation:

- A spade for digging foundations/burying the power cable;
- A rope winch/pulley and rope for raising/lowering the tower;
- A rock drill (if using rocks for anchors).

As a bare minimum with which to be able to operate and perform both preventative and basic corrective maintenance, the following tools are necessary:

- Spanners (for adjusting guy ropes and generator);
- Screwdrivers (for removing blades and adjusting electrical components);
- Multimeter (for testing electrical components);
- Sandpaper, paintbrush & paint (for repainting blades and corroded metal parts);
- Grease (for lubricating bearings);
- Deionised water (to top up battery electrolyte);
- Electrical tape (for insulating electrical connections);

- Rope winch/pulley and rope (for lowering the tower).

A complete list of the tools required to operate and maintain the PV-wind hybrid system in the rural Nicaraguan community of Cuajinicuil and their associated costs is given in Appendix E.

2.4.4 Technical knowledge

Different forms and levels of technical knowledge are required for each of the processes identified in Figure 2-3:

- *Research* – research capacity and theoretical knowledge of renewable energy systems with specific expertise in wind power and rural electrification.
- *Manufacture* – knowledge of basic manufacturing techniques (with the aid of Piggott's (2013) open-source construction manual).
- *Site selection* – theoretical knowledge of renewable energy systems coupled with a practical understanding of system layouts and site conditions.
- *System design* – theoretical knowledge of renewable energy systems and the cost/availability of specific components in a particular place.
- *Installation* – theoretical knowledge of renewable energy systems and practical knowledge of civil and electrical engineering.
- *Operation* – a practical understanding of the basic operating principles of renewable energy systems.
- *Maintenance*
    - Preventative and basic corrective maintenance: a practical understanding and basic theoretical knowledge of renewable energy systems.
    - Advanced corrective maintenance: similar to installation and system design.
- *Upgrade* – similar to installation and system design.

2.4.5 Capital

The flow of capital throughout the ecosystem facilitates each of its key processes:

- *Research* – to fund the design and testing of new ideas and the collection of data from the field.
- *Manufacture* – to establish a workshop to produce SWTs, to purchase tools, materials and labour.
- *Site selection* – to pay for expertise and measurement equipment.
- *System design* – to hire technical expertise.
- *Installation* – for labour, transportation, components and construction materials.
- *Operation* – in community systems, a salary is often paid to an operator who looks after the system on a day-to-day basis on behalf of the community

- *Maintenance* – to purchase replacement parts, tools, consumables and labour of the community technician
- *Upgrade* – similar to installation.

2.5 Who needs to do it – identifying the key actors in SWT-based electrification

The ecosystem processes Figure 2-3, together with the flows of goods, capital and knowledge that drive them have now been discussed, which leaves only the species within the ecosystem – the actors that make it all happen. Table 2-5, Table 2-6, Table 2-7 and Table 2-8 are intended to act as a guide to the reader to indicate where each of the contextual factors described in the following section are expected to have the most influence on each stage of the technology lifecycle described in Figure 2-3. Although these tables are based upon the case study evidence described later in this thesis, it was necessary to use a certain degree of subjective judgement in order to create them, as it simply was not possible to observe the impact of each particular factor at every single stage of the rural electrification process given the limited number of cases under study.

2.5.1 Enabling environment

The enabling environment encompasses wider contextual factors that can influence the viability of SWTs in a particular location. Practical Action's (2012) energy access ecosystem analogy categorised these contextual factors into the dimensions of finance, capacity and policy. However, Figure 2-2 shows the addition of environmental factors that are known to affect the viability of wind power in a particular local context.

Table 2-5: The areas of the technology lifecycle over which the enabling environment has the biggest influence.
X = Major influence, x = minor influence

	Research	*Manufacture*	*Site selection*	*System design*	*Installation*	*Operation*	*Maintenance*	*Upgrade*
Environment								
Population density			*X*	*X*	*X*	*X*	*X*	*x*
Wind resource	*x*	*x*	*X*	*X*				
Other renewable resources	*x*	*x*	*X*	*X*				
Environmental hazards	*x*	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Traditional productive activities			*X*	*X*	*X*			
Dispersion of settlements			*X*	*X*		*x*	*X*	
Obstructions			*X*	*x*				

	Research	*Manufacture*	*Site selection*	*System design*	*Installation*	*Operation*	*Maintenance*	*Upgrade*
Topography			X	x			x	
Demographics			X				X	
Finance								
End-user micro-finance					X	X	X	X
Donor funds	X	X	X	X	X			
Private funds		X	x	x	X	x	X	X
Government funds	X	X	X	X	X	x	x	x
Policy								
SWT priority in rural electrification strategy	X	X	X	x	X			
Security			X				X	
Product quality standards		X				X	X	
Capacity								
Energy data availability	X		X					
Wind power awareness level			X		X	x	x	
Technical understanding	X	X	X	X	X	X	X	X

2.5.1.1 Finance

As discussed above, the availability of funds is critical for every step in the process outlined in Figure 2-3. Government, donor and carbon funds are often used to fund research and pilot projects, whilst government and private funds are more critical for the scaling up of a proven technology with a viable delivery model (Practical Action, 2012). The most difficult issue regarding finance is how to provide access to capital at the community level, as a significant barrier to the uptake of renewable energy systems is the high upfront cost required to purchase the technology (Practical Action, 2012). Although LMSWTs may have lower upfront costs than solar PV, they require a different financing model that includes significant maintenance costs. Innovative financing models such as micro-finance (MicroEnergy International *et al.*, 2006) loans and pay-as-you-go schemes (Rolffs *et al.*, 2014) can reduce this barrier and energy-based enterprises can allow end-users to make the regular payments (Practical Action, 2012).

2.5.1.2 Environment

In particular, the case study work conducted in Nicaragua (Chapter 5) has shown that hazardous environmental conditions can frequently lead to failures in SWTs. Lightning strikes can destroy electrical systems and SWTs are huge conductors deliberately placed above their surroundings (lightning arrestors and operators that switch off the system during a storm can reduce damage, however neither is 100% effective). Hot, humid, coastal environments greatly increase corrosion (galvanising metal parts, greasing guy wires and replacing wooden parts with fibreglass can reduce corrosion, however they each add significantly to the cost of the system). Extreme winds such as tropical storms, typhoons, hurricanes and cyclones can easily tear down a SWT.

Of course, the wind resource is absolutely fundamental to the success of SWT electrification. Not only is a resource of sufficient magnitude required throughout the year, but areas of complex terrain significantly increase the complexity of assessing the resource and therefore add to the level of risk, as the potential energy yield at any particular site is very difficult to predict (Ferrer-Martí *et al.*, 2011). The case study work in Scotland (Chapter 6) has shown that low levels of wind resource at certain times of year can be mitigated by using hybrid systems if there are other renewable resources available that peak in that same season. Alternatively, in certain local contexts, the availability of the wind resource can be matched with traditional productive activities, for example if it is windy in the dry season, farming communities could use a wind power system to power a water pump for irrigation with the excess energy in this season, whilst domestic appliances such as lighting are powered all year round (e.g. section 5.2.2).

The dispersion of houses and the level of social cohesion within communities govern the choice between more economical micro-grids and more flexible individual household SWTs (Ferrer-Martí *et al.*, 2011). Whilst few off-grid technologies can compete economically with large scale centralised grid distribution of electricity (Figure 1-2), the case study work in Scotland (Chapter 6) has shown that in the right context, SWTs can provide electricity at a lower unit cost than small diesel/petrol generators. In some parts of the world (e.g. the Scoraig peninsula – Chapter 6), it is simply not possible to exploit hydro or solar resources throughout the year, meaning that SWTs become the only alternative to costly small scale diesel/petrol generation.

Identifying areas where suitable wind resources, favourable settlement patterns, lack of alternative renewable resources and low levels of environmental hazards all occur simultaneously is of critical importance, as all four have a vital role to play in deciding whether SWTs are the most appropriate technology for a particular region.

2.5.1.3 Capacity

The case study work in Nicaragua (Chapter 5) has highlighted the following factors relating to capacity at the national level as having a critical effect on the viability of SWTs in any particular country: the availability of energy data (such as the wind resource maps and the distribution of people without access to electricity); the level of technical capacity relating to SWTs amongst market actors and supporting services; and the general level of awareness of wind power and other renewable energy technologies.

2.5.1.4 Policy

The inclusion of decentralised, renewable and/or specifically wind-based rural electrification in national or regional policy can create very favourable conditions for the dissemination of SWTs, as illustrated by the case studies in Inner Mongolia (section 2.6) and Nicaragua (Chapter 5). For example, a reduction in import tax on wind energy system components, government subsidies for wind power systems or the adoption of national standards to ensure product quality. Conversely, if rural energy policy favours other technologies over wind, it may be very difficult to introduce the technology as the odds are already stacked against it (e.g. solar PV tax exemptions in Nicaragua illustrated by Figure 5-34). Practical Action (2012) state that the level of corruption/ease of doing business can also influence the ability to which all the other actors are able to function, however these factors are likely to affect all energy technologies equally. In contrast, the threat of theft is likely to have an more detrimental effect on technologies that are easy to dismantle, have a high resale value and/or must be located far from a residence.

2.5.2 Supporting services

Supporting services are existing institutions and infrastructure, whose presence can assist the development of SWT-based rural electrification in a particular location. Table 2-6 shows that these supporting services have most impact in the research that they conduct and the identification of windy areas. However, transportation infrastructure affects all operations that involve travel or delivery of goods.

Table 2-6: The areas of the technology lifecycle over which supporting services has the biggest influence.
X = Major influence, x = minor influence

	Research	*Manufacture*	*Site selection*	*System design*	*Installation*	*Operation*	*Maintenance*	*Upgrade*
Transportation		X	X		X		X	X
Consumer & industry associations	x		x					
Universities & research institutions	X		x					
Rural energy agency	x		X	x				
Utility-scale developers	X	X	X	X				
The grid	X	X					x	

2.5.2.1 Transportation

The existing transportation infrastructure in a particular place has a huge influence on the viability of SWTs. Obtaining construction materials, power generation equipment and appliances with which to build a wind power system is more difficult and more costly in areas with poor transportation links (Bennett *et al.*, 2011), however the case study work in Nicaragua (Chapter 5) has shown that the it is the level of access to the installation site itself that has the biggest impact on the viability of SWTs. Remote communities by their very definition are difficult to get to, however some journeys are exceptionally challenging. For example, a three hour off-road journey is challenging, however some communities may only be reached by an eight hour boat ride (e.g. Monkey Point in Nicaragua). This adds greatly to the transportation costs, as not only must a suitable vehicle be acquired and filled with fuel, but the engineer/technician who is making the journey must also be paid a wage and travel expenses for each day they are away (see section 5.3.4.2).

Many journeys must be made during the lifetime of a wind power system: to assess the wind resource during site selection; to carry the heavy components and construction materials during installation; and to bring spare parts for maintenance when things go wrong. The more arduous the journey, the more important it becomes to avoid it, else the costs of wind-based electrification will quickly spiral out of control. For this very reason, much of the work conducted by NGOs leads to ribbon developments radiating out from their base of operations down the corridors of accessibility created by the existing transportation infrastructure. Of course, this is in direct contrast to the needs of the most impoverished communities, as they are generally the most remote and such developments can cause them to fall even further behind.

2.5.2.2 Rural energy agency

The rural energy agency is the government department responsible for developing policies towards wind-based rural electrification. They may also be able to commission relevant research and play a role in identifying wind areas through the development of wind resource maps.

2.5.2.3 Consumer & industry associations

Consumer and industry associations can assist in identifying windy areas, directing research and sharing the knowledge gained through research. WindEmpowerment (2013) is an international association that provides a knowledge sharing forum for social, economic and technical issues relating to locally manufactured wind power technology for rural electrification. The membership currently consists of 39 organisations in 25 different countries (see Appendix G), as well as many independent participants. Piggott and the majority of the organisations featured in Figure 2-9 are founding members and have made a commitment to open information sharing with the goal of improving the sustainability of the technology based on the pooling of their collective knowledge and experience (Wind Empowerment, 2013). Similar associations at the national level (e.g. Renovables[16]) can also lobby their respective rural energy agencies for policy changes

[16] The Nicaraguan renewable energy association.

2.5.2.4 Universities & research institutions

Universities and research institutions can play a vital role in developing SWT technology, piloting innovative delivery models, running evaluatory studies and sharing the knowledge gained through research (e.g. section 2.6 and Figure 4-26).

2.5.2.5 Utility-scale developers

Successful utility-scale wind farm projects can have a positive feedback for SWTs, through the development of common resources, such as wind maps, as well as through direct knowledge transfer programmes or financial support through CSR (Corporate Social Responsibility) obligations.

2.5.2.6 The grid

Having access to grid electricity makes manufacturing at scale viable and the introduction of grid-tied SWTs can strengthen the ecosystem for off-grid SWTs

2.5.3 Market actors

Market actors can exist solely within the SWT industry, although they will often also be involved in other complementary industries such as the supply of solar PV power generation equipment or the manufacture of agricultural machinery. These market actors are responsible for a wide range of actions relating to the implementation of energy access projects (Practical Action, 2012), such as the manufacture and supply of equipment and appliances, the delivery of technical knowledge for system design, site selection, installation, operation, maintenance, and upgrade, as well as the supply of tools and spare parts for installation, maintenance and upgrade (see Table 2-7).

Table 2-7: The areas of the technology lifecycle over which market actors have the biggest influence.
X = Major influence, x = minor influence

	Research	*Manufacture*	*Site selection*	*System design*	*Installation*	*Operation*	*Maintenance*	*Upgrade*
Raw material suppliers		X					x	x
Manufacturers	x	X					X	X
Renewable energy equipment suppliers			X	X	X	x	X	X
Service centres						x	X	x
Training centres			x	x	x	X	X	x

2.5.3.1 Construction material suppliers

As discussed previously, the availability of construction materials in a particular place shapes the technology produced by the manufacturers. Piggott's (2013) open-source design offers a great deal of flexibility to manufacturers, in that they can take the basic concept and adapt it based upon the construction materials available in their location. For example, if there are no importers of permanent magnets, then less powerful, but more widely available ferrite magnets may be chosen over the standard neodymium magnets (Sumanik-Leary *et al.*, 2014); or if local scrap yards carry a regular supply of reclaimed water pipe, then a tower can be constructed much more economically than if purchasing brand new tubular steel (e.g. WindAid in Peru – see Chapter 4).

2.5.3.2 Manufacturers

The manufacturers of SWT technology have one of the biggest roles to play, as the quality and cost of the machinery they produce is critical to the success or failure of SWTs in that particular place. The production of poor quality SWTs can irreparably damage the reputation of the technology in a particular place, even if reputable manufacturers also exist (Vanheule, 2012).

2.5.3.3 Renewable energy equipment suppliers

Renewable energy equipment suppliers may stock both locally manufactured and imported technology and can often perform site selection, system design and installation, as well as offering maintenance services and upgrades (e.g. Ecami, SuniSolar or TecnoSol in Nicaragua – see Chapter 5).

2.5.3.4 Service centres

A network of service centres can bridge the gap between the manufacturers or renewable energy equipment suppliers and the community technicians or end-users (Batchelor *et al.*, 1999). They are located in remote regions, which are far from the manufactures or renewable energy equipment suppliers, but close to the end-users. They keep stocks of spare parts and offer access to the tools and technical knowledge required to perform maintenance (see Figure 2-13).

2.5.3.5 Training centres

Training centres offer technical knowledge to the end-users and community technicians on how to operate and maintain a renewable energy system and may also offer more advanced courses on site selection, system design, installation and upgrade (e.g. CEDECAP in Peru – see Chapter 4).

2.5.4 Community, enterprise and household

Table 2-8 shows that it is the remote communities themselves have the greatest influence on the sustainability of the technology once it is installed. However, their involvement in the entire process, from research to upgrade, will help to ensure that the resulting technological solutions will be best suited to providing them with the energy services that they are most in need of in the way that is most appropriate to their current level of expertise. For example in Inner Mongolia, the fact that most end-users already had experience with motorbikes, meant that they were already capable of repairing many standard mechanical components such as bearings, as well as many DC electric components, such as batteries (Batchelor *et al.*, 1999).

Table 2-8: The areas of the technology lifecycle over which communities, enterprises and households have the biggest influence.
X = Major influence, x = minor influence

	Research	*Manufacture*	*Site selection*	*System design*	*Installation*	*Operation*	*Maintenance*	*Upgrade*
Community technicians		*x*	*x*	*x*	*X*	*X*	*X*	*x*
Neighbouring installations					*x*	*X*	*X*	
End-users			*x*	*x*	*X*	*X*	*x*	
Energy-based enterprises						*X*	*X*	*x*

2.5.4.1 Community technicians

The community technicians are responsible for performing preventative and basic corrective maintenance on the renewable energy systems installed in their community. They reduce the need for engineers to travel long distances out to their remote community every time a failure occurs and empower the community to take control over their own energy supply. Their level of formal education is typically low, so transferring the knowledge required to successfully maintain a renewable energy system is a challenging, but essential part of the process of rural electrification (Sumanik-Leary *et al.*, 2013). They are also often responsible for the day-to-day administration of the renewable energy system, such as collecting fees, purchasing consumables, ordering spare parts, etc. (e.g. Scoraig – see Chapter 6) although in other communities, this role is fulfilled by a separate administrator (e.g. Cuajinicuil or Monkey Point – see Chapter 5). The techniques used for end-user empowerment listed in the following section are equally valid for community technicians, however participation in the construction of a SWT has also been shown to be a particularly effective method of transferring the high level of technical knowledge required to maintain multiple SWTs, as this practical learning opportunity is particularly effective for people with low levels of formal education, but highly developed practical skills, such as farmers (Sumanik-Leary *et al.*, 2013).

2.5.4.2 Neighbouring installations

Having similar SWT installations in nearby communities can offer support to community technicians through the sharing of tools, spare parts and technical knowledge. They make the establishment of service centres to support the maintenance of all the SWTs in a given area economically viable and can also act as a demonstration project for other communities to see the technology in action.

2.5.4.3 End-users

The end-users are the people who gain access to the energy services that the electricity generated by the renewable energy system is designed to provide. Again, they often have a very low level of formal education, making the process of empowerment with the knowledge required to be able to make best use of the energy that their new system provides is essential (for example by managing their energy use around the availability of renewable resources and by purchasing energy efficient appliances). The empowerment process should also involve the transfer of the technical knowledge required to successfully operate their system, as they are often the first people to identify faults through abnormal behaviour, such as strange noises coming from the machine. End-user empowerment can be achieved through the involvement of end-users in the installation process, dedicated training sessions, printed manuals and the support of a service centre and/or neighbours with similar SWT installations (see section 7.3.4).

2.5.4.4 Energy-based enterprises

Energy-based enterprises can be a particularly effective method for generating revenue with which to cover the costs of the system (Practical Action, 2012). For example refrigeration for food products in a shop (as in Monkey Point – see Chapter 5), water pumping for irrigation (as in Cuajinicuil – see Chapter 5) or power tools for a workshop (as in Scoraig – see Chapter 6). Whilst it is rare that they are able to cover the entire costs of the system (see Figure 5-16), it is also rare that a donor or governmental agency will be willing to fund more than just the initial capital costs of an SWT installation (Ferrer-Martí *et al.*, 2010). This is particularly problematic for SWTs, as the maintenance costs are typically much higher than for other renewable technologies (see Table 6-1).

2.6 Test case study: Inner Mongolia

Batchelor *et al.* (1999), Xiliang *et al.* (1999) and Lew (2000) all agree that the Northern Chinese autonomous region of Inner Mongolia stands in a class of its own when considering the scale of use of LMSWTs (known in this context as Household Wind Generators, HWGs): by 1997 there were 137,000 HWGs installed in the region supplying 18.5MW of electricity. The following section is designed to test the framework described in this chapter, by applying it to review the available literature and draw out the key factors that lead to the successful dissemination of HWGs in this particular local context.

Figure 2-11: One of the hundreds of thousands of HWGs that was operating in Inner Mongolia at the end of the 1990s (Batchelor et al., 1999).

The stability in the institutional support provided by the Chinese government through the framework of the Inner Mongolia Science & Technology Commission (IMS&TC) was invaluable during the development and dissemination of wind power technology in the region and allowed HWGs to grow from a research project to widespread use over the course of 20 years (Batchelor *et al.*, 1999; Xiliang *et al.*, 1999). Local universities and research institutions were supported to develop over 20 models of HWG from 50W-5kW and the establishment of service centres by the IMS&TC allowed the technology to be disseminated across the region, despite the large distances between the manufacturers and the end-users (Batchelor *et al.*, 1999).

Public acceptance of a new technology can be aided through its official endorsement by respected local, regional and national authorities. To achieve this, the IMS&TC ran demonstration programmes throughout the early 1980s to introduce the product to potential users and the government subsidised 15-20% of the initial purchase cost (Batchelor *et al.*, 1999). The subsidy not only provided financial assistance to purchasers, but also reassurance in the form of government endorsement (Batchelor *et al.*, 1999). The fact that consumer choice was restricted at the time that HWGs were introduced (petrol/diesel generators were the only alternative) made promotion of this technology relatively straight forward (Batchelor *et al.*, 1999).

Figure 2-12: Wind/PV demonstration system (Batchelor et al., 1999).

China's strong manufacturing industry allowed for production of the entire wind power system to take place within the country (Lew, 2000). The wind turbines were produced within Inner Mongolia itself, whilst the components of the electrical system (batteries, charge controller, inverter etc.) could be sourced from elsewhere in China for a fraction of the cost at which they are usually exported to other nations. HWGs were purchased by herdsmen themselves (Batchelor *et al.*, 1999); however the fact that they were manufactured locally meant that this money was reinvested into the local economy instead of being sent abroad.

A network of HWG service centres was established by the IMS&TC to ensure the availability of affordable spare parts and the accompanying skills and knowledge to perform repairs (Batchelor *et al.*, 1999). Service centres were opened in every "*banner*" (county), with the most successful counties extending the service network even further into all levels of society: "*banner*, *sumu and gatsa*" (Batchelor *et al.*, 1999: 33). At "*gatsa*" (village) level, a literate person was trained in installation and maintenance to deal with everyday issues, at "*sumu*" (subdivision of a "*banner*") level, maintenance courses were offered and only the most serious problems were then referred to the "*banner*" level, greatly reducing the distances that users had to travel to obtain the necessary knowledge, tools and spare parts to keep their HWG in operation (Batchelor *et al.*, 1999). This also had the effect of creating jobs and building capacity in rural areas. What is more, the fact that motor vehicles are common amongst herdsmen meant that a similar maintenance infrastructure already existed and that many people already had technical knowledge of the key components (bearings, generators and DC electricity) (Batchelor *et al.*, 1999).

Figure 2-13: IMS&TC service centres are well stocked and carry out most repairs - users pay for parts only, as labour and overheads are covered by government subsidies (Batchelor et al., 1999).

Batchelor *et al*. (1999) found that the evolution of the Inner Mongolian HWG into a product that adequately meets the needs of the end-user (mainly herdsmen) was one of the greatest contributors to its success. Effective feedback loops such as those shown in Figure 2-14 are necessary for the technology to develop in accordance with the needs of the users. Finding and addressing the weakest link/s in the system is vital and in this case, feedback through the service centres ensured that the main source of failures (blades and bearings) could easily be repaired by the user on the redesigned models, therefore drastically reducing downtime (Batchelor *et al.*, 1999). Both wind energy training courses and printed instructions were also used to empower the end-users with the knowledge to be able to successfully operate and maintain their own wind power system, with the support of the service centre when necessary (Batchelor *et al.*, 1999).

Whilst the sheer number of HWGs installed in Inner Mongolia may be impressive, it means little if the number of operational turbines is much smaller. Whilst it was not possible to quantify the current operational capacity, Batchelor *et al*. (1999) revealed that reliability was stated by herdsmen as one of their main reasons for choosing wind power, as although early models were unreliable, feedback collected by service centres informed research institutions and manufacturers on how best to adapt and improve the product and consequently. It was also found that it was the smaller companies who relied heavily on sales of HWGs (and therefore responded to this feedback) that thrived (Batchelor *et al.*, 1999).

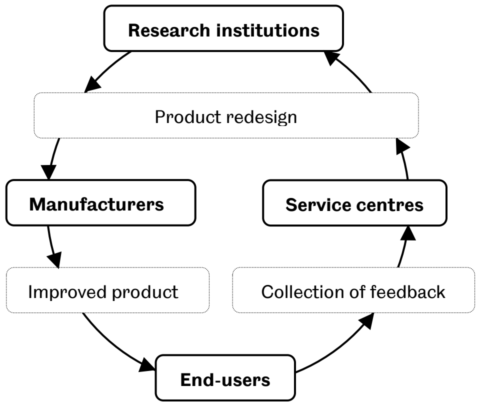


Figure 2-14: The role of the various intermediaries involved in the feedback loops.

HWGs were actually quite unpopular when they were first introduced with the intention of providing electric lighting alone (Batchelor *et al.*, 1999). Fortunately, the opening of the first broadcasting station in 1980 led to HWGs being sold together with televisions rewired to work on DC and only then did the technology gain widespread adoption (Batchelor *et al.*, 1999).

In Inner Mongolia, households are often very isolated and although family ties are strong, community links are not (Batchelor *et al.*, 1999). Early machines designed to provide power for a community were neglected and as a result, the HWG was redesigned for a single household. Batchelor *et al.* (1999) showed that herdsmen typically used an average of 130kWh/yr, whilst a typical turbine, such as the FD2-100[17] from the Shangdu Livestock Machinery Factory, was able to generate 490kWh/yr (260kWh/yr after battery and inverter losses) from a typical wind resource of 4.6m/s. Interestingly though, Batchelor *et al.* (1999) found that electrification did not bring immediate economic benefit in Inner Mongolia, however the improvement in quality of life from lighting and television/radio entertainment meant that wind energy was highly valued by herdsmen.

The correlation between the geographical distribution of the renewable resource and demand for electricity was very favourable: the plains of Inner Mongolia contain not only 40% of China's exploitable wind resource, but also hundreds of thousands of households too remote for grid connection (Xiliang *et al.*, 1999). As mentioned previously, assessment of the wind resource is difficult and expensive. The region was deliberately targeted by the Chinese government, as not only is it windy, but the simple, flat terrain and lack of trees makes individual site assessment unnecessary (Batchelor et al., 1999), i.e. if a herdsman were to find out from their neighbour that they have enough energy for two lights, a television and a radio, then it's very likely that they would also have enough energy to power the same appliances.

Wind power should be seen as complementary to other decentralised power sources, in particular PV, as the wind and solar resources often peak at differing times of day and in opposite seasons. Lew *et al.* (1997) have shown that a combination of wind and PV can be more effective in meeting household

[17] Rotor diameter: 1.5m, RAEY: 549kWh/yr, rated power: 100W @6m/s.

demand throughout the year than either a wind or PV only system of the same cost. As a result, newer Inner Mongolian systems tend to be hybrids (Batchelor *et al.*, 1999: ,).

Leary *et al.* (2012) compared the cost of the HWGs with those used in a similar electrification project in Peru and found that every single component in the wind power system was at least three times cheaper in Inner Mongolia. For example, 2x60Ah lead acid batteries were quoted as costing just $75, whilst in Peru an equivalent 120Ah battery was found to cost $225. In fact, an entire 100W wind power system could be purchased in Inner Mongolia for just $312. There may also be a difference in the quality of the components; however the success of HWGs in Inner Mongolia shows that the use of lower quality components is viable when technical knowledge, tools and spare parts are available through a network of service centres at an affordable price. The government's decision to establish and subsidise these service centres (see Figure 2-13) created a stable supply chain that was capable of properly supporting the technology deployed in the field throughout its entire lifetime, inspiring consumer confidence in the longevity of the product they were purchasing. Part of this difference can also be explained by inflation as the prices used were quoted in US$ from 1999, however it is clear that the fact that the entire wind power system could be manufactured within China greatly reduced the cost of the technology and made it available to a much larger cross-section of the population.

Even though the equipment could be purchased relatively cheaply, potential users of the technology still required access to sufficient capital to make this initial purchase. Renewable energy systems typically have much higher initial purchase costs than their fossil fuelled equivalents (ESMAP, 2007), which often poses a significant barrier to their uptake, requiring innovative micro-financing or pay-as-you-go options to make them viable in the marketplace (MicroEnergy International *et al.*, 2006). In this respect, Inner Mongolian herdsmen had a significant advantage: sheep and goats provided them with readily exchangeable assets with which to purchase HWGs (Batchelor *et al.*, 1999).

2.6.1 Summary of the Inner Mongolian experience

The experience of HWGs in Inner Mongolia has shown that it is possible for LMSWTs to be successful on a large scale. In contrast to the other case studies described in this thesis, where local manufacture refers to Piggott-derived technology employed in small-scale pilot projects, a range of different designs were manufactured within Inner Mongolia and sold on the free market. Using the framework described earlier in this chapter, the following factors were found to be instrumental in the success of the technology in this local context:

Enabling environment

- Environment
  - Good correlation between the geographical distribution of the wind resource and of households without access to electricity.
  - Simple, flat terrain without any trees made individual site assessments unnecessary, greatly simplifying the installation process and reducing risk.

    - Hybrid PV-wind systems are even more effective at filling the batteries throughout the year.
    - Large physical distances between houses, so HWGs designed to comfortably meet demand[18] for a single household given the available wind resource.
    - Few environmental hazards.
- Policy
    - Inner Mongolia was identified from an early stage as an appropriate region for SWTs, which was soon followed by strong and stable institutional support was given to foster the development of a wind power industry over the course of 20 years.
- Capacity
    - Public acceptance was gained by offering official endorsement of the technology through subsidies and demonstration programmes.
    - Capacity for SWT manufacture was built within Inner Mongolia itself, whilst capacity for operation and maintenance was built right down to the household level by the establishment of the service centre network.
- Finance
    - Low initial purchase costs due to local manufacture and government subsidy.
    - Maintenance services available locally at an affordable price due to government subsidies for service centres.
    - Herdsmen had access to capital necessary to make the initial purchase and cover ongoing costs in the form of sheep & goats, meaning that the establishment of energy-based enterprises was not necessary.

Supporting services

- IMS&TC played the critical role in the development of HWGs in Inner Mongolia, co-ordinating universities and research institutions to develop HWG technology, establishing the service centre network and collecting feedback from end-users.

Market actors

- The Chinese approach to local manufacture blended the benefits of the economies of scale from higher volume manufacture with the proper support for the technology at the local level by establishing the network of service centres.
- Manufacture of the entire wind power system took place within China and the HWGs themselves were produced in Inner Mongolia, drastically reducing costs, shortening the supply chain and boosting both the local and national economy.

[18] The wind resource is highly unpredictable, so designing a system that produces a higher annual energy yield than predicted annual energy demand is necessary to ensure that demand can be met a t all times throughout the year.

- Successful product redesign based on feedback from the service centres led to the evolution of the HWG into a reliable product that not only adequately met the needs of the end user, but was also available on the open market for an affordable price.

End-users

- HWG sale/service centres were established in all counties to offer access to the technology and the relevant maintenance services at a local level.
- HWGs were most successful in the counties where maintenance services were offered even more locally.
- A similar maintenance infrastructure already existed for motor vehicles, which use many of the same components as HWGs.
- The end-users were empowered to operate and maintain their own wind power systems with wind energy training courses, printed manuals and the support of the service centres when necessary.
- A holistic, system level view to providing the required energy services to the end-user was taken, ensuring that the HWGs were able to offer a significant improvement in quality of life to herdsmen (primarily through electric light, radio and television).

2.7 Conclusion

In this chapter, the concept of SWTs existing inside a socio-technical system was introduced. This socio-technical system can be seen as an ecosystem in which collaboration and competition drives key actors to provide energy services in rural areas using SWTs. Research, site selection, system design, manufacture, installation, operation, maintenance and upgrade are the technical processes that drive this ecosystem. The flow of capital and technical knowledge facilitate the assembly of construction materials, equipment and appliances into wind power systems capable of providing the end-users with the energy services they require.

Just like natural ecosystems, the SWT ecosystem is influenced by the environment it exists within. Policy, finance and capacity are the three of the four dimensions that make up the enabling environment that can promote the rapid growth of SWT-based rural electrification projects. However, the environment dimension is seen as a pre-requisite for the other three, as for example, no matter how favourable the national rural electrification policy is to SWTs, if there is negligible wind resource in a particular place, then SWTs simply will not work. The key actors within the ecosystem can be categorised into supporting services (universities, rural energy agencies etc.), market actors (suppliers, manufacturers etc.) and community level actors (energy based enterprises, community technicians etc.). The SWT ecosystem framework will be used throughout this thesis to analyse the socio-technical systems found in each case study (Peru, Nicaragua and Scotland) and identify the critical factors that have led to the success or failure of LMSWTs in each place.

The framework was employed to investigate the factors that led to the successful dissemination of LMSWTs in Inner Mongolia as a test case study and proved to be a useful tool by adding structure to the existing evidence drawn from the literature. It was found that strong and stable institutional support fostered the development of SWTs over the course of 20 years by first identifying Inner Mongolia as a region with high wind resource and simple terrain, which therefore eliminates the need for individual site assessment. The establishment of a network of service centres to offer maintenance services locally prevented end-users from having to travel large distances to gain access to the tools, spare parts and technical knowledge that they needed to repair their machines. The decision to manufacture within Inner Mongolia rather than import SWTs offered affordable technology and a strong supply chain for spare parts. Access to capital was not an issue as herdsmen could simply exchange animals at the local market in order to make the initial purchase. Holistic system design that focussed on meeting the needs of the end-users was found to be the final key to success.

Chapter 3. Methodology: a multidisciplinary analysis of case studies to build theory

3.1 Introduction

This research takes an inductive approach (Eisenhardt, 1989) to identifying the factors that affect the sustainability of rural electrification with SWTs and how these factors vary between places. The previous chapter has outlined the need to see SWTs as existing within a socio-technical system, which is different in each local context (Practical Action, 2012). As a result, a series of case studies on rural electrification initiatives where SWTs have been employed were studied to discover what was important in each place. Data was collected and analysed using a variety of methods, from participant observation in a specific community to energy systems modelling across the lifespan of a generic renewable energy system. The data was then analysed within each case before comparing between cases to look for patterns. Tentative hypotheses were created from these patterns (Figure 3-1) and their validity tested using the evidence from the case studies and manipulation of the models built upon them. Proven hypotheses then became part of the overarching theoretical framework that describes the complex interactions between the various components of the socio-technical system and ultimately determines the sustainability of SWTs in rural electrification initiatives (Trochim, 2006).

> *"...while deduction certainly is a part of science, it is the less interesting, less challenging part. It is discovery that attracts me to this business, not the checking out of what we think we already know." (Mintzberg, 1979: 584)*

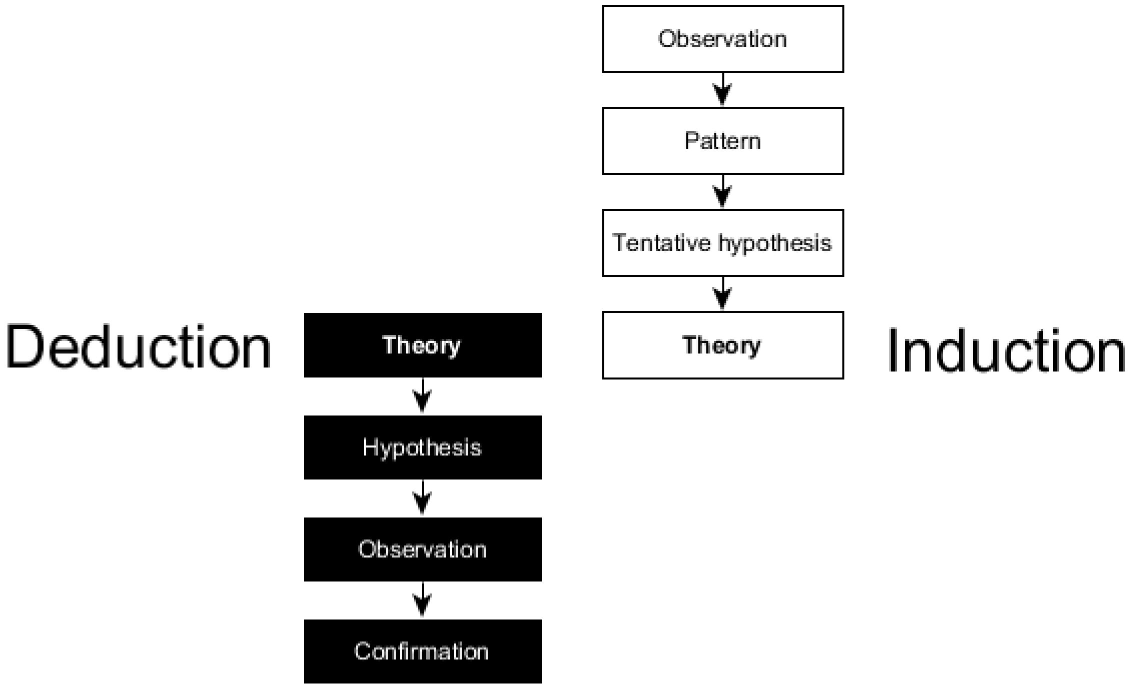


Figure 3-1: Comparing a) deductive (hypothesis-testing) and b) inductive (theory building) methods of acquiring knowledge. Adapted from Trochim (2006)

'Building Theories from Case Study Research' by Eisenhardt (1989) provides a comprehensive guide to this bottom-up approach to investigation and was used as a guide during this research. Eisenhardt's

methodology extends the work of Glaser & Strauss (1967) on building grounded theory, Miles and Huberman (1984) on qualitative methods and Yin (1981; 1984) on the design of research based upon case studies to produce a complete roadmap to take the author from defining the research question all the way [19]to reaching closure. It describes an iterative process by which theory is generated in close agreement with the data, ensuring that the findings are firmly grounded in reality. The approach was successfully employed by Yadoo (2011) in her analysis of delivery models for decentralised rural electrification, which featured case studies from Nepal, Peru and Kenya, and has provided useful guidance during this research on the application of Eisenhardt's methodology in the field of rural electrification.

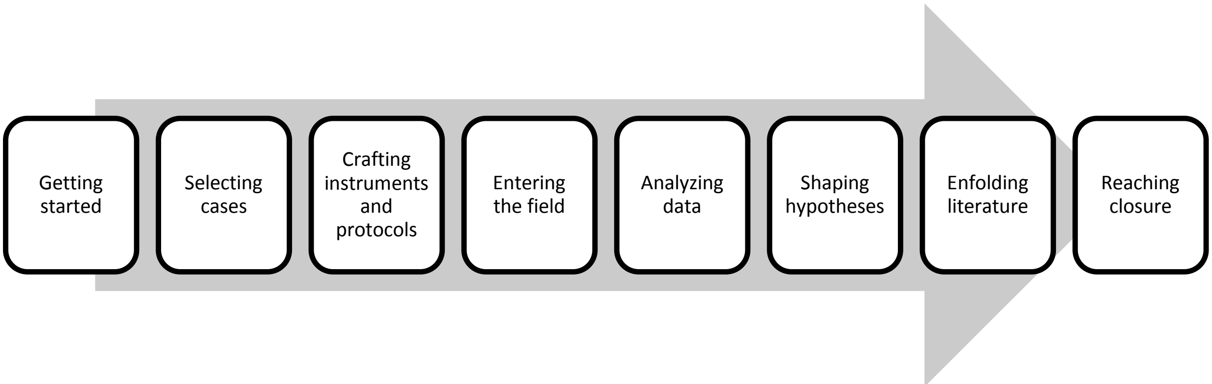


Figure 3-2: The process of building theory from case study research according to Eisenhardt (1989).

3.1.1.1 Getting Started

To avoid "*preordained theoretical perspectives or propositions*" that could introduce researcher bias, "*theory-building research is begun as close as possible to the ideal of no theory and no hypothesis under test*" (Eisenhardt, 1989: 536). However, just as in deductive research, Mintzberg (1979: 585) states that a well-defined research question is essential in order "*to collect specific types of data systematically*". This research endeavours to answer the following:

- *Which factors critically affect the sustainability of SWT rural electrification initiatives?*
- *How and why these factors vary between places?*
- *What are the implications of these insights for intervention in support for SWT rural electrification initiatives?*

Eisenhardt (1989: 536) recommends the use of a priori constructs "*to help shape the initial design of theory building research*" so that if any of these constructs do emerge as being critical, then "*strong, triangulated measures on which to ground the emergent theory*" will already exist. Accordingly, the following constructs were developed:

- *How does the modularity of SWTs compare to solar PV?*

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- *How much maintenance do SWTs require and what is needed to make this happen?*
- *Are mass-produced SWTs ever more appropriate for rural development projects than LMSWTs?*
- *How does the wind resource itself compare to other renewable resources?*

This is by no means an exhaustive list and many other constructs became apparent as the research began to develop, such as:

- *What influence do environmental hazards have on the viability of SWTs in a particular local context? Do they affect other decentralised generation technologies in the same way?*

3.1.1.2 Selecting cases

Cases were originally selected from the population of rural electrification initiatives employing SWTs in developing countries. Theoretical, as opposed to random sampling was deliberately employed, since statistical sampling was not the goal here, as it is in traditional hypothesis testing studies (Glaser and Strauss, 1967). In fact, due to the limited number of cases that could be studied in sufficient depth, extreme examples were selected to fill polar types, where the specific issues within the system under analysis were "*transparently observable*" (Pettigrew, 1988: 275). Figure 3-3 shows the selected case studies in three of the four corners of the scale/sustainability domain; finding an example from the fourth corner would have been very difficult as in order to reach scale, a certain degree of sustainability is usually required.

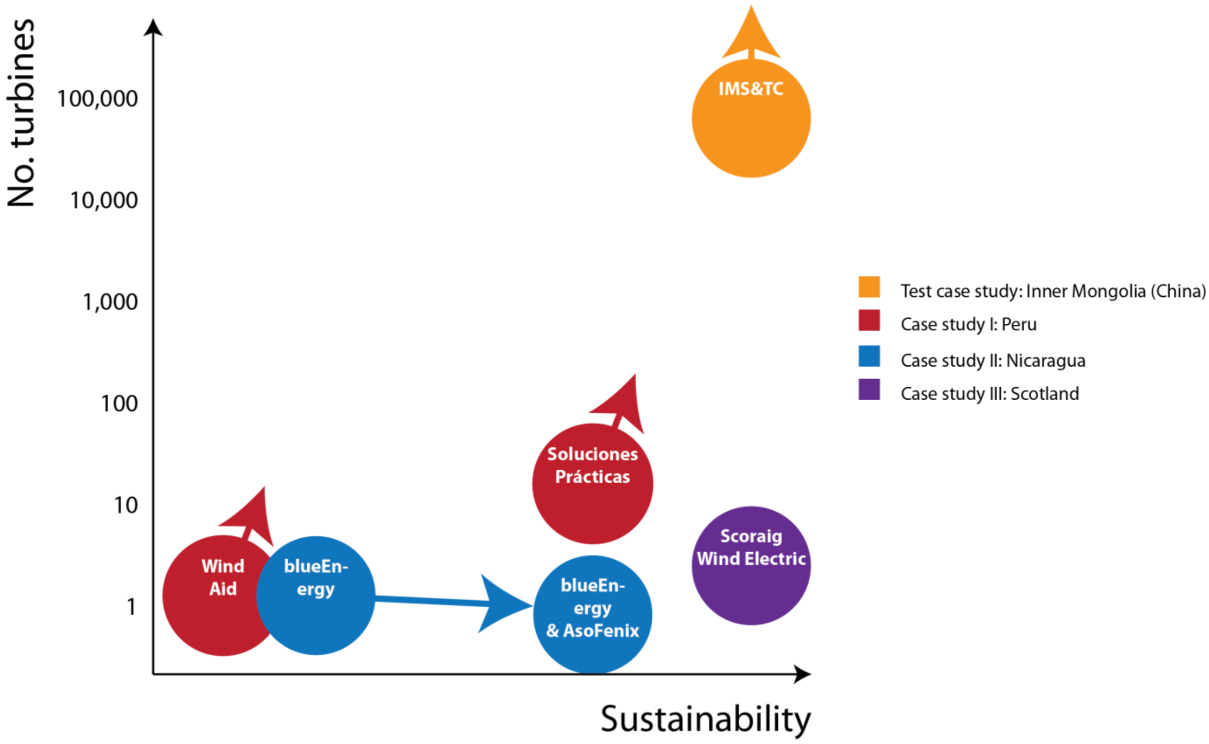


Figure 3-3: Variation in the scale and sustainability of the LMSWT rural electrification initiatives studied in each case study. Arrows indicate the future directions of each initiative within the scale-sustainability domain.

Test case study: Inner Mongolia

A review of the literature surrounding SWTs in Inner Mongolia was conducted first as it is widely acknowledged to be the most successful dissemination of SWTs anywhere in the world, with over 100,000 in operation at the turn of the century (Batchelor *et al.*, 1999; Xiliang *et al.*, 1999; Lew, 2000). The many lessons learned from this initiative were considered highly valuable in understanding not only the factors that contribute to the sustainability of SWT rural electrification initiatives, but also how they can be scaled up across a viable region.

Case study I: Peru

The first case study was chosen to highlight two very different approaches to LMSWT pilot projects. The influence of the delivery model, in particular the maintenance strategy, adopted by two different NGOs, WindAid and Soluciones Prácticas[20] was examined to determine its influence on the sustainability of these pilot projects. Soluciones Prácticas, who receive the majority of their funding from international donors, have partnered with a Peruvian enterprise to produce their LMSWTs and invest significant time and money in the empowerment of community members to be able to operate and maintain their own LMSWTs.

Conversely, WindAid operate under a '*voluntourism*' model, whereby internationals with an interest in, but generally little prior experience with, wind energy and development pay to attend a five week wind turbine construction course. The course culminates in the installation of the turbine in a previously selected unelectrified Andean community and the fees that the participants pay cover the costs of the project. WindAid engineers perform all but the most minor maintenance operations on the equipment they install. The fact that both were operating in the same region, the Northern Peruvian Andes, meant that the influences of the enabling environment (existing transportation infrastructure, wind resource, frequency of lightning strikes etc.) were identical and the differences in organisational strategy could be more easily observed.

Figure 3-4: Contrasting approaches in the Peruvian Andes: a) a community training session on LMSWTs run by Soluciones Prácticas (Ferrer-Martí et al., 2010) and b) WindAid volunteers and community members installing an LMSWT together (Photo courtesy of James Low).

[20] The Peruvian branch of the UK development specialists, Practical Action.

Case study II: Nicaragua

blueEnergy was selected for the second case study specifically because of their announcement that they would no longer be building or installing LMSWTs on the Caribbean coast of Nicaragua due to the lack of wind resource, high number of failures and difficulty in performing maintenance in remote locations (Bennett *et al.*, 2011). This provided the perfect opportunity to study the variety of factors that played a part in this decision, as building a theory of success also requires intimate knowledge of failure (Pettigrew, 1988). What made the case study even more interesting was that the final LMSWT built by blueEnergy was a technology transfer project between blueEnergy and the Nicaraguan NGO, AsoFenix. The external environment in the central highlands where AsoFenix operate is much more favourable for LMSWTs as the wind resource is higher, lightning strikes are less frequent and corrosion is less prevalent (it is far from the coast and humidity is lower). What is more, the transportation infrastructure in this region is also far more developed and the communities are generally much more cohesive. Studying these identical LMSWTs was an ideal opportunity to investigate the influence of the two very different local contexts in which they were installed.

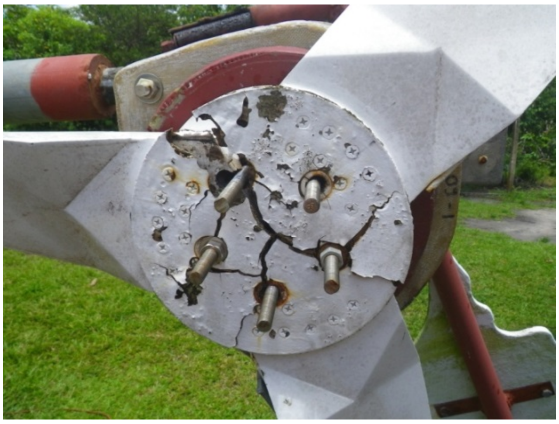


Figure 3-5: Transplanting a technology that was a) crumbling to pieces on the Caribbean coast of Nicaragua (blueEnergy, 2011) to b) the much more hospitable central highlands.

As part of this case study, a market assessment was conducted for the international NGO, Green Empowerment, with the aim of determining how scalable SWTs were across the rest of Nicaragua. Green Empowerment provides technical and financial support for rural electrification initiatives in many developing countries and commissioned the project to determine what future support (if any) they should offer to the SWT sector in Nicaragua. During the project, they offered guidance on the specific questions that should be addressed by the research and logistical assistance with the field work conducted in Cuajinicuil with AsoFenix through their in country representative. This gave the opportunity to put the theory developed to date into practice and work with a team of SWT experts to develop a methodology for determining how the place-specific factors that affect SWT viability vary across the country and therefore how likely SWTs are to be successful in each part of the country.

The study also required an assessment to be made of the current state of the SWT ecosystem in Nicaragua, so that Green Empowerment could best target any future interventions to strengthen it.

Case study III: Scotland

Finally, Scoraig Wind Electric was chosen for the third case study to provide an example of a socio-technical system that operates almost entirely at the local level. Although not in a developing country, the remote location of the Scoraig peninsula on the Northwest coast of Scotland is similar to the remote communities studied in the previous cases due to the lack of existing infrastructure. There is no connection to the National Grid or the mains water supply and there are not any roads connecting it to the rest of the UK. Almost all of the infrastructure on Scoraig has been put there by members of the community themselves and is therefore both small in scale and able to operate almost completely independently from the rest of the country. LMSWTs have been successfully providing electricity to the Scoraig peninsula's small community for the last thirty years, clearly showing that Piggott's SWTs can be sustainable (i.e. a long term solution) in the right local context. Employing the techniques developed during the preceding case studies in Scoraig gave a valuable understanding of the factors that had contributed to the success of the technology in this local context, as well as providing a fascinating insight into how the technology employed in so many development projects across the globe operates under virtually ideal conditions (see Table 8-1).

Figure 3-6: a) The barren and windswept Scoraig peninsula in 1953 (photo courtesy of Scoraig.com) and b) Hugh Piggott sat outside his comfortable wind-powered home in 2012.

3.2 Crafting instruments and protocols

Eisenhardt (1989: 537) notes that "*theory building researchers typically combine multiple data collection methods*" as triangulation between the various methods provides stronger substantiation for any constructs that may emerge. This research combined interviews, surveys, observations, archival sources, photographic evidence, geo-referenced data and technical performance testing to build up a much more complete view of the influences of each specific construct on the overall system.

In fact, combining data types can be "*highly synergistic*", with quantitative data able to prevent false conclusions being drawn by "*vivid, but false impressions in qualitative data*" (Eisenhardt, 1989: 538). For example, estimations of the wind resource in a particular community by local residents can often be surprisingly different to what is measured using an anemometer and datalogger. However, qualitative evidence is often able to offer an explanation for trends seen in the quantitative data. This permits identification of constructs that may not have been salient with quantitative data alone (Eisenhardt, 1989: 538). The post-installation analysis methodology developed during this research (introduced in Chapter 4 and extended in Chapter 5 and Chapter 6) is by definition a mixed methods approach, as the numbers mean little without further exploration into the reasons behind them. For example, in Cuajinicuil, Nicaragua, the poor performance of the mini-grid's PV array had little to do with the technical reliability of the system, as only one failure had occurred in the two years since installation. Nor was a weak supply chain or lack of local technical knowledge to blame, as the well-trained community technician regularly travelled to the capital, Managua. However, the accompanying interviews revealed that in fact it was the lack of productive uses of the electricity[21] that meant that the community still had little income and as a result, the fund that the community had collected from each household to cover maintenance costs was not sufficient to purchase a replacement part. Mintzberg (1979: 587) states:

> *"For while systematic data create the foundation for our theories, it is the anecdotal data that enable us to do the building. Theory building seems to require rich description, the richness that comes from anecdote. We uncover all kinds of relationships in our hard data, but it is only through the use of this soft data that we are able to explain them"*

Although fieldwork in Nicaragua was always planned, the opportunity arose to work as part of a team with three fellow investigators to conduct a national market assessment for SWTs (Marandin *et al.*, 2013). This gave the author an invaluable opportunity to see how support for SWT rural electrification initiatives was currently given. Working with these other wind power experts and engaging with the organisation that was supporting SWTs in Nicaragua (Green Empowerment) allowed the author to become part of the system itself. By taking this ethnographic approach to data collection, the author was able to gain much greater insight into the inner workings of the socio-technical system, as becoming part of the mechanism by which support is given can offer an ideal opportunity for participatory learning when the goal is to understand how support should be given. Of course, the key challenge is to remain objective throughout the process, which was assisted by the recording of both

[21] Whilst the system had been designed to power both a water pump for an irrigation system to improve agricultural yields by extending the growing season and a blender for fruit processing, as the majority of the fruits in the region ripened at the same time, meaning that it was not possible to sell them unless they could be processed and preserved. However, the digging of the well took longer than expected and the fruit preservation business had yet to be established, meaning that at the time of the evaluative visit (December 2012), there were no additional revenue streams available to the community.

“*unfiltered reflections*” (Yadoo, 2011: 37), as well as descriptions of actual events in the field diary (please see Appendix H for a sample extract from the field diary).

In addition to the use of multiple data collection methods, Eisenhardt (1989: 538) strongly recommends the use of multiple investigators to “*enhance the creative potential of the study*” through “*complementary insights*” and increase confidence in the findings when observations from several investigators converge. In Nicaragua, the author worked with a variety of different investigators, each of whom added their own perspective to the study. For example, the semi-structured interviews of key wind power experts were conducted by the author and one other member of the team, which allowed for a discussion on the approach before the interview and on the findings afterwards. Of course, the findings or methodological approaches of each investigator didn’t always agree. In such cases, it was necessary for each investigator to present their evidence or proposed methodology and to collaboratively evaluate each possible option in order to determine the most viable way forward.

During the field work in the remote communities themselves, the author was accompanied by members of the implementing organisations. The collaboration began with the design of the interviews and surveys (see Appendix I for further details), which were developed together to ensure that they were culturally appropriate to each community and did not duplicate already existing data. The interviews and surveys were also conducted as a team, alternating between handling the questions, taking notes and observing. This gave the interviewer “*the perspective of personal interaction with the informant, while the note-taker retains a different, more distant view*” and the observer is able to see the entire process in action, increasing the chance that each “*will view case evidence in divergent ways*” (Eisenhardt, 1989: 538). The findings were discussed after each interview/survey, as well as at the end of each day, to compare these contrasting viewpoints. A team meeting was also held after returning from the field to discuss the evidence and begin the analysis.

However, this collaboration raises two distinct issues: that of researcher bias and that of the authorship of the work presented for the PhD. The fact that members of the implementing NGOs were involved in the evaluation of their own project creates a conflict of interest: they may have wanted to portray their project in a particular way in order to reflect favourably on themselves in order to obtain future funding, as the organisation that commissioned the market assessment also funded the projects that were being evaluated. However in both communities, this was not found to be an issue, as in fact both organisations had a negative view of small wind for rural electrification and were not interested in obtaining further funding for such projects.

The issue of authorship is more difficult to address, as it is almost impossible to separate the work conducted by the author with that conducted by the other three members of the consultancy team. For example, whilst the author selected the questions for the semi-structured interviews with wind power experts in Nicaragua, another member of the consulting team created the list of interviewees from his existing connections within the country. The interviews themselves were conducted together, with both parties alternating between questioning and note-taking, however the other team member wrote up all the interview transcripts. The final report submitted for the market assessment was written by all four members of the consultancy team. For inclusion within this thesis, it was restructured and many sections were completely rewritten, however some of the work is still presented in its original form. It is argued that it would not have been possible to gain such insight in any other way than becoming part of the system itself. What this thesis adds to the original market assessment is reflection on each of the decisions made during the original study and contextualisation of the analysis within the theoretical framework described in Chapter 2. The framework was built upon the evidence from all of the case studies and therefore has developed significantly since the market study was conducted (November 2012-January 2013). As a result, using it to look back at the evidence from the market study can now offer new insight.

In fact, Table 3-1 shows that much of this thesis is based on previously published work. Chapter 4 is based on a conference paper that was reviewed by members of the NGOs under study[22] due to the inclusion of potentially sensitive data on turbine reliability. During the technical performance measurements in Scoraig (Sumanik-Leary *et al.*, 2012), Piggott took on a supervisory role, directing the research. However, only the resulting power curve data is presented in Chapter 6, as it is used as an input for the energy systems models. The remainder of the work presented in Chapter 6 was produced independently by the author[23]. The remaining publications were also produced independently, although (Sumanik-Leary *et al.*, 2013) is based upon the work from the Cuajinicuil case study in Nicaragua that was conducted during the market assessment (Marandin *et al.*, 2013).

Table 3-1: Published literature on which this thesis is based.

	Previously published literature
Chapter 1	(Leary *et al.*, 2012) – Locally manufactured small wind turbines for sustainable rural electrification
Chapter 2	(Leary *et al.*, 2012) – Locally manufactured small wind turbines for sustainable rural electrification
Chapter 4	(Leary *et al.*, 2012) – Post installation analysis of locally manufactured small wind turbines: case studies in Peru
Chapter 5	(Marandin *et al.*, 2013) – Market assessment for small scale wind turbines in Nicaragua
	(Sumanik-Leary *et al.*, 2013) – Participatory manufacture of small wind turbines: a case study in Nicaragua
Chapter 6	(Sumanik-Leary *et al.*, 2012) – Power curve measurements of locally manufactured small wind turbines
	(Sumanik-Leary *et al.*, 2013) – Locally manufactured small wind turbines: how do they compare to commercial machines?

[22] No alterations were made to the content as a result of these reviews.
[23] With the exception of the work presented in Sumanik-Leary *et al.* (2013), which was reviewed by Piggott prior to publication.

3.3 Entering the field

Whilst in the field, detailed notes were kept in the form of a research diary to record "*unfiltered reflections*" (Yadoo, 2011: 37) on the day's events (see Appendix H). Not only were they designed to capture the necessary anecdotes required to explain the interesting relationships uncovered by the research (Mintzberg, 1979), but also to begin the process of analysing the data. Research to build theory from case studies often involves overlapping data analysis with data collection both to "*speed analyses*" and allow "*adjustments to data collection*" (Eisenhardt, 1989: 538). Working collaboratively in Nicaragua provided further opportunity to overlap data analysis with collection during the second case study. Beginning the analysis whilst still in the field resulted in revision of the research methods employed within each country on multiple occasions, such as the previously mentioned reformulation of interview and survey questions between the two communities visited in Nicaragua.

Figure 3-7 displays the research methods employed in each case study and shows the major differences between the methods employed across the three countries. Eisenhardt (1989: 539) justifies such changes in the case of theory building research as the aim is "*not to produce summary statistics about a set of observations*", but to "*understand each case individually and in as much detail as possible*". Whilst technical performance data already existed for the LMSWTs employed in Peru and Nicaragua, enquiry about similar data in Scotland led to the opportunity for the author to take such measurements together with Hugh Piggott, the internationally renowned small wind expert and inventor of much of the technology studied during this research. As such data requires long-term collection and therefore multiple extended trips to the field, this unwittingly became the perfect opportunity for participant observation in Piggott's home community of Scoraig.

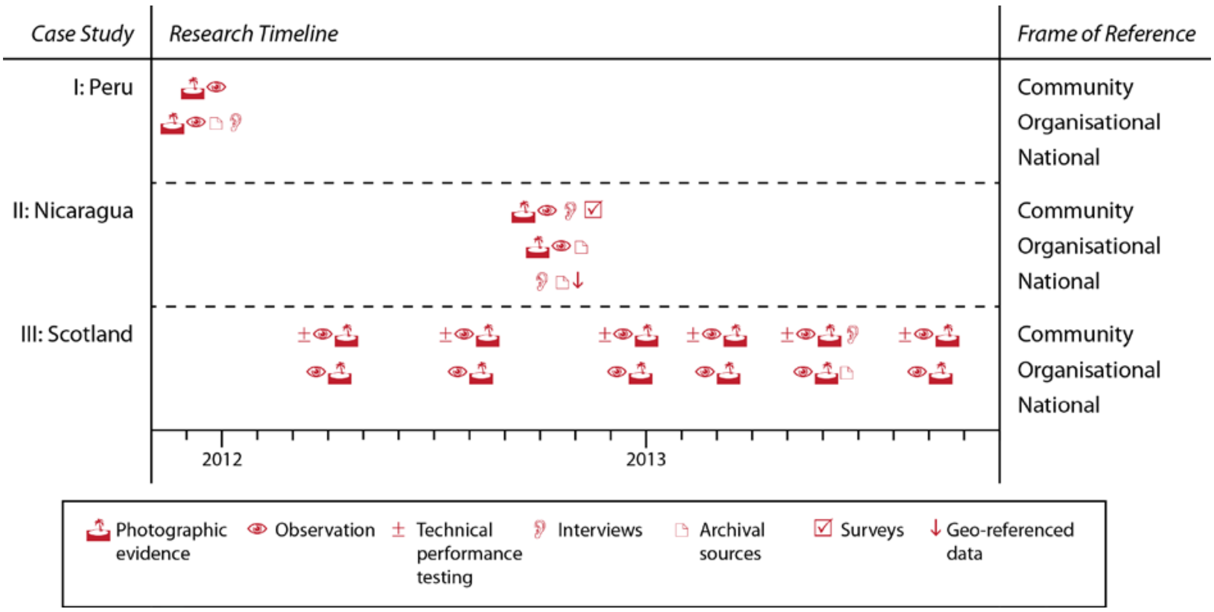


Figure 3-7: Timeline of data gathering methods employed during field work.

As mentioned previously, field work in Nicaragua had always been planned, ever since the announcement that blueEnergy were no longer employing LMSWTs on the Caribbean coast due to a variety of contextual factors. This offered a valuable opportunity to employ contrastive inference when comparing against the other more successful cases. However, the opportunity to take part in the previously mentioned market assessment (Marandin *et al.*, 2013) provided an ideal chance to gain significant additional insight into these contextual factors by working with local experts who were well connected within the country and highly motivated to conduct the study. It also offered the opportunity to conduct much more detailed ethnographic work within the communities themselves to provide further insight into the interaction of the end-users with the technology. In addition to this, there was also the opportunity to assess the influence of the spatially varying parameters using Geographic Information System (GIS) mapping techniques, both of which had been suggested as a result of the analysis of the data collected in Peru. Eisenhardt (1989: 539) argues that it "*makes sense to take advantage*" of these new opportunities for data collection if "*such an opportunity is likely to better ground the theory or provide new theoretical insight*" as a form of "*controlled opportunism*".

Indeed, the value of the time spent in the field became alarmingly apparent as the research was taking place, resulting in increased time spent in the field for each subsequent case study. Whilst the field work in Peru was completed in just 3 weeks, 5 weeks were spent in Nicaragua and a total of 3 months in Scotland (over the course of a year and a half). The differences between methodologies can also be explained by the fact that the author began the PhD as an engineer with little experience of social science (especially qualitative) methodologies, yet finished as a multidisciplinary researcher capable of drawing upon techniques from across the disciplines to thoroughly investigate the construct under study. The techniques employed in each case study are therefore also a reflection of the experience gained by the author. For example, in the case of the collection of both quantitative and qualitative data, in order to build up a complete picture of what had happened to each SWT since it was installed and establish the underlying reasons why this had occurred (post-installation analysis), it was initially unclear as to which factors played a critical role and therefore what data to collect. In the Peru case studies, the focus was on the technical reliability of the SWTs and the delivery model employed by the implementing organisations. However, after reviewing this case study together with the case study in Nicaragua, it was determined that the way that the end-users interact with the technology on a daily basis is one of the fundamental reasons why wind power can succeed in certain local contexts and not others. As a result, the technique of participant observation was added to the repertoire of methodologies employed in Scotland and yielded incredibly fruitful results.

The progress in the development of the post-installation analysis methodology can be seen in Figure 4-23 which shows a timeline plot of the SWTs studied in Peru with a simple green for operating and red for out of service. Figure 5-13 shows that in Nicaragua, a yellow option was added to reflect the fact that when certain faults occur, the system can continue producing energy whilst awaiting repair. In Scotland, this technique was extended even further to include symbols indicating when repairs, upgrades and replacements occurred, which were referenced to the textual descriptions of each SWT (see Figure 6-24). What is more, Figure 3-7 shows that a number of (primarily qualitative) data collection techniques were added as the research progressed to add depth and contextualise the quantitative data. The development and addition of individual research methodologies are discussed individually in each case study as they are introduced.

Furthermore, not all the research methodologies were applicable to each case. For example, conducting a full market assessment for SWTs in Scotland was unnecessary as 100% of the population already has access to electricity. However, in Nicaragua it provided valuable insight into the potential of the technology in this particular local context. It should also be acknowledged that working in Scotland was easier than either of the previous case studies, due to the combined effect of the lack of cultural and language differences and the experience that the author had built up during the previous two case studies. As a result, it would be beneficial to apply the techniques used in Scotland to the other two case studies in order to gain further insight into the role that wind power plays in the everyday lives of rural communities in the Peruvian Andes and both the Caribbean coast and central highlands of Nicaragua (please see section 8.6 for further information on improvements that would have been made if planning the research again).

3.4 Analysing data

Whilst analysing data stands "*at the heart of building theory from case studies*", Eisenhardt (1989: 539) states that it is "*the most difficult*" and "*least codified part of the process*". To cope with the "*staggering volume of data*" in this open-ended enquiry, it was essential to become "*intimately familiar with each case as a stand-alone entity*" and allow "*the unique patterns of each case to emerge*" before pushing to "*generalise patterns across cases*" (Eisenhardt, 1989: 539).

On return from the field, all interviews were transcribed, quantitative data was organised into spreadsheets and the field diary was typed up and organised to include the photographic evidence. In addition to this, after completing the field work in each country, Table 3-1 shows how much of the within-case data was analysed, written up and published. This gave the author a "*rich familiarity with each case*" (Eisenhardt, 1989: 540) and the feedback received from the conferences at which the work was presented, the organisation who commissioned the market assessment in Nicaragua (Green Empowerment) and from other readers & reviewers of the works proved extremely valuable. If the comments agreed with the findings, they offered confirmation of the analysis performed to date and if they did not, then new perspectives were gained. This feedback also gave the opportunity to improve the generalizability of the resulting theory by comparing these cases to other cases with which the audiences may have been familiar. This feedback also proved valuable for refining the methodologies employed in subsequent cases, as mentioned previously.

With a firm grasp of the intricacies of each case, the "*cross-case search for patterns*" began (Eisenhardt, 1989: 539). A systematic approach was adopted as "*people are notoriously poor* *processors of information*" (Eisenhardt, 1989: 539), often leaping to conclusions based on limited data (Kahneman and Tversky, 1973), unintentionally dropping disconfirming evidence (Nisbett and Ross, 1980), and allowing themselves to be excessively swayed by more elite respondents (Kahneman and Tversky, 1973) or the vividness of the account (Nisbett and Ross, 1980). To avoid reaching "*premature and even false conclusions as a result of these information processing biases*", the data was analysed in "*many divergent ways*" (Eisenhardt, 1989: 540). Figure 3-8 shows the wide variety of analysis techniques and the key pathways that were used to process the data collected from each case study into comparable forms[24], thereby allowing patterns between cases to emerge. As previously mentioned, not all data collection methodologies were employed in each case and even if they were, the way in which each methodology was employed may well have been different. For example, the interviews conducted in Peru were with the NGO staff only, whilst in Nicaragua, national wind power experts, NGO staff and community members were interviewed. Although interviews were also conducted in Scotland, much of the information that is comparable to the data obtained through interviews in previous case studies was obtained through participant observation. The framework described in Chapter 2 was then used to categorise this processed data in different ways, focussing its insight into the following key issues that could easily be compared between cases:

1. What needs to be done? (manufacture, site selection, etc.)
2. What is needed to perform these actions? (tools, technical knowledge, etc.)
3. Who needs to do it? (supporting services, market actors, etc.)

These three different perspectives all offer different insight into the evidence gathered from each case study.

[24] As far as possible, given the variety of data collection methodologies employed in each case.

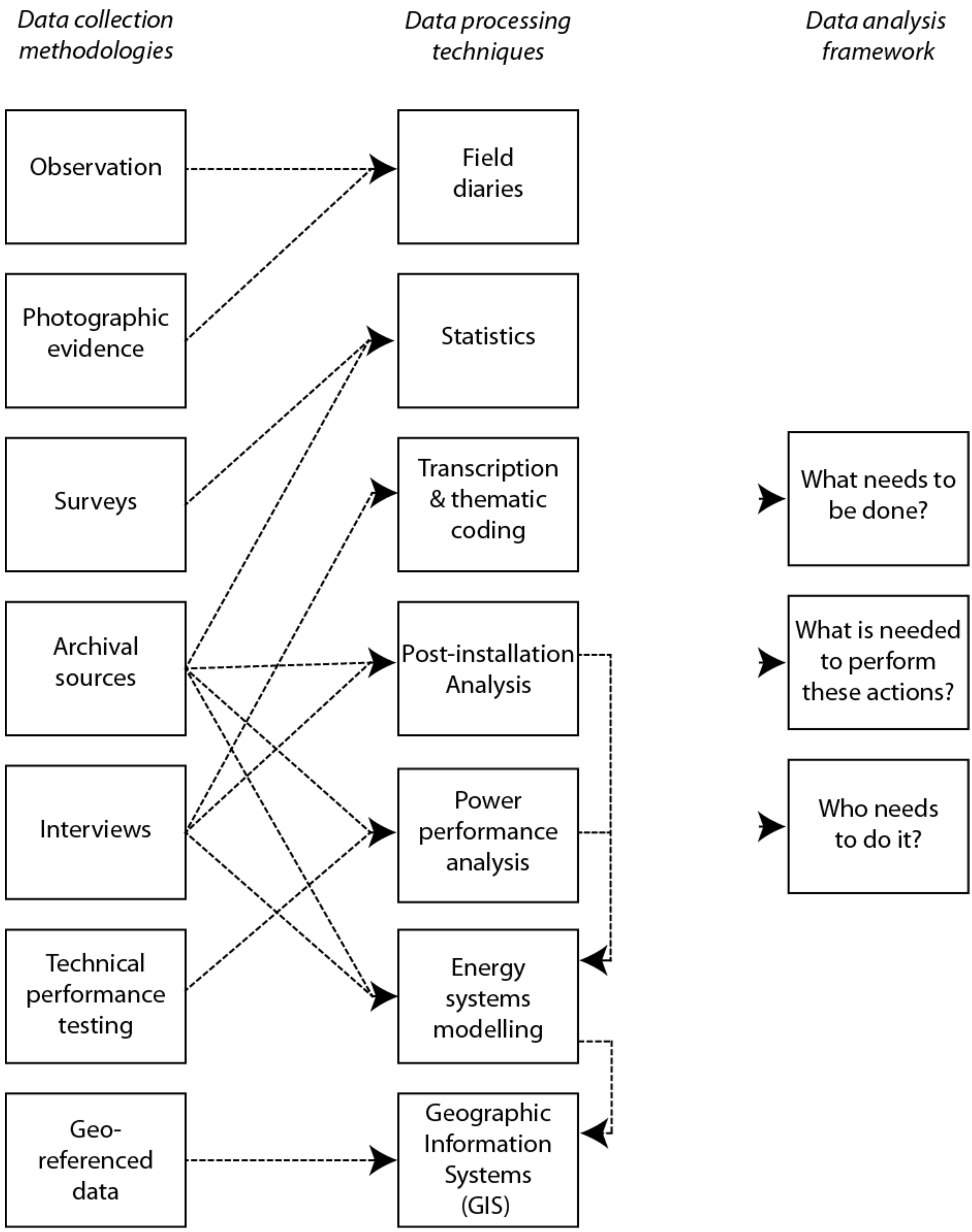


Figure 3-8: Schematic of the major analytical pathways used to build theory from case study data during this research.

3.5 Shaping hypotheses

Eisenhardt (1989: 541) describes how "*overall impressions, tentative themes, concepts, and possibly even relationships between variables*" begin to emerge throughout the analysis stage. An iterative process ensues to systematically compare "*the emergent frame with evidence from each case*"

(Eisenhardt, 1989: 541) using "*replication logic*" in place of summary statistics, such as F values (Yin, 1984). Figure 3-9 shows an example of this process, where analysis of the data from blueEnergy/AsoFenix's pilot project in Nicaragua yielded the hypothesis that participation in the manufacture of an LMSWT is essential to ensure he transfer of sufficient local technical knowledge to be able to operate and maintain it. This emergent hypothesis was compared against each other case individually, revealing two important conflicts:

1. In Inner Mongolia, there was no end-user participation in the manufacturing of the LMSWTs, yet these same end-users were clearly capable of successfully operating them and performing the majority of the maintenance themselves. However, the widespread dissemination of the technology allowed end-users to gain practical experience with the technology through interaction with LMSWTs belonging to their neighbours. What is more, demonstration models were also on show at regional service centres.
2. In Peru, Soluciones Prácticas offered a practical training programme to community technicians at their renewable energy demonstration centre, CEDECAP (see section 4.3.3.2).

This resulted in the revision of the hypothesis to recognise these alternative practical learning opportunities. The revised hypothesis was then re-checked against each of the case studies and on finding that they were all now in support of it, it was accepted as a construct to be included in the final theory. This process (as shown in Figure 3-9) is of course a simplified version of reality, as theory is constantly compared with data, sharpening constructs by "*refining the definition*" and "*building evidence*", "*iterating toward…an empirically valid theory*" (Eisenhardt, 1989: 541). The diverse range of data sources and analysis techniques employed by this study (see Figure 3-8) provided a wide variety of evidence from which to draw, greatly speeding up this process and increasing the validity of the resultant theory.

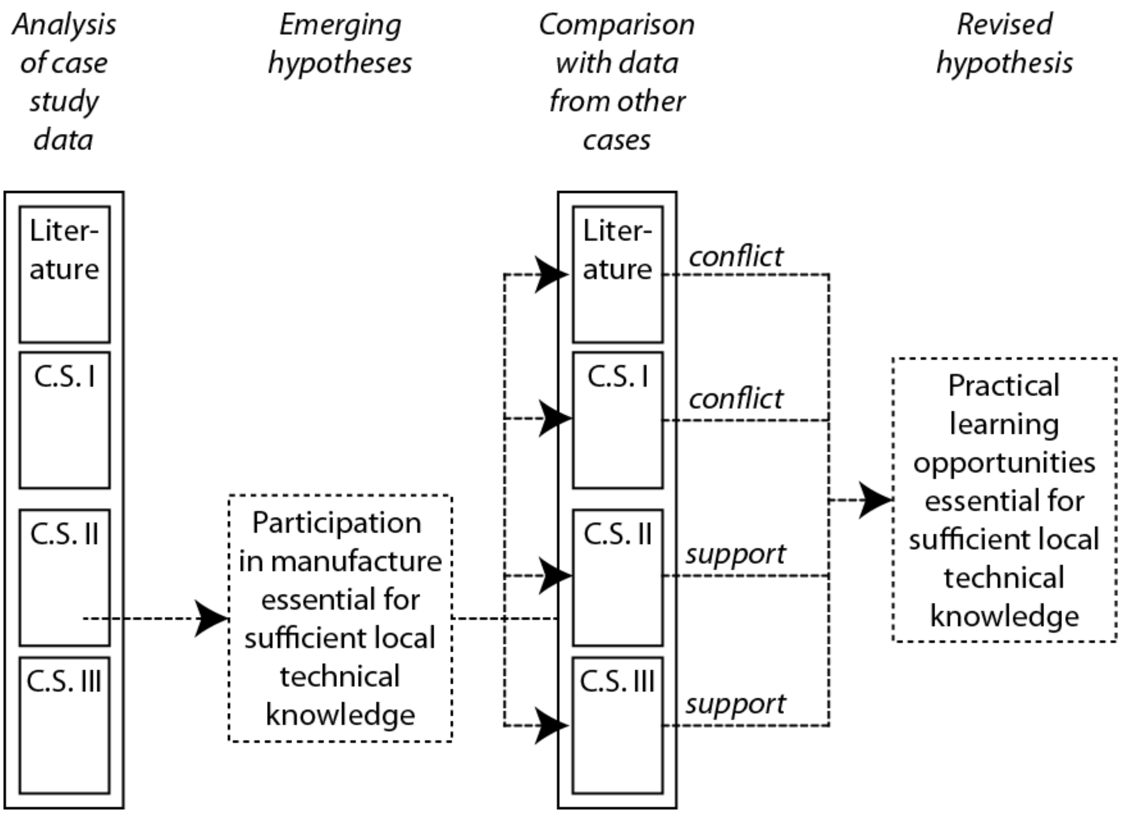


Figure 3-9: Example of the iterative process of the revision of emerging hypotheses through comparison with data from other cases.

Not only is the support of a relationship across all cases essential for producing "*theory that closely fits the data*", but a "*good understanding of the dynamics underlying the relationshi*p" is also required to establish its "*internal validity*" (Eisenhardt, 1989: 541-542). The qualitative data can often offer such an explanation: in this case, notes from the field diary refer back to a conversation with the former head of blueEnergy's energy programme, who had just spent 2 years training communities on the Caribbean coast of Nicaragua in the O&M of LMSWTs. He claimed that teaching electrical theory to poor farmers was easy; as long as you can relate it to something they already know. In this case, using practical methods of training to replicate the practical ways in which farmers learn to work their land from their family and friends, combined with practical analogies to systems with which they are already familiar[25] is much more likely to be successful than dry academic theory, as many of these farmers have had little formal education and may not even be able to read.

No matter how rigorous the process, theory building is ultimately "*more judgemental*" than traditional hypothesis testing research, as statistical methods cannot be applied due to the variation in evidence available in each case and the reliance on qualitative data (Eisenhardt, 1989: 543). To address this issue, the evidence and details of the data processing techniques employed within each case study are

[25] For example, explaining electrical theory through an analogy with an irrigation system, i.e. water flow rate = electrical current, water pressure = electrical voltage and water pipe diameter = electrical resistance

carefully documented in Chapters 4-6, whilst the cross-case analysis techniques are presented in Chapter 7, offering the reader the opportunity to "*apply their own standards*" (Eisenhardt, 1989: 544).

3.6 Enfolding literature

Eisenhardt (1989: 545) states that "*tying the emergent theory to existing literature enhances the internal validity, generalizability, and theoretical level of theory building from case study research*" and is "*particularly crucial…because the findings often rest on a very limited number of cases.*" During the course of this research, Practical Action's (2012; 2013) Energy Access Ecosystem model was developed and was found to be highly complementary to the emerging theory. Practical Action's framework seeks to identify the influence of the enabling environment on the dissemination of generic energy access technologies, whilst this research applies it specifically to SWTs. As a result, Practical Action's framework was incorporated into the resulting theory, with the following advantages:

- Wider generalizability to alternative local contexts and perhaps even different technologies, due to its consideration of a broader range of influencing factors at the international, national, organizational and community levels.
- Stronger internal validity as the influences of confounding variables could be identified and accounted for.
- Higher conceptual level as the constructs developed independently of each other in either model receive validation if in agreement with each other, whilst further insight is added if they contradict.

In addition to the published literature, the LMSWT-specific findings were cross-checked with members of WindEmpowerment. WindEmpowerment (2013: 1) is an "*association for the development of locally built SWTs for sustainable rural electrification*", tying together the many people and organisations across the globe that are working with LMSWTs, including academics, practitioners, hobbyists, trainers and social entrepreneurs. Being a member of WindEmpowerment requires both an interest in and experience with LMSWTs, essentially providing the author with a self-selecting, pre-engaged supply of experts in the field. By discussing the constructs identified during this research with this group of LMSWT specialists, the aforementioned advantages were furthered (in particular the generalizability of such constructs due to the wide variety of local contexts in which they work[26]). For example, the corrosive effect of the highly saline coastal air is well documented in the WindEmpowerment forums, however it was found that proximity to the coastline alone is not a strong indicator for corrosion problems as Scoraig is a coastal community yet does not suffer anywhere near the level of corrosion seen on the Caribbean coast of Nicaragua. Through further consultation in the WindEmpowerment (2013) discussion forums with other member organisations, it was determined

[26] WindEmpowerment has member organisations in 25 countries, across every continent (see Appendix F).

that it was in fact the combination of coastal locations with the hot and humid tropical climate that creates this highly corrosive environment.

3.7 Reaching closure

Glaser and Strauss (1967) define theoretical saturation as "*the point at which incremental learning is minimal because the researchers are observing phenomena seen before.*" Ideally this is the point at which to stop adding cases. However, Eisenhardt (1989: 545) recognises that "*pragmatic considerations such as time and money…dictate when case collection ends.*" In the case of this research, the addition of further cases with particular phenomena of interest[27], such as pay-as-you go financing (as opposed to fixed tariff or metered, but regularly billed) or imported (as opposed to locally manufactured) technology, would serve to extend the theory in these areas and it would therefore be of value to add such cases to the study. However due to time restrictions, it was decided that studying a smaller number of cases in a greater depth would provide a firmer basis from which to build the conceptual framework, leaving open the possibility of adding further cases to refine it at a later date. The second stage of reaching closure is "*when to stop iterating between theory and data…again, saturation is the key*," i.e. "*the iteration process stops when the incremental improvement to theory is minimal*" (Eisenhardt, 1989: 545).

3.8 Evaluation of the chosen methodology

The creative insight necessary to generate novel theory "*often arises from the juxtaposition of contradictory or paradoxical evidence*" (Eisenhardt, 1989: 546), something that frequently occurs when building theory from case studies or working between academic disciplines. Reconciling evidence across data types, among multiple investigators and between cases and the literature "*increases the likelihood of creative reframing into a new theoretical vision*" and actually has the potential "to generate theory with less researcher bias than theory built from incremental studies or arm-chair, axiomatic deduction" (Eisenhardt, 1989: 546). What is more, it is likely that the emergent theory will be testable using deductive methods, as the constructs from which it is made up will have already been measured during the process of building the theory (Eisenhardt, 1989).

The iterative nature of this process also makes it likely to yield empirically valid theory, as it is "*so intimately tied with evidence*" (Eisenhardt, 1989: 547). However, the risk is that the resulting theory becomes "*overly complex*" and is "rich in detail" due to the "*staggering volume of…data*" yet "*lacks the simplicity of overall perspective*" (Eisenhardt, 1989: 547). The lack of "*quantitative gauges such as regression results*" means that theorists "*may be unable to assess which are the most important relationships and which are idiosyncratic to a particular case*" (Eisenhardt, 1989: 547). Even if the resulting theory can be shown to be "*novel, testable and valid*" across the population from which it drew its cases, this population is often far more limited than theory generated apart from direct

[27] See section 8.6, for complete recommendations of additional interesting phenomena and specific cases where they could be observed

evidence (Eisenhardt, 1989: 547). For example, the theory generated during this research may well hold within the population of SWT rural electrification initiatives under study during this research, however will it necessarily apply to similar initiatives in very different local contexts (see section 8.6 for examples of such?

Understanding socio-technical systems, such as SWTs in rural electrification initiatives inherently requires the use of techniques from both engineering and the social sciences, as people influence the behaviour of the technology, yet the technology influences the behaviour of the people. The most interesting constructs that emerge from theory building using case study research are by definition very difficult to predict. Therefore, the ability to draw upon a much wider range of data collection and analysis methodologies gives the researcher a much greater arsenal from which to draw their weapon of choice when a particular need arises, meaning that they are much more likely to have the ability to properly investigate whichever phenomena do happen to occur. However, the researcher risks becoming the '*jack-of-all-trades and master of none*' as the limited time in which the study must be conducted allows for only so much time to be devoted to the learning of new data collection and analysis techniques or even the refining of existing ones.

The peer-review of multidisciplinary research can also prove difficult due to lack of specialists in such a broad area. Conventional science involves the incremental empirical testing and extension of existing theory, meaning that there are often many specialists with an intimate knowledge of a particular subject area, as these specialists have often been conducting this incremental empirical testing and extension themselves for many years. So whilst it may be relatively easy to find a specialist in wind turbine blade aerodynamics, socio-technical systems or economic modelling of renewable energy technologies, finding a specialist in building theory on SWTs from case studies that is capable of properly assessing the multitude of data collection and analysis techniques employed during this research is extremely difficult. As a result, some parts of the research may not be properly scrutinized and the resulting theory is likely to be weaker in these areas. A potential solution to this issue is to publish the research in separate parts, each of which are relevant to a specific discipline.

3.8.1 Positionality

The author's original motivation for this research came from an extra-curricular project with Engineers Without Borders (EWB) Sheffield that involved the construction of a 2.4m Piggott turbine at The University of Sheffield that began in 2009. The experience was not only informative, but also inspirational to many, as demonstrated by the large amount of attention that the project received not only within the university, but throughout the city and beyond. Wind turbines in the UK are often seen as a symbol of sustainability, towering high above their surroundings and clearly displaying the renewable power they are generating with the blades spinning around for all to see. There is no doubt that this initial hype surrounding the author's first experience with the technology created a significant bias in favour of it when beginning the research.

Figure 3-10: The EWB-Sheffield 2.4m Piggott turbine on display at the Peace in the Park festival in Sheffield in 2010. Photo courtesy of Pete Hodge.

However, as the research progressed and it became apparent that many of the SWTs installed around the globe were falling into disrepair, this bias started to swing towards the other direction. The realisation that most places in the world are not suitable for SWTs and that they are so strongly dependent on the socio-technical system around them gave the author a harsh dose of reality.

Whilst engineers frequently claim objectivity in their research, social scientists take a much more pragmatic view, declaring their positionality and the influence it may have on the research:

> *"There is no neutrality. There is only greater or less awareness of one's biases."*
>
> *Rose (1985: 77)*

In this case, it certainly cannot be said that the research produced is independent of the views/beliefs of the author, nor can it be said that the views/beliefs of the author are independent of the research. The two are uncontrollably intertwined and have evolved together throughout the duration of the research. The author began with the attitude: "*this is a great technology, how can we make it even more efficient?*" The research began as a very engineering focussed project, i.e. the optimisation of SWT blades for production by hand in the developing world. However, as the author learned more about the technology, the critical importance of the socio-technical system and the limitations of the applicability of the technology to specific local contexts, then this blind faith in the technology was gradually brought down to earth.

3.8.2 A reflexive journey wandering the insider-outsider continuum

Corbyn and Buckle (2009: 55) argue that "*the issue of researcher membership in the group or area being studied is relevant to all approaches of qualitative methodology as the researcher plays such a direct and intimate role in both data collection and analysis.*" Of course, the key benefit of membership is acceptance, enhancing "*trust and openness*" with the informants and permitting entry to groups and access to information that "*may otherwise be closed to 'outsiders'*" (Corbyn and Buckle, 2009: 58). However, the risk during data collection is that informants may "*make assumptions of similarity and therefore fail to explain their individual experience fully*" or that during data analysis, the researcher may emphasise shared factors and/or deemphasise discrepancies between the informant's experience and their own.

Ergun and Edemir (2009: 16-17) note it is not a "*simplistic binary divide*" between insider and outsider statuses, proposing instead that researcher identities lie somewhere on the "*continuum between insiderness and outsiderness.*" Indeed, nor is this status static, as relationships with individuals and groups are constantly re-evaluated throughout the course of the research and beyond (Naples, 1996). Adler and Adler (1987) defined three membership roles (Table 3-2) that assist researchers in positioning themselves on the continuum.

Table 3-2: Membership roles of qualitative researchers engaged in observational methods according to Adler and Adler (1987).

Membership roles	*Participation in core group activities?*	*Committed to group values and goals?*
Peripheral member researchers	No	No
Active member researchers	Yes	No
Complete member researchers	Yes	Yes

With regard to this research, the difficulty partly lies in defining the group under study. Whilst SWTs are certainly the technology under study, the group under study has varied throughout the research. Not only has the field work been conducted in three different countries, but also within three different frames of reference: national, organisational and community. Ergun and Edemir (2009: 18) state that "*the degree of a scholar's insiderness, or the degree to which scholars manage to overcome their outsiderness, is believed to determine easy access to informants, reliability of collected data, and the success of the fieldwork.*" It is certainly a notion that has had a profound effect during the course of this research, with the fieldwork conducted in the latter case studies being much more successful than that of the earlier cases[28].

[28] The order in which the case studies were conducted was determined opportunistically: the fieldwork in Peru was conducted at the same time as the author was attending the *International Simposium for Small Scale Wind Energy in* Lima, Peru; whilst the field work in Nicaragua was conducted when the opportunity to conduct the market assessment arose; and the field work in

The author's status as an engineer offered him insider status with the technical members of staff in each of the organisations with which he worked. Being able to discuss technical issues allowed him to gain the trust of these individuals, which later facilitated discussions on a wider range of issues. In Monkey Point, Nicaragua, the most remote of all the communities visited during this research, the wind power system was out of service when the author arrived. The switch had corroded, breaking the electrical connection, but with a little cleaning it was easy enough to fix. This relatively simple action allowed the author to gain the trust of the community technician, which made the upcoming interview significantly more fruitful.

Figure 3-11 illustrates the relative position of the author on the insider-outsider continuum to demonstrate the differences between scales and case studies, and even within case studies. Of course, the position on the scale is highly subjective and cannot be identified with any degree of accuracy, however it is useful in showing that the author was able to gain more of an insider status in the latter case studies and when working at the organisational and national scales. The reasons behind this and their implications on the research are discussed in the following section.

Scotland was conducted after the author had been invited by Piggott to work with him in his home community. See section 3.1.1.2 for further details.

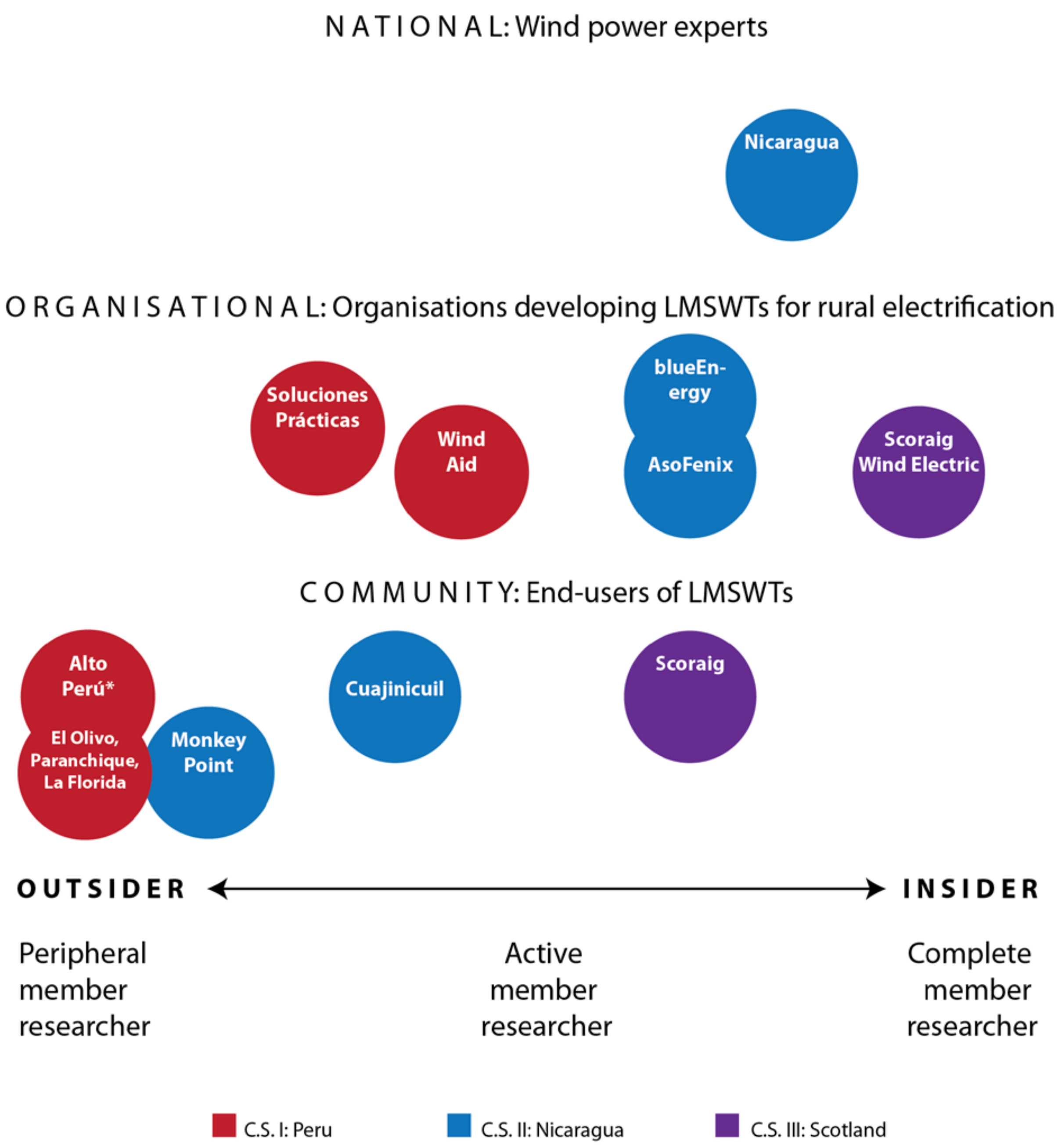


Figure 3-11: Approximate location of the author's position on the insider-outsider continuum and with regard to Adler and Adler's (1987) membership roles.

3.8.2.1 At the national scale

National scale field work was only conducted in Nicaragua, as it was a requirement of the market analysis commissioned by the US-based NGO, Green Empowerment (Marandin *et al.*, 2013). On arrival in Nicaragua, the research greatly benefited from the insider status of the leader of the consultancy team, Lâl Marandin (within the group of wind power experts in Nicaragua). Although not Nicaraguan by birth, his long-term residency in the country and his position as one of the founders of the NGO blueEnergy and the national association for renewable energy, '*Renovables*', as well as his recently launched business providing turn-key renewable energy solutions, PELICAN[29] allowed the research to tap into his extensive network of contacts. This not only allowed rapid identification of the most relevant participants for interview, but also the most likely method of securing an interview with them, for example, approaching a well-known informant with a friendly email or alternatively using the '*academic angle*' for more high profile participants to increase the "*trustworthiness*" of the request (Ergun and Erdemir, 2009: 32).

It is possible that Marandin's position, particularly his commercial role, could have led to "*concealment of information*" (Ergun and Erdemir, 2009: 17). However this is seen as unlikely, as none of the commercial actors interviewed were in direct competition with PELICAN and all reported that all of their wind turbine installations had encountered significant problems, demonstrating their openness about what could potentially damage the reputation of their businesses. Marandin's insider status as one of the most experienced small wind actors in the country could also have led informants to miss out information relating to their own experience, assuming this would already be known by Marandin. However, as all the interviews were conducted in pairs (Marandin and the author), this was thought to have a minimal effect on the information disclosed, as the author was unfamiliar to the participants. This therefore encouraged the full explanation of points that they may not have even brought up if talking to Marandin alone. As a result, this combination of insider-outsiderness, brought about partly by logistical necessity, proved to be an unexpectedly successful interview strategy.

3.8.2.2 At the organisational scale

Shortly after beginning this research project, the association WindEmpowerment[30] was formed and around 6 months later, the author became a member of the executive board. The author's position as a) a researcher in the field of SWTs, and b) a member of the executive board of WindEmpowerment, gave him a certain degree of insider status and trustworthiness when working with the various implementing organisations throughout the research, as they shared the common goal of providing sustainable electricity access to remote communities using SWTs. The direct consequence of this was the ease of access to information. For example, on arriving in Peru, the author received full details of a reliability study recently carried out by Soluciones Prácticas, which categorised each of the failures that had occurred with each LMSWT the organisation had installed. In a more commercial context (e.g. from a high profile, high volume manufacturer such as Bergey or Ampair), this information would be extremely difficult to obtain, as having a high failure rate or a significant number of dangerous failures (such as flying blades), could potentially jeopardise the reputation of the company. The sensitivity of this data could have been dealt with by anonymising the names of the organisations and informants, however due to the author's position in WindEmpowerment and the relatively small community it encompasses, it was deemed more appropriate to offer each NGO the opportunity to

[29] Central American Clean Energy Generation in Nicaragua (Producción de Energía Limpia Centroamericana en Nicaragua).

[30] All of the organisations studied during this research are members of WindEmpowerment, the global association for the development of LMSWTs for sustainable rural electrification.

review any documents produced from the data prior to publication. As mentioned previously, the review process did not result in any changes to the documents.

In fact, it is likely that the field work in Nicaragua would have been far less successful if the author had not been part of WindEmpowerment, as the author would almost certainly not have been invited to join the consultancy team for the previously mentioned market analysis. Being part of this team not only facilitated access to the wind power experts at the national scale, but also to the organisations blueEnergy and AsoFenix, as they both received funding and technical training from the commissioners of the study, Green Empowerment. What is more, two of the other members of the consultancy team were founding members of blueEnergy. It is also unlikely that the opportunity to work with Scoraig Wind Electric to perform the technical power curve measurements and ultimately carry out the final case study would have arisen if it hadn't been for the author's role in WindEmpowerment.

Representing the community of LMSWT actors through WindEmpowerment could also create an expectation to defend the "*cultural intimacy*" of the group (Herzfeld, 1997: 1). For example, disclosing information about the failure of certain projects could embarrass the organisation concerned, whilst disclosing information about the difficulties faced by the technology could embarrass the community as a whole. Making such information publically available could result in loss of income by damaging the reputation of the organisation or of the technology, with even the non-profit organisations (who do not rely on consumer preferences to source their funding) potentially suffering loss of donor funding. Nevertheless, this was also deemed to have minimal impact on the findings, as WindEmpowerment is merely a knowledge sharing network, set up by the members to enable them to share their experiences for the benefit of the development of the technology in the context of rural electrification. The open-source nature of the technology means that it is the collective experience of the members that guides its continual development and honesty and openness in its evaluation is therefore necessary to ensure that it continues to evolve to better meet the needs of the members and ultimately of course, the end-users. Respect for this goal can be demonstrated by the sharing of internal documents describing the failure of wind power in blueEnergy's rural electrification initiative on the Caribbean Coast of Nicaragua (Bennett *et al.*, 2011) with the author by disgruntled NGO staff and the disclosure of additional information after completing the field work in Peru:

> *"I hesitated reporting on it to you, but thought you certainly deserved to know - as I know that your goals are to make this work better for all of us so we can really evaluate using wind for rural energy."*
>
> *Kevin Michael VerKamp – Founder and Director of WindAid, personal communication 5th May 2012*

3.8.2.3 At the community scale

Ergun and Edemir (2009: 17) state that researchers are often given outsider status if they are "*a stranger or foreigner.*" There is no escaping the fact that conducting fieldwork as a white, middle class European in rural communities in developing countries is going to leave the researcher in very much of an outsider position. However, whilst the issue of the author's insider-outsider status "*is an essential and ever-present aspect of the investigation*," Corbyn and Buckle (2009: 59) recognise that it is not necessary to be a member of the group under study in order to "*appreciate and adequately represent the experience of the participants*." In fact, it may well be that outsiders are able to draw upon "*the wider perspective, with its connections, causal patterns, and influences*" (Corbyn and Buckle, 2009: 59). They claim that the most important factor is the ability to be "*open, authentic, honest and deeply interested in the experience of one's research participants*" (Corbyn and Buckle, 2009: 59) and this was indeed the attitude adopted by the author. Whilst the community-based field work in Peru consisted of little more than a brief tour of the equipment installed, it was in Nicaragua that the opportunity to fully immerse oneself in the cultural experience of living with a SWT-based electricity supply in a remote community arose. Interestingly the experience in the two communities visited, Monkey Point and Cuajinicuil, was very different. In Monkey Point, the author was very much treated as an outsider, whose questions were answered, but not elaborated upon and was left alone apart from mealtimes. Whilst in Cuajinicuil, he was welcomed into the community in much more of an active member role. As a result, the interviews lasted longer as more information was disclosed. The author was also invited to take part in social activities and offered food and drink at many of the homes that were visited and the author was treated very much as "*someone to be impressed*" (Adams, 1999: 347).

The reason for these differences in acceptance could be due to the language barrier – the author speaks fluent Spanish (spoken in Cuajinicuil), but almost no Creole (spoken as a first language in Monkey Point with Spanish as a second language). It could also be due to the fact that the renewable energy system installed in Cuajinicuil has been much more successful than in Monkey Point or the fact that blueEnergy was founded by internationals, whilst AsoFenix was founded by a Nicaraguan who grew up in a village nearby. This could have created an insider status for the NGO within the community from the beginning of the project, which could then have been attributed to the researcher by default.

In contrast to the field work conducted in Peru and Nicaragua, working in Scotland was far easier. There was no language barrier and in fact, many people even spoke with the same accent as the author, as many of the current inhabitants of the Scoraig peninsula had moved there from South-east England, with some even having grown up in the same county as the author! This common cultural identity allowed the author to take on much more of an insider role within the community, giving access to far more information than in any of the communities previously visited. The fact that everybody on the Scoraig peninsula has experienced life in the grid-connected, mainstream UK environment in which the author has grown up, lives and is writing this very sentence gave a stark contrast to the experiences of the informants living in the recently electrified communities in the Peruvian Andes or Nicaraguan Central Highlands.

The author's long term presence in the community due to the nature of the technical performance measurements (which required installing equipment in the homes of the informants selected for interview) permitted a much closer relationship to develop with the informants than ever could have happened during the relatively fleeting visits to the communities in Peru (a few hours) and Nicaragua (a few days).

What is more, Scoraigers are well accustomed to outsiders, with WWOOFers[31], couch surfers[32] and many other visitors frequently arriving from around the world. Many come specifically to see Piggott's wind turbines, with two wind turbine construction courses hosted on the peninsula every year. As a result, the author was seen as just '*another of Hugh's wind turbine fanatics*' and invited to participate in community activities, such as dinner parties and gigs, in much the same way as most newcomers are in this particularly open community. During the technical performance testing, Piggott and the author were invited into each home to chat over tea and often lunch or dinner as well, in part due to Piggott's respected status within the community, his good relationship with his neighbours and of course the friendly nature and welcoming attitude towards strangers of the hosts themselves. Along with the extended periods living off-grid at the Piggott household, it was these friendly conversations that inspired the inclusion of specific household case studies into this research, as it became apparent that unlike El Alumbre in Peru, each energy system (and therefore the experiences of each end-user) was very different.

This greater level of insiderness, familiarity with the geography of the community and lack of language barrier allowed the interviews in Scotland to be conducted by the author alone, whilst those in Nicaragua were conducted with members of the implementing NGO present. Although it was stated at the beginning of every interview that the author was not affiliated with the NGO, the fact that he was accompanied by NGO staff is likely to have affected the responses of the participants, potentially omitting information which could reflect negatively on the implementing NGO and portraying the information in a way that may encourage the NGO to make more or less interventions in the community in the future. In fact, in Monkey Point, one of the interviews was interrupted by a passing worker from a nearby plantation, asking the author to provide him with solar panels.

3.9 Conclusion

To determine the factors that critically affect the sustainability of SWTs in the context of rural electrification and how these factors vary between places, the study of a number of cases of existing

[31] World-Wide Opportunities on Organic Farms: a network of organic farms that welcomes volunteers from across the globe with an interest in sustainable farming practices.
[32] A global network of individuals offering a space on their couch (or spare bed) for free to travellers as an alternative to a hostel/hotel

SWT rural electrification initiatives was conducted. Case studies in Peru, Nicaragua and Scotland were chosen and a mixed methods approach to data collection and analysis was adopted. The case study evidence was used to build the theoretical framework described in Chapter 2. The subsequent chapters describe the case study evidence, whilst Chapter 7 makes cross-case comparisons between them. As part of the research process, the author became part of the system that provides support for SWT rural electrification initiatives, giving valuable insight into how the findings of the research could be put into practice. The quality of the findings from each case study were found to be proportional to the amount of time spent in the field, the number and variety of methods employed and the degree of cultural familiarity and insiderness with the particular group under study.

Chapter 4. Peru

Figure 4-1: The author holding a broken blade that flew off of the 2.5kW wind turbine installed in the Andean community of Paranchique by WindAid.

"Nobody is really interested in going back to someone else's project…[or] in reporting how many of their projects are no longer functioning."

Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012

4.1 Introduction

The approach to wind-based rural electrification in Peru has been very different to the Inner Mongolian experience. Here, NGOs have been using Piggott-derived wind turbine technology to electrify a number of rural communities. The intention is for these communities to serve as demonstration projects for local and regional authorities to replicate and disseminate on a larger scale. This chapter presents the first case study: the comparison of the delivery model employed by two of these NGOs, Soluciones Prácticas and WindAid. The technique of post-installation analysis is employed here to discover what has happened to each individual SWT, since it was installed by one of these two NGOs and therefore determine the factors that have affected the overall sustainability of the two rural electrification initiatives.

4.1.1 Rural electrification in Peru

According to the IEA's World Energy Outlook (2010), 67% of the country's rural population do not have access to electricity, whilst Yadoo (2011) claims the number could be as high as 77% as not all homes within areas that have electricity coverage are actually connected. Although it is hard to pinpoint an exact figure of the number of people without access to electricity, Figure 4-2 shows the dramatic improvement in the number of electrified households across Peru over the past 20 years. Effective government policies have channelled funds accumulated from the country's booming mining industry into ambitious programmes of grid extension, raising the percentage of electrified rural homes (according to official government statistics) from just 7.7% in 1993 to 63% in 2012 (MEM, 2012). In 2007, the DGER[33] was created and progress skyrocketed primarily due to the "*implementation of a diverse range of financing mechanisms*," including credit from the World Bank, agreements with mining companies and effective government policies in the form of the PNER[34] and LGER[35] (DGER, 2011: 1).

[33] Department of Rural Electrification (Dirección General de Electrificación Rural).
[34] National Rural Electrification Strategy (Plan Nacional de Electrificación Rural).
[35] LGER (Ley General de Electrificación Rural).

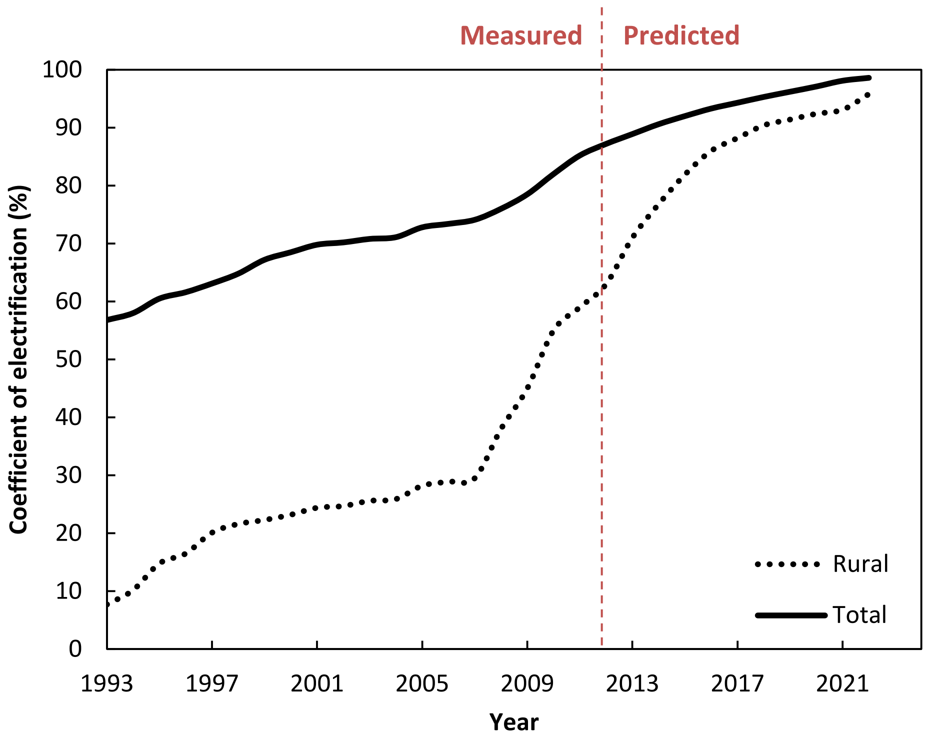


Figure 4-2: Coefficient of electrification in Peru. Data source: MEM (2012).

Until recently, decentralised energy solutions were given little attention in the Peruvian government's rural electrification agenda (DGER, 2011). However, many of the country's poorest people live in the remotest areas and this left them without any hope of gaining access to electricity for many years to come. NGOs such as Soluciones Prácticas and WindAid addressed this issue by introducing decentralised power generation technologies such as micro-hydro, PV and LMSWTs. The success of many of these pilot projects, together with their other activities such as establishing demonstration centres and political lobbying has meant that today, these technologies are included in official government policy (MEM, 2012),

Figure 4-3 shows the hierarchy under which the various technological options available for rural electrification in regions where grid extension is "*technically or economically unfeasible*" should be employed according to the Peruvian government's national rural electrification strategy, the PNER[36] (MEM, 2012: 7). Geographically speaking, Peru is an extremely diverse country, with some of the highest mountains, densest jungle and driest desert in the world within its borders. As a result, the renewable energy resources available across the country vary widely and consequently, the PNER also recommends specific regions in which each renewable technology is most viable (see Figure 4-3). The intense equatorial sun causes water from the vast Pacific Ocean to evaporate, forming clouds which are then forced up over the high peaks of the Andes, forming a thin strip of high wind potential. The rain that falls in these mountains collects into streams and rivers running down both eastern and western slopes, creating a vast hydroelectric potential. To the east sits the dense jungle of the Amazon

[36] National Rural Electrification Strategy (Plan Nacional de Electrificación Rural).

basin, where although the clouds that give the rainforest its name dramatically lower the region's solar potential, PV is left as the only viable technology, as the air is still and the ground is flat[37]. Between the Andes and the Pacific sits a thin strip of dry land, with some of the highest solar potential in the world and strong winds blowing in from the ocean.

[37] River current turbines are an experimental technology that has the potential to generate power from hydro resources with no head, but high flow rates such as the Amazon.

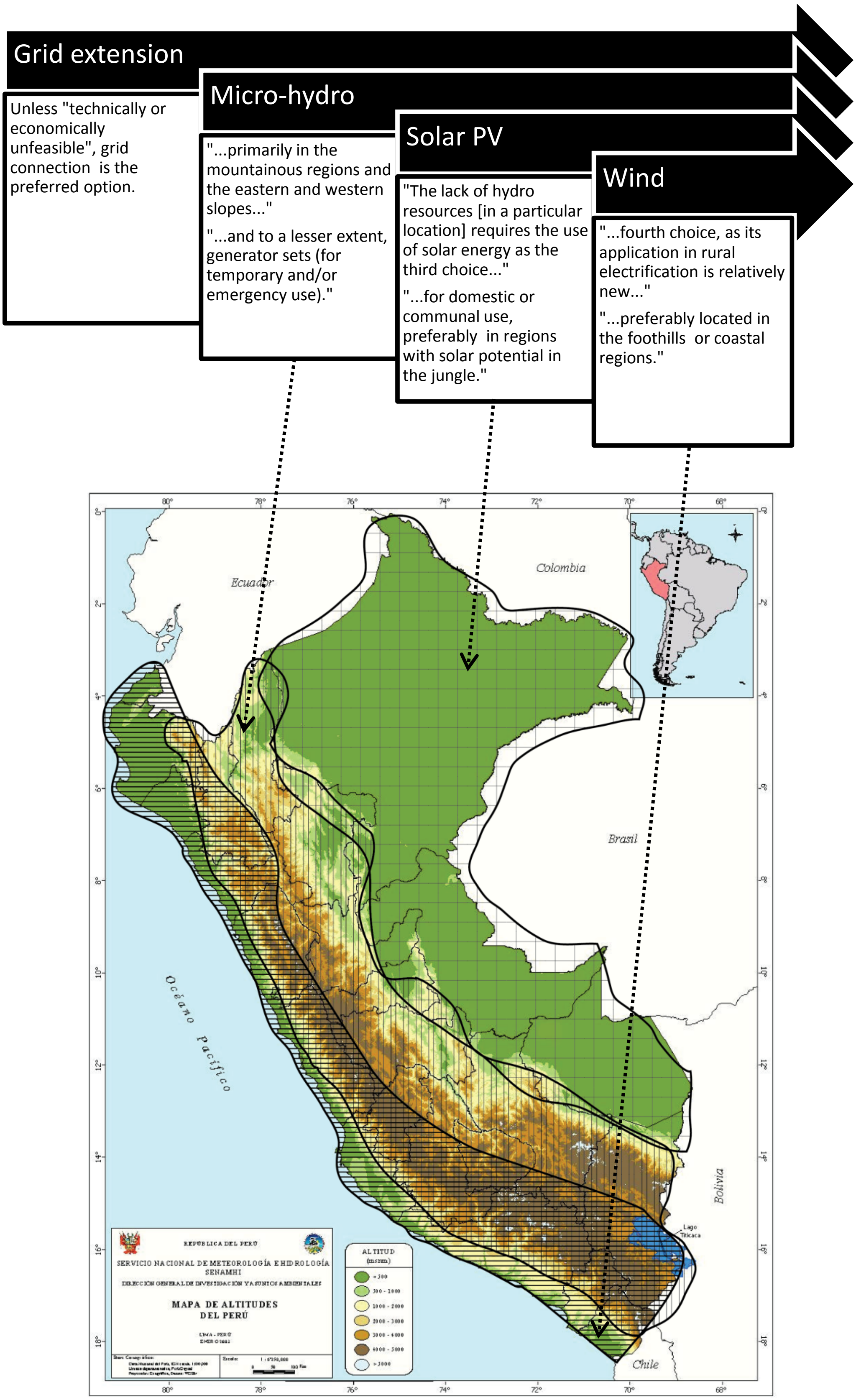


Figure 4-3: Hierarchy of rural electrification technologies and graphical representation of their respective priority zones within Peru according to the PNER (MEM, 2012). Image adapted from MEM (2003).

The availability of data on energy access in Peru is also now very good, with government sponsored solar, wind and hydro resource maps all now available to the general public (MEM, 2003; MEM, 2008). Figure 4-4 shows an example of the government sponsored free online GIS-based tool designed to illustrate the geographical distribution of these three key renewable resources, as well as the existing electricity distribution network, electrification projects and unelectrified communities (DGER, 2013). It can be seen that the department of Cajamarca has one of the lowest electrification rates in the country (MEM, 2012), however Figure 4-5 shows that it has some of the best wind resources. SWTs have been gaining popularity as a means of rural electrification in Peru during the last fifteen years, with three organisations now manufacturing SWTs: WindAid, Soluciones Prácticas[38] and Waira. As a result, Soluciones Prácticas recently hosted an international networking event designed to bring together the SWT ecosystem members from Peru and other Latin American countries (see Figure 4-6). The event was designed to share knowledge and foster collaboration between the various actors, which consisted of policy makers, manufacturers, renewable energy equipment suppliers, academics and more.

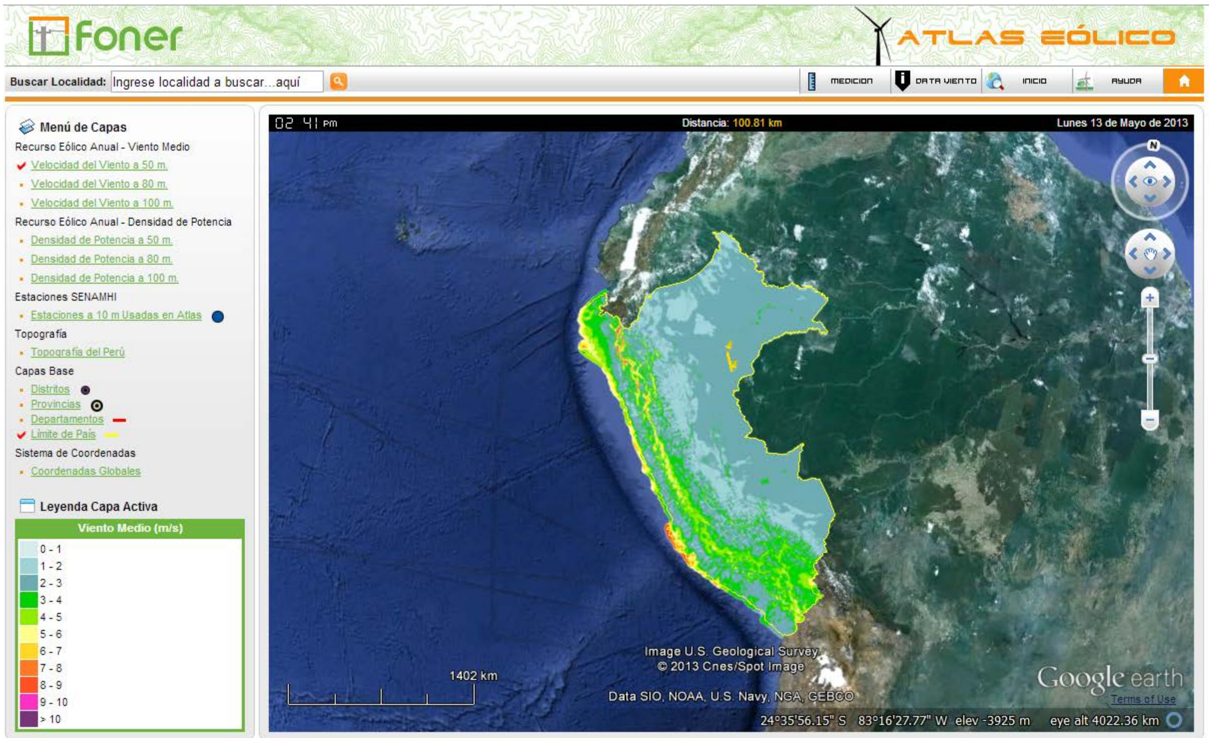


Figure 4-4: Screenshot of the new publically available GIS enabled Peruvian wind atlas.

[38] Designed by Soluciones Prácticas and manufactured by Tepersac.

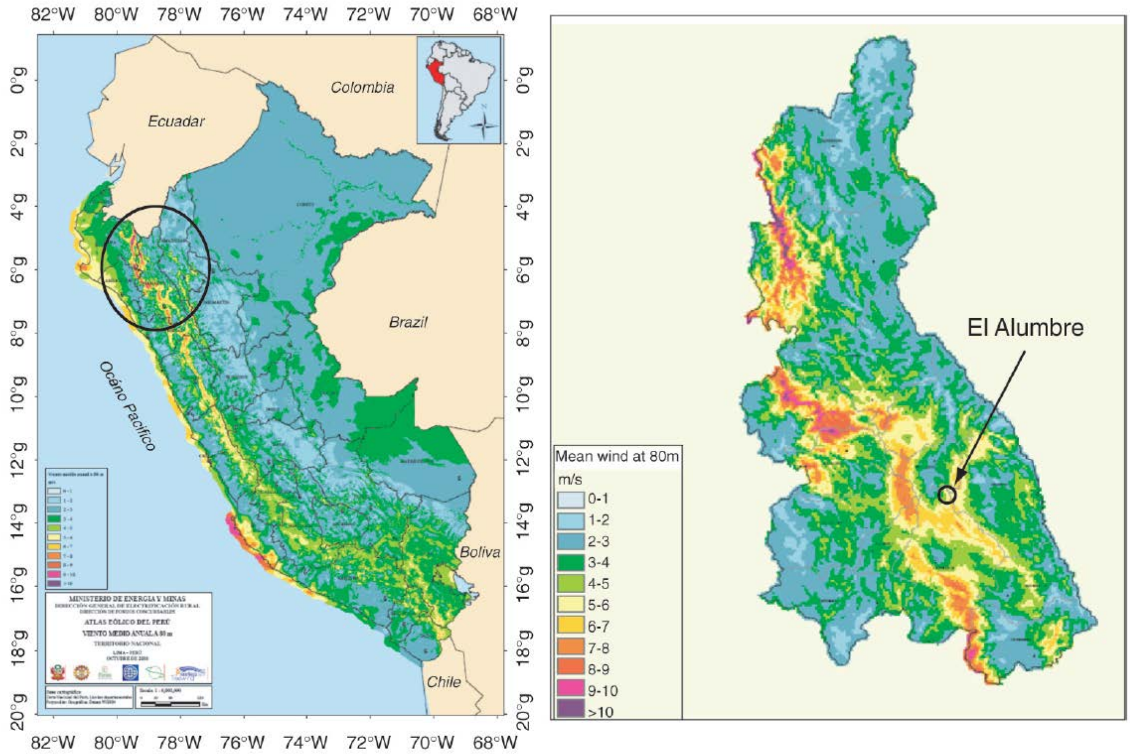


Figure 4-5: 80m wind map of Peru, with detail of the municipality of Cajamarca image adapted from Ferrer-Martí *et al*. (2010), original data from Meteosim Truewind (2008).

Figure 4-6: The International Symposium for Small Scale Wind Energy hosted by Soluciones Prácticas in Lima[39] was designed to promote collaboration between members of the small wind sector in Latin America.

4.1.2 Soluciones Prácticas

Soluciones Prácticas is the Latin American branch of the international NGO, Practical Action. In Peru, it employs over 100 people, the vast majority of whom are Peruvian. Their main role is developing and implementing small-scale appropriate technology solutions for poverty alleviation across a diverse range of fields, from agriculture to climate change adaptation. Within the field of renewable energy,

[39] The event was organised by The Wuppertal Institute in Germany and the US-based NGO, Green Empowerment.

Soluciones Prácticas was one of the first to employ micro-hydro power generation technology for rural electrification in the 1980s (see Figure 4-7). They pioneered the local manufacture approach by using off-the-shelf components, such as a pump as a turbine and a motor as a generator. Their commitment to "*putting people first, not technology*" (Practical Action, 2011: 1), means that they invest a significant amount of time and effort into training community members to operate and maintain the technological systems that they design.

Figure 4-7: Poster on the wall of Soluciones Prácticas' regional office in Cajamarca showing the many contributions that the NGO has made to improve energy access in Peru over the last 25 years.

Following on from the micro-hydro technology development programme, Piggott was employed by Soluciones Prácticas during the late 1990s as a consultant to assist with the design of an axial flux generator for SWTs that could be built in both Sri Lanka and Peru. The IT-PE-100 (Chiroque and Dávila, 2008) is a small, domestic machine with a 1.7m diameter rotor, capable of producing 300W at 11m/s and an RAEY[40] of 519kWh/yr. This was followed by the development of the larger SP-500 (Chiroque *et al.*, 2008) with a 4m diameter rotor that produces 1,000W at 11m/s and an RAEY of 1,855kWh/yr (see Figure 4-8). Following the production of a number of prototype models, El Alumbre in the mountainous region of Cajamarca was selected as the first community for Soluciones Prácticas' wind-based rural electrification programme, as the NGO was already active in the region and local wind maps (Figure 4-5) suggested that the community had a viable wind resource. Wind turbines have subsequently also been installed as part of hybrid renewable energy systems in two further communities, Campo Alegre and Alto Perú. However, only the data from El Alumbre is analysed in this chapter as this is where the most complete record exists.

[40] Rated Annual Energy Yield. See *Glossary* for definition.

Figure 4-8: Soluciones Prácticas' SP-500 in the Andean community of Alto Perú.

Although the Andean communities in which Soluciones Prácticas operate have a more cohesive sense of community than in Inner Mongolia, individual household scale micro wind turbines in the same style as the HWGs of Inner Mongolia were installed as distances between households varied considerably (see Figure 4-13). Here thirty three IT-PE-100s were installed for individual homes (see Figure 4-9) and two SP-500s for the local school and health centre in two phases. Firstly, in January 2008, twenty one households received IT-PE-100s and a single SP-500 was installed at the secondary school, then in January 2009, twelve domestic IT-PE-100s and another SP-500 for the health post were installed in the second phase. Follow-up work by Ferrer-Martí *et al.* (2010) has shown that the initiative has been successful in bringing about social change: 57% of households now use electric light to weave or knit in the evenings and members of neighbouring communities come to charge their mobile phones for a small fee.

Figure 4-9: A SWT in front of the 4000m Andean peaks around El Alumbre, Peru (Soluciones Practicas, 2013).

4.1.3 WindAid

WindAid is a social enterprise founded by the American entrepreneur Michael VerKamp in 2006 with the aim of exploiting the country's wind resources to improve the inadequate levels of electrification. VerKamp adapted Piggott's (2013) open-source design to create WindAid's 2.5kW wind turbine for production in Peru. The turbine has a 4m diameter rotor that is capable of producing 2.6kW at 10m/s and an RAEY of 4,877kWh/yr (see Figure 4-10).

Figure 4-10: WindAid's 2.5kW turbine installed at La Florida in the Huamachuco area.

WindAid began as a purely commercial operation, selling its turbines to businesses operating in remote areas, such as chicken farms or hotels. In 2009, WindAid's volunteer programme was established to address the difficulty faced by rural communities in finding sufficient capital to purchase a wind turbine. The volunteer programme invites international participants to travel to Peru and build a wind turbine with WindAid (see Figure 4-11). The construction process lasts around 4 weeks and culminates in the installation of the wind turbine in a remote Andean community. The materials and overheads for the construction of the wind turbine are paid for by the volunteers, who pay around US$2,000 for the 5 week programme. In return, the volunteers receive a practical wind energy training course, along with the experience of staying in a remote Andean community and providing them with a renewable energy system. The community is therefore able to receive this system free of charge. Communities are generally selected with the assistance of US volunteers placed in the area by Peace Corps, although the author is aware of at least one self-selecting community[41].

Figure 4-11: A British volunteer winds coils for the generator under the supervision of Cuban-American and Peruvian permanent staff members.

[41] A community leader travelled all the way to Trujillo (a day's journey on public transport) to request a SWT from WindAid for his community.

4.2 Methodology

As described in Chapter 2, LMSWTs require both preventative and corrective maintenance in order to keep them in operation. To perform this maintenance, technical knowledge, tools and spare parts are required and the roles determining who will perform which parts of the maintenance must be clearly defined. The provision for access to maintenance services is one part of the delivery model, which also encompasses the collection of fees for the service of providing access to electricity. The aim of this chapter is to investigate the effect of different delivery models on the sustainability of the wind-based rural electrification projects they were designed for. Two separate NGOs that have been using locally manufactured technology for wind-based rural electrification projects in Peru are compared: Soluciones Prácticas and WindAid. Both NGOs operate in the Northern Andean region of Cajamarca[42], meaning that the enabling environment (government policy towards SWTs, transportation infrastructure, environmental hazards, etc.) in which they operate are identical. As a result, the difference between their delivery models and the impact this has on the post-installation performance of the wind turbines they have installed can be more easily observed.

This study uses a mixed methods approach, combining interviews and observation with a post-installation analysis of each of the LMSWTs installed by the two NGOs. The methods used to obtain this data were different for each organisation, due to the differing availability of existing data and opportunities for data collection that were available at the time. However, the methods used to analyse the data once it had been collected were identical, making comparison between the two datasets possible.

4.2.1 Data collection

4.2.1.1 Soluciones Prácticas

Semi-structured interviews were conducted with each organisation's wind programme managers to determine the key features of their delivery model (see Appendix I for questions used to guide the interviews), including:

- The amount and quality of training offered to the community operators/administrators and end-users.
- The delivery model (tariffs, responsibilities for O&M etc.) for the wind-based rural electrification projects.
- The action taken to address recurring technical failures.
- The supply chain for spare parts.

Relevant reports and other internal documents describing the design, installation and management of their wind programme were reviewed, along with the published works by Ferrer-Martí *et al.* (2010; 2012) and Ranaboldo *et al.* (2013).

[42] Although WindAid also opérate in the Huamachuco area, just south of Cajamarca.

Interviews with the community operator/administrator and a selection of end-users in the community of El Alumbre were planned, however a state of emergency was declared in the region at the time due to protests against the opening of a new gold mine in the region, which local people claimed would contaminate their water supplies. Instead, an observational visit was made to a similar LMSWT rural electrification project in nearby Alto Perú, some smaller LMSWT installations on the coast, the university wind tunnel used to re-design the over-speed protection system and the renewable energy demonstration centre, CEDECAP[43]. A field diary was kept during this time, containing both written and photographic evidence (please see Appendix H for an example extract).

Soluciones Prácticas requires community operators/administrators to keep a maintenance log that records any failures with the wind power systems installed in their community. This historical data was collected and recorded in an Excel spreadsheet in November 2011 by Javier Samper of the Universidad Politécnica de Valencia on behalf of Soluciones Prácticas. Although not complete, this data was used as an input for the post-installation analysis, with estimations made for any incomplete entries. The most complete data set was available for the Andean community of El Alumbre, which covered 35 turbines from the day they were installed (January 2008 or January 2009) until October 2010 and covered a total of 28,206 days of turbine operation.

4.2.1.2 WindAid

At the time of this research, there was no published literature on WindAid, few internal reports and no record of failures was kept in the communities with which they were working, as the vast majority of maintenance was performed by WindAid engineers. To address this lack of information, the author accompanied WindAid staff for one week. The visit included time in the workshop, where LMSWTs were manufactured, the lodgings where the volunteers stayed and a maintenance visit to the three of the Andean communities where WindAid had installed LMSWTs (El Olivo, Paranchique and La Florida). During this time, much of the information obtained from the interviews and literature reviews mentioned previously was obtained either by observation or through informal questioning. Again, a field diary and photographic evidence was used to record these observations.

The post-installation record for each of the turbines installed by WindAid was generated retrospectively by questioning the members of the organisation's technical team who performed each of the maintenance operations. This data covers 7 turbines and begins when each turbine was installed (June 2009 onwards) and finishes when the observational visit took place (December 2011), covering a total of 1,848 days of turbine operation.

[43] Centre for Demonstration and Training (Centro de Demonstración y Capacitación): established in Cajamarca by Soluciones Prácticas in 1997 for the demonstration of appropriate renewable energy technologies to students, policy makers, engineers and community members, as well as providing training on the installation, O&M of these technologies.

4.2.2 Data analysis

On returning from the field, the field diaries, interview transcriptions and photographic evidence were reviewed to determine the key features of the delivery model adopted by each organisation. After conducting the post-installation analysis (described below), this qualitative data was again reviewed and related to the quantitative data in order to offer explanations for the trends observed. The framework described in Chapter 2 was used to categorise the evidence, thus providing a basis for comparing between the high volumes of data collected on each organisation. The data relating to each organisation was first analysed individually, in order to build up a more complete picture of the strategies adopted by each organisation. The framework was then used to compare corresponding data between organisations and to determine the impact these strategies on the success of each organisation's rural electrification projects.

4.2.2.1 Post-installation analysis

Analysing the post-installation record of each turbine installed by both Soluciones Prácticas and WindAid can give measurable indicators of the success or failure of a particular delivery model. To process the quantitative data collected from both organisations, a database was created, with each record in the database corresponding to the post-installation record of a single turbine. Each record contained the following information:

- Installation date.
- For each failure that may have occurred:
  - Date of failure.
  - Length of downtime (i.e. no. days until a repair was performed).
  - The part that failed (e.g. blade, generator, tower etc.).
  - The fault that occurred (e.g. snapped blade, burnt out generator, collapsed tower).
  - The reason why the fault occurred (e.g. high winds, corrosion, faulty electronics).
  - Where a spare part was supplied from (spares kept in the community, spares kept at a service centre or the manufacturer).
  - Any additional information.
- Date at which the data ends.

An example record is shown below in Figure 4-12. It refers to the IT-PE-100 LMSWT installed by Soluciones Prácticas on the 15th January 2008 at the home of Benicio Chávez Chávez in El Alumbre. On 28th September 2008, the rectifier burnt out in high winds. A spare was kept in the community and it was changed the same day that the fault was discovered. On 13th December the generator was taken down because it wasn't producing energy; however there was not enough information in the original log book transcription to be able to complete the record, so the information in red had to be estimated from other entries where the generator had failed. In this case, other failures had occurred due to high winds that same week, so it was assumed that this was the cause. The timeline at the bottom shows the operational status of the turbine from the day it was installed until the day that the dataset ends: either operating (green) or out of service (red).

Installation site:	Benancio Chávez Chávez						
Turbine type:	IT-PE-100						
Date	**Downtime (days)**	**Back online**	**Part code**	**Fault code**	**Reason code**	**Supply code**	**Comments**
15/01/2008							Installation
28/09/2008	1	29/09/2008	RECT	BURN	HIGH	COMM	Battery wasn't charging for a week
13/12/2008	7	20/12/2008	GENE	BURN	HIGH	COMM	Generator taken down because it wasn't generating anything
11/05/2010	2	13/05/2010	INVE	ELEC	ELEC	COMM	Inverter changed
16/08/2010	12	28/08/2010	INVE	ELEC	ELEC	COMM	Inverter changed
21/10/2010							Data ends

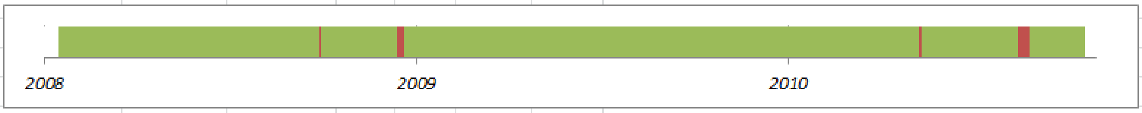


Figure 4-12: Example record in the post-installation analysis database. Red text indicates data missing from the original transcription of the log book that had to be estimated from other complete records. Red on the timeline indicates that the turbine is out of service.

This technique is based upon previous work by (Bennett *et al.*, 2011), in which they displayed the operational status of the turbines they were responsible for maintaining on the Caribbean coast of Nicaragua (see Figure 5-2). The technique was used mainly for visual impact, immediately showing the reader that the turbines had spent more time out of service than in. The technique is extended here with a greater level of accuracy (1 day as opposed to 1 month) and a greater number of turbines (42 instead of 4) and a greater amount of operating time (30,054 days as opposed to 2,520). What is more, it is backed up by a supporting database, which gives details of what failed, how it failed, why it failed and where spare parts were supplied from. The database facilitates the calculation of the following statistics:

- The average number of failures per component per turbine per year:

$$Failure\ rate = \frac{total\ no.failures\ per\ component}{total\ \ no.years\ since\ installation} \tag{3}$$

- The Mean Time Between Failures (MTBF) is a measure of reliability, taking into account the frequency with which faults occur:

$$\mathrm{MTBF} = \frac{\sum no.days\ between\ failures}{total\ no.failures} \tag{4}$$

- In addition to the number and frequency of failures, the time taken to repair each is also important. The resilience of the system is measured by the Mean Time To Return (MTTR):

$$\text{MTTR} = \frac{\sum no.days\ from\ when\ fault\ occurs\ until\ repair\ completed}{total\ no.failures} \tag{5}$$

- The final metric is the availability, which is a combination of both reliability and resilience and indicates the percentage of time that the system is in operation:

$$\text{Availability} = \frac{\sum no.\ \ days\ not\ able\ to\ produce\ energy}{total\ no.\ \ days\ since\ installation} \tag{6}$$

4.3 Evaluation of delivery models

4.3.1 Site selection & system design

Although Figure 4-5 may suggest that El Alumbre has a wind resource of 4-6m/s, the situation is not as simple as in Inner Mongolia, where the flat, barren plains allow the wind to sweep straight through. El Alumbre is located in the Peruvian Andes: some of the most complex terrain in the world. Firstly, the wind resource map gives average wind speeds at 80m hub height as it has been designed for wind farm developers. Translating this down to the 7-10m hub height of the LMSWTs installed by Soluciones Prácticas is not a simple task, as at this height the influence of very localised obstructions (such as houses, trees and rocks) becomes significant. Using a simple correction for flat terrain estimates a wind resource of 2.64-3.96m/s (converted from the 4-6m/s at 80m from Figure 4-5 to a 10m hub height). However, Figure 4-13 shows that it in fact varies much more: from 1.26-8.24m/s. Even small hills can funnel the wind around them and significantly alter the spatial distribution of the wind resource, so the fact that El Alumbre is perched on top of the Andes makes this wide variation unsurprising.

Unfortunately, the majority of the community is situated in the valley - the area with lowest wind resource. As a result, the technology failed to meet demand for quite a number of households. Recent work by Ferrer-Martí (2009) and Ferrer-Martí *et al.* (2011) on the El Alumbre project has shown that linking a number of households together in the form of a mini-grid could have had significant benefits in terms of both the initial capital cost of the system and its ability to meet the needs of the users. This would have allowed the use of larger, more economical micro wind turbines, located at points of high wind resource. However, as household metering was required and for some isolated users the cost of the connection still outweighed the gains from joining the mini-grid, the optimised cost was only 20% below that of the lowest cost configuration of isolated household systems that was capable of meeting demand. However, Leary *et al.* (2012) showed that in fact, this is still many times higher than the cost of the technology employed in Inner Mongolia.

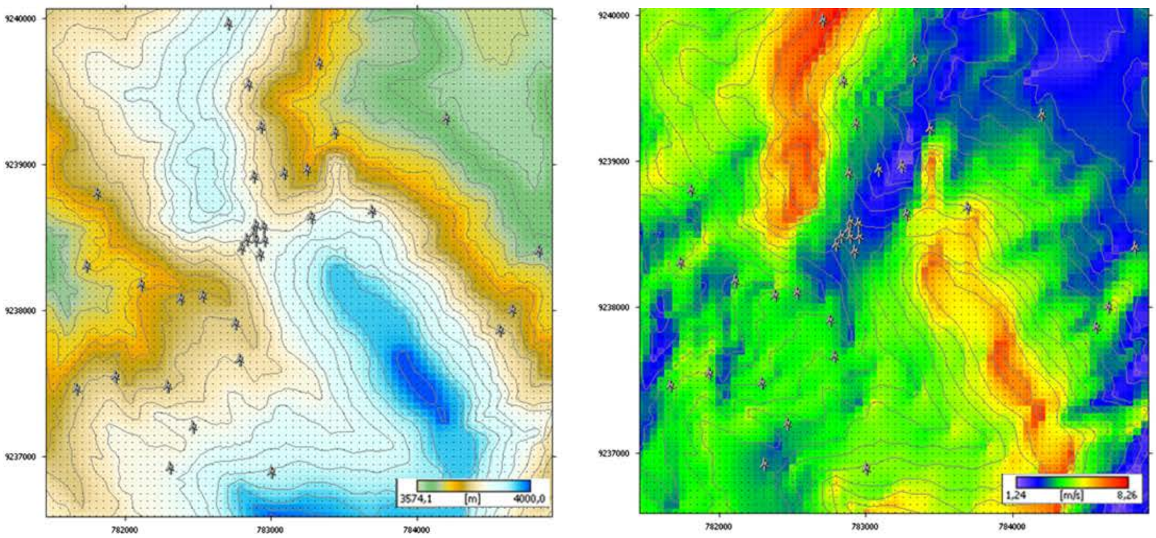


Figure 4-13: a) Topographical[44] and b) 10m wind resource maps[45] of the rural community of El Alumbre showing the location of the 35 LMSWTs installed in the community (Ferrer-Martí et al., 2012).

Figure 4-14 shows that simply quoting the annual average wind speed does not present a complete picture of the wind resource available at a particular place. In fact, during some months, a good wind resource does exist in El Alumbre, even in the valley. However, in others there is almost nothing and due to the cubic relationship shown in (1), the power available in September 2007 was 117 W/m^2, whilst in December 2008 it was just 11W/m^2 – an order of magnitude less. The decision to supply power to each household solely from the wind meant that in the months where the wind resource was below 3m/s, almost no energy would have been harvested. As a result, Soluciones Prácticas elected to install LMSWTs as part of hybrid energy systems in subsequent electrification projects in the Andean communities of Campo Alegre (PV-wind hybrid household generators) and Alto Perú (separate PV-wind, PV and micro-hydro mini-grids), the performance of which are currently under investigation (Ferrer-Martí *et al.*, 2010).

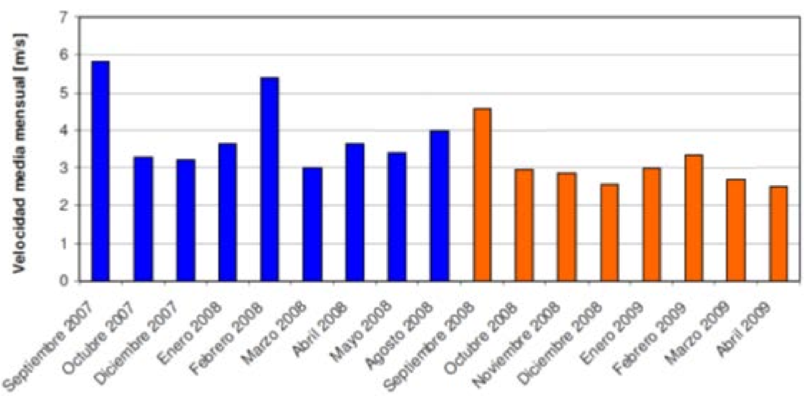


Figure 4-14: Monthly variation in wind resource measured at El Alumbre, Peru (Ferrer-Martí, 2009).

[44] Shows elevation as height above sea level.
[45] Shows wind speeds at 10m above ground level, i.e. for wind turbines with a 10m hub height.

What is more, in addition to the wind's velocity, Equation (1) shows that the density of the air, which also critically affects the available power. Temperature, humidity and barometric pressure changes due to local weather patterns can all have an effect, but it is small compared to that of altitude, which can reduce the available power by 33% at 4000m above sea level (see Figure 4-15). El Alumbre is located at 3,700m above sea level, resulting in a further 30% reduction in the power that would be available in winds of the same speed at sea level. The one redeeming feature of the wind resource at El Alumbre is the fact that there are no trees to obstruct the flow (see Figure 4-9).

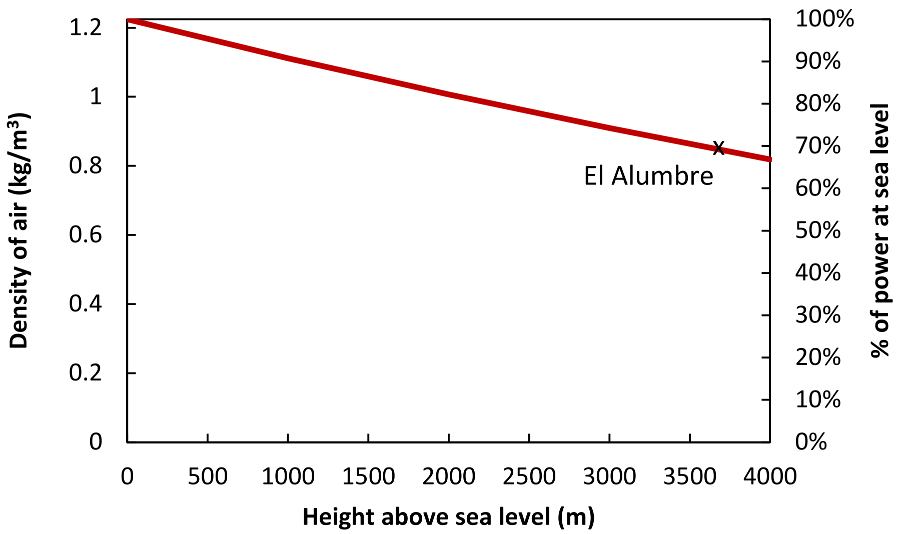


Figure 4-15: Variation in air density and corresponding reduction in available power with altitude[46].

In contrast to the household wind generators installed by Soluciones Prácticas, the much larger 4m diameter LMSWTs installed by WindAid are designed to provide power to a community building such as a health centre or a school. In many of their installations, community members can bring batteries from their household to the turbine for charging. This is certainly not as convenient as having an individual household generator and would score one tier below (tier 1, as opposed to 2) on Practical Action's (2013) indicative household electricity framework (see Figure 1-4). However, the advantage is that the single LMSWT can be located at a point of high wind resource, as opposed to next to every single household, regardless of the wind resource at that particular site. The buildings to be electrified are deliberately selected due to the suitability of the site, however only a basic resource assessment is conducted. A national wind map is used to check whether the site is likely to be in a windy area and a basic site assessment is conducted by visually assessing the topography, i.e. choosing hilltop sites with few trees. However, as demonstrated by the evaluative work conducted by Ferrer-Martí *et al.* (2012) in El Alumbre, the wind resource is extremely difficult to predict in complex terrain and as far as the author is aware, no such evaluations have been conducted at WindAid installations, leaving no record of either the wind resource or energy production at any of the sites. Unfortunately, the risk with larger

[46] Air density values also include a temperature drop of -6.5°C per 1000m in accordance with International Standard Atmosphere data.

generators is that if the site on which it is installed is not ideal, then the electricity supply for the entire community will be drastically reduced (see Figure 4-16).

Figure 4-16: Wind turbine installed by WindAid at El Olivo on a ridge, but between a tree and the powerhouse.

Interestingly, Soluciones Prácticas are planning to increase the size of their LMSWTs to mitigate the problems they have encountered with the variability of the wind resource. They have recently commissioned Peruvian wind turbine manufacturer Waira to install a 5m diameter machine (rated at 3kW at 10m/s) at a test site on the coast. Conversely, WindAid have now developed a smaller turbine rated at 500W.

4.3.2 Capital

The two organisations have very different funding mechanisms, both of which introduce separate issues. For example, although Soluciones Prácticas are a non-profit organisation, they receive large sums of money from international donors, to whom they have an obligation to present their projects in a favourable light. WindAid operate both a social enterprise and *'voluntourism'* model, which has the potential to speed up product development, as the volunteers bring new ideas, whilst the production of additional machines for commercial customers increases their manufacturing experience and allows them to benefit from the economies of scale that come with higher volume production much sooner (see Figure 4-17). However, it also creates a conflict of interest, as the interests of the volunteers and commercial customers are often put ahead of the end-users in the remote communities, entrenching their role of as *"passive beneficiaries"* (Cross, 2012: 1). For example, the role of the carbon fibre used in blade manufacture (see Figure 4-27) is primarily as a marketing tool, as many volunteers want the experience of working with carbon fibre and the commercial customers are more likely to buy a product seen to be *'high-tech'*. However, if the communities are to be expected to pay for maintenance in the future, they are the ones who will have to find even more money if their turbine ever loses a blade.

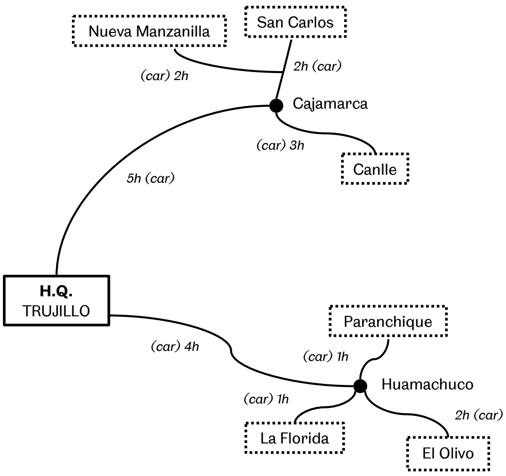
Figure 4-17: Delivery of the new CNC miller and plasma cutter to WindAid's workshop, which will allow them to cut rotor discs and manufacture moulds for composite parts (such as the blades) themselves – one of the benefits of manufacturing on a larger scale.

4.3.3 Operation and maintenance (O&M)

4.3.3.1 Supply Chain

The diversity of Peru's landscape presents a particularly difficult logistical challenge. Whilst travel along the thin strip of desert beside the coast is relatively easy, any travel further inland requires ascending over 3,000m up into the Andes. On arriving in the mountains, roads to these remote communities are often little more than dirt tracks winding back and forth across the mountainside. For example, the journey to El Olivo from WindAid's workshop in Trujillo requires a 4 hour car journey on a winding but paved road to Huamachuco, followed by a 2 hour drive on a dirt track full of hairpin bends and across a river via a ford that is only passable by 4x4 in the dry season. Getting equipment and appliances out to these remote Andean communities for the installation is extremely challenging, however getting spare parts, tools and technical knowledge there on a regular basis for maintenance has proved even more difficult. Although WindAid and Soluciones Prácticas face almost identical logistical challenges, their approaches to creating supply chains out to these remote communities through this complex terrain have been very different.

WindAid are based in Trujillo, where they also manufacture their own wind turbines. Figure 4-18b shows two Andean regions in which they have installed wind turbines: Cajamarca and Huamachuco. All spare parts are supplied from Trujillo and few tools are kept in the community. Very basic corrective maintenance can be performed by some end-users with telephone instructions from WindAid; however the vast majority of corrective maintenance requires an engineer to travel from Trujillo. Only the most basic preventative maintenance is carried out (topping up batteries with distilled water etc.).



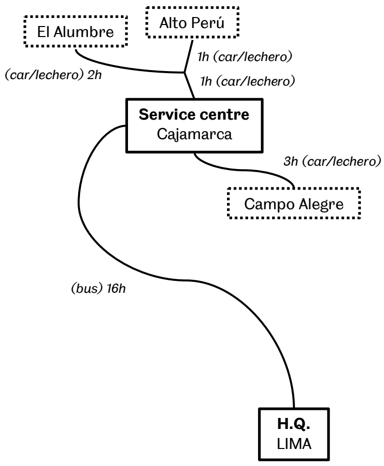


Figure 4-18: Network diagram showing the physical locations of the key actors in the supply chain for a) WindAid and b) Soluciones Prácticas.

The IT-PE-100 and SP-500 were developed in Lima, where the headquarters of Soluciones Prácticas is located (see Figure 4-18a). The turbines are manufactured here by a Peruvian private enterprise, Tepersac, who specialise in the production of renewable energy equipment. Soluciones Prácticas have additional regional offices around the country, including Cajamarca. As this is the region where all three of their wind-powered communities are located, the Cajamarca office is therefore able to operate as a service centre, offering technical knowledge, tools and spare parts to the community technician and bridging the geographical gap between the installation site and the manufacturer.

In the event of a failure in El Alumbre, components are replaced from a stock of spare parts kept in a store room within the community consisting of three complete systems (blades, generator, tail, controller, inverter, and dump load), ten rectifiers, a selection of nuts and bolts and electrical cabling with terminals (see Figure 4-19). The operator/administrator has the following tools available within the community to perform both preventative and basic corrective maintenance operations: a toolbox containing spanners, pliers, screwdrivers, Allen keys, a hammer and electrical tape; cleaning equipment; a multimeter; and sandpaper, paintbrushes and rustproof paint.

Figure 4-19: Toolbox, Spare blades, nose and other miscellaneous parts stored in the battery shed in Alto Perú (an even more extensive stock exists in El Alumbre).

If a repair cannot be made within the community, the failed part will be sent back to Cajamarca on the lechero's truck[47], where it is received by the service centre in Cajamarca for inspection. If it is possible to repair the part, it is sent back to the Lima office by bus and finally to the original manufacturer, Tepersac. Batteries and towers are also supplied from Lima.

4.3.3.2 Knowledge transfer

During installation of the systems, WindAid encourage all community members to actively participate in the labour intensive tasks such as the raising of the tower and digging of the anchors. The community are encouraged to form a wind committee to look after the O&M of the turbine, but the way in which this is done is left up each individual community. Little technical training is given as almost all maintenance is performed by WindAid engineers who travel up from Trujillo in the event of a failure. For safety reasons, WindAid do not allow the communities to lower the tower by themselves. Funds are collected by the wind committee for the battery charging services that the wind turbine

[47] Truck that collects milk from the communities, where the main form of income is often dairy farming. The truck also transports goods and passengers during its normal service for a fee.

offers, however they are rarely enough to cover the maintenance costs and the balance is paid by WindAid. Figure 4-20 shows WindAid staff performing a check-up on the battery bank fed by the 2.5kW LMSWT installed in El Olivo. The photograph reflects the 'hands-on' approach that WindAid take to O&M, i.e. WindAid do everything they possibly can themselves.

Figure 4-20: The two community members responsible for the wind turbine look on whilst WindAid staff rewire the inverter at El Olivo.

In contrast, Soluciones Prácticas focus on the empowerment of community members to be able to operate and maintain the renewable energy systems they install themselves, which is described in detail by Ferrer-Martí *et al.* (2010). In addition to encouraging participation in the installation of the systems, Soluciones Prácticas offered basic training to all members of the community on the limitations of the system, how to take care of it and how to make best use of the energy it provides. They also received printed manuals to keep as a reference guide. The next stage in the training process involved the nomination of members of the community in an open meeting for the position of the operator/administrator of the wind power system. The eight nominees attended a comprehensive training programme at CEDECAP (see Figure 4-21) on the O&M of a wind power system, covering both technical and business skills and ending in a written exam to check for comprehension. An operator/administrator is then elected by a panel of community leaders and project organisers based on the test scores, their reputation within the community and their involvement with previous community projects. The top candidate becomes the operator/administrator, whilst the second acts as an assistant. Regular re-elections ensure that the operator/administrator is fulfilling their role as expected. This model respects the existing power dynamics present in the community (as the community leaders form part of the selection committee), whilst also prioritising individuals with the technical ability and motivation to perform the role (as their test scores and conduct in previous community initiatives are both taken into account).

Figure 4-21: Mural depicting the role of CEDECAP in rural energy empowerment in Peru.

After selection, the operator/administrator runs the wind energy system as a micro-enterprise: each family pays a small fee for the electricity they receive (US$3 per month), which goes towards a reserve fund to pay for maintenance costs and a wage for the operator/administrator (US$10 per month). However, the fund collected by the community is also not enough to cover maintenance, again, leaving Soluciones Prácticas to cover the difference. The roles of the operator/administrator are as follows:

- Perform monthly check-ups on each turbine and, when necessary, preventative maintenance (see Table 2-3) on each turbine.
- Perform basic corrective maintenance when failures occur and keep a logbook to record any such incidents.
- Send any parts requiring advanced corrective maintenance off to the service centre for repair and install a replacement.
- Collect the monthly fee from the end-users for the provision of electricity.

Comparing Figure 4-22 with Figure 4-20 clearly illustrates the different approaches taken by the two organisations. The electrical installation in Figure 4-20 is very much a *'black box'* to the untrained eye – components are sat on the floor with wires shooting out all over the place. In contrast, the neatly laid out control panel shown in Figure 4-22 is much easier to understand, especially for people without any prior experience with electrical systems, i.e. the community technicians.

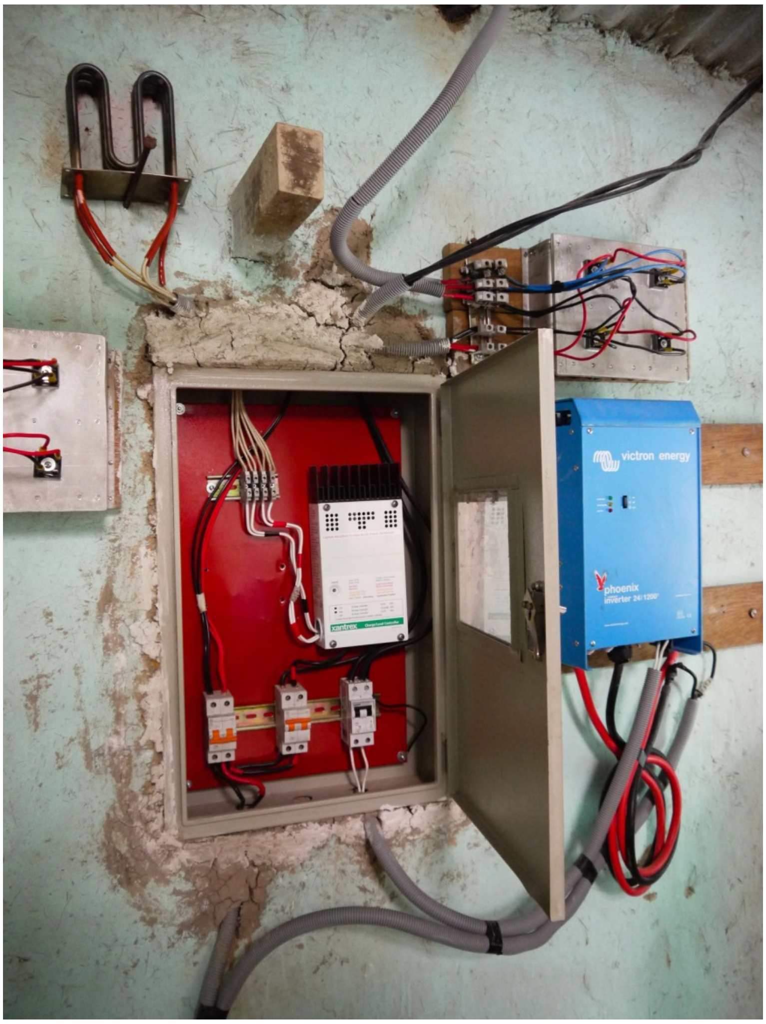


Figure 4-22: A much tidier and therefore easier to understand electrical system installed by Soluciones Prácticas.

4.3.3.3 Post-installation Analysis

Figure 4-23 is a graphical representation of the post-installation record for both the thirty-five turbines installed in El Alumbre by Soluciones Prácticas and the seven turbines installed in the Cajamarca/Huamachuco area by WindAid. Each turbine is represented by a bar, with green sections of that bar indicating time when the turbine was operating normally and red sections showing when it was out of service. Figure 4-24 compares the data obtained for both organisations using the three key performance indicators defined in equations (4), (5) and (6): the Mean Time Between Failures (MTBF), the Mean Time to Return (MTTR) and the Availability.

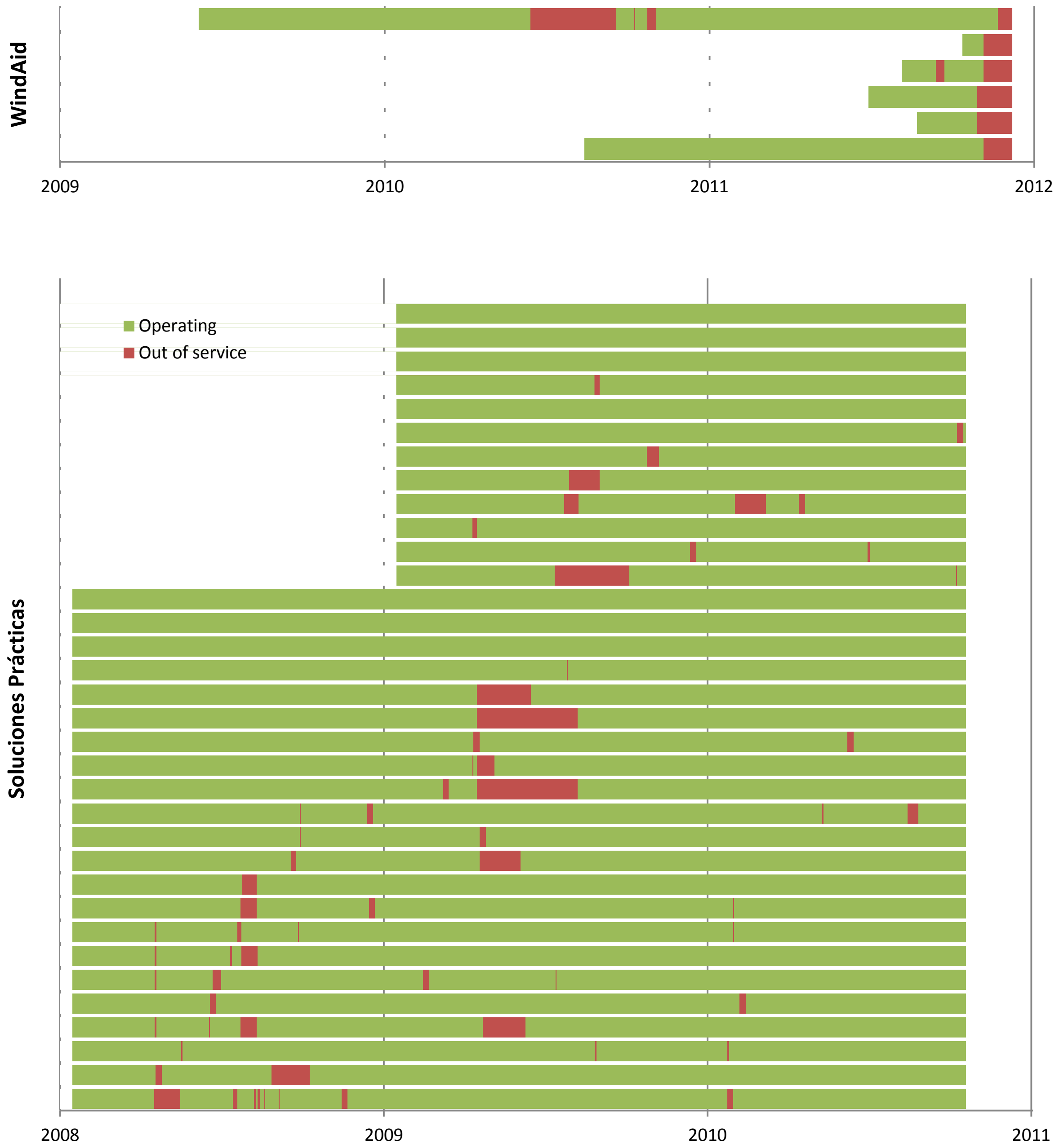


Figure 4-23: Timeline plots showing the uptime (green) and downtime (red) of each turbine in the database for a) WindAid and b) Soluciones Prácticas.

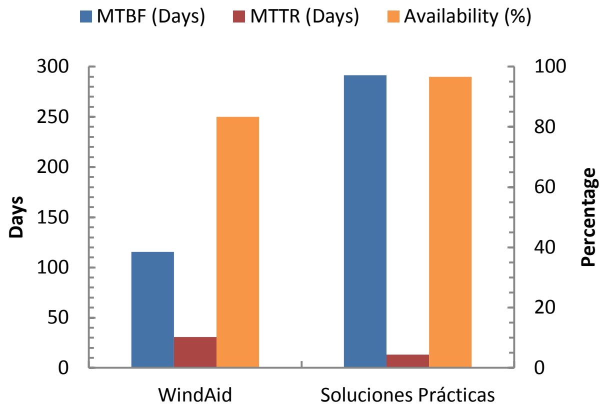


Figure 4-24: Comparison of three key performance indicators: Mean Time Between Failures (MTBF), Mean Time To Return (MTTR) and technical availability.

4.3.3.3.1 Reliability

WindAid's MTBF of one hundred and fifteen days is less than half that of Soluciones Prácticas' two hundred and ninety four days, indicating that their LMSWTs fail more than twice as frequently. This can be partly explained by the fact that the operator/administrator in El Alumbre is able to perform sufficient preventative maintenance and therefore greatly reduce the probability of technical failure. However, manufacturing quality also has a significant effect on the frequency of failures: WindAid developed their first wind turbine 10 years after Soluciones Prácticas and have produced around 10 times fewer turbines in total. As a result, Soluciones Prácticas' increased manufacturing experience has greatly reduced the number of design flaws. What is more, their turbines are produced by a specialist company, who has manufactured renewable energy technology since the 1980s. This is in contrast to WindAid's turbines, which are produced by international volunteers with little or no prior experience of manufacturing. Although they are overseen by permanent technical members of staff, the potential for introducing errors in the manufacturing process is clearly greater. In addition to this, the basic training and printed manuals given to the end-users by Soluciones Prácticas has allowed for swift identification of any irregularities in system operation by the end-users. When reported to the operator/administrator, appropriate action has then been performed before a major failure has occurred.

4.3.3.3.2 Resilience

With regard to resilience, the difference between WindAid and Soluciones Prácticas is even greater, with MTTRs of thirty one and four days respectively. For Soluciones Prácticas, the presence of the fully trained operator/administrator in the community means that whenever a technical failure does occur, they are able to perform a repair as soon as possible. The comprehensive technical training programme and well defined management model (Ferrer-Martí *et al.*, 2010) clearly sets out the roles of the operator/administrator (including the ways in which they should interact with other relevant actors) and empowers them to be able to fulfil these roles. The fact that several potential operator/administrators were trained means that there is always somebody on hand to provide technical assistance, even if the appointed operator/administrator is unavailable. The stock of spare parts and tools kept in the community also plays a key role in getting the wind power systems up and running again as soon as possible. For example, Figure 4-25 shows that rectifiers are one of the most problematic components for Soluciones Prácticas; however replacing a rectifier is cheap and very simple. With the spare parts and tools on hand, as well as the knowledge of how to do so, the majority of the failed rectifiers were replaced within twenty four hours.

On the contrary, all of WindAid's turbines suffered technical failures in November 2011. As a result, the communities they served were left without power for over a month, until the technical team were able to find time to travel up to each of the communities in the mountains. In fact, due to the long travel time between the Huamachuco and Cajamarca regions, only the three communities in the Huamachuco area were visited by the author.

> *"I just returned from our three installations near Cajamarca, with the intentions of putting the three back into service. Unfortunately, one of the wind generators which had stopped after a minor earthquake was unable to be fixed on site (not only would it not yaw, the tower is apparently fused to the generator structure) so it is being shipped back to Trujillo. The other two we were able to restore service (replacing the blades on one, and installing an inverter on the other)."*
> *Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012*

It is unknown when the communities in the Cajamarca area were next visited by WindAid's engineers. Extended periods without power significantly reduce the value of the energy system to the community (Hirmer and Cruickshank, 2014), as any vaccines stored in fridges will have deteriorated and any businesses based on its operation may well have gone bankrupt. This in turn further reduces the amount of effort that the members of the community are willing to put into maintaining the system in the future. In fact, this was spiral of decline was found to be one of the major contributing factors to the decision of the Nicaraguan NGO, blueEnergy, to put a halt to its wind power programme (Bennett *et al.*, 2011; Leary *et al.*, 2012).

4.3.3.3.3 Root Cause Analysis

With his 30 years of experience with LMSWTs, Piggott (2013: 9) rightly states that "*small wind turbines are nothing but problems*." A root cause analysis was conducted using the information from the database shown in Figure 4-12 to identify of the reasons why each problem has occurred. Using this information, the subsequent section (4.4) details appropriate modifications to the design and adjustments to the O&M procedures or the supply chain (to ensure the availability of spare parts when failures do occur). Figure 4-25 shows the breakdown of the average number of failures per turbine per year by component.

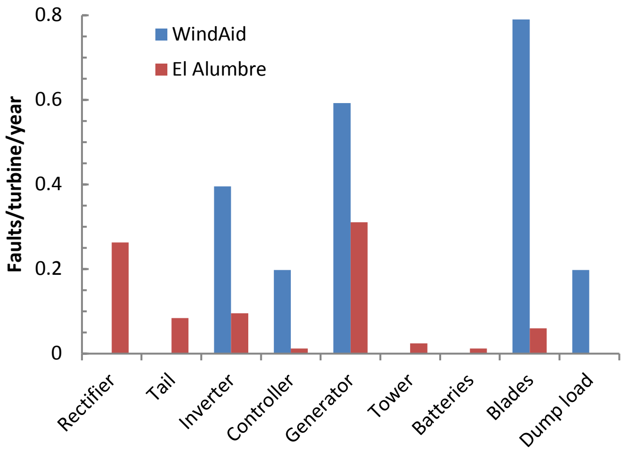


Figure 4-25: Normalised comparison of the breakdown of faults per component experienced by both WindAid and Soluciones Prácticas.

Design faults

Both the major problems for Soluciones Prácticas have been caused by the failure of the over-speed protection system in high winds. The lack of an emergency brake that would allow the user to stop the turbine in high winds meant that failures were very likely to occur whenever the winds stayed over 12m/s for an extended period of time, as the machines were generating an excessively high amount of power. Whilst the furling system designed to protect the machine from these high winds would function correctly for the majority of machines, around 20% of the mechanisms would jam and it was only a matter of time before either the generator would burn out and/or the rectifiers would blow. This has been the root cause of 46% of their failures. The tails are also often broken in high winds (10% of failures), but would not have been protected by the over-speed protection system. The twisting up of the power transmission cables inside the tower has often resulted in the cable ripping out of the back of the generator and is responsible for 13% of failures.

Corrosion of the permanent magnets[48] in the generator have caused problems for both WindAid (10% failures) and Soluciones Prácticas (6% failures).

Manufacturing faults

Safety is critical with wind turbines, as the machines spin at high speed on top of a tower and can easily harm a bystander if a part were to fall. In El Alumbre, poor quality welding has led to two towers collapsing and three turbines falling from the top of the tower, whilst 30% of WindAid's failures have been due to blades flying off (see Figure 4-1)[49]. Fortunately nobody was hurt during any of these incidents, but it is of critical importance to address these modes of failure, especially when

[48] When water gets into the magnets, they swell and cause the stator to rub on the rotor, preventing the turbine from rotating.
[49] These could also be considered as design faults, as the blades were redesigned afterwards to prevent this from happening.

considering that many of the turbines are installed at homes or schools where children will be present.

Operating faults

Finally, WindAid experienced an inverter failure caused by a user plugging in a large television and drawing too much current.

4.4 Recommendations

A series of recommendations were made with the aim of reducing the downtime of the wind power systems installed by each organisation. Some the issues identified above have already been addressed and as a result, the following section describes both the solutions found by Soluciones Prácticas and WindAid and those proposed as a result of this research.

4.4.1 Soluciones Prácticas

The success of Soluciones Prácticas' delivery model has ensured high levels of availability for the wind power systems that they have installed. However, there are some persistent technical issues that still need to be resolved:

4.4.1.1 Manufacturing faults

When manufacturing in low volumes (<100 units), ensuring quality is challenging (Craig, 2013), as a result the quality of welding should be checked before leaving the workshop and rechecked regularly for cracks and corrosion to avoid dangerous structural defects.

4.4.1.2 Design faults

The problems with the over-speed protection system are already being addressed by Soluciones Prácticas, who are using the wind tunnel shown in Figure 4-26 to characterise the over-speed protection system and improve its reliability. An emergency brake that will allow the operator to stop the turbines in high winds is also under development. The issues of twisting up of electrical cables inside the tower and the breaking of tails are also being addressed with simple modifications to the design[50].

[50] The twisting of the cables inside the tower caused the cable to tear at the point where it connected to the stator. A stronger and more rigid connection was designed to prevent this, similar to that recommended by Piggott (2013). Thicker plywood and stronger bolted connections were used on the redesigned tails. Full details of these design modifications are given by Chiroque (2011).

Figure 4-26: An IT-PE-100 in the wind tunnel been constructed by Soluciones Prácticas at the Universidad Nacional de Ingeniería in Lima.

During the manufacture of the generator, when the permanent magnets are placed on the steel rotor disc, their magnetic attraction causes them to hit the disc with significant force and often chips the brittle protective coating. WindAid have recently modified the design of their generator to include a thin layer of resin directly onto the steel rotor disc to act as a cushion when the magnets are placed on top. This design modification could equally well be applied to Soluciones Prácticas' turbines and would be likely to significantly reduce their corrosion problem. An alternative is to switch to ferrite, as opposed to neodymium magnets, that are not as powerful but do not suffer from corrosion problems.

4.4.2 WindAid

The large distances between the communities that WindAid works with and their headquarters, coupled with the lack of technical training for wind committee members has caused significant downtime and needs to be addressed if their wind power systems are to be considered sustainable.

> *"…the reality is that Cajamarca was too far from our base to have done these projects at the time. We were on horseback for 6 hours on Thursday at 3800 meters, most the time in rain, followed by a 3 hour drive. These are not practical places to be doing trials…"*
> *Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012*

The fact that the wind committee members are not even allowed to lower the towers of their own SWTs means that they are essentially a 'black box' technology, just like PV, as they are "*entirely dependent on the intervention of specialist engineers should something go wrong*" (Cross, 2012: 1). In fact, this is even more problematic than for solar PV, as SWTs are likely to experience faliures much more frequently.

4.4.2.1 Knowledge transfer

In the WindAid model, the enthusiastic international volunteers have a vital role to play in providing financing for projects that otherwise simply may not have happened. What is more, their status as rich foreigners arriving in a poor rural community gives them an elevated status as people "*to be impressed*" (Adams, 1999: 347). Whilst this may be an effective tool to mobilise the community for the initial installation, after the international volunteers return to their home countries at the end of the installation, this initial enthusiasm is likely to disappear and the community is likely to be left without the ability or motivation to maintain the SWT built by the volunteers, as they have also taken the technical knowledge they gained during the construction course with them. In fact, it is the volunteers who contribute the greatest amount of their time and effort to each SWT, as they spend five weeks building and installing each turbine, whilst the community members spend just one.

In order for the WindAid model to become more sustainable, an improvement in the technical abilities of the wind committee members is necessary to reduce their dependence on WindAid engineers. Although setting up a new demonstration centre similar to CEDECAP may be impractical due to the significant costs involved, negotiation between the two organisations could allow WindAid to use the facilities already established there. Another possibility is to establish a revolving demonstration and training programme whereby members of the latest community to receive a wind turbine visit the previous installation site and is trained by both WindAid staff and members of the previous community. In fact, WindAid are experts in knowledge transfer, however the problem is that the people they are transferring knowledge to aren't the ones that really need it. The fact that they are funded by the fees that the volunteers pay means that they are focussed on providing them with the best possible experience. However, this takes the spotlight away from the people living in the remote communities in which the SWTs are installed. As a result, these remote communities are now dependent on WindAid for spare parts, technical knowledge and tools.

In fact, since a comprehensive wind energy training programme is given to the international volunteers when the turbines are produced, this provides the perfect opportunity for members of the newly formed wind committee to learn by participating in the construction alongside volunteers. Added benefits of this approach are an increased sense of ownership of the turbine for members of the wind committee (due to the increased time and effort that they are able to contribute to the project) and greater opportunity for the cultural exchange that the international volunteers travelled to Peru to experience. Increased understanding of system capabilities should also prevent problems such as the use of appliances with excessive power ratings, as in the case the large television mentioned previously.

4.4.2.2 Service centres

The problem will also be alleviated by the fact that WindAid plan to select future communities in closer proximity to each other within the Huamachuco area, However, with 10 further installations planned for 2012, it was recommended that WindAid also establish a service centre in Huamachuco that will be able to perform maintenance and offer access to tools and spare parts to the surrounding communities without the need for WindAid staff to travel up from Trujillo.

> *"We are now talking, very seriously, about doing a franchise in San Marcos…and are going to bring someone from San Marcos to be trained and participate in a programme."*
> *Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012*

4.4.2.3 Design faults

> *"I'm the first to admit that what we have installed are prototypes. Going back to these projects is like an analogy of WindAid - I see so many things that we don't do anymore, and that were done wrong."*
> *Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012*

Finally, the issue of flying blades was initially addressed by modifying the design to reduce the weight and appears to have now solved the problem. The original blades were made of solid epoxy resin, which was replaced by a much lighter fibreglass/carbon fibre composite shell with a foam core (see Figure 4-27).

Figure 4-27: WindAid's new foam core glass-fibre blades with two steel spars and an outer layer of carbon fibre.

4.4.2.4 Capital

WindAid's funding model currently only accounts for the initial installation costs, leaving them out of pocket for any maintenance that must be performed. Potential solutions include increasing the fees for volunteers, developing productive uses of the electricity generated by the turbines they have installed so that communities can pay for maintenance and/or improving the ability of the communities to perform maintenance by improving access to the necessary tools, spare parts and technical knowledge.

4.5 Evaluation of methodology

Although generally successful in identifying the key issues surrounding the long term sustainability of the socio-technical systems for maintaining high levels of technical availability, the study suffered from the following limitations:

- The operator may not have remembered to complete the maintenance logbook used to obtain the data for Soluciones Prácticas' installations in El Alumbre. What is more, the data was originally transcribed for a separate project and as a result, it did not always include all of the required information. Consequently, estimations had to be made based on knowledge of the system and previous complete entries.

- The data for WindAid was generated retrospectively and as a result may be incomplete or incorrect as the first turbine was installed two and a half years before the data was collected.
- The datasets are quite limited in size, especially the WindAid dataset.
- The lack of qualitative data from the community itself reduces the ability of the post-installation analysis to discover the non-technical reasons that cause the indicators (MTBF, MTTR and availability) to sway one way or the other. For example, there is no knowledge of how well the operators/administrators/wind committees carried out their roles, or the opinions of the end-users themselves on LMSWTs as an alternative to solar PV and micro-hydro.
- It would be interesting to extend the analysis to include economic data, for example, the cost of replacing a generator or the average annual cost of O&M for each combination of turbine and delivery model. The additional training offered to the community by Soluciones Prácticas also had a significant additional cost, which should be compared to the cost of driving WindAid engineers up to the communities each time a failure occurs.
- A simple black and white 'operating' or 'not operating' status does not allow for the fact that a turbine could still be operating whilst awaiting repair. For example, if the rotor disc was rubbing on the stator, the turbine could continue to produce power until the machine seizes up completely, which may be many months from when the fault was first noticed. This is obviously desirable for the end-user, as it does not interrupt the supply of electricity.
- The post-installation performance of a wind power system at any one point in time is governed by the following three key factors:
    1. Technical availability – whether the system is operating correctly without any technical failures.
    2. Meteorological availability – the amount of wind available at that moment in time or that has been available recently and stored in batteries.
    3. Utilisation – how much power the user requires at any one time.

  It is only when these three factors coincide that the wind power system can be said to be fulfilling its function, i.e. delivering sufficient energy to the end-user at the time when each energy service is required. This study investigated purely the technical availability of the LMSWTs installed in Peru.

4.5.1 Epilogue

After returning to the UK and writing up the case study work in Peru, the author received the following response from WindAid:

"Having reached Nueva Manzanilla via San Marcos, we were told in the village that there was a shorter route to Cajamarca...Much to my surprise, we came upon [one] of the Soluciones Prácticas' wind generators...it's tail tethered in one direction, and not spinning... then another,

and another, and another. Through this valley we came upon at least 7 of them, not one of them turning...we came upon a couple [of] women...and had a long conversation. She said that none of the turbines but one (which we later saw) was working - and had not been for more than a year, and that no one had been there for a very long time, and they had heard that the project was 'finished'. This surprised me because of your report, but did not surprise me because this is exactly what I had heard before. As I had suspected, they simply reported on what reflected well upon themselves...my point being... Soluciones Prácticas - as I suspected - spoon fed you their results."

Kevin Michael VerKamp, Founder and Director of WindAid, personal communication, 5th May 2012

It is unknown why the LMSWTs in El Alumbre were out of service during this visit, as the data obtained for this study ends in October 2011. It is known that civil unrest in the region prevented Soluciones Prácticas from visiting the community for a significant amount of time from late 2011 onwards, but whether this was the only contributing factor is unclear. However, it did confirm the need to collect qualitative data from the communities themselves to verify and enhance the information gathered from the implementing organisations and the obvious bias that working with data collected in solely this manner presents. Ultimately, it is the end-users themselves that are best informed about the impact this new technology has had on their lives and without taking their perspective into consideration, this research cannot be considered complete.

4.6 Conclusion

This case study has highlighted that the high temporal and spatial distribution of the wind resource (together with the cubic dependence of power production on wind speed), the availability of maintenance services and the high level of technical knowledge required to assess the wind resource and manufacture SWTs are all critical components in the socio-technical system that governs the sustainability of SWT rural electrification initiatives.

The delivery models chosen by both WindAid and Soluciones Prácticas were studied and correlated with the post-installation record of the turbines they have installed in the Northern Andean region of Peru. It was found that the increased level of training, together with the stock of tools and spare parts given to the community of El Alumbre by Soluciones Prácticas allowed them to successfully operate and maintain the equipment installed in their community (indicated by the significantly higher levels of turbine availability). However, the decision to install individual household turbines in El Alumbre meant that energy yields were disappointing due to the lack of wind resource at the majority of households. Even though relatively high quality wind maps are available in Peru, they are designed for utility-scale wind developers, not for SWTs and therefore the siting of individual projects is still very much a 'lucky dip' unless an individual site assessment is carried out prior to installation. Both organisations also struggled to achieve the necessary quality given their limited experience with manufacturing SWTs (design and manufacturing faults accounting for the majority of failures).

Just like the SWTs installed by Soluciones Prácticas and WindAid, the methodologies employed during this case study were prototypes. They were capable of drawing broad conclusions, however they were crude and unrefined; the final message received from WindAid was merely a confirmation of this fact. The lack of qualitative data from the community itself meant that this research could only see part of the full picture.

> *"I believe that the researcher who never goes near the water, who collects quantitative data from a distance without anecdote to support them, will always have difficulty explaining interesting relationships (although he may uncover them)."*
> *(Mintzberg, 1979: 587)*

Chapter 5. Nicaragua

Figure 5-1: The author is shown the 1kW LMSWT that powers the remote community of Cuajinicuil in the central highlands of Nicaragua.

5.1 Introduction

Small-scale renewable energy based systems hold a strategic importance in providing access to electricity in isolated regions of Nicaragua, whilst also reducing the country's dependence on fossil fuels. However, the role that SWTs could play in this was unclear. Chapter 3 describes how the field work conducted in Nicaragua was conducted as part of a market assessment (Marandin *et al.*, 2013), commissioned by the international NGO, Green Empowerment, and funded by the WISIONS Initiative. These two organisations provide technical and financial support for SWTs as a technology for rural electrification across a range of developing countries. The market assessment was designed to guide any future interventions that they may make in Nicaragua.

- To identify the key factors that have affected the sustainability of SWT rural electrification initiatives.
- To determine how and why these factors vary between places.
- To establish the implications of these insights for intervention in support for SWT rural electrification initiatives.

Whilst this study could be seen as purely consultancy, it provided a valuable opportunity to pursue the research questions outlined at the beginning of this thesis in section 1.3.2 by gathering a mix of data specific to the Nicaraguan context and data that is generalisable to other local contexts. In fact, as will be shown throughout the course of this chapter, there is no such thing as '*the Nicaraguan context*', as the levels of access to electricity, renewable resources, environmental hazards and many more place-specific factors vary greatly across the country.

What is more, participation in this study presented the opportunity for the author to become part of the system under study (i.e. the systems that provides interventions to support SWT rural electrification initiatives). By working with wind power experts to conduct the study, the author was able to gain an insider perspective on how support for SWTs could be given and therefore how best to guide this support in the future. The methodological implications of this team working scenario are discussed in detail in Chapter 3, including the various measures taken to increase the objectivity of the work, such as the field diary that was used to record the author's "*unfiltered reflections*" (Yadoo, 2011: 37), as well as actual events (see Appendix H).

In addition to the increased opportunities for data collection offered by the increased level of access that being an insider, working as part of a team with people that were so familiar with SWTs in the Nicaraguan context allowed the research to gain a much greater depth than if the author had conducted it alone. Other team members offered complementary insights and the opportunity to overlap data analysis with data collection enabled the framework described in Chapter 2 to grow significantly. Although the framework was not included in the market assessment itself, it was built upon the knowledge gained during this study. In this chapter, the evidence from the market study is presented within the context of this thesis. First, the key factors that have affected the sustainability of existing SWT rural electrification initiatives in Nicaragua (and abroad) were identified. How these factors vary across the country was then evaluated and finally, the implications of these insights for any future interventions in support that could be offered by Green Empowerment and the WISIONS Initiative for SWTs in Nicaragua were determined. This chapter is therefore structured as follows:

The current state of small wind in Nicaragua

- A case study of a small wind pilot project in which the post-installation analysis methodology developed in the previous case study was employed to determine whether the project could be considered successful and if so, what the critical factors for success had been.
- Interviews with national wind power experts to identify the key barriers facing small wind in Nicaragua and to gather information on the current state of the small wind power ecosystem in the country.

Predicting the future for small wind in Nicaragua

- Determining how the factors identified in the previous section vary across the country (and therefore how scalable SWTs are in Nicaragua) through the construction of a Geographic Information System (GIS).

Strengthening the small wind ecosystem in Nicaragua

- Constructive advice on where to target future interventions designed to enable the potential for SWTs identified in the previous section to be realised.

5.2 The current state of small wind in Nicaragua

5.2.1 Small wind on the Atlantic Coast

> *"blueEnergy made the hard decision in 2011 to stop implementing small wind for our community energy projects in the Caribbean: the wind resource is not optimal, solar PV became competitive and it's hard to ensure the necessary quality at low volume."*
> *Mathias Craig, Director and Founder, blueEnergy, November 2012*

For over 7 years, blueEnergy installed SWTs along the Atlantic Coast of Nicaragua, however due to the combined effects of the remote nature of the communities, the increasing cost-competitiveness of solar, coupled with the extremely unfavourable environmental conditions (low-winds, lighting strikes, corrosion and hurricanes) and the lack of interest on behalf of the communities to maintain the systems, the vast majority fell into disrepair and all but 3 have now been uninstalled and replaced by solar panels. The following figure shows the operational status of four of blueEnergy's turbines during 2010 and 2011:

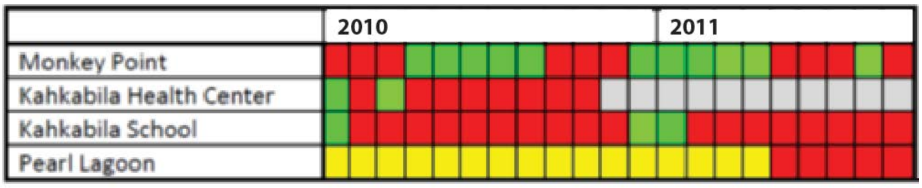


Figure 5-2: Operational status of four blueEnergy wind turbines: red = offline, yellow = online, but awaiting repair, green = online, grey = uninstalled. Adapted from Bennett et al. (2011).

Table 5-1 shows an excerpt from the maintenance logs kept by blueEnergy engineers visiting the turbine in Monkey Point to perform maintenance. It clearly shows the immense challenges facing small scale wind in this region:

Table 5-1: Maintenance logs for blueEnergy's wind turbine in Monkey Point (Bennett et al., 2011).

Problem – Activities	**Date**
Installation work. One phase of the stator doesn't work. Problem with the solar controller	Jun 2007
Replace stator, trimetric and solar charge controller (Phocos). Lilian connected to the system (2 weeks after installation).	Jun 2007
Stator burnt, brought back to Bf.	Aug 2007
Replace stator. Install battery charger. Hub a bit loose. Inverter doesn't work. Send to Managua. Remove solar controller.	Oct 2007
Rotors rubbed on stator. Fixed with resin. Problem come from the hub.	Nov 2007
Blade painting. Remove something making noise inside the alternator.	Nov 2007
Change the batteries, connect the new inverter. Bring back the Trimetric to Bf. Rise the tower.	Dec 2007
Stator burnt ???	
Put back the Trimetric	Mar 2008
Turbine free spinning, stator burnt since 2 months ? Install new body with a 50 turns #11 wire.	Mar 2008
Install a 12V battery charger in Bomboy house	Jun 2008
Remove battery charger. Install the new grounding.	Jun 2008
Install meters and breakers in Lilian's house. Remove inverter, damage by a lightening. Trimetric doesn't work, brought back to Bf. Install 12V inverter. Tail vane maintenance.	Aug 2008
2 batteries pretty dry (1.5 gallon to refill them !). Remove Trimetric. Change the vane.	Octo 2008
Batteries in bad shape. Replace one. Change the 12V inverter for the 24V original one. Reinstall the Trimetric. Repair school lights.	Jan 2009
Rotors rubbed on stator due to the shaft rear nut which got loose. Fixed up with Epoxymil.	End of march
Mother board of inverter burnt. La loma inverter lent to MP so that the system can still function.	Aug 2009
Mother board replaced and inverter installed	And counting

5.2.2 Cuajinicuil: a new approach in a new local context

Despite blueEnergy's decision not to install any new wind turbines in its community electrification projects on the Caribbean coast, a collaborative project with the Nicaraguan NGO AsoFenix was initiated in 2009 to establish whether the technology could be viable in a different local context: the central highlands. The community of Cuajinicuil is located in the municipality of San José de los Remates in the department of Boaco (see Figure 5-3) and was chosen for this pilot project because of its excellent wind resource (see Figure 5-4). In May 2010, a PV-wind hybrid system was installed to charge batteries and supply 14 households interconnected via a micro-grid, whilst individual PV systems were installed at 4 more distant households. A 1kW bD4 wind turbine manufactured in Bluefields by blueEnergy was installed alongside a 540W PV array.

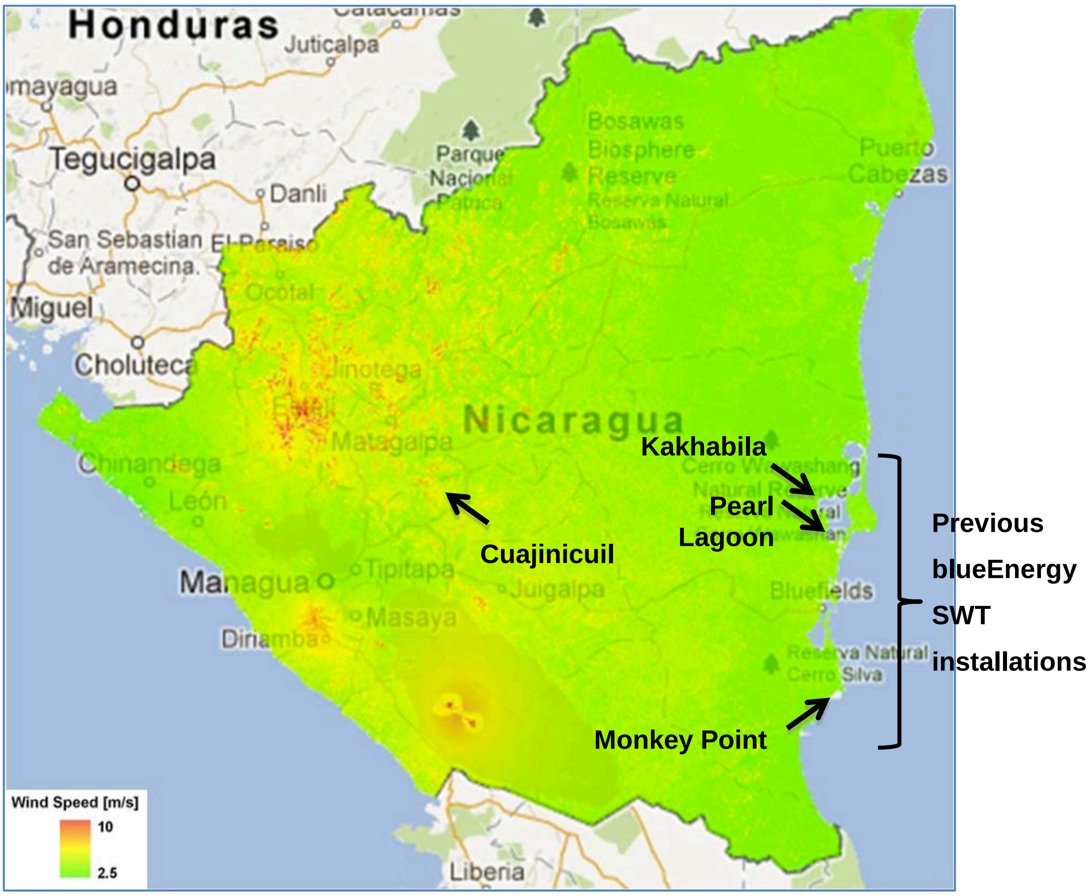


Figure 5-3: Location of Cuqjinicuil and the previous blueEnergy SWT installations on the Caribbean coast (only those listed in Figure 5-2 are shown) in relation to the wind resource available in Nicaragua (30m hub height). Adapted from ENCO (2013).

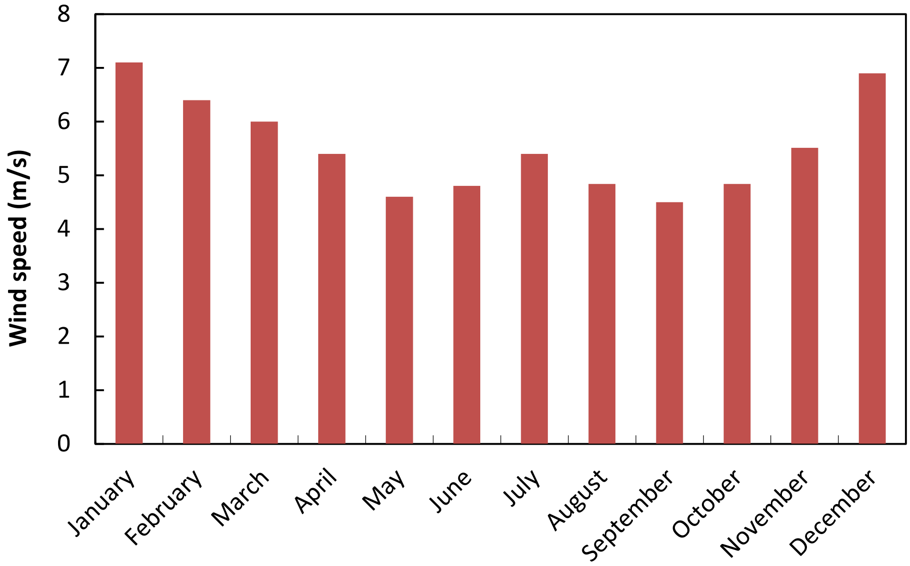


Figure 5-4: Annual variation of average wind speed[51] at Cuajinicuil, Boaco (O'Toole, 2010).

5.2.2.1 Knowledge transfer

A new method of technician training was also trialed during this project – participatory manufacture. The case study work conducted in Peru has shown that the level of technician training given in wind-based rural electrification projects varies wildly from a quick chat after installation to multiple days of specialist training at a renewable energy demonstration centre. Whilst many organisations around the globe run educational courses based around the construction of a SWT and many others promote their use in rural development projects, the author is unaware of any that have previously linked the two together such that the end user becomes the student in the course.

The members of the community chosen to be responsible for operating and maintaining the system after installation were invited to travel to Bluefields and take part in the manufacture of the wind turbine that was to be installed in their community. Figure 5-5 shows the participants and organisers of this construction/training course that was held at blueEnergy's workshop in Bluefields. This practical approach to knowledge transfer is much more likely to be effective than conventional theoretical methods when working with people who may have had little formal education, but already have excellent practical skills, such as farmers.

[51] Please see end of section 5.2.2.3 for a discussion on the accuracy of this data.

Figure 5-5: 1 kW Piggott turbine manufactured during a small scale wind power workshop led in 2010 by blueEnergy in Bluefields, RAAS[52], Nicaragua (O'Toole, 2010).

For the domestic PV systems, the implementing NGO, AsoFenix also held a 2 hour training session for the users the day before the installation of the systems, covering the basics of electricity, how to perform electrical installations, measuring electrical quantities, installation of PV systems, and safety.

5.2.2.2 Methodology

Data collection

Data was collected on both the pilot project in Cuajinicuil (implemented by AsoFenix and blueEnergy) and the previous electrification projects on the Caribbean coast (implemented by blueEnergy).

Evaluation of Cuajinicuil pilot project:

- Interviews with director and social/technical staff at the implementing NGO, AsoFenix (similar to those described in Appendix I).
- Review of design and installation reports relating to the project.
- Four day evaluative visit to Cuajinicuil:
    - o Interviews with community leaders and community technicians (see Appendix K).
    - o Questionnaires filled out by all available end-users (see Appendix L).
    - o Observations and photographic evidence recorded in field diary (see Appendix H).

Evaluation of previous SWT electrification projects on the Caribbean coast:

- Interviews with directors and social/technical staff at the implementing NGO, blueEnergy (similar to those described in Appendix I).
- Review of design and installation reports relating to the projects.

[52] Southern Atlantic Autonomous Region (Región Autonomo Atlántico Sur).

- Three day evaluative visit to Monkey Point, RAAS:
    - o Interviews with selected end-users, community leaders and community technicians (similar to those described in Appendix K and Appendix L).
    - o Observations and photographic evidence recorded in field diary (see Appendix H).

Data analysis

In addition to the conventional analysis of interview and field diary data (as described in sections 4.2.2 and 3.4), the post-installation analysis technique developed during the previous case studies in Peru was also employed here. The methodology was extended to recognise when the system was operating, but awaiting repair (indicated by yellow bars in Figure 5-13). What is more, it was also extended to include economic variables, such as a comparison of the amount of money collected by the community to pay for O&M, the actual O&M costs (parts, labour and transportation) and the costs of the community training programme.

Energy systems modelling

The Cuajinicuil PV-wind micro-grid was modelled in the energy systems modelling software, HOMER[53], to establish the sensitivity of various parameters on the economic viability of the system. The software simulates the supply and demand of energy throughout the year by dividing it up into hourly intervals. The key input data can be categorised into energy resources, equipment, energy demand and economics. With this data, HOMER calculates the power generated by each power source during each hour of the year and feeds it into the batteries. Energy demand from the domestic loads is also drawn from the batteries on an hourly basis, providing that there is enough stored energy to do so. The modelling process allows visualisation of the energy flow throughout the system and the cash flow throughout the system lifetime. It also calculates various measures that can be used to compare between various technological options, such as the Levelised Cost of Energy (LCoE), Levelised Generating Cost (LGC), Net Present Cost (NPC).

The LGC compares the total costs across the whole lifetime of an energy generation project with the total energy it generates across its lifetime. Using the discount rate, future costs are discounted back to the present day to give their net present value. This represents the amount of money you would need to have today to pay that cost in a certain number of years from now, given that you could earn interest on that money until that time. A similar process is conducted for the energy yield for each year until the end of the system lifetime. The total discounted costs ($) are divided by the total discounted energy yield (kWh) to give the LGC ($/kWh), which represents the value at which each kWh of energy would need to be sold at in order for the energy project to break even:

[53] Version 2.86 beta was used for all the energy systems modelling conducted during this research.

$$LGC = \frac{\sum_{t=1}^{n} \frac{C_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (7)$$

LGC = Levelised Generating Cost (US$/kWh)
n = System lifetime (years)
C_t = Capital costs in year 't' (US$)
M_t = O&M costs in year 't' (US$)
F_t = Fuel expenditures in the year 't' (US$)
E_t = Electricity generated in year 't' (kWh)
r = Discount rate (set as 10% ((ESMAP, ,) (2007)))

However, not all the energy produced by the system is useful. For example, on windy days when the batteries are already full, excess energy is sent to the dump load. The LCoE is calculated using an identical methodology, however it uses the electricity supplied to the end-user (i.e. energy demand), as opposed to the electricity generated in each year:

$$LCoE = \frac{\sum_{t=1}^{n} \frac{C_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{D_t}{(1+r)^t}} \qquad (8)$$

LCoE = Levelised Cost of Energy (US$/kWh)
D_t = Electricity demand in year 't' (kWh)

The breakdown of the costs used as inputs for the model is shown in Figure 5-6. To reflect the true costs associated with the local manufacture of the wind turbine, overheads of 30% and 50% were added to all materials and labour costs respectively. As will be discussed later in section 5.3.1, a commercial scenario that does not rely on volunteer labour was assumed. The system was modelled over a 25 year period, with replacement of the batteries (7 years), wind turbine (15 years) and inverter (15 years) scheduled to occur during this time period. A discount/real interest rate of 8% and an exchange rate of C$24.01=US$1 was used to model the current financial climate in Nicaragua. This accounts for the fact that money required for O&M or replacement costs is not needed until later years and could therefore be invested in other things until then and is otherwise known as the opportunity cost of capital. Figure 5-7 shows the effect of the discount rate, with Figure 5-7a) showing the nominal cash flow, i.e. undiscounted and Figure 5-7b) showing the discounted cash flow, i.e. weighted according to the opportunity cost of capital.

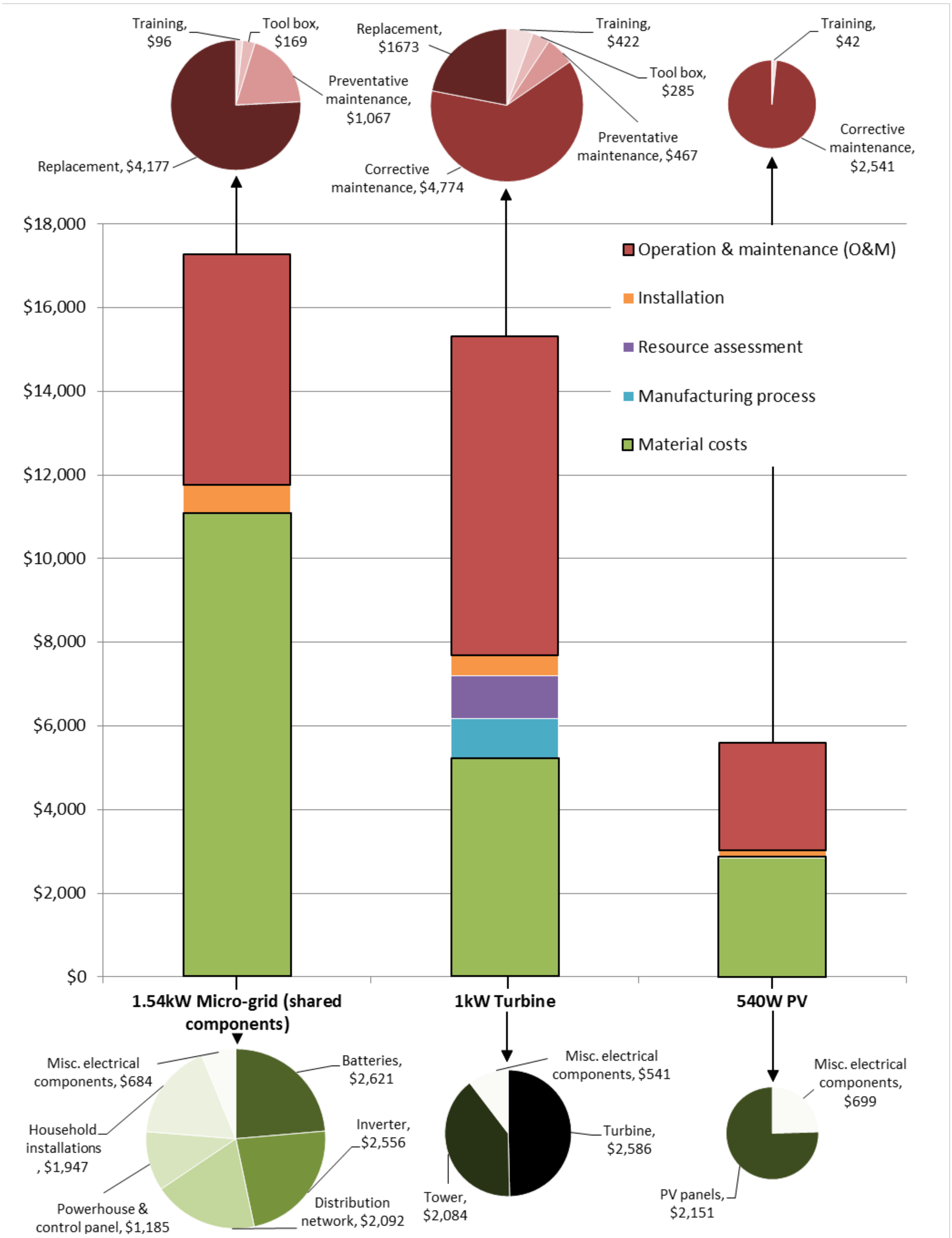


Figure 5-6: Breakdown of the net present costs of the major system components in the Cuqjinicuil micro-grid (modelled in HOMER with a real interest rate of 8% over a 25 year period).

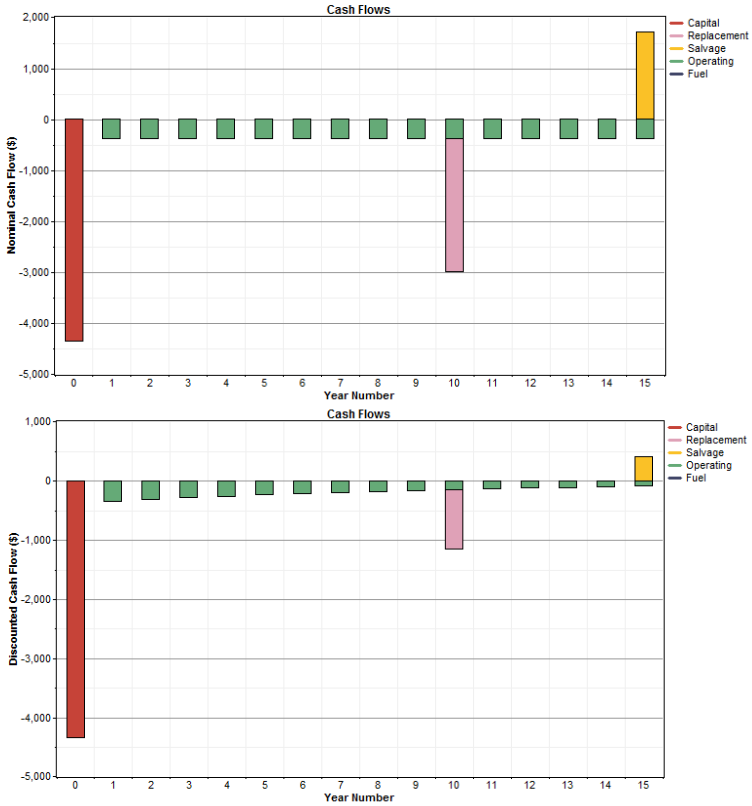


Figure 5-7: a) Nominal and b) discounted cash flows for a hybrid renewable energy system.

5.2.2.3 Results of energy systems modelling

In Figure 5-6, the costs are first categorized into those associated with the 1kW wind (e.g. tower, wind study), the 540W solar array (e.g. PV panels, installation of panels) and those that are shared between the two (e.g. inverter, training on principles of electricity). It's possible to see that the cost per watt of the wind turbine (US$5.21/W) works out at just below that of solar panels (US$5.27/W) when including only the cost of the materials. However, when including the resource assessment (wind: installing an anemometer on a met mast at the site and logging data for a year – PV: zero), manufacturing (wind: labour costs for the construction of the wind turbine – PV: zero) and installation costs (wind: transport of tower and turbine to site, digging and concreting of anchor points, laying of underground cable to powerhouse – PV: transport of panels to site, fabrication of aluminium frames and installation on roof of powerhouse) to give the installed cost, the balance tips the other way to US$7.70/W and US$5.59/W respectively.

Despite the comprehensive technician training programme, the increased maintenance requirements of the wind turbine push the gap even wider when including O&M costs ($15.32 and $10.38), showing that watt for watt, wind is a more expensive solution. However, this does not take into account the energy yield of the two renewable technologies. In fact, Cuajinicuil has an excellent wind resource (5.77m/s annual mean wind speed), making it one of the best sites for a small scale community wind project in the country. In contrast, the solar resource (4.94 kWh/m^2/day mean annual insolation) is only average (for Nicaragua). Figure 5-8 shows the optimal system architectures for the levels of solar and wind resources that are found in Nicaragua.

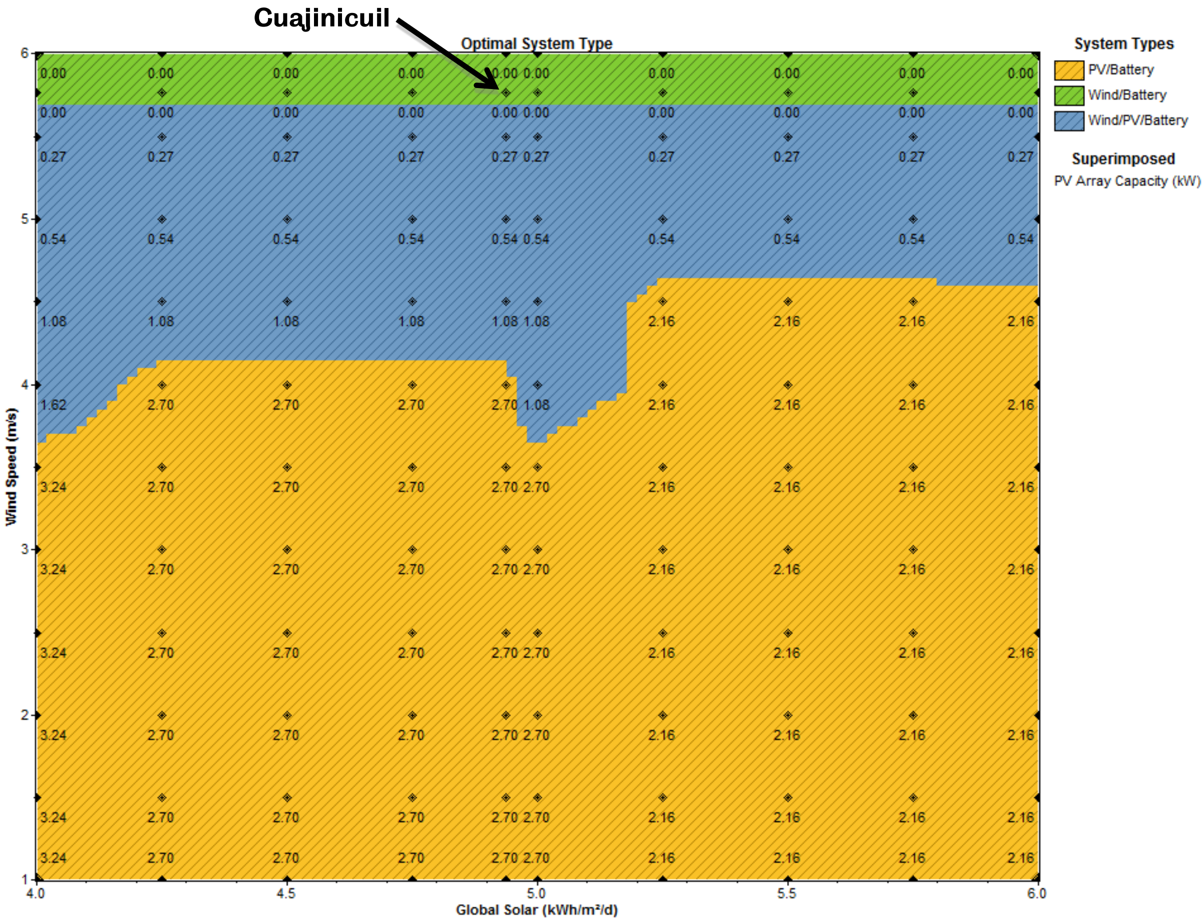


Figure 5-8: Selection of the most economically viable options for renewable energy supply in Cuqjinicuil under varying solar and wind resource scenarios. The HOMER simulation was constrained to use 0, 1 or 2 wind turbines and 0-5.4kW of PV in 0.27kW modules[54].

It can be seen that as the wind resource increases (moving up the vertical axis), the optimal system changes from a PV-only (yellow) to PV-wind hybrid (blue) at 3-4 m/s and again to wind-only (green) at 5m/s. In contrast, the level of solar resource (moving right along the horizontal-axis), impacts the transition point from PV-only to PV-wind hybrid, but has little impact on the transition to wind-only. It can therefore be concluded that in this local context, the optimal system architecture has a strong dependence on the wind resource, but only a very weak dependence on the solar resource. Figure 5-9 shows the variation in LCoE between the most cost-effective system typologies, as modelled in HOMER. Wind is clearly the most cost effective system, due to the superior energy yields on this excellent wind site.

[54] Hence the discontinuity at the border between the yellow and blue regions.

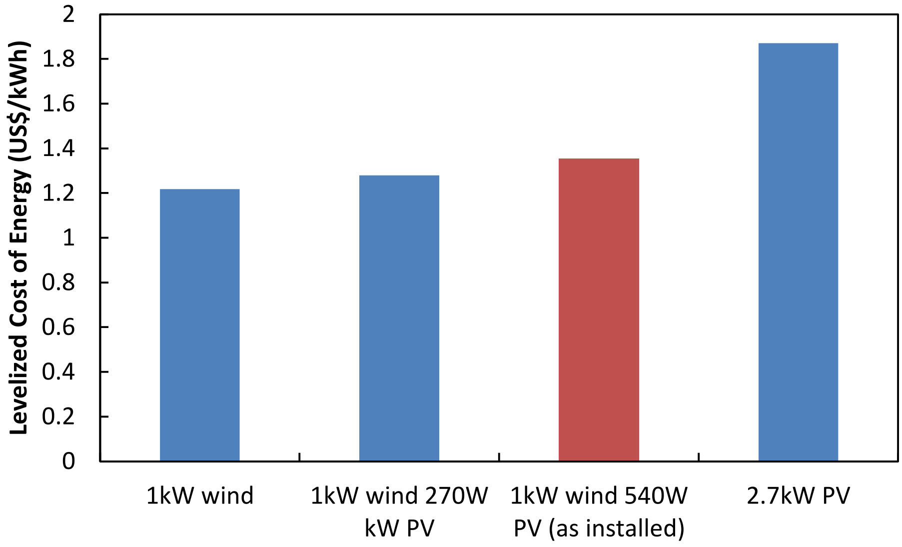


Figure 5-9: Comparison of LCoE for the most economical wind, PV-wind hybrid and PV systems with the 1.54kW PV-wind hybrid installed in Cuajinicuil.

In fact, the wind resource in Cuajinicuil is so great that the model suggests that it would have been possible to have met current demand with a wind-only system. However, this is contradicted by end-user testimony:

"Since the [solar] controller was damaged, we spent three days without electricity because there wasn't much wind…we went back to the old days with candles"
Rosa Zenayda Valerio Huembes, Cuajinicuil Community Leader, November 2012

"When there's wind in summer, the power never fails. When its winter, the wind disappears, leaving just a few hours [per day] with electricity…in November the wind and sun come back and the amount of electricity is incredible"
Anastacio Valerio, Cuajinicuil PV-Wind End-user, November 2012

Figure 5-10 shows the modelled seasonal variation of the power production of both renewable sources, clearly in accordance with the end-user testimony, with regard to the significant reduction in available energy during winter months (May-October).

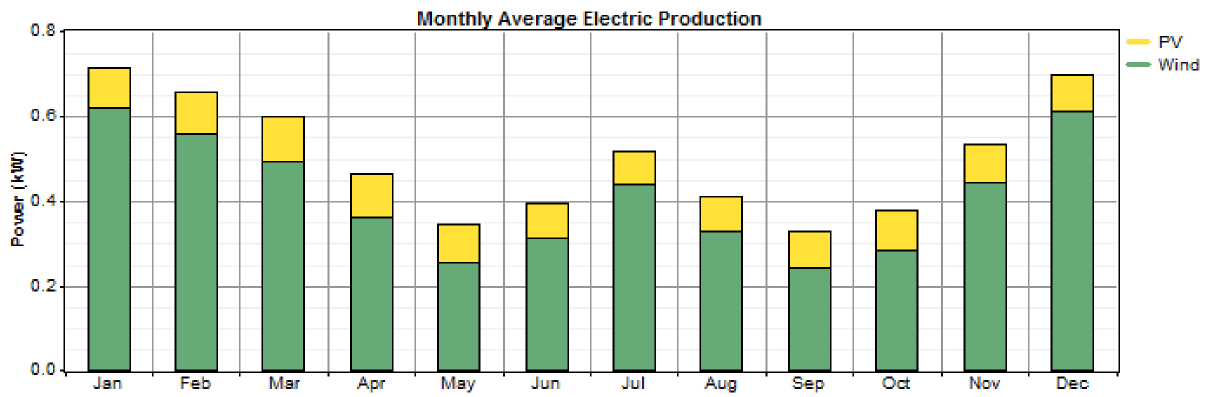


Figure 5-10: Seasonal variation of the energy production of the two renewable sources feeding the Cuajinicuil micro-grid (modelled in HOMER).

Figure 5-11 below shows the state of charge of the batteries in either the hypothetical wind only system recommended above or the PV-wind hybrid as installed in Cuajinicuil. Whilst the wind only system is capable of meeting demand for most of the year, the batteries would run very low in winter, and it would be unable to meet the load for 11% of the year. This verifies the end-user testimony that when the solar controller went offline, there was insufficient energy. In contrast to this, the PV-wind hybrid has just a few days where the batteries are completely empty and is only unable to meet the load 3% of the time. This contradicts the users' experience from when the full hybrid system was operating, as the HOMER model also includes the water pumping that wasn't yet in operation.

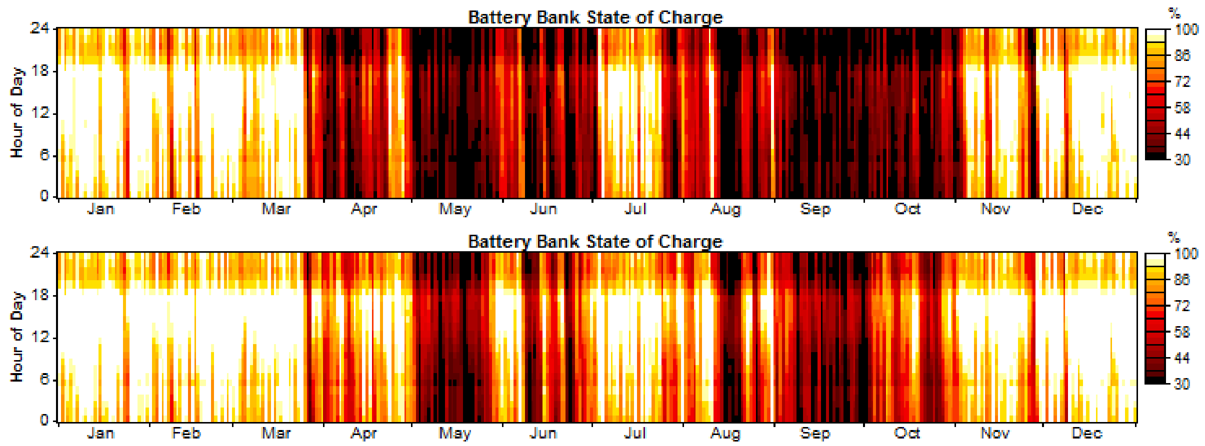


Figure 5-11: Battery bank state of charge for the 1kW wind system (top) and 1kW wind, 540W PV hybrid system (bottom) as modelled in HOMER.

The discrepancy between the model and reality could be explained by inaccuracies in the input data, the most likely of which would be:

- Underestimated demand - some users reported that others had been using prohibited high power appliances, such as irons.

- Overestimated wind resource – as illustrated in Figure 4-14, inter-annual variation can be as much as 2m/s, in addition to this, the Cuajinicuil wind study was only conducted for 4 months, as opposed to a whole year.
- Inaccurate power curve –improperly measured power curve data can cause significant over or underestimates in energy yield (see Appendix B for more details).

5.2.2.4 Operation and Maintenance (O&M)

For community electrification projects, O&M is absolutely critical for ensuring project sustainability. Many people who live without access to electricity do so because they live in remote areas and the cost of extending the national grid is far too high compared with the amount that they are able to pay for the electricity. The electricity produced by decentralized generation is almost always more expensive than that supplied by the grid (per unit), often due to the efficiencies of scale that centralized generation is able to exploit. What is more, any failures in the generating equipment require either a lengthy journey by an engineer from a nearby population centre or an extensive programme of training for community members. Even if maintenance can be performed by a community member, they will need access to the necessary tools and spare parts, both of which will be much harder to obtain due to the remote location of the community. These additional costs are not usually taken into account when calculating lifecycle costs for energy projects.

As discussed previously, maintenance operations can be divided into two categories:

1. Preventative maintenance – actions designed to reduce the frequency of failures.
2. Corrective maintenance – performing repairs when failures occur.

Preventative maintenance

Interviews with the community technicians and administrator were conducted to determine the amount of time and money spent on preventative maintenance every year by the community. Not only are more tasks required in order to maintain the wind turbine than the solar panels, but it is important to note that each task is more complicated. For example, the most complex task required to maintain the solar panels is climbing onto the roof to clean them at most once a month, something that one person can do alone in less than half an hour with virtually no training. In fact, the preventative maintenance required of the solar systems is so simple that the end-users of the domestic (55 W) solar systems are capable of doing it all themselves.

In contrast, Figure 5-12 shows that the wind turbine requires a well-trained technician for over 100 hours/year, to perform daily checks to make sure it is operating properly (listen for strange noises, check that it is following the wind direction etc.) and to lower it every six months for a service (grease bearings, repaint blades and metal parts, tighten nuts & bolts, untwist power cable etc.), as well as before any hurricanes or big storms. This also requires the assistance of the whole community to lower the tower and a full check-up takes at least 2 days. In fact, the community once spent 4 days without electricity after a check-up because there were not enough people around to raise the tower again.

With regard to safety, just lowering the tower is already far more dangerous than any of the required operations for the solar systems:

> *"[the turbine] is incredibly dangerous. It's not easy to raise and lower this thing. It's very costly and very dangerous."*
> *Anastacio Valerio, Cuqjinicuil PV-Wind End-user, November 2012*

However, this risk does have a hidden benefit:

> "Solar is easier to use...but wind is more secure because nobody is going to be able to run away with it!"
> *Daling Gonzalez, Cuqjinicuil Technician, November 2012*

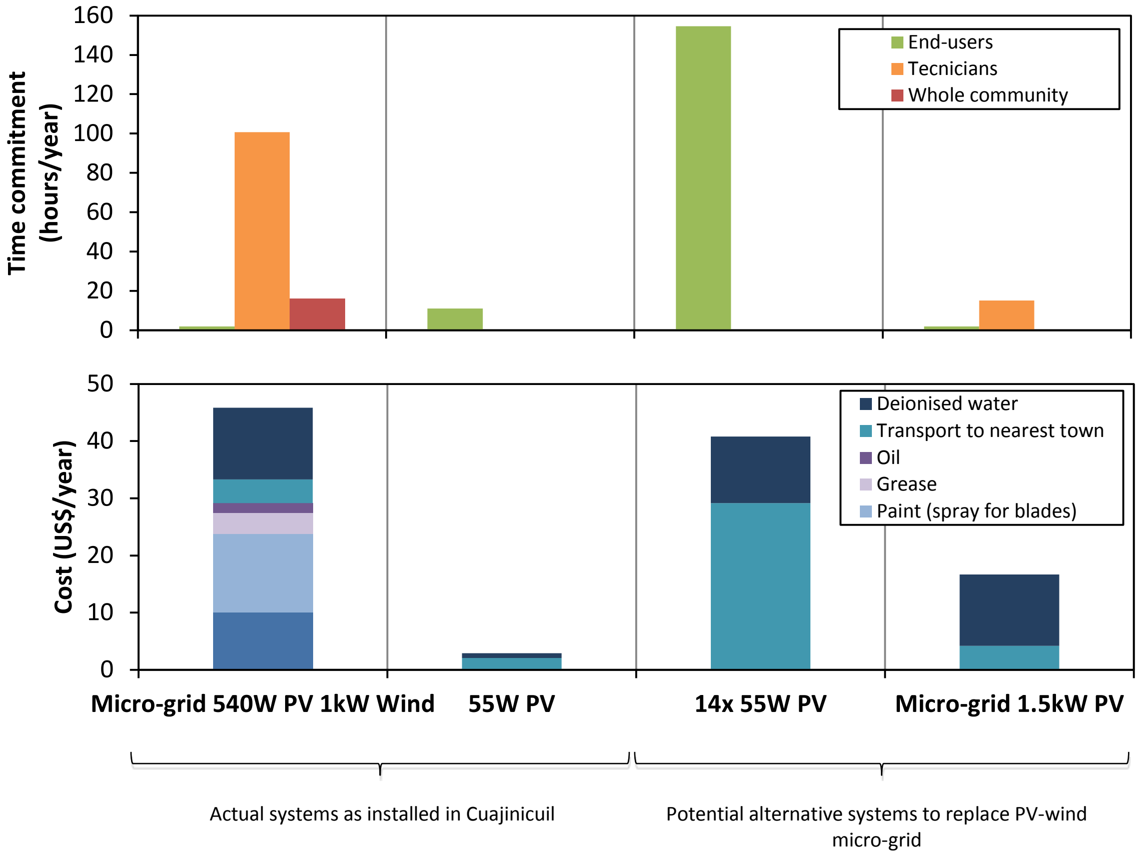


Figure 5-12 – Comparison of a) the time commitment and b) the costs required to perform the necessary preventative maintenance for the actual renewable energy systems installed in Cuqjinicuil with 2 potential PV only alternative systems for the micro-grid. Data obtained from interviews with community technicians.

Also shown in Figure 5-12 are two potential alternatives for the electrification of the 14 houses connected to the micro-grid: 14 individual household PV systems (55W each) and a PV only micro-grid

(1.5kW). With regard to time, the first option would require over 150 hours/year from the end users, however this is split between the 14 households and equates to just 11 hours/year each. The second option would require just 15 hours/year of technician time, an 85% reduction on the installed PV-wind system. In terms of cost, both options require around US$12/year to keep the batteries hydrated and the only real difference between the two is the transport costs required to get all 14 users to the shop selling deionised water vs. as single trip by the community technician, putting the costs of consumables 11% and 64% respectively below that of the existing PV-wind micro-grid.

Corrective maintenance

Wind turbines are mechanical devices that sit on top of tall towers and spin at high speed, deliberately exposed to the full force of wind and all that comes with it (rain, sun, lightning etc.). As a result, regardless of the quantity and quality of preventative maintenance performed, failures are inevitable:

> *"…wind turbines are surprisingly troublesome pieces of equipment…because of all the little things (and some big things) that go wrong."*
> *(Piggott, 2013: 9)*

Figure 5-13 shows the amount of time that each energy system has spent out-of-operation, for maintenance. It's important to note that the hybrid nature of the PV-wind micro-grid gives it a much higher reliability than either system alone as it can continue to provide energy to the community until both sources (or the shared storage and distribution system) go offline. The data presented in Figure 5-13 is summarized in Figure 5-14 with the aid of three key metrics conveying reliability, resilience and a combination of the two.

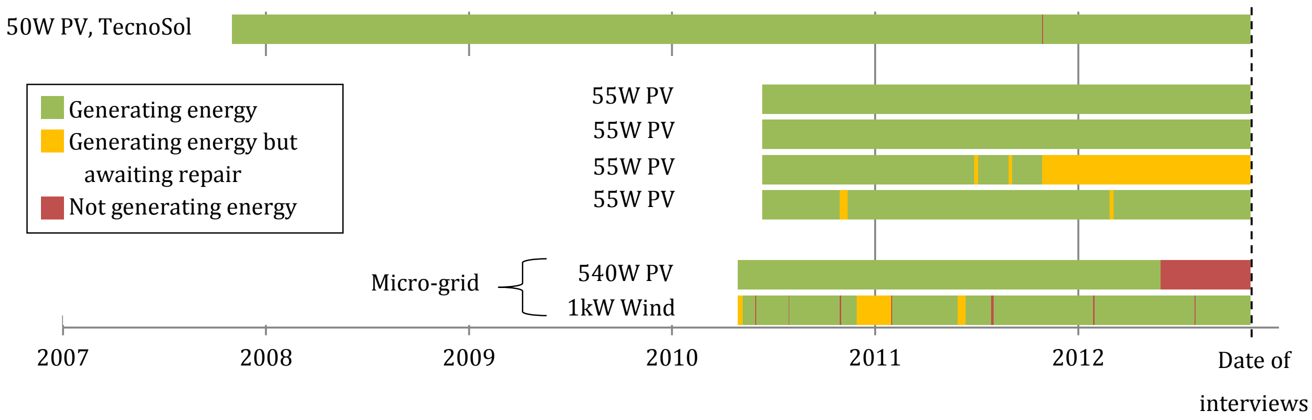


Figure 5-13: Diagram of the downtime experienced due to routine preventative maintenance or pending corrective maintenance for each renewable energy system in Cuajinicuil.

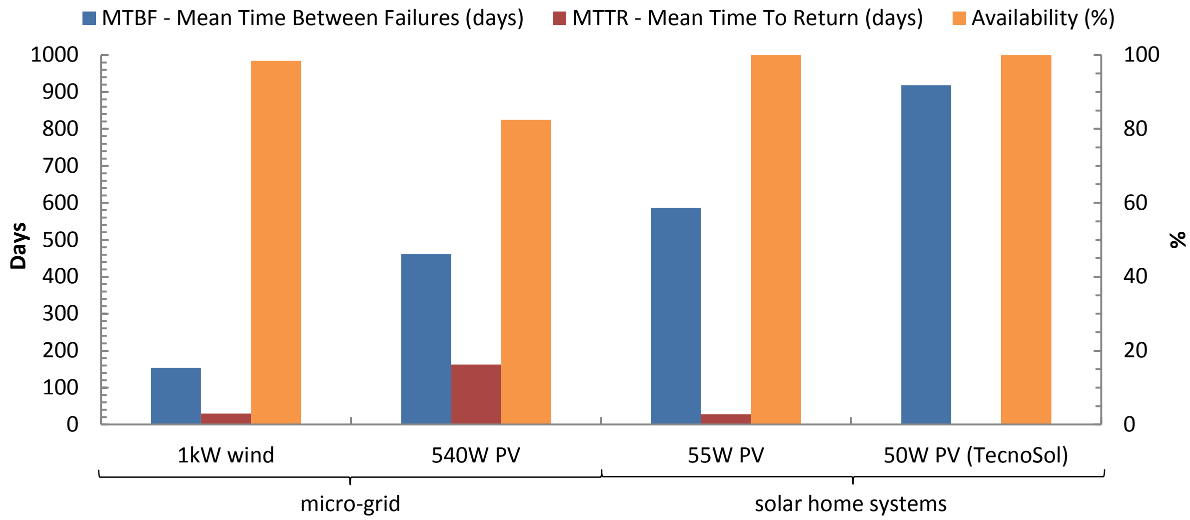


Figure 5-14: Comparison of the reliability and resilience of the various renewable energy systems in Cuqjinicuil.

The Mean Time Between Failures (MTBF) is a measure of reliability, taking into account the frequency with which faults occur (see equation (5)). At 154 days, the MTBF for the wind system is more than three times smaller than even the worst of the solar systems. What is worse is that if the metric had included times when the tower was lowered for preventative maintenance, it would have been just 70 days. This is comparable to the findings of the Peruvian case study: 115 (WindAid) and 291 days (Soluciones Prácticas). Fortunately, it is expected that this number will increase over the lifetime of the installation:

> *"...I would expect a couple of problems in the first year and one per year thereafter"*
> *(Piggott, 2013: 9)*

As a result, the opinion of the AsoFenix staff on the locally manufactured turbine was quite negative. In fact, Figure 5-16 shows that design faults led to the replacement of three separate parts of the SWT in the first year alone. Clearly, despite manufacturing SWTs in Nicaragua for over five years, the low volume production (<30 units) meant that many design flaws were still present. Consequently, AsoFenix expressed a preference for using imported technology in any subsequent SWT electrification projects.

In addition to the number and frequency of failures, the time taken to repair each is also important. The resilience of the system is measured by the Mean Time To Return (MTTR – see equation (6)). In spite of what may have been predicted, at 162 days it is actually the solar system that has the highest MTTR. However, this is not a fair reflection on the technical performance of the system, as replacing the controller is simple, however the community currently has insufficient funds with which to purchase a replacement charge controller (see Figure 5-16), which burnt out in June 2012 when ants invaded the control panel– something that could equally well have happened to any of the wind power system's electrical components.

Figure 5-15: Invasion of the fuse box by ants that led to the failure of the solar controller in June 2012. Photo courtesy of Bryan Ferry.

In addition to this, one of the solar home systems has been awaiting a repair for over a year now; however it is the fuse that has blown in the inverter and as they no longer have a television, they are happy to continue using the DC light bulbs alone. This has pushed the MTTR of the 55W PV systems up to 28 days, just below that of the wind system, which was expected to be much higher due to the longer supply chain for spare parts coming from the Bluefields, the increased complexity of the repairs and the need to lower the turbine. The short time in which each of the faults with the wind system were fixed is testament to the skill of the community operators, who due to the success of the technician training programme, were able to fix all of the problems themselves apart from the replacement of the rotor and stator discs in the generator, which is one of the most complex repairs in the whole system.

In Peru, it was found that the wind power systems could be fixed even quicker (MTTR of just 3 days for Soluciones Prácticas) by having more spare parts available in the community. The replacement of the rotor & stator in Cuajinicuil took over 60 days as a new part had to be made from scratch, shipped across the country and installed by an engineer. In contrast, the Peruvian community were able to keep three entire spare systems in the community as they had installed many smaller turbines (as opposed to the single larger SWT in Cuajinicuil). If more communities in the Cuajinicuil region were to install SWTs, then a service network could be established that would allow the system to get back into operation much faster.

The final metric is the availability (see equation (7)), which is a combination of both reliability and resilience and indicates the percentage of time that the system is capable of producing energy. Even though the wind system has been out of service for at least 4 days per year for preventative maintenance check-ups, has been taken down to replace the rotor and stator discs and both the dump load and rectifier have been replaced, the overall availability of the wind system (98%) is unexpectedly better than that of its solar counterpart in the mini-grid (82%). This is again due to the ongoing lack of funds for a new solar controller, combined with the fact that the wind turbine was able to continue operating whilst the faults were occurring (e.g. a switch with a bad connection was simply left closed). In Peru, SWTs were found to have availabilities of 83% (WindAid) and 97% (Soluciones Prácticas).

However, as expected the 50 and 55W solar home systems performed even better than the wind system (100% availability) as the only interruption to energy production for these systems was the changing of the battery of the 50W TecnoSol system at the end of its life.

Whilst preventative maintenance has a negligible cost for the solar and minimal cost for the wind systems, Figure 5-6 shows that corrective maintenance makes up 46% and 30% of the NPC of the solar and wind generation systems respectively. The costs associated with each of the incidents shown in Figure 5-13 are shown below in Figure 5-16, alongside the maintenance fund collected and managed by the community leaders. Each household pays a tariff equivalent to 30C$ ($1.25) per month, although payment is only collected at convenient times, such as after produce has been sold at market. The tariff was set at a level equivalent to the previous average household expenditure on kerosene, dry cell batteries, diesel and other energy products. Only one household has repeatedly failed to make payments, which has led the community leaders to consider cutting their supply of electricity.

Whilst the fund easily covers the consumables required for preventative maintenance, the costs of each failure are huge in comparison. Fortunately for the community, the first 4 failures were deemed to be design flaws and installation faults, and as a result, they were paid by the NGOs that implemented the projects. However, when the solar controller burned out in June 2012, there was nowhere near enough money to pay for a replacement, let alone cover the installation cost.

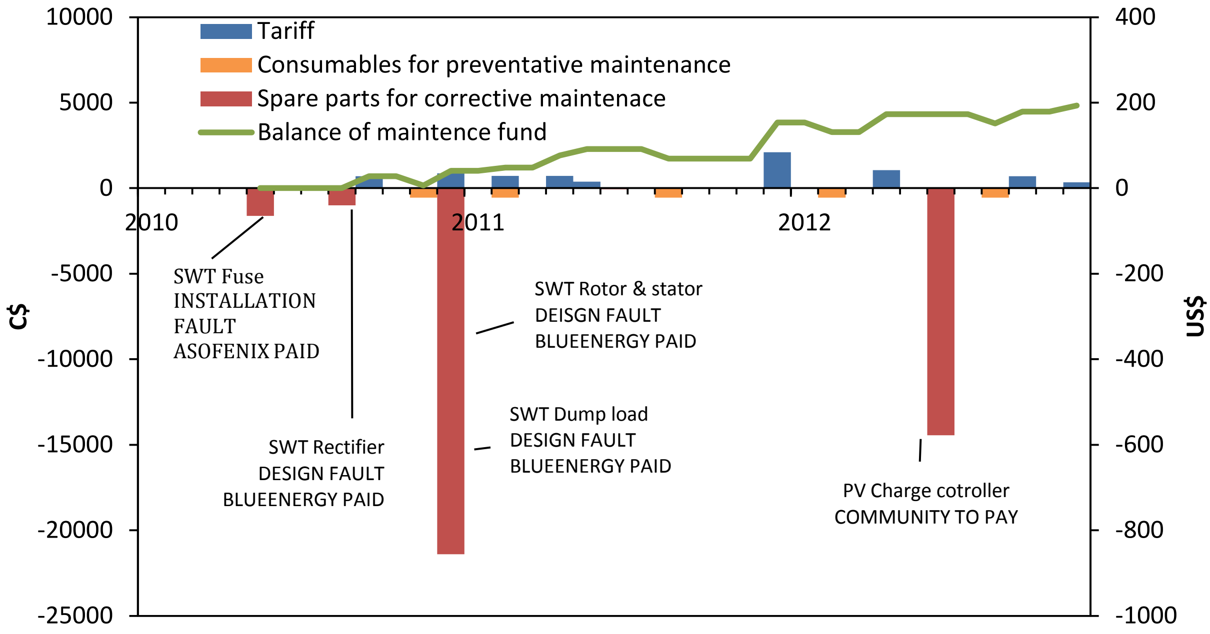


Figure 5-16: Comparison of the maintenance fund collected by the community and the maintenance costs incurred by the system since operation. Please note that the cost of spare parts in this illustration does not include installation costs.

Sensitivity analysis

Despite making up a significant portion of the total costs, the O&M costs of the renewable energy system in Cuajinicuil are a lot lower than if there had not been any technician training. If there had been no training given, initial capital costs for the wind system would have decreased by 5%, the PV system by 1%, and the rest of the project by less than 1%. As a result, instead of the community technicians being able to fix most of the problems (with assumed negligible cost), an engineer would have had to visit the community for each repair, leading to an increase in O&M costs by 7% for the PV system, and 27% for the wind system (due to the higher number of failures). These cost increases assume that the engineer would take the bus to the community and back, for repairs that don't require large spare parts; this would be a trip of 3 hours followed by a 2 hour walk, each way. If, instead, they were to drive a pickup (2.5 hours followed by a 40 min walk), as is more realistic for a commercial installer, they would rise by 16% and 76% respectively. The result is an increase in the NPC of the system from $37,420 to $39,013 and $41,810 respectively, however it has little impact on the optimal system architectures with varying solar and wind resources shown in Figure 5-8.

In fact, the only issue that might seem to influence the decision on the optimal system architecture for Cuajinicuil is the upfront cost of the solar panels. The panels installed in Cuajinicuil were purchased three years ago at a cost of $500 per 135 W panel (3.70 $/W), it would not be unrealistic to assume that panels could now be acquired at half that price (IRENA, 2012). If the panels were to continue to fall to a quarter of their original price and an engineer in a pickup were to perform all maintenance (a worst case scenario for wind) then Figure 5-17 shows that although the optimal system architecture in

Cuajinicuil still would not change, however for the majority of other sites in Nicaragua with inferior wind and/or superior solar resources, an all-solar installation would likely be chosen.

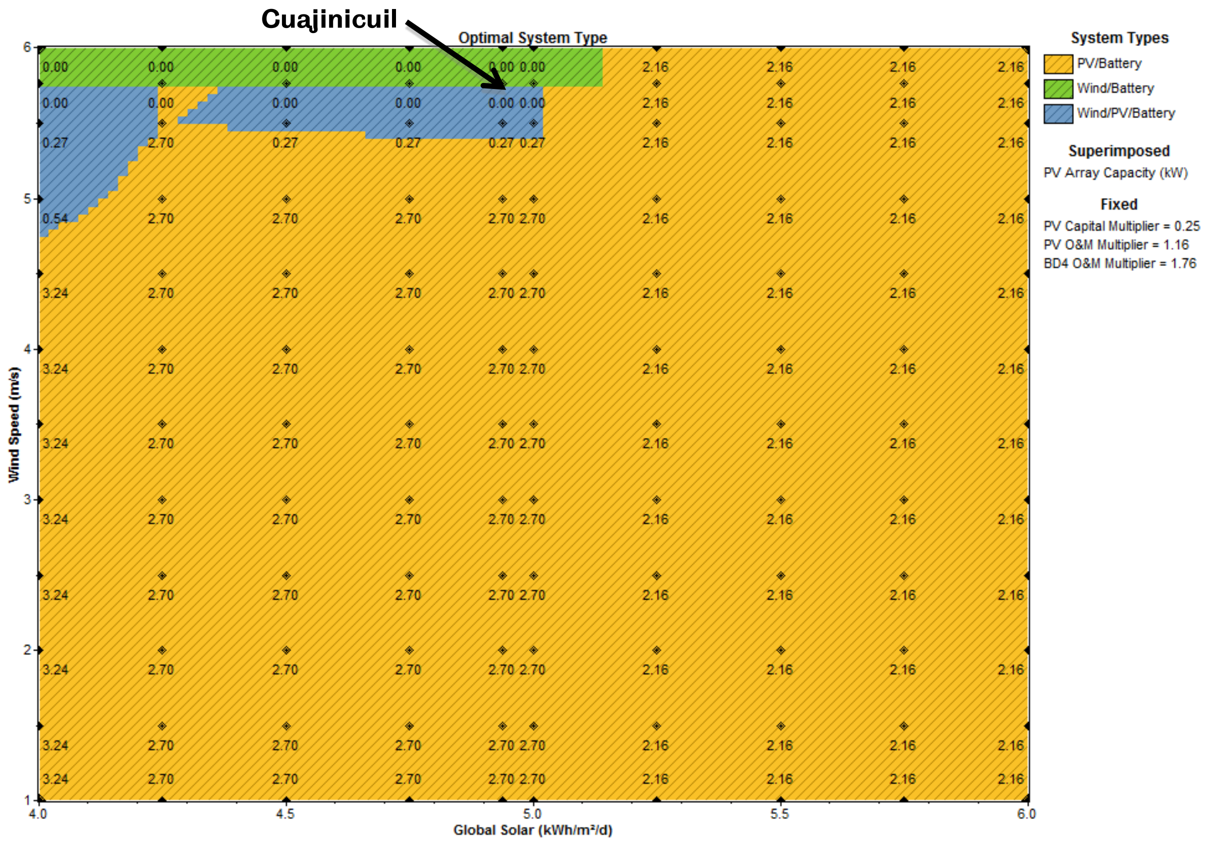


Figure 5-17: Alternative selection of optimal system architectures based on the 'worst case scenario' for wind.

Evaluation of community & technician training programmes

The fact that the community technicians were involved in the manufacture and installation of the SWT and that significant time and effort was put into training them has meant that, despite the quantity and complexity of maintenance required by the wind power system, they are capable of performing almost all of it:

> *"It's great that AsoFenix suggested that the guys learn about the installation and theory of the system....that they're prepared, so that they can respond to situations...no matter what happens to the turbine, because going to Managua would be very difficult...it would take a long time"*
>
> *Rosa Zenayda Valerio Huembes, Cuqjinicuil Community Leader, November 2012*

Not only is their level of knowledge impressive, but also their dedication as they aren't paid for all the work they do on the system:

“They’ve worked hard to learn for the benefit of the community”
Carlos José Gonzalez, Cuajinicuil Community Leader, November 2012

"I maintain the turbine because I love it!"
Bryam Antonio Bolaños Delgadillo, Cuajinicuil Technician, November 2012

During the field survey, 75% of those who were asked about the community technicians’ job performance rated it as good, 25% as average, and none deemed it bad. In fact, since the installation of the renewable energy system in Cuajinicuil, one of the technicians has now worked with AsoFenix in the installation of over 20 PV systems and a micro hydro project in other communities. The engineers from AsoFenix have even inspired him to study to become an engineer himself! He currently travels 3 hours each way to Managua every Saturday to take classes to prepare him for university entrance exams.

It is necessary to have somebody with this level of knowledge and enthusiasm for the technology that lives in the community because there are so many technical problems to solve with a wind system:

"They’re really active…they’re always checking over things, repairing the battery shed, cleaning the batteries, filling them with water …its really nice because if there’s a problem, they know how to fix it.”
Rosa Zenayda Valerio Huembes, Cuajinicuil Community Leader, November 2012

In fact, during the evaluative visit, this is exactly what happened: the technicians heard a strange sound the night before lowering the tower to install an anemometer. When the tower was lowered the next day, the rotor and stator were touching in one tiny portion of the rotation. The technicians adjusted the spacing between the two discs and avoided what could have developed into a major problem (see Figure 5-18).

Figure 5-18: Inspection of the rotor and stator by the Cuajinicuil technicians to prevent a potential future failure.

One unfortunate downside to all this training is the potential for 'brain drain', i.e. despite the fact that the technicians now have so much more technical knowledge than the rest of the community, there are few other opportunities in the local area in which they can use their new skills. They may therefore choose to leave the community to seek a better paying job in the nearby towns and cities and abandon their maintenance responsibilities:

> *"We're in the process of becoming sustainable…it would be good to train more people because…for example, one [technician] already left, he's in Costa Rica…another suddenly has to go off and study in Managua or work far away and won't be spending much time here."*
> *Rosa Zenayda Valerio Huembes, Cuajinicuil Community Leader, November 2012*

Despite this, the technician training programme in Cuajinicuil has undoubtedly been a success, with a number of capable and motivated individuals now in charge of the renewable energy system and able to perform the vast majority of maintenance without an engineer ever having to leave their office. However, the key question is really whether or not it is possible to find people as motivated and technically able in other communities.

Whilst the users of the PV-wind hybrid system only really have to clean the bulbs from time to time to remove smoke residue or dust, the users of isolated PV systems have a similar role to the technicians, i.e. to care for their system in addition to the electrical generation. However, they aren't worried about the maintenance because there are only a few, simple tasks, and the likelihood of faults occurring is very low. The PV users were found to be especially careful with the equipment installed in their homes as they were very conscious of the fact that they were responsible for paying for replacement parts. Figure 5-19 shows the electrical system of one of the individual PV system users, which he has covered in plastic to protect it from the high levels of dust in the air.

Figure 5-19: Leoncio Gonzalez, an end-user of a 55W PV household system with his well-protected electronic components.

An important role that all users have is to manage their use of electricity, especially during winter when both wind and solar resources are low. Almost all interviewees mentioned the need to save energy at such times and the steps they took to do so. Despite not having meters installed to monitor individual usage on the micro-grid, only 1 user complained of unfair overuse of the electricity by other users.

Overall, just like the technician training, the community training can also be considered a success. Users are aware of their roles within the system and are capable of fulfilling them. Opinion of the project is very high, with 100% of the 12 interviewees agreeing that the renewable energy systems are better than the energy sources they used to have before the project:

> *"I would like renewable energy to be promoted even further, so that we don't pollute the environment ... to get more out of the resources we have here."*
> *Rosa Zenayda Valerio Huembes, Cuajinicuil Community Leader, November 2012*

It should be noted that the sense of community in Cuajinicuil is also much stronger than the multi-ethnic communities of the Caribbean coast. The community is made up almost exclusively of one big extended family, whilst the communities on the Caribbean coast are made up of many different families of mestizo[55], indigenous[56] and afro-Caribbean[57] origin. Yadoo (2011) notes that a "*rosy rhetorical image of close-knit rural communities*" (Walker *et al.*, 2010: 2662) often hinders community renewable energy projects, as the reality is that each community is different and properly understanding these differences from the outset is vital. Operating and maintaining a SWT requires the support of the community it is installed in, as even if a single motivated individual is technically able to perform the maintenance, the management of the system and the collection of fees to cover maintenance costs require the cooperation of the other community members. What is more, the motivation of an individual to carry out their maintenance responsibilities is likely to be much higher if they value the respect they receive from the rest of the community for providing them with electricity.

5.2.2.5 Evaluation

The greater variety of methods (specifically the addition of qualitative data from the community itself) employed in the Cuajinicuil and Monkey Point case studies offered a much deeper understanding of the issues affecting the viability of SWTs than the case study work described in the previous chapter. However, the focus on two specific communities has reduced the generalizability of some of the findings. For example, the fact that the charge controller in the solar system failed in the first two years after installation artificially inflates the operation and maintenance costs of the system shown in Figure 5-6, as this type of failure is quite rare.

5.2.2.6 Conclusion

The Cuajinicuil case study illustrates that most of the barriers faced on the Atlantic coast can be overcome in the more favourable context of the central highlands and with a comprehensive technician training programme:

Table 5-2: The barriers facing small wind on the Atlantic coast and the steps taken to address them in the Cuajinicuil pilot project.

Barrier	*Successfully addressed?*	*Justification*
Environmental hazards	Yes	Less frequent lightning strikes in the central highlands & lower salinity due to distance from the coast.
Lack of local technical knowledge for O&M	Yes	Comprehensive training programme for multiple community technicians including participatory manufacture.
Long supply chain for tools & spare parts	Yes	If the LMSWT was to be manufactured by AsoFenix in Managua, the supply chain would be reduced from an 8 hour boat ride to a 3 hour car journey.

[55] Of both Spanish and indigenous decent.
[56] Miskito, Rama, Sumo and other smaller ethnic groups.
[57] Garifuna or Creole.

Barrier	*Successfully addressed?*	*Justification*
Lack of motivation to perform O&M	Yes	Community ties in the central highlands are much closer than those in the multi-ethnic communities of the Caribbean coast. Empowerment of community technicians through training programme also successful.
Lack of wind resource	Yes	Average wind speeds on the Caribbean coast were below 4m/s, whilst in Cuajinicuil it is estimated at 5.77m/s.
Lack of funds for O&M	Not yet	The irrigation and fruit processing projects in Cuajinicuil have not yet been set up, leaving the community struggling to pay for the maintenance of the systems.
Lack of quality due to low volume manufacturing	Not yet	Not possible until many more systems have been manufactured.

If the issue of establishing productive uses of the electricity generated by SWTs can be addressed and a manufacturing base can be set up to produce higher volumes of SWTs in either the capital, Managua, or a town in the windy parts of the central highlands such as Estelí, then the technology has the potential to succeed. The subsequent sections seeks to determine how scalable the technology is by evaluating the current state of the small wind ecosystem in Nicaragua and presenting a methodology for estimating the size of the market for SWTs and applying it to the Nicaraguan context.

5.2.3 The small wind ecosystem in Nicaragua

5.2.3.1 Methodology

A series of semi-structured interviews were conducted with Nicaraguan SWT experts. Interviewees were selected from a variety of sectors, including academia, NGOs, renewable energy suppliers and the government. For a list of interviewees and a full description of the interview design, sampling and questions, please refer to Appendix I.

5.2.3.2 Enabling environment

Environment

Environmental hazards

blueEnergy's troubled installations on the Atlantic coast indicate that the high incidence of lightning strikes (see Figure 5-20) and the corrosion caused by the hot and humid coastal environment greatly increase the maintenance requirements in this region. It is known that both corrosion and lightning strikes are less prevalent in the central highlands; however the severity of the environmental hazards present in the rest of the country is unknown. Environmental factors have a much bigger impact on SWTs than solar PV, as by design, SWTs are deliberately installed in places where they face the full force of the weather and are therefore much more likely to suffer from failures due to continual exposure to a combination of wind, rain, sun, salty air and lightning strikes. In comparison, a set of solar panels is relatively protected, as it is often below the tree line, is completely sealed and has no moving parts.

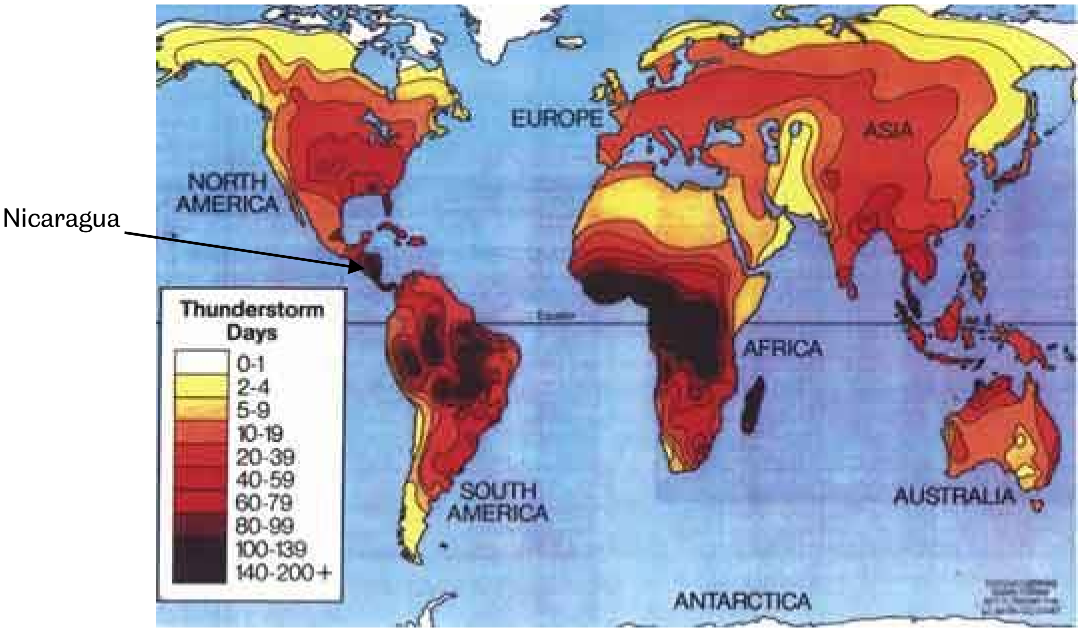


Figure 5-20: Nicaragua has the highest frequency of lightning strikes of anywhere in the world (Dreyer, 2010).

Wind resource

The map shown in Figure 5-21 was produced by the SWERA programme, which is a collaboration of more than 25 worldwide partners, managed by the United Nations Environment Program (UNEP)[58]. The wind data utilized for estimating the wind potential in Nicaragua consisted of data from ocean satellites, private developers and government agencies. The four existing utility-scale wind projects east of Lake Nicaragua[59] have performed exceptionally well since the first one came online in 2009. Data from megawatt scale projects in development northeast of Lake Nicaragua also confirm the class 4-6 wind regimes shown in the map[60].

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[58]The wind estimates for the map were developed using the NREL's Wind Resource Assessment and Mapping System (WRAMS) in conjunction with GIS mapping tools utilizing wind and surface elevation data (NREL, 2006).
[59] AMAYO, EOLO, Blue Power, and Alba Generación.
[60] Hato Grande wind project in development by MesoAmerican Energy.

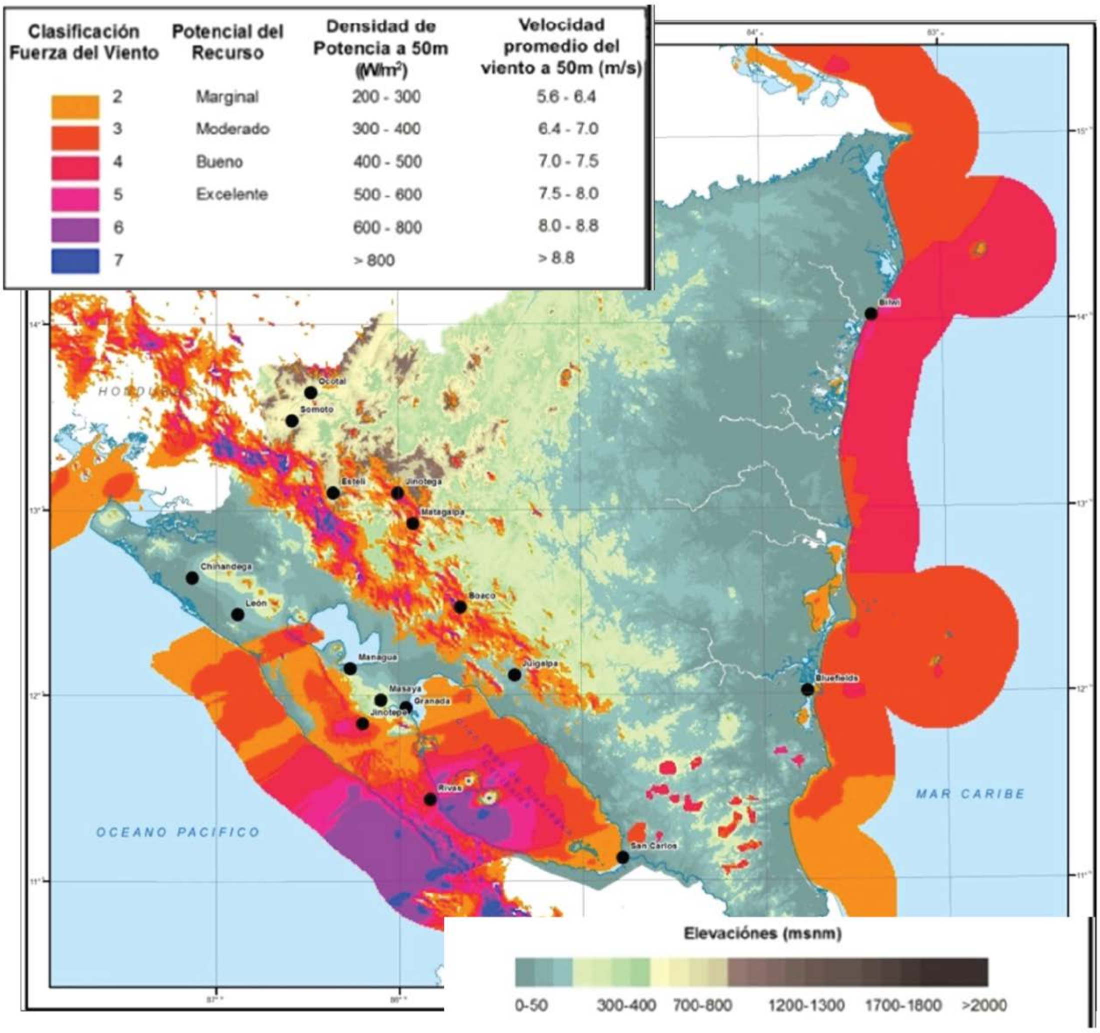

Figure 5-21: Wind map of Central America at 50 m height. Adapted from SWERA (2008).

"Regions with good wind include El Crucero, Lake of Nicaragua, some areas of the Momotobo, Rivas and the Izimuth region and the mountainous regions in Jinotega. Most areas [in Rivas] are close to the grid."

Lesther Ortiz, Sales Manager, TecnoSol S.A, October 2011

On the Atlantic coast, ocean satellite data indicates the presence of class 3-4 winds on exposed shorelines and islands. However, no ground data measurements have confirmed such wind regimes. The only such measurements used for the SWERA modelling was a single met station at the Puerto Cabezas airport on the north-eastern shore, indicating a class 2 wind regime. The wind data from blueEnergy and ENCO's measurements on Corn Island (approximately 75km off the Atlantic Coast) clearly show class I wind regimes in the southern region of the Atlantic Coast, with the likely presence of class 2 wind in the northern region.

The results of the most recent wind mapping project by ENCO Central America are shown in the wind map in Figure 5-3. The map shows high wind regimes on the western coast, supporting the SWERA maps. In addition to meteorological data from the Puerto Cabezas airport, the analysis also utilized data from a meteorological station at the Bluefields airport, as well as 9 months of measurements from a 20m tower on Corn Island. Due to the scarcity of input data on the Atlantic Coast, the map reveals little more about the coastal data, except that it is much lower than the class 4-6 regimes found in the western regions of Nicaragua.

> *"[SWTs could work in] the areas with over 6m/s on the 30m ENCO map, which will probably be more like 5m/s at SWT hub height of 10m. The central highlands, the Pacific coast more than the Atlantic coast (although there are some high points in the RAAN[61] and RAAS"*
> *Tim Coone, Director, ENCO Central America S.A., October 2012*

While the wind maps show the presence of wind trends for various areas in Nicaragua, the installation of small wind generators must be based upon local evidence of suitable conditions. Local topography can greatly impact wind conditions that will determine the economic viability of small wind generation.

The wind data recorded by blueEnergy and ENCO Central America was compared with the historical data from INETER over the last ten years and all of the data was found to exhibit the same trends of maximum winds occurring during the winter months of December through March and the minimum winds during the rainy months of June through August. Figure 5-4 shows this variation as measured at the site of the first case study in section 5.3.6, Cuajinicuil.

Topography

Rural Nicaragua is almost entirely covered by dense jungle, making towers of at least 15m essential in almost all areas. The central highlands present both challenges and opportunities with regard to wind power. Transportation in these regions is more difficult and the valleys are sheltered from the wind, however communities located at the tops of hills (such as Cuajinicuil) can access a higher wind resource than the surrounding area. The jungles of the Atlantic coast are particularly dense, making travel by boat a necessity for the majority of journeys in this region.

Viability of other renewable resources

Figure 5-22 shows the locations where renewable energy resources can be expected to generate electricity that would be cost competitive with the current generation costs on the national electric grid. Strong wind resources lie along the southern Pacific region, biomass potential along the Pacific lowlands, geothermal potential along a fault line running northwest by southeast on the Pacific Coast, and hydro potential in the central portion of the country, exploiting elevation drops from the central highlands down towards the Atlantic Coast.

The majority of the best renewable energy resources lie exclusively in the west and central regions of the country, with no high power density renewable resources on the Atlantic Coast. However, unlike the western and central regions of the country where renewable energy generation technologies need

[61] Northern Atlantic Autonomous Region (Región Autonomo Atlantico Norte).

to compete against power generation from large thermal plants on the national grid, power generation for many communities along the Atlantic coast comes from small diesel generators. Whereas the average bulk power price in 2012 for the central grid is close to 0.11 $/kWh, the average generation cost among the mini-grids is closer to 0.60 $/kWh, opening opportunities for the integration of both wind and solar generation technologies at the larger scale.

Figure 5-22: Locations where renewable production could compete with centralized grid production prices (ESMAP, 2007).

"I would recommend small scale wind only if there was no other alternative. In my opinion, it needs to be combined with solar PV, in order to reduce the dependence on wind fluctuations"
Roberto Sosa, Project Director, CHF International, November 2012

The wind resource is highly intermittent, even more so than most other renewable sources of energy. For off-grid installations, both solar and hydro have the potential to provide power and keep the batteries topped up during times of low wind. Figure 5-23 demonstrates that on the daily timescale, wind and solar complement each other well. The solar resource is only available during the day, yet wind is available through the night and whilst the wind may stop for a few days, solar provides at least a small amount of power every day.

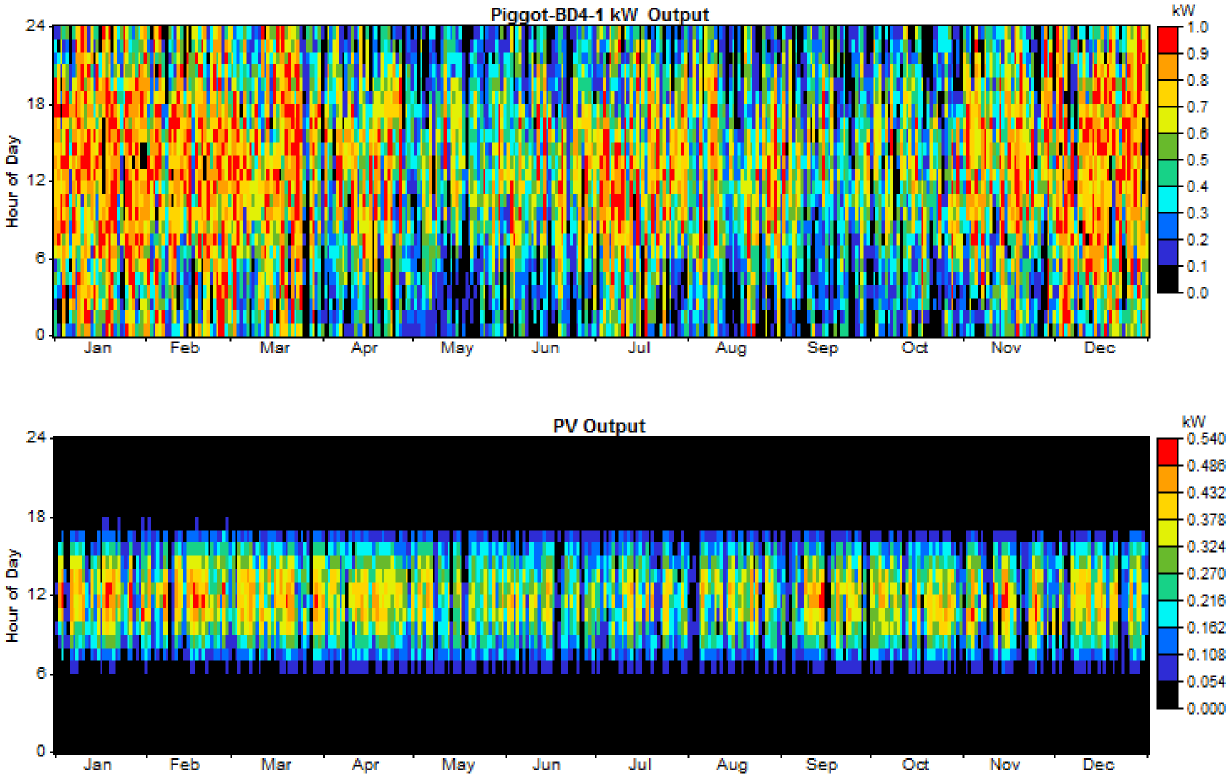

Figure 5-23: Hourly average power production of the 1kW bD4 wind turbine and 540W PV array installed in Cuajinicuil (modelled in HOMER).

The two resources are also complementary on the weekly timescale: during storms, when there is little solar radiation, winds are likely to be strong. Likewise, when high pressure systems with low winds are present, the sky is likely to be clear, allowing battery systems to remain charged. However, the two resources are not so complementary on a seasonal basis: the low wind months of June to August correspond to the months of lowest solar radiation (see Figure 5-24). This low production period is typically used to determine the capacity sizing for off-grid PV-wind hybrid systems that are needed to meet a constant load throughout the remainder of the year.

"Most projects have a time of year for which they're successful, but for the rest of the year not."
Douglas González, Director of Operations, Suni Solar S.A., November 2012

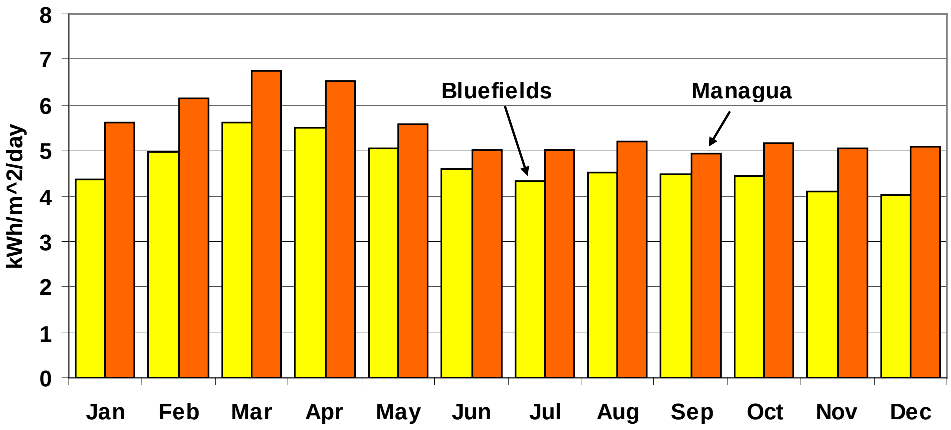

Figure 5-24: Solar horizontal radiation for the Pacific (Managua) and Atlantic (Bluefields) coasts of Nicaragua. Data source: NASA (2013).

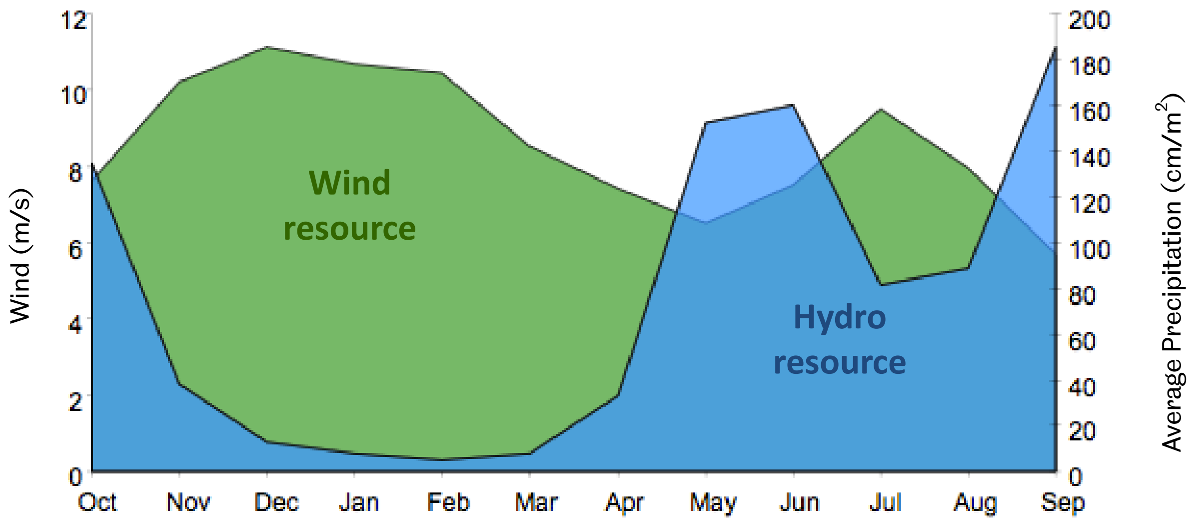

Figure 5-25: Wind and Hydro power complementarity in Central America, where most hydro projects are run-of-the-river. Adapted from Globeq Mesoamerican Energy (2012).

Wind and hydro power display a very interesting seasonal complementarity in Nicaragua, which has proven to be of strategic importance at the utility-scale (Globeleq Mesoamerica Energy, 2012), but could also be applied at the community level for small-scale wind and pico-hydro. Most micro-hydro projects in Nicaragua are run-of-the-river and depend directly on precipitation at that particular moment in time (i.e. there is no inter-seasonal storage) that can drop from over 200cm/m^2 and in some areas to almost 0. Because of the 6-month long dry season (from November to April) each year, most projects yield a yearly capacity factor of about 50%, however these months happen to be the months with the strongest winds. Figure 5-26 shows the location of existing hydroelectric projects and those with proven hydro potential.

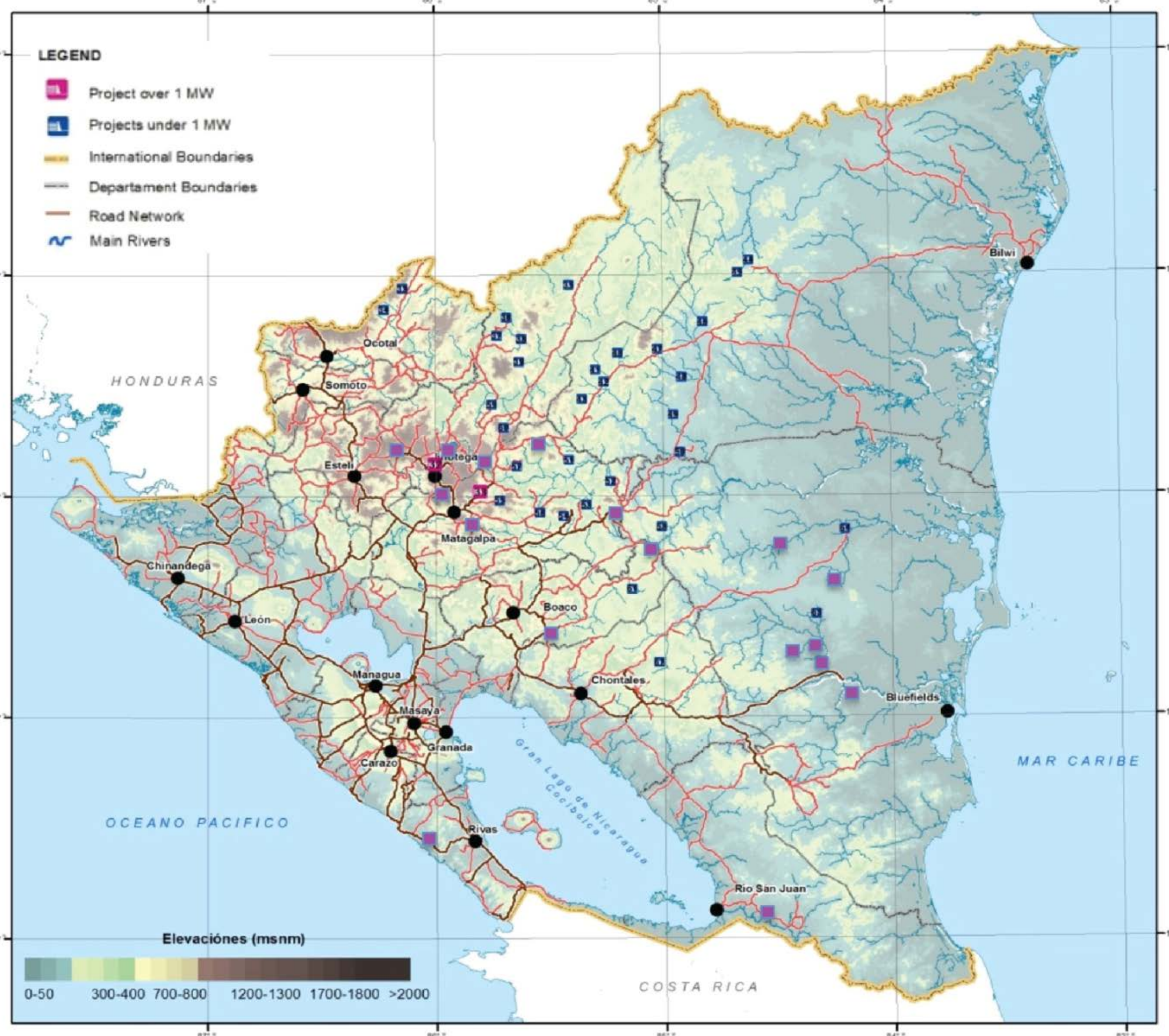

Figure 5-26: Map of regions with hydroelectric potential in Nicaragua. Data source: MEM and Asociación Renovables.

Figure 5-27 shows the solar resource map of Nicaragua, which is also produced by SWERA. It is clear to see that the variation of the solar resource across the country is very low compared to that shown in the wind maps in Figure 5-21 and Figure 5-3. The Atlantic coast has a lower level of solar radiation (4-5kWh/m^2/day) due primarily to the more humid and cloudy environment, whilst the Pacific coast has (5-6 kWh/m^2/day). As a result, solar PV on the Atlantic coast would be expected to produce around an energy yield 20% lower than an equivalent installation on the Pacific coast.

"In our experience, it's easiest to design electrification project with solar PV systems. Mostly because the resource is easier to predict….We don't know the eligible sites very well, which causes customers and vendors to eventually make mistakes and lose money."
Aracely Hernandez, Head of Wind Projects, MEM, November 2012

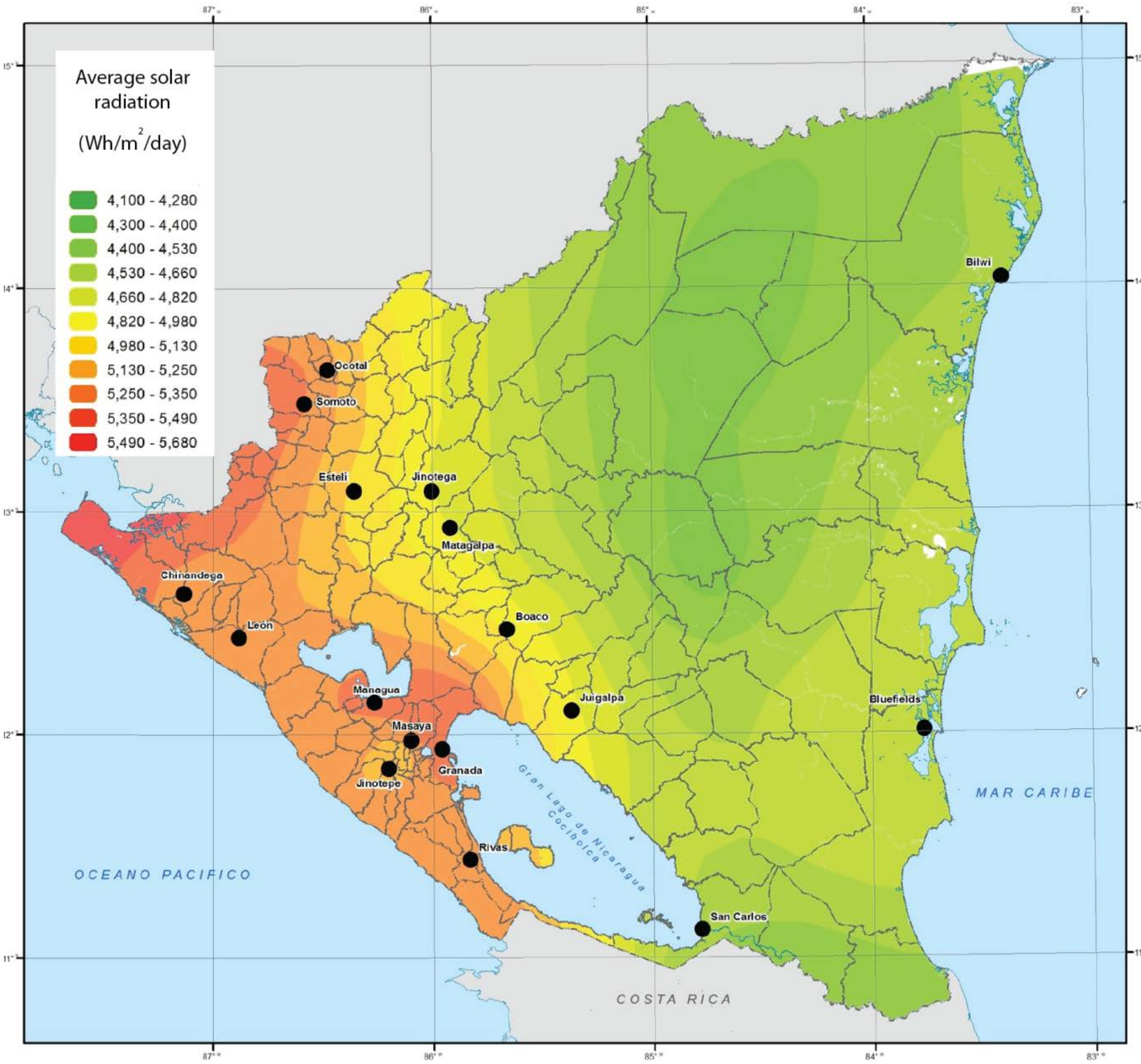

Figure 5-27: Map of the solar resource in Nicaragua. Data source: SWERA (2008).

Interestingly, the price of solar PV has decreased significantly in recent years is likely to continue (IRENA, 2012).

"Wind used to be cheaper than solar. The price curves have now reversed."

Max Lacayo, Sales Manager, ECAMI S.A., November 2012.

Demographics

Nicaragua has one of the highest levels of poverty in the western hemisphere, with 45% of the population living on less than 1 $/day (Mostert, 2007). Figure 5-28 shows the distribution of extreme poverty[62] in Nicaragua, clearly showing that the Atlantic coast is much poorer than the Pacific coast, with close to 80% of the population living below the poverty line (INIDE, 2005).

[62] Extreme poverty is defined by the lack of at least 2 of the 5 basic services: density of people / house, proper lodging, access to water and sanitation, low level of education and economic dependency.

Assumes a 10% cost of capital

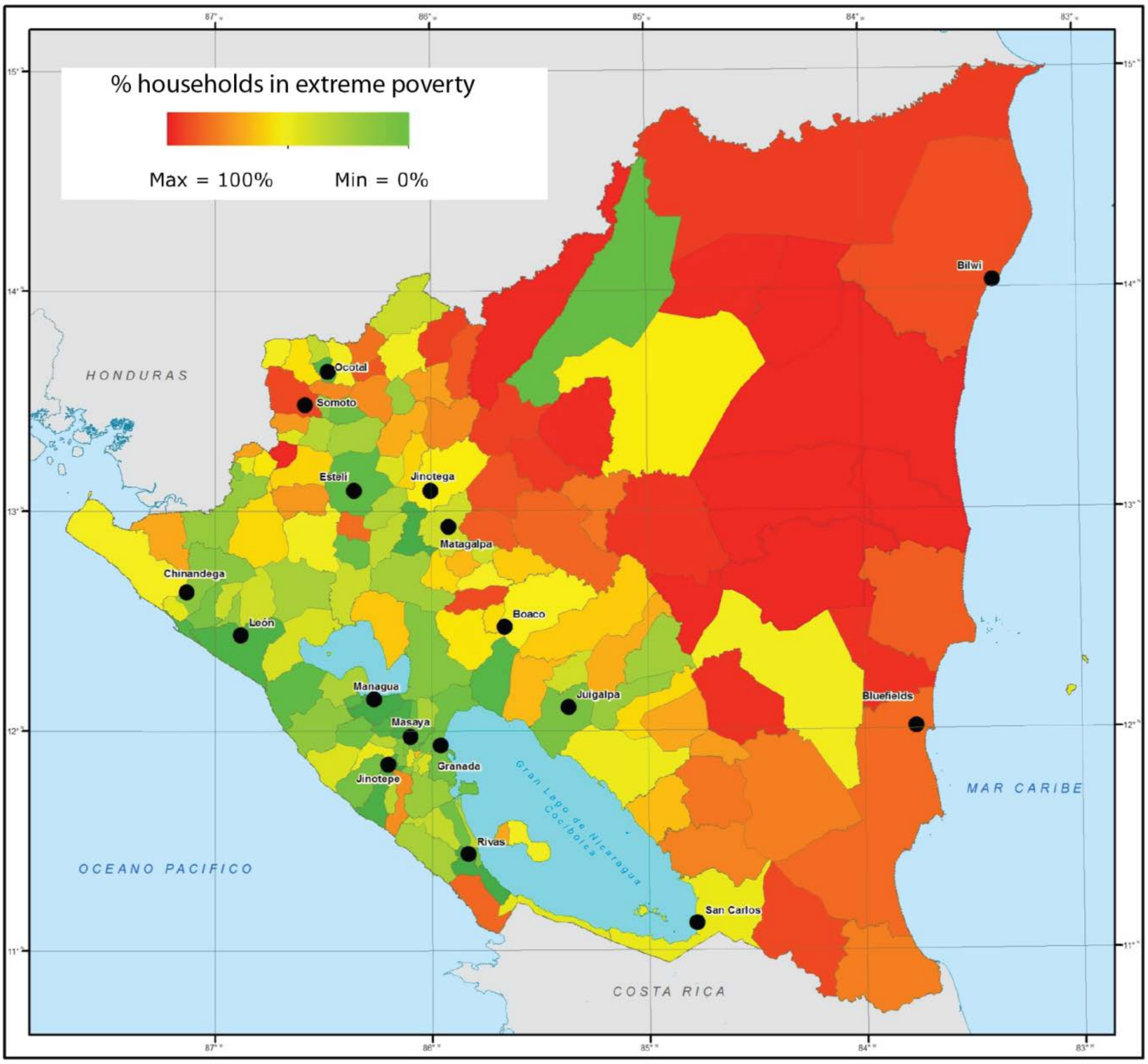

Figure 5-28: Distribution of people living in extreme poverty in Nicaragua. Data source: INIDE (2005).

Policy

Government regulating bodies and key legislation

A government flagship project, known as PNESER[63], was designed in 2008 and funded by a large group of multilateral banks and development agencies. It launched in 2011, and will continue to foster change in the coming years, focusing on grid extensions, renewable energy projects, and a limited amount of distributed generation. While diesel mini-grids, run by ENEL[64], represent the historically favoured solution for medium and large off-grid population centres, many small-scale hydropower sites have been developed during the last 10 years (under the PERZA[65] and PCH[66] programmes) to improve

[63] National Sustainable Electrification and Renewable Energy Program (Plan Nacional de Electrificaión Sostenible y de Energías Renovables).
[64] National Electric Company (Empresa Nacional de Electricidad).
[65] Rural Electrification Program for Remote Areas (Programa de Electrificación Rural en Zonas Aisladas).

access to electricity in the north and north-eastern regions. More recently, small-scale solar projects have been promoted by the MEM[67].

Legislation of the small-scale wind sector

Electric power generated from wind is not subject to specific legislation other than that contained in *Law 532: Promotion of Electricity Generation from Renewable Resources* (Law 532, 2005, p. section5), which only requires licenses for utility-scale projects (>1MW). While the Nicaraguan VAT and import duties for deep cycle batteries and PV panels have been waived under the regulations created by the Law 532, 2005, these exemptions do not cover small-scale wind turbines or any power electronics required for both grid-tie or isolated installations. This creates a significant price disadvantage for small-scale wind systems, compared to solar PV, as explained in Figure 5-34 and Table 5-8.

> *"The regulatory framework doesn't apply to small scale wind."*
> *Aracely Hernandez, Head of Wind Projects, MEM, November 2012*

The current lack of feed-in tariff legislation prevents the installation of grid-tied small-scale wind power installations, A new law governing distributed generation is expected in 2014, however it is unclear whether this will allow individual users to receive the feed-in tariff or whether it will be aimed at larger scale generators. Marandin *et al.* (2013) found that the installed cost of a grid-tied 5 kW SWT in Nicaragua is 5% lower than an isolated system, however the high cost of battery replacement makes the lifecycle costs (undiscounted) of a grid-tied system 18% lower. If individual users could access the feed-in tariff proposed in the upcoming law for distributed generation (expected in 2014), they could sell an estimated 30% surplus energy back to the grid at $0.11/kWh, which would make grid-tie systems 31% cheaper overall. This would have the knock on effect of strengthening the small wind ecosystem by increasing the number of SWT suppliers, building capacity to install and maintain SWTs etc.

Capacity

Wind power awareness level and technical knowledge

There is a lack of general and technical knowledge about wind power at all levels: institutional (no specific existing technical training programme), private sector (not enough installations in the last 10 years to develop strong expertise), and among the general public. Although commercial utility-scale wind power is a success story in Nicaragua, the lack of a track record of successful and visible small-scale wind power installations makes it very difficult to grow the market from a public perception perspective.

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[66] Hydroelectric Mini-grids (Pequeñas Centrales Hidroeléctricas).
[67] Nicaraguan Ministry of Energy and Mines (Ministerio de Energía y Minas).

"There is a general lack of information about the specifics of wind power, both on the vendors' side and with regard to the general public"
Jeronimo Zeas, Head of the Wind Studies Department, UNI[68], November 2012

Energy data availability

Data on access to electricity is relatively scarce in Nicaragua, as the 2005 Population Census (INIDE, 2005) was the last nationwide survey of the socio-economic status of the Nicaraguan population. However, this lack of detailed information is currently being addressed in Nicaragua by the Sustainable Energy for All (SE4All) initiative.

"Contrary to solar, wind projects suffer from the lack of existing information about the available wind resource."
Douglas González, Director of Operations, Suni Solar S.A., November 2012

In the central and western regions of Nicaragua there has been considerable interest in mapping the wind regimes by both the government and private wind farm developers. However, the wind maps that are currently publically available are not of high enough resolution or accuracy to reliably plan small-scale wind projects at a resolution below that of the municipality. A reasonable amount of measurements and analysis of the wind potential have been done on the Pacific coast of Nicaragua. More limited data exists regarding the central highlands and the lower wind regimes on the Atlantic coast. It is worth noting that while the United Nations Environment Program (UNEP) and the private company ENCO Central America have built their own wind maps, the Nicaraguan Ministry of Energy & Mines (MEM) does not yet have its own. However, measurements are currently underway (see Figure 5-29), with completion expected by the end of 2016.

[68] National Engineering University (Universidad Nacional de Ingeniería).

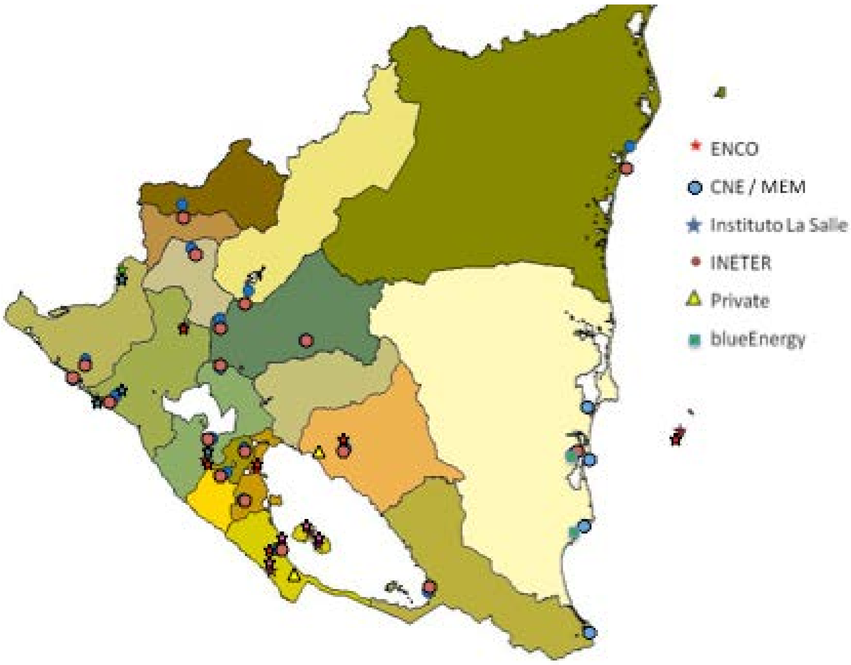


Figure 5-29: Map showing known wind measurements in Nicaragua. Image courtesy of ENCO.

There are a number of publicly and privately available sources of wind data for Nicaragua, listed in Table 5-3.

Table 5-3: Wind resource data available for Nicaragua

Source	Website	Data type
UNEP/SWERA[69]	http://maps.nrel.gov/ (maps & data available online)	Free statistically modelled wind map
INETER[70]	http://www.ineter.gob.ni/ (maps not available online; data at http://cdo.ncdc.noaa.gov)	Free historical met data – hourly measurements at 10 m
MEM	http://www.mem.gob.ni/ (maps & data not available online)	30 m, 50 m
ENCO	http://www.encocentam.com (maps available online)	Free (low resolution only) 30, 50, 100 m statistically modelled wind map
UCA[71]	http://www.uca.edu.ni/ (maps & data not available online)	Wind and solar measurements since 1984
UNI	http://www.uni.edu.ni/ (maps & data not available online)	UNI – Wind and Solar measurements
blueEnergy	http://www.blueenergygroup.org (maps & data not available online)	10 m hourly data from various sites in the RAAS

[69] Solar and Wind Energy Resource Assessment Program.
[70] National Institute of Territorial Studies (Instituto Nacional de Estudios Terrirotoriales).
[71] Central American University (Universidad Centro Americana).

There have been extensive wind measurements in various locations on the Pacific side of Nicaragua, closest to population centres. On-site measurements throughout the Pacific show class 4-6 wind sites, suitable for commercial as well as small-scale wind. There are already a number of commercial, megawatt-scale, wind farms in the southern Pacific region, producing power for the national grid. On site measurements are lacking for the Central Highlands, but the government has contracted measurements at several promising sites in Estelí, Jinotega and other departments. There have been significantly fewer measurements throughout the Atlantic coast, when compared with the rest of the country. However, a number of wind measurement studies have been conducted in the southern region, as well as small wind installations by the NGO blueEnergy. Both the wind studies and installations confirm these Class 1 wind regimes, with slightly greater winds expected in the north. Marandin *et al.* (2013) gives further details of the wind resource measurements taken across the country.

5.2.3.3 Supporting services

Rural energy agencies

The primary regulatory entity in the off-grid electricity sector in Nicaragua is the Ministry of Energy and Mines (MEM), which is in charge of producing the development strategies for the national electricity sector, specifically the DGERR[72].

Utility-scale actors

There are world-class wind sites on the Pacific Coast, suitable for commercial-scale wind production. There is an estimated potential of 760 MW wind production where there is good road and grid access, primarily on the Pacific Coast. Other high potential areas which are currently less accessible, could add a further 2000 MW. Nicaragua's first wind farm (AMAYO I, 40 MW) was inaugurated at the beginning of 2009 and in May was generating some 700 MWh daily. A second phase, adding 23 MW, was authorized in November 2009 and started producing in 2011. Whilst utility-scale wind power is driven primarily by demand for electricity in urban areas, they offer the potential to build capacity for wind power in general in Nicaragua:

> *"The successful example of utility-scale wind farms in Nicaragua may provide a positive feedback for small scale wind."*
> *Manuel Madriz, Energy Specialist, PRONicaragua, November 2012*

Currently, there are a total of five wind farm projects on the Pacific coast, at different stages of development, representing a total capacity of almost 300 MW. Most of these new projects will have to

[72] Department for Electricity and Renewable Resources (Dirección General de Electricidad y Recursos Renovables).

wait for the inauguration of the SIEPAC[73] project and the creation of the regional electricity market, for them to be integrated into this larger regional grid. In the central highlands, modelled data indicates the presence of class 4-6 winds, but there are not currently any known wind installations in this area. The Ministry of Energy and Mines is currently contracting measurements in six priority sites, which include the central highlands and northwest. Table 5-4 and Table 5-5 list the private generators and project developers currently working with utility-scale wind power in Nicaragua.

Table 5-4: Private utility-scale wind generators currently operating in Nicaragua.

Company	Project size and location	Date of initial operation	Planning new projects?
AMAYO (AEI) 1 + 2	*63 MW, Rivas*	*2009*	*No*
MesoAmerica Energy – GlobelEq	*40MW, Rivas*	*2012*	*Yes, El Crucero / Hato grande*
BLUE POWER	*40MW, Rivas*	*2012*	*No*
ALBA EOLICO	*40MW, Rivas*	*2013*	*?*
OSTAYO	*20MW, Rivas*	*2014?*	*Project in development*

Table 5-5: Wind project developers currently operating in Nicaragua.

Company	Project types	Main competencies
ENCO, S.A.	*100kW to 1MW*	*Wind measurements, Feasibility studies*
PELICAN, S.A.	*100kW to 1MW*	*Project development, execution, financing*
ACN, S.A.	*General*	*Project execution, construction*
MultiConsult, S.A.	*General*	*Feasibility studies*

Existing transportation infrastructure

Nicaragua is extremely divided, with all the major population centres located on the Pacific coast. Accordingly, the country's transportation network in this region is relatively well developed, with paved roads linking all the major cities. In contrast, the autonomous regions on the Atlantic coast, the RAAN and the RAAS consist of dense jungle navigable in the most part only by boat. About 50% of Nicaragua's 5.8 million people are classified as urban, with over one-quarter of the total population living in the capital city of Managua (INIDE, 2005).

[73] Interconnected Central American Electricity Grid (Sistema Interconectada de Electricidad para América Central).

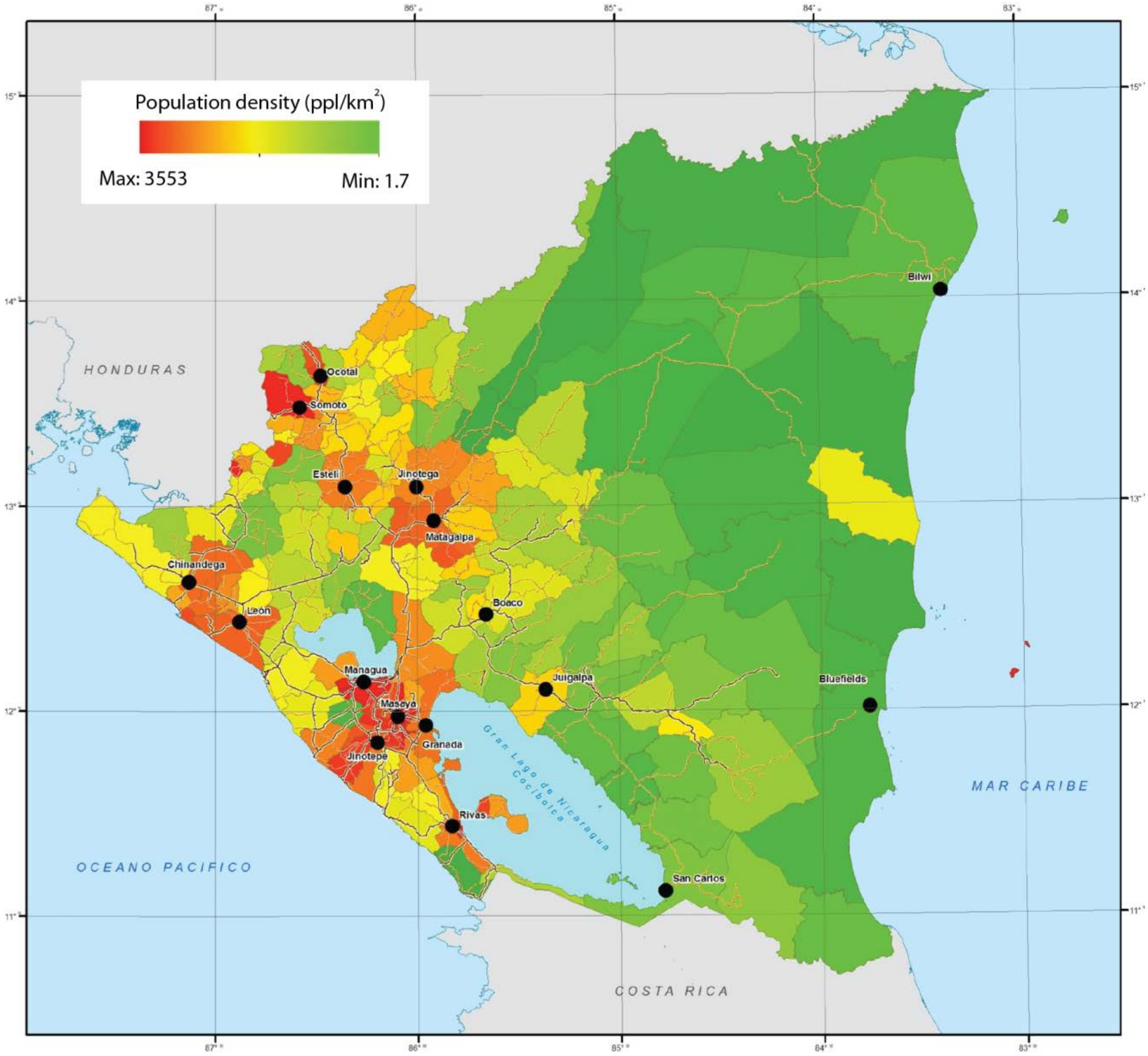


Figure 5-30: Population density and major road network in Nicaragua. Data source: INIDE (2005).

Existing electricity distribution and generation infrastructure

Since the national energy crisis in 2006[74], Nicaragua has been undergoing an energy revolution, drastically changing a country that featured a high dependence on fossil fuels, an unreliable national grid and over 50% of its population without access to electricity. Today, Nicaragua has a plan to go almost 90% renewable (MEM, 2009) and build a reliable grid that extends to remote areas and is interconnected with its Central American neighbours. In 2011 Nicaragua ranked 2nd second in Latin America in terms of receiving foreign investment in renewable energy projects (Bloomberg, 2012).

Nicaragua has the lowest rate of electrification in Central America, with between 72% (MEM, 2009) and 78% (CEPAL, 2011) of the population having access to the centralized grid. The figure for rural

[74] The unbundling and privatization process of the 1990s did not achieve the expected objectives, resulting in very little generation capacity added to the system. This, together with its high dependence on oil for electricity generation (the highest in the region), led to an energy crisis in 2006 from which the country is still recovering.

electricity access is estimated to be much lower, at approximately 40%[75]. Again, the country is divided geographically, as only 40% of the Atlantic coast has access to electricity (INIDE, 2005). The backbone of the Nicaraguan electricity system is the National Interconnected System (SIN[76]), which covers more than 90% of the highly populated regions (the entire Pacific, Central and Northern regions of the country). Figure 5-22 below shows the structure of the national electric grid and the location of stand-alone, isolated, generation and distribution systems.

Figure 5-31: Structure of the SIN and isolated generation in Nicaragua. Image courtesy of ENEL.

The transmission system primarily serves the high population centres located on the Pacific Coast and central highlands of the country. The smaller, isolated communities on the Atlantic Coast make it harder to economically justify the extension of the transmission system, which typically ranges from 15,000 to 20,000 $/km (Flavin and Aeck, 2005). As a result, ENEL[77] operate isolated generation and

[75] Estimate based on discussions with the MEM. The national census does not differentiate urban from rural in its electrification figures nor do the distribution concession operators.
[76] National Interconnected System (Sistema Interconectado Nacional)
[77] The Nicaraguan Electricity Company (Empresa Nicaragüense de Electricidad) was formerly a state owned utilty, which today operates only in the areas that are not profitable enough to attract bids from the private sector.

distribution systems with generation capacities less than 10 MW (and usually below 1 MW) and are almost exclusively powered by diesel generators or small hydro. Many of these isolated generation systems have recently been connected to the national grid, leaving less than 10 communities in Nicaragua relying exclusively on ENEL mini-grids.

Figure 5-32 shows that the LGC of a diesel generator set is dominated by the fuel cost. Until the recent crude oil price rises, there were few small-scale generation technologies that were cost competitive with diesel generation, with the exception of small-scale hydro. With current diesel fuel costs close to 1.00 $/litre, a diesel generator will produce power in the range of 0.30 $/kWh to 1.00 $/kWh, depending on the efficiency and scale at which it is operating.

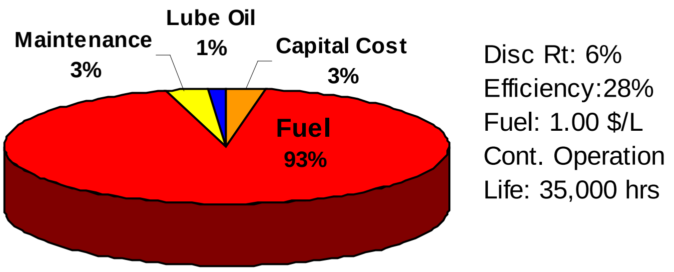


Figure 5-32: Lifecycle costs for a 225kW diesel generator on continuous duty (Casillas, 2012).

While electricity distribution using a mini-grid is a practical approach to meet the needs of users in the larger towns and villages (i.e. the 'urban' populations), it quickly loses its cost effectiveness for communities comprised of houses that are widely distributed throughout the countryside, as most farming communities typically are. The remote nature of these populations, the dependence on imported fuel (in the case of diesel systems), and lack of steady incomes for the users are all problems that result in low capacity factors and have hindered access to adequate electricity services for the vast majority of the rural population. It is here where smaller-scale distributed electrification solutions such as solar home systems and wind/solar battery charging stations may provide the most economic near term solutions.

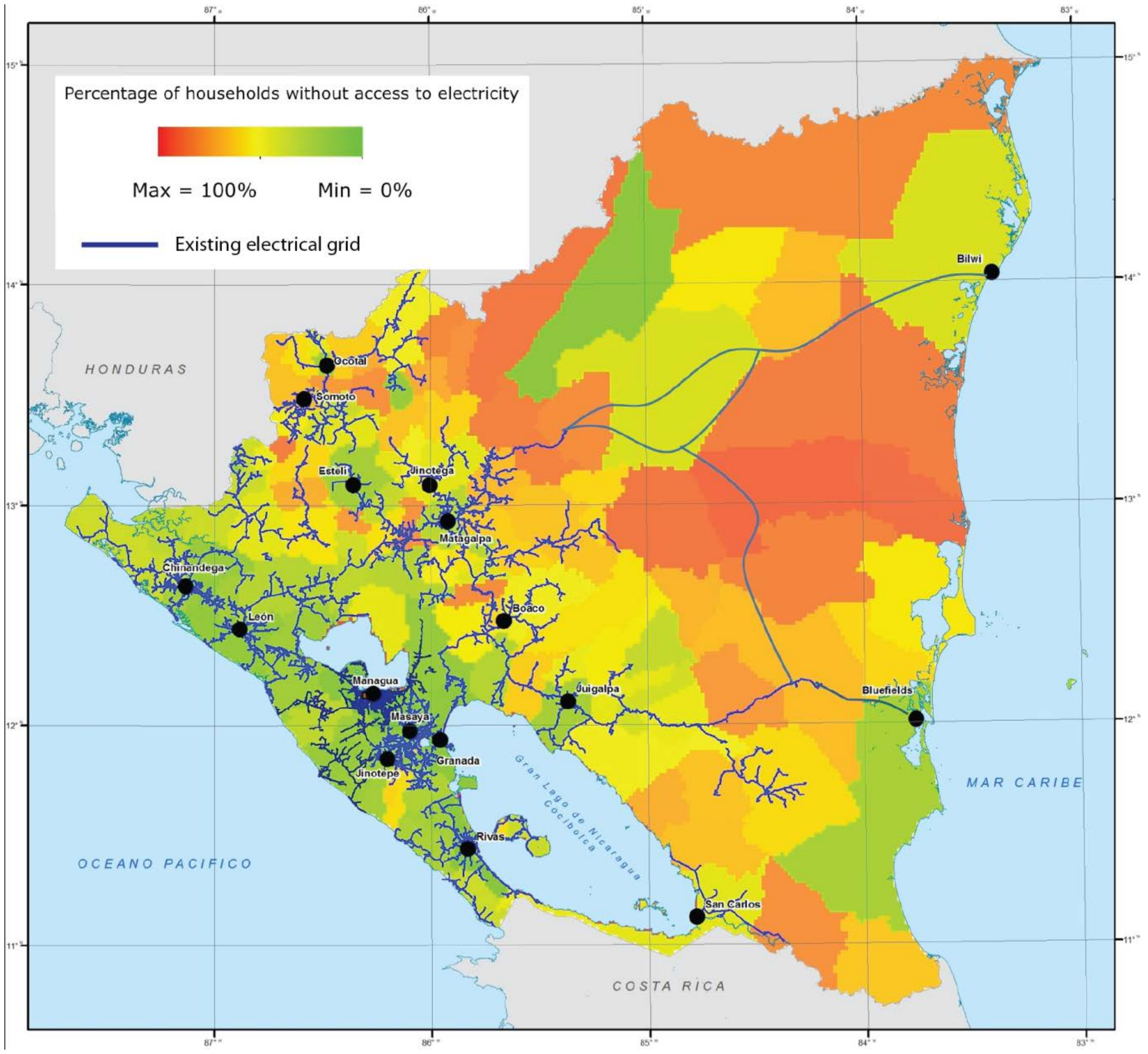


Figure 5-33: Access to electricity in Nicaragua. Data source: MEM.
Note: For diesel mini-grids, please refer to Figure 5-31. The municipalities of Jinotega and El Cua are now interconnected but suffer from frequent grid failures.

5.2.3.4 Market actors

NGOs providing rural electricity access

Table 5-6 shows the four NGOs that play a significant role in rural electrification in Nicaragua. Due to the lack of actors to perform complementary roles within the remote local contexts in which they operate, many of these NGOs perform a variety of the traditional roles within a small wind ecosystem. For example, blueEnergy manufactures SWTs, supplies SWTs, offers SWT maintenance services and provides SWT training for the remote communities in the RAAS.

Table 5-6: Non-profit organization providing rural electrification services in Nicaragua. Source: Asociación Renovables.

Organisation	*Concession holder*	*Region*	*R.E. technologies*	*# clients / beneficiaries*	*Currently installing SWTs?*	*Total # SWTs installed*	*Core competencies*
ATDER-BL	Yes	El Cuá	Hydro	About 15,000			
APRODELBO	Yes	San José de Bocay	Hydro	About 5,000			
AsoFenix	No	Boaco	Hydro, solar, wind and biomass	About 5,000	No	~4 (1/4 operating)	Piggott 1 kW and 500 W
blueEnergy	No	Atlantic coast of the RAAS	Solar (mainly) , wind	About 3,700 direct 5,900 indirect	No, with exceptions for R&D projects	~12 (2/12 operating)	Piggott 1 kW and 500 W
FEMUPROCAN					No	1 (1/1 operating)	Rural development
Peace & Hope					No	1 (0/1 operating)	Development

Suppliers

Private vendors

"In the last three months, perhaps two to three percent of our clients have inquired about small scale wind systems"

Lesther Ortiz, Sales Manager, TecnoSol S.A., October 2011

The key small-scale energy system suppliers in Nicaragua are shown in Table 5-7, whilst Figure 5-35 shows the location of their network of stores around the country.

Table 5-7: Private renewable energy equipment suppliers.

Company	Currently selling SWTs?	# SWTs installed	Models	Solar	Batteries & power electronics
TecnoSol, S.A.	Yes, but very limited sales	About 5	Kestrel 600 W & 2,000 W. SouthWest WindPower Air-X & Marine 400 W	Yes	Yes
ECAMI, S.A.	Yes, but very	About 20	Bergey 1,000 W	Yes	Yes

Company	Currently selling SWTs?	# SWTs installed	Models	Solar	Batteries & power electronics
	limited sales		SouthWest WindPower 400 W		
Suni Solar, S.A.	Yes, but very limited sales	About 15	Kestrel SouthWest WindPower Air-X 400 W	Yes	Yes
ENICALSA, S.A.				Yes	Yes
Era Solar, S.A.				Yes	Yes
Nica Solar, S.A.				Yes	Yes

"We've had mostly bad experiences with small scale wind…we have witnessed a clear shrinking of our clients' interest for small scale wind systems, as well as from our providers."
Max Lacayo, Sales Manager, ECAMI S.A., November 2012

International supply chains

Figure 5-34 shows a representation of the international supply chain for the various components of small scale wind or solar PV systems. Based on the sale price in the manufacturing country, the products undergo a series of cost increases due to transportation (insurance, FOB[78] costs), import duties (when applicable) and related costs (handling), and finally the vendor's margin. Table 5-8 summarizes these price increases for small scale energy systems sold in Nicaragua, which increase prices for goods imported into the country by 20% to 85%, depending on the component and the profit margins of the various intermediaries.

[78] Freight On Board.

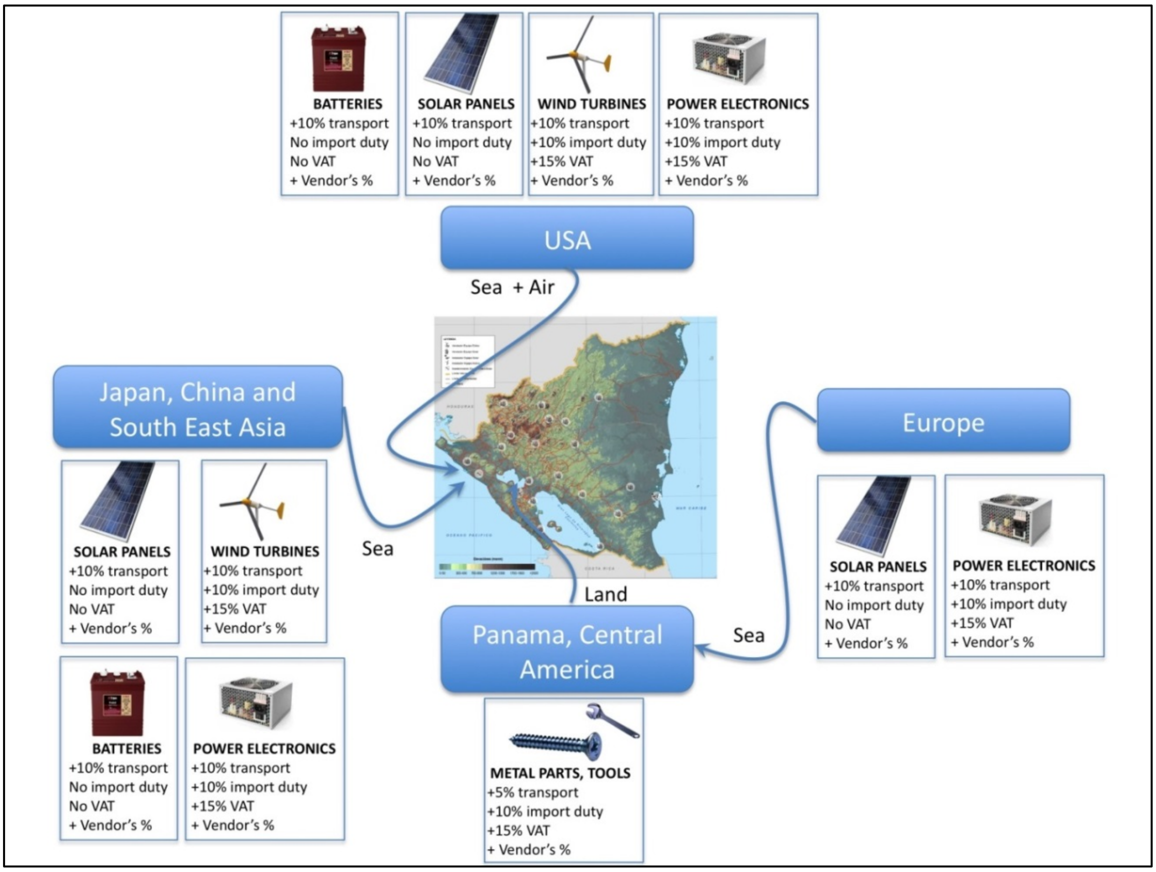


Figure 5-34: International supply chain diagram on technology origin and modelled effect on prices.

Table 5-8: Minimal price increase in Nicaragua due to the international importation supply chain.

Component	Min. transport costs to Managua	Import Duty	VAT (if applicable)	Nicaraguan Vendor's margin	Total modelled price increase in Nicaragua[79]
Wind turbines	*10%*	*10%*	*15%*	*10% to 40%*	*45% - 85%*
Solar panels	*10%*	-	-	*10% to 30%*	*20% - 40%*
Batteries	*10%*	-	-	*10% to 30%*	*20% - 40%*
Construction materials	*5%*	*10%*	*15%*	*5% to 20%*	*35% - 50%*

Service centres

Figure 5-35 shows the location of small scale wind and solar maintenance service providers in Nicaragua:

- TecnoSol, S.A. has by far the most extended network of retail stores; however it is important to note that the majority of regional stores do not stock most of the goods sold in the capital, Managua, and their local technical expertise is limited.

[79] On original retail price.

- ECAMI, S.A. is the second broadest provider of maintenance services as it has opened at least 8 retails stores in the last 2 years.
- SuniSolar, S.A. is in third place in terms of geographical coverage.

Few locations have the ability to carry out maintenance on either solar or wind systems, leaving only those living close to Managua, Bluefields, and León with access to maintenance services.

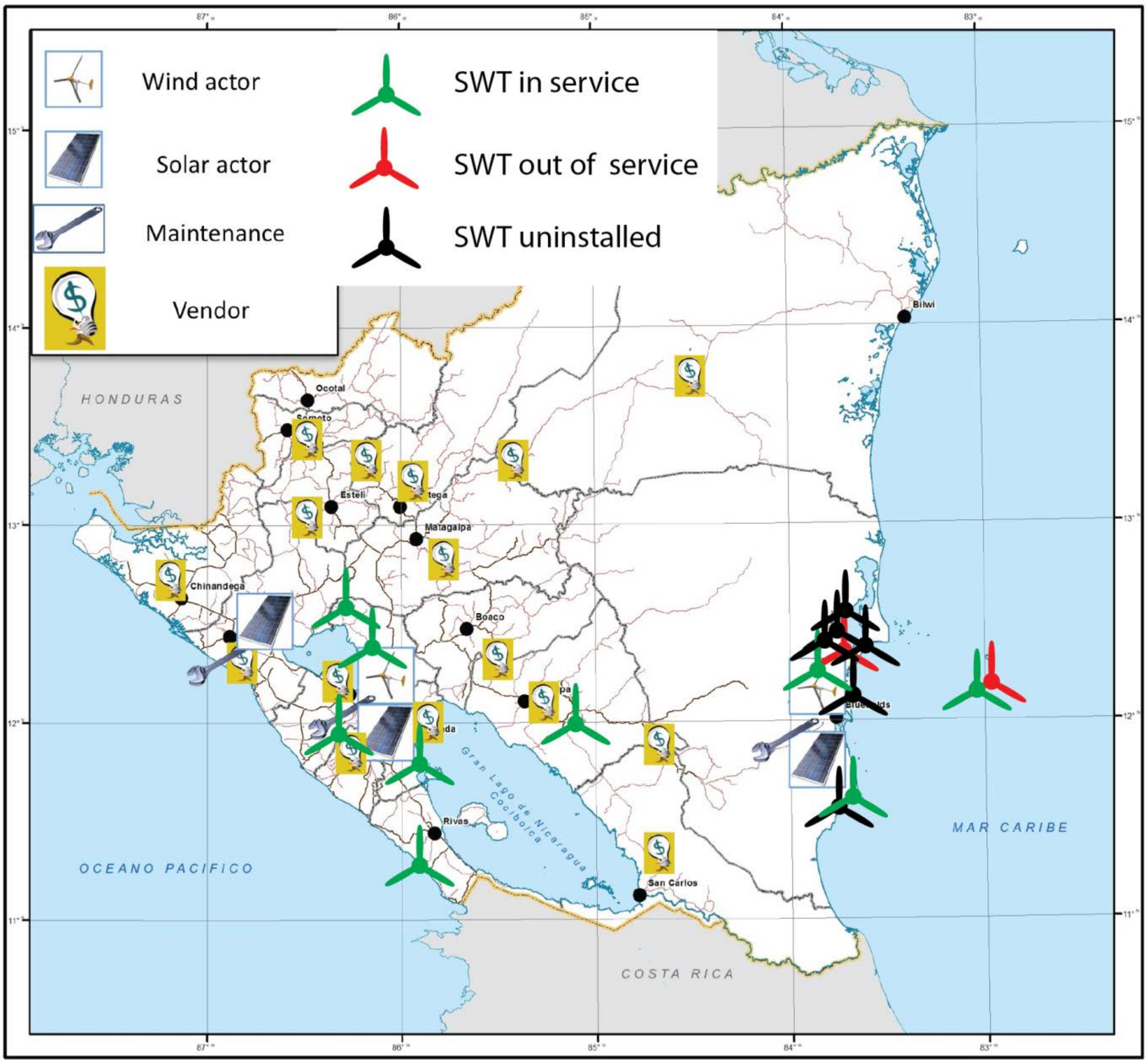


Figure 5-35: Locations of vendors and maintenance service providers, together with SWT installation sites.

"Our maintenance plans are corrective, not preventative. We've never been able to offer a preventative plan to the owners of our systems"

Douglas González, Director of Operations, Suni Solar S.A, November 2012

Existing small wind projects

Figure 5-35 also shows the locations of SWT installations and their operational status. It's clear to see that the density of existing installations is low, meaning that there is almost no knowledge shared between users, leaving them entirely dependent on the maintenance services offered in the urban centres of Managua, Leon or Bluefields. In particular, the installations on the Caribbean coast have suffered significantly due to the long distances that must be travelled to reach the maintenance services on offer in Bluefields. As a result, the majority of these machines have now been uninstalled and replaced by solar PV. It should be noted that many of the SWT installations on the Pacific coast are private installations by individuals with the technical capacity and motivation to maintain them.

Consumer & industry associations

The Asociación Renovables (Renewables Association) coordinates the Nicaraguan renewable energy sector and lobbies on behalf of the various market actors.

Academia (Universities and technical schools)

> *"There could be potential, but the equipment needs to improve, the real output needs to be clarified and expectations must be well managed."*
> *Jeronimo Zeas, Head of the Wind Studies Department, UNI, November 2012*

Table 5-9: Academic institutions offering technical training relating to wind power.

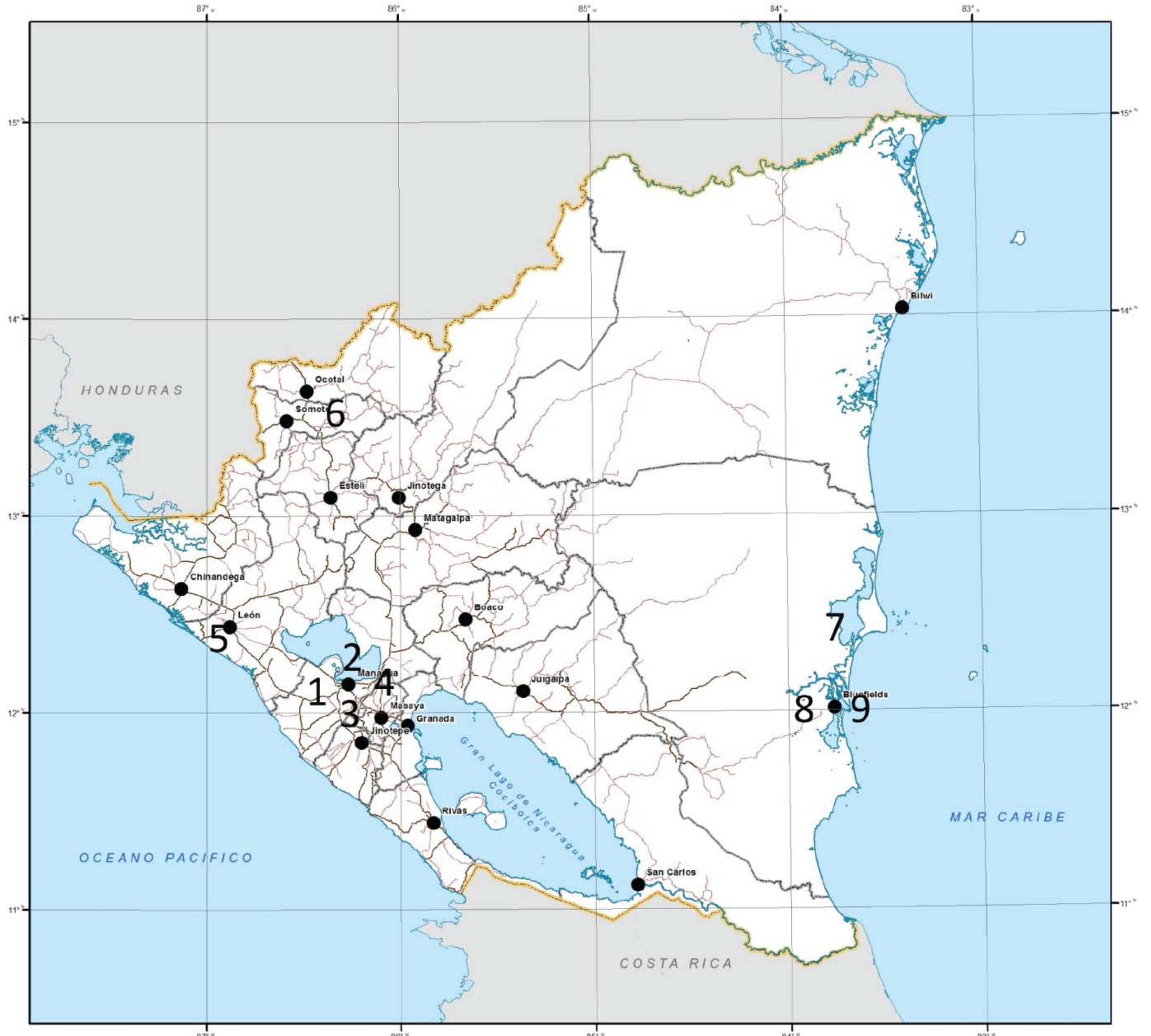
Institution	Wind power curriculum?	Educational SWTs?	Other activities
UNI	*Yes (wind power class as part of Renewable Energy Master's)*	*Yes, 1 kW Piggott*	*Wind studies*
IPLS, ULSA[80]	*Yes*	*Yes, 1 kW and 2 kW*	*Had a 240 kW interconnected turbine*
INATEC[81]	*Yes*	*Yes, in Bluefields IPCC (with blueEnergy)*	*Currently developing wind power labs.*
UNAN[82]	*Yes (Renewable Energy Masters)*	*No*	

Training centres

Figure 5-36 shows the lack of availability of information about wind power in most of the country, minimizing the ability for users to install and service the equipment, and also the ability to be trained on small-scale wind applications.

> *"There is a lack of technical knowledge to be able to perform maintenance. It is likely to prevent people from even wanting to buy a SWT in the first place."*
> *Susan Kinne, Director, Grupo Fénix (UNI – PFAE), November 2012*

[80] IPLS: La Salle Politecnic Institute (Instituto Politécnico La Salle), ULSA: La Salle University (Universidad La Salle).
[81] National Technological Institute (Instituto Nacional Tecnológico).
[82] National Autonomous University of Nicaragua (Universidad Nacional Autónoma de Nicaragua).



#	Institution	Competency
1	UNI Managua	University, Master, RE lab
2	UNAN Managua	University
3	UNA Managua	University – RE lab
4	AsoFenix Managua	Technical training
5	ULSA / IPLS Leon	Technical trianing, RE lab
6	Grupo Fénix, Totogalpa	Technical training
7	INATEC – FADCANIC Pearl Lagoon	Technical training
8	blueEnergy	Technical training
9	INATEC - IPCC	Technical training

Figure 5-36: Locations of academic institutions and technical training centres.

5.2.3.5 Conclusion

There is a lack of technical capacity relating to SWTs in Nicaragua and a negative perception of the technology due to the lack of successful installations. In fact, the two are critically linked, as it is the lack of technical capacity that has led to so many failed installations due to the installation of SWTs in areas without sufficient wind resource, low manufacturing quality and the lack of access to maintenance services. Successful demonstration projects are absolutely vital to prove the value of the technology to policy makers, businesses and the general public, however the lack of successful SWT installations in Nicaragua is holding the sector back and giving the technology a bad reputation. However, the success of utility-scale wind means that technical capacity relating to wind power is growing and the public perception of wind power generation is improving.

Unfortunately, the poorest region of the country (the Atlantic coast) not only has the lowest wind resource, but also has the most prevalent environmental hazards and is the least accessible (hindering access to maintenance services). As a result, SWTs are not an appropriate technology for helping the poorest of the poor in Nicaragua.

5.3 Predicting the future for small wind in Nicaragua

5.3.1 Introduction to the LGC/GIS methodology

This section presents a methodology for operationalising the SWT ecosystem framework with the goal of determining the size of the market for SWTs in Nicaragua. In addition to the varying level of renewable resources available in each part of the country, this research has shown that there are many other place-specific factors that influence the viability of small wind power across the country. For example, the existing transport infrastructure in each place has a huge influence on the costs of installing and maintaining a wind power system, whilst the number of people without access to electricity determines the size of the market in a particular area. To evaluate these spatially varying constraints, a Geographic Information System (GIS) was constructed, covering the entire country.

A two stage filtering process was used to determine the size of the market for SWTs in Nicaragua, based on the following steps:

1. Elimination of municipalities where other off-grid generation technologies are more economically viable (based on the Levelised Generation Cost, LGC):

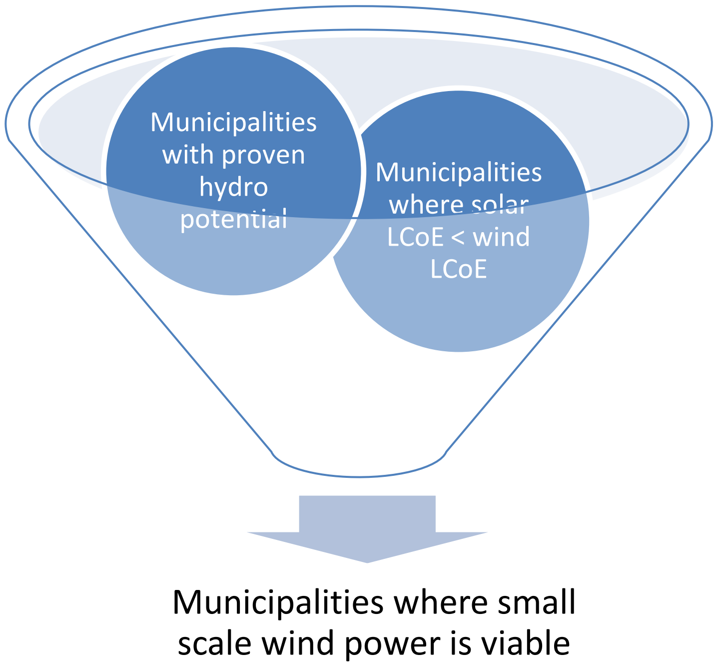


Figure 5-37: Renewable resources municipal level filter.

2. Elimination of population within each of the selected municipalities that either already have access to electricity, or would not be able to pay for electricity from a SWT:

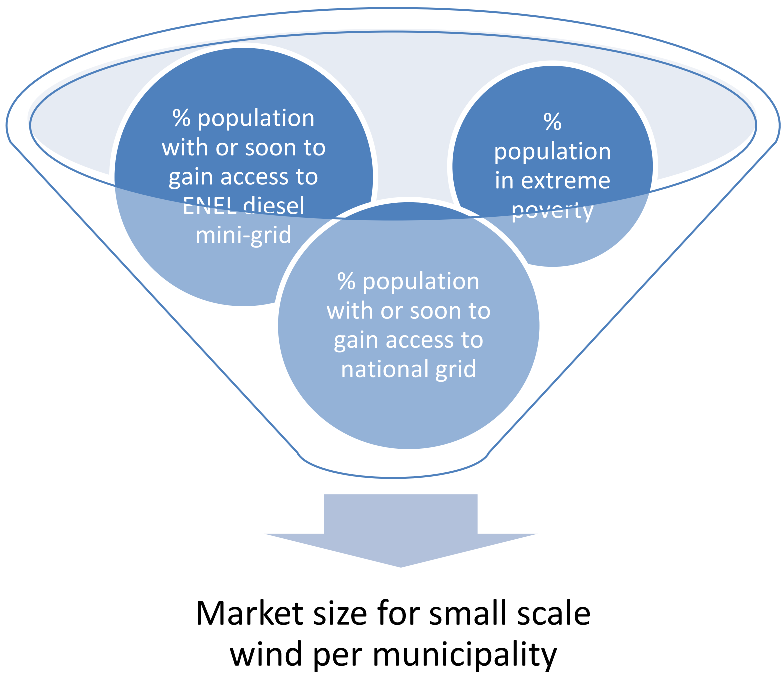


Figure 5-38: Market size per municipality filter.

A homogeneous national financial context has been assumed for the entire country as although deemed to be particularly relevant for remote regions' (which operate in very different economic climate to the urban centres), determining the cost of capital and other economic parameters for each municipality was deemed outside the scope of this study. Please note that these economic models developed in this study assume a commercial model, such as that taken by the Nicaraguan suppliers of renewable energy equipment, TecnoSol, Ecami and SuniSolar. This is in contrast to the volunteer model adopted by the NGOs blueEnergy and AsoFenix, in which many of the labour costs are zero as they employ many international volunteers, who often even pay for their own overheads. While this is seen as a viable model for introducing new technologies, it is not sustainable in the long term as it does not continue to build local capacity and will not allow the organization to scale up the technology to reach all those that could benefit from it.

5.3.2 Data sources

As mentioned previously, a significant amount of the data employed in this study is based upon data from the most recently available population census (INIDE, 2005). As the census was conducted at the level of the municipality, this therefore defines the resolution of the present market study. The main sources of information used for this study were: site visits, interviews, reports maps, GIS layers and other data sets. The most important of which are summarised in Appendix M, along with the key variables used in this analysis and the sources from which they are derived.

5.3.3 The power generation hierarchy

Figure 1-2 shows estimated LGCs for off-grid energy solutions by the World Bank's Energy Sector Management Assistance Program (ESMAP, 2007). Whilst it provides a useful reference, these costs assume the renewable technologies are installed at a good site (good resource and easy access) and are calculated using global prices for materials and labour, which are also likely to now be out of date, in particular the price of solar PV, which has continued to fall (IRENA, 2012). What is more, Figure 5-34 shows that these global prices are not applicable in the Nicaraguan context. However the following assumptions are drawn from it:

- Where connection is economically feasible, grid (SIN) interconnection will always be preferred over isolated generation.
- Where a suitable resource exists, hydro will always be far more cost effective than either wind, solar or diesel. Therefore any municipalities with significant proven hydro resources are assumed to choose this over small wind.
- The ENEL diesel mini-grids that are already established (varying scales from 0.12 MW and up) are assumed to be chosen in preference to SWTs, as the infrastructure is already in place.

In the following section, a comparison is made between solar and wind to determine the most appropriate renewable resource to electrify the remotest parts of each municipality. As the previous section (5.2.3) has highlighted, introducing a new technology requires a significant investment in the supporting infrastructure. As a result, conducting such a comparison at this stage can help to avoid becoming 'locked-in' to a technology that may not be the most appropriate for that particular region. In this comparison, current costs from the Nicaraguan market are modelled across a range of site conditions (varying levels of existing transportation infrastructure and renewable resources) to produce an estimate of typical LGCs that could be expected for both small wind and solar PV in each municipality.

5.3.4 Filter I: Renewable resources at the municipal level

5.3.4.1 Modelling hydropower in Nicaragua

The CABEI[83] estimates the following averages for small and medium scale hydropower projects in Nicaragua:

- $2.75/W to $4.5/W initial costs (installed capital)
- 50% to 70% Capacity factor (for run off river projects, depending on site quality)
- 2%[84] of total installed capital costs for O&M of small-scale hydro projects (<5 MW)

[83] Central American Bank for Economic Integration workshop for Economic Analysis of RE projects, Managua Nov. 2012.
[84] The IPCC SRREN Full Report estimates annual 0&M costs at 2.5% of installed capital costs.

Using the above data, the LGC of a hydropower project in Nicaragua of 1 MW is estimated to be in the range of \$0.10/kWh to \$0.15/kWh. This verifies the assumption given above that if a site has hydropower potential, economically it will always be preferable to small-scale wind[85]. Figure 5-26 illustrates the location of established hydroelectric projects and sites with significant proven hydro resources. These existing projects and potential sites were categorised by municipality and divided by the corresponding figure for population to produce an estimate of the total hydro resource per capita for each municipality. If a municipality was found to have greater than *0.3 kW of hydro potential/installed capacity per capita*, then it was considered to have sufficient hydro resource to meet the demands of all of its inhabitants and therefore was filtered out of the analysis. It was assumed that any excess electricity would be fed into the national grid rather than used to widen energy access in surrounding municipalities.

This threshold was determined by averaging the figure used for commercial contracts in Nicaragua with DISNORTE-DISSUR (2kW/household) with that used by ENEL in the RAAN and RAAS (1kW/household) and then dividing by the national average of 5 people per household to give 0.3kW per person. In the Cuajinicuil case study, peak demand for domestic applications was found to be just 0.03kW per person. However high power appliances such as irons and kettles are prohibited and productive uses of the electricity such as water pumping or agricultural processing are also not included, any one of which could easily push peak demand up to or beyond the 0.3kW per person threshold established above.

The potential for micro-hydro schemes of comparable power output to the SWTs discussed in this thesis (100W-1kW) are not considered in this part of the analysis, as they are very site specific. They may therefore are seen as complementary to small wind in any given region, as many communities will not be located close enough to a suitable water course.

> *"I would say that small scale hydro power is valid in about 10% of cases at a national scale in Nicaragua"*
> *Jaime Muñoz, Director, AsoFenix, November 2012*

5.3.4.2 Modelling small scale wind and solar in Nicaragua

To get a complete picture of how small scale wind compares with small scale solar in a rural development context, both renewable technologies were modelled across the following three scales:

- 100 W – representing an individual household system
- 1 kW – representing a community system for around 10 households, and/or community buildings and/or small businesses.

[85] It should be noted however, that hydropower does have the following disadvantages: slower and much more complicated financing than small-scale wind projects and the construction of distribution lines, which might not be financially viable for particularly remote households.

- 10 kW – representing a community system for around 100 households and/or community buildings and/or small businesses.

The analysis was designed to reflect the realities of employing the technology in a rural development context. This involves including a number of costs that would not normally be included in the LGC calculation:

- Community/technician training – it is assumed that the techniques described in the Cuajinicuil case study (section 5.2.2) will be employed to ensure that the community and local technicians are adequately equipped to be able to perform all but the most complex O&M tasks. This includes the provision of a toolbox and the delivery of relevant training.
- Existing transportation infrastructure – households without access to electricity are usually without it because they are located in remote regions, where there is little existing transportation infrastructure. This increases the costs of resource assessment, community/technician training, installation and O&M due to the need to travel further and using more costly forms of transport (4x4s or boats as opposed to buses or cars), combined with increased labour costs due to the greater length of time spent travelling (wages, food and accommodation).

Figure 5-39 shows the economic inputs for the LGC calculations. It should be noted that at the 1 kW scale, two wind turbines are included: the Bergey XL.1, which would be imported from the USA and the blueEnergy BD4, which would be manufactured in Nicaragua. The analysis was conducted using the energy systems modelling software, HOMER. Where possible, quotes were obtained from local suppliers (Ecami, TecnoSol and SuniSolar), however where the equipment was not available for purchase in Nicaragua, the price offered by an overseas supplier (e.g. Bergey or Southwest Windpower) was used and the relevant supply chain costs from Figure 5-34 were added. O&M, installation, resource assessment and community/technician training costs were modelled on those calculated during the Cuajinicuil case study (section 5.2.2).

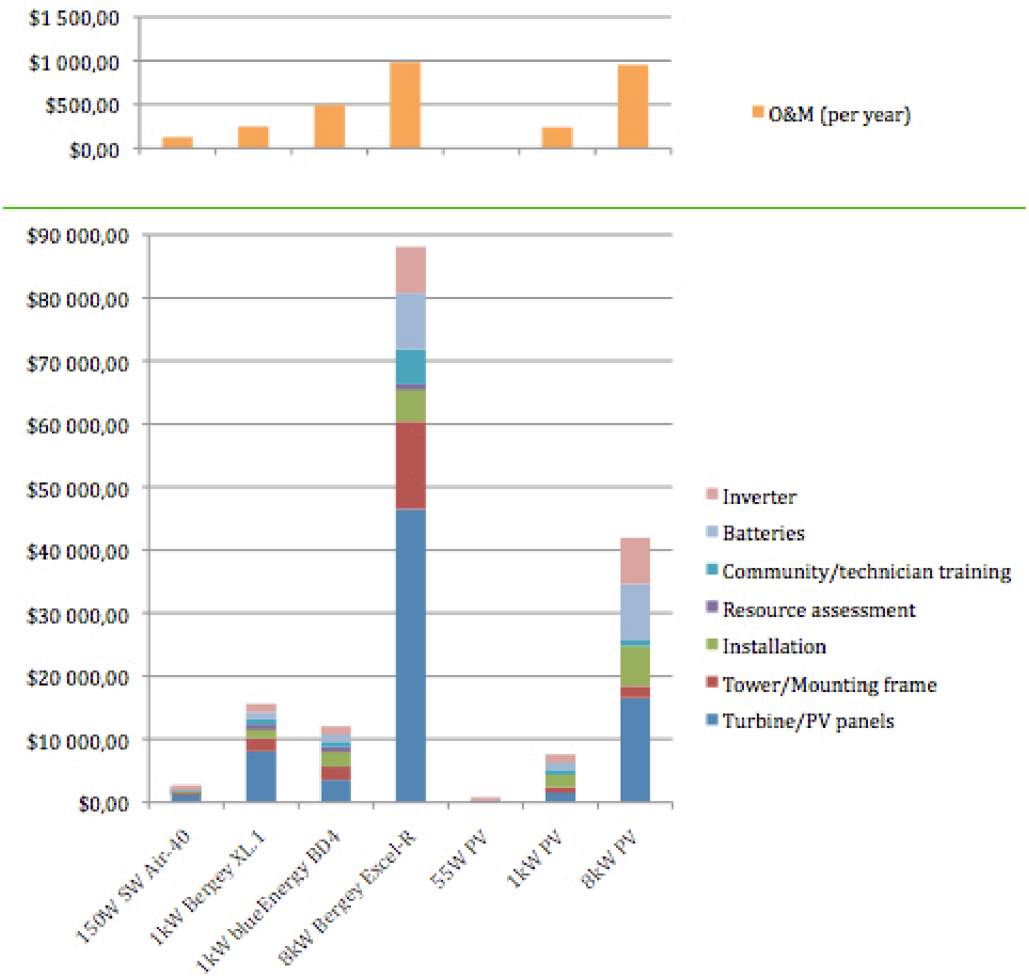


Figure 5-39: Breakdown of wind and solar power system costs at the 100 W, 1 kW & 10 kW scales.

A significant difference between the two systems, especially at the 1 kW scale is the resource assessment. The wind resource varies so much more wildly than the solar resource on both the national, regional and local scale and has a much bigger impact on the energy yield of a SWT than for a solar panel due to the cubic relationship of power to wind speed (see equation (1)). As a result, the only way to get a reliable prediction of the amount of energy a turbine will produce prior to installation is to erect a mast with an anemometer and data logger to measure the wind resource for a full year[86].

> *"Solar PV seems like the logical way to go. Wind power can be considered, but only once the resource is proven."*
>
> *Douglas González, Director of Operations, Suni Solar S.A., November 2012*

The LGC of the modelled wind power systems as a function of different mean annual wind speeds, along with the LGC of the modelled solar power systems as a function of mean solar radiation is shown in Figure 5-40. The range of each of the horizontal axes reflects the likely solar and wind resources available for rural development projects in Nicaragua. It can be seen that scale has a big

[86] Even then, inter-annual variations such as those shown in Figure 5-4 will invariably mean that the actual energy yield is almost always different to whatever may have been predicted.

effect on the LGC for both technologies, however the resource has a much bigger effect on the economic viability of wind projects due to the cubic relationship between power and wind speed.

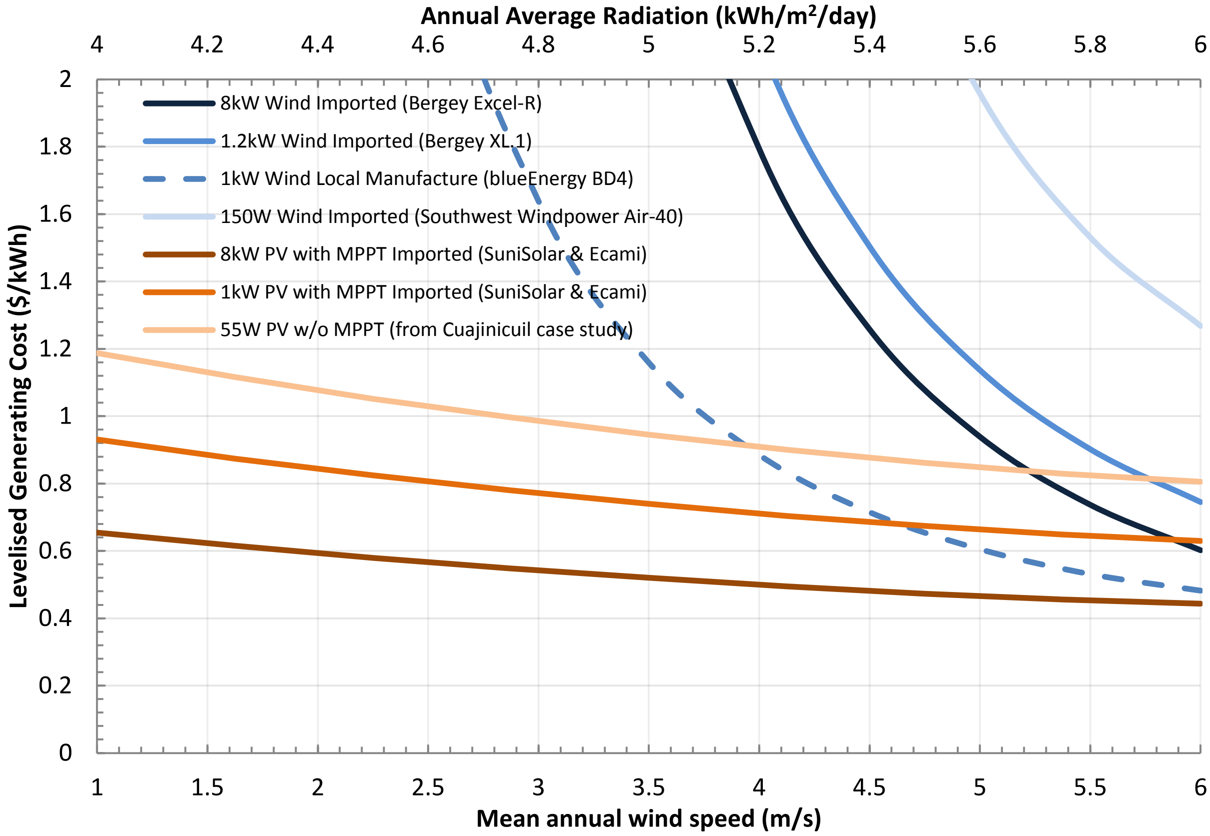


Figure 5-40: LGC for wind and solar PV systems at the 100 W, 1 kW and 10 kW scales across the range of solar and wind resources typically available for small scale technologies in Nicaragua.

There is also a significant difference between the locally manufactured 1 kW wind turbine and the imported 1 kW turbine. This is partly due to the high costs of importing equipment into Nicaragua (see Figure 5-34), as well as the conditions for which the turbine is optimized. With a rotor diameter of 4.2m, the blueEnergy BD4 has been designed to have a peak efficiency at the lower wind speeds present across most of Nicaragua and therefore becomes competitive with solar PV at around 4.5 m/s annual mean wind speed. In contrast, the Bergey XL.1 has a rotor diameter of just 2.5 m and is optimized for reliable operation in sites with a better wind resource. O&M data was not available for the imported turbines, as a result the figure calculated for the locally manufactured blueEnergy BD4 was simply halved (and scaled for the 100 W and 10 kW turbines) to reflect what is assumed to be their superior reliability[87]. Of course, this assumes that a suitable supply chain for spare parts would be established to support the dissemination of imported technology on a larger scale. As the locally manufactured blueEnergy BD4 is the only SWT that could be cost competitive with solar PV given the renewable resources available in Nicaragua, the following analysis is conducted at the 1kW scale.

[87] Of course, in reality, the issue of the international supply chain for spare parts will push O&M costs, however Figure 5-41 clearly shows that imported SWTs are not competitive, even with this generous assumption in their favour.

Modelling the influence of existing transportation infrastructure

In addition to the availability of renewable resources, the existing transportation infrastructure with which potential sites can be reached for resource assessment, training, installation and O&M plays a major role in determining the costs of implementing small scale energy solutions in each municipality. As SWTs are bulkier to transport and less reliable, installation and O&M costs both increase by a higher percentage than they do for solar PV. In addition to this, the need to conduct a resource assessment on site[88] before installation further increases the cost of wind projects in remote regions. The difficulty of accessing sites in each municipality is modelled using the population density (INIDE, 2005) and is classified it into one of the three following categories:

- Poor access – remote regions with less than 25 ppl/km^2
- Average access – rural regions with between 25 and 100 ppl/km^2
- Good access – rural, semi-rural and urban regions with above 100 ppl/km^2

Table 5-10: Costs used to estimate a typical return journey to an installation site from an equipment supplier.

Table 5-10: Costs used to estimate a typical return journey to an installation site from an equipment supplier in municipalities with varying levels of existing transportation infrastructure.

	Poor access	*Average access*	*Good access*
Minimum trip length	2 days Travel allowance: $25 Wages: $40	1 day Travel allowance: $12.50 Wages: $20	½ day Travel allowance: $6.25 Wages: $10
Mode of transport when bringing heavy items, e.g. installation of wind turbine	Private boat 6 hour journey $400 round trip	Pickup truck 3 hour journey $62.50 round trip	Pickup truck 1 hour journey $22.92 round trip
Regular mode of transport	Public boat 6 hour journey $33 round trip	Public bus 4 hour journey $10 round trip	Public bus 1.5 hour journey $3.50 round trip

Figure 5-41 shows the influence that the level of access has on each of the transport dependent costs included within the LGC of the 1kW wind or solar systems. It can be seen that operating in remote regions has more of an impact on the costs associated with a wind system than a similar sized solar system. This is because of the need to use a more expensive means of transport to bring in the bulky towers required not only for the wind turbine, but also for the preceding resource assessment. Surprisingly, the difficulty of access actually has little influence on the O&M costs. This is because the costs are modelled on the Cuajinicuil case study described previously, in which the community training programme has been hugely successful, to the point where the equipment supplier has only needed to revisit the community once to install a new generator. All other O&M has been conducted

[88] Likely to involve at least one observational visit and ideally also the installation of an anemometer on a tower the same height as the turbine for a full year with multiple visits to collect recorded data.

by the community technicians themselves (who regularly visit the capital where the supplier is located). The overall influence of these transport dependent costs on the final LGCs of each generating technology at the 1 kW scale is shown in Figure 5-42.

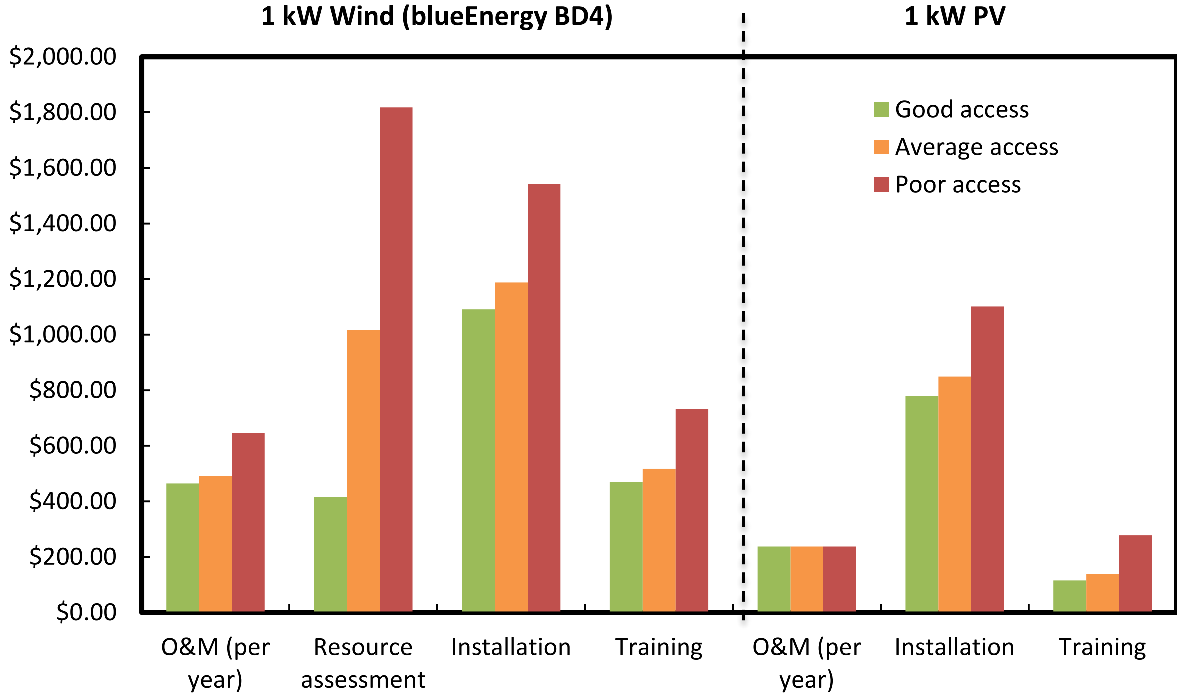


Figure 5-41: Influence of level of access on the transport dependent costs associated with the 1 kW wind and PV systems.

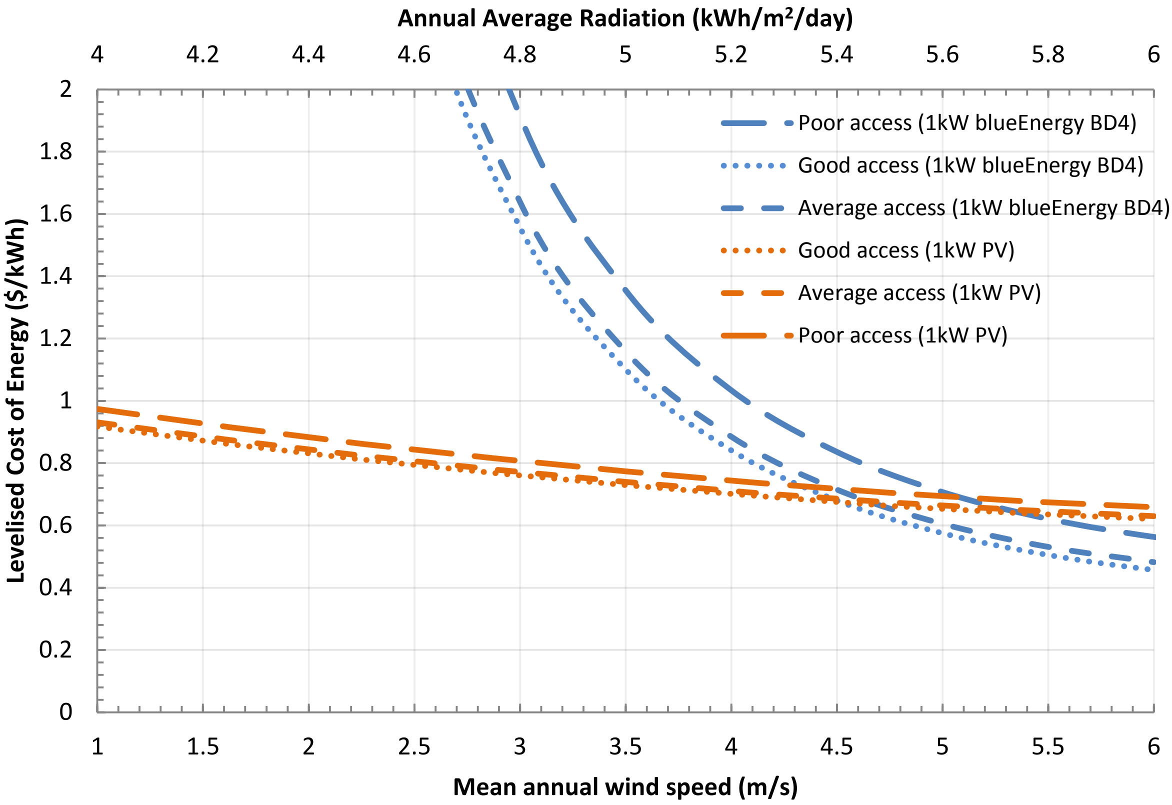


Figure 5-42: Influence of the ease of accessing a site on the LGC of 1kW wind and solar systems.

5.3.4.3 Results of first filter: renewable resources at the municipal level

The solar and wind resources shown in Figure 5-21 and Figure 5-27 were averaged to give a single value for each municipality. The modelled solar and wind economic data from Figure 5-42 was then used to estimate a typical LGC for both wind and solar power systems installed in each municipality, which takes into account the existing transportation infrastructure in that particular place. Figure 5-43 shows that there are thirty one municipalities where SWTs have a lower LGC than solar PV, with twenty on the south Pacific coast, ten in the central highlands and just one on the Atlantic coast.

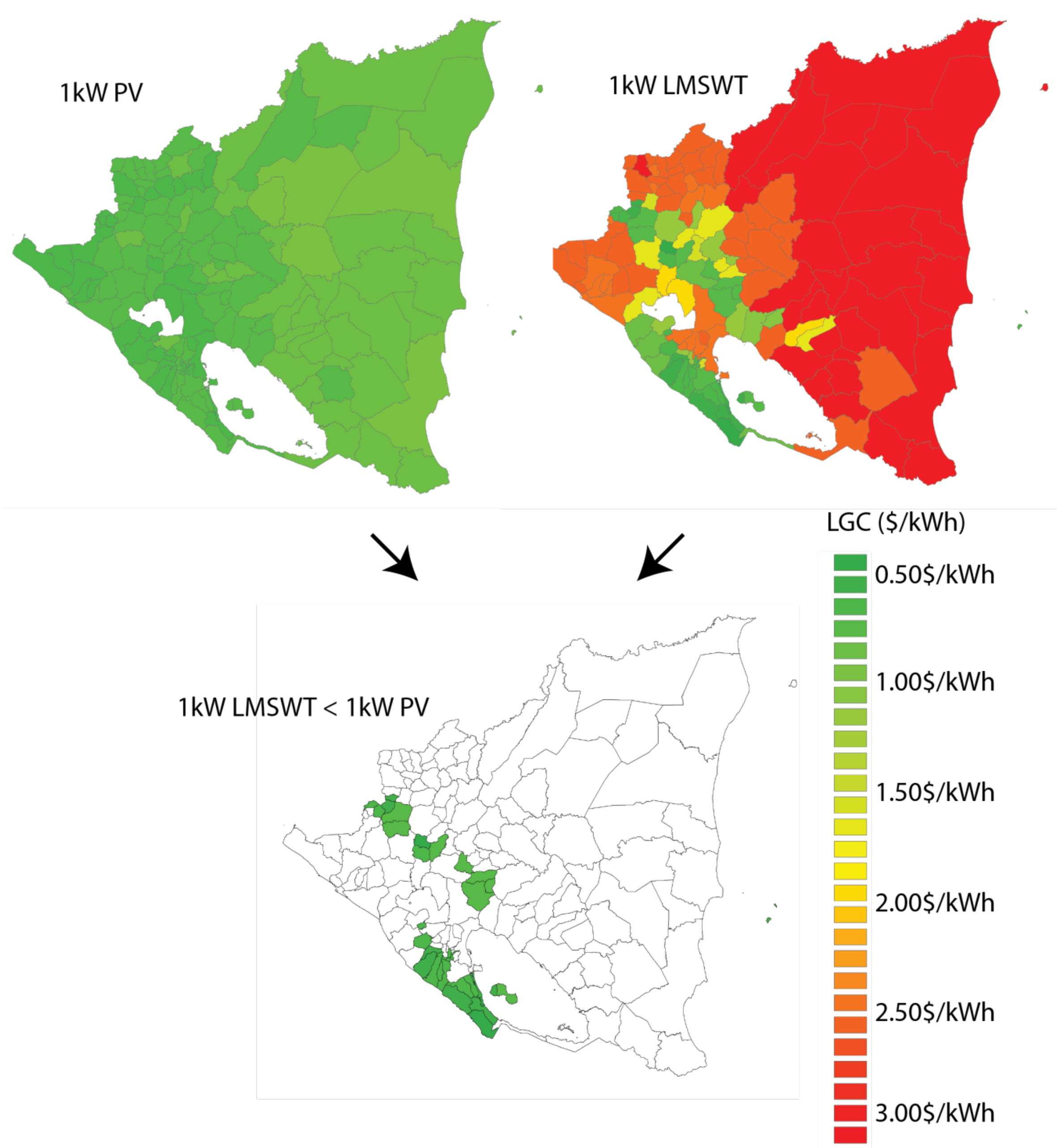


Figure 5-43: Comparing typical LGCs of 1kW scale wind (locally manufactured) and solar systems in each Nicaraguan municipality, taking into account the existing transportation infrastructure in each region. The municipalities where wind has a lower LGC are shown below.

5.3.5 Filter II: determining the market size in each municipality

For each municipality where the first filter has determined that small wind is the most appropriate technology for rural electrification, the market size (number of people for whom small scale wind power would be applicable) is calculated as follows:

Market size per municipality = total population of municipality – population with access to national grid or ENEL diesel mini-grid - population in extreme poverty

5.3.5.1 Existing access to the national grid or ENEL diesel mini-grids

Figure 5-33 displays the electrification rates of each municipality. Those that already have access to the national grid have no need for electricity from a SWT and therefore in each eligible municipality, this percentage of the population was subtracted from the total market size. Due to the fact that no ENEL diesel mini-grids (see Figure 5-31) operate in any of the municipalities that have passed through the first municipal level renewable resources filter, it has not been necessary to directly compare SWTs with current diesel installations. Indeed, it is very unlikely that SWTs could ever replace these diesel mini-grids, as they serve the urban populations of these municipalities (where they can operate at scales at which they are economic), whilst small scale wind turbines are best suited for rural locations (they do not work well in urban locations due to the turbulent and diminished wind resource, lack of space and complaints from neighbouring houses). Figure 5-44 shows that whilst there are many municipalities on the Pacific coast that have excellent wind resources; the majority of the population in this region already have access to electricity. However, in the central highlands, the opposite is true.

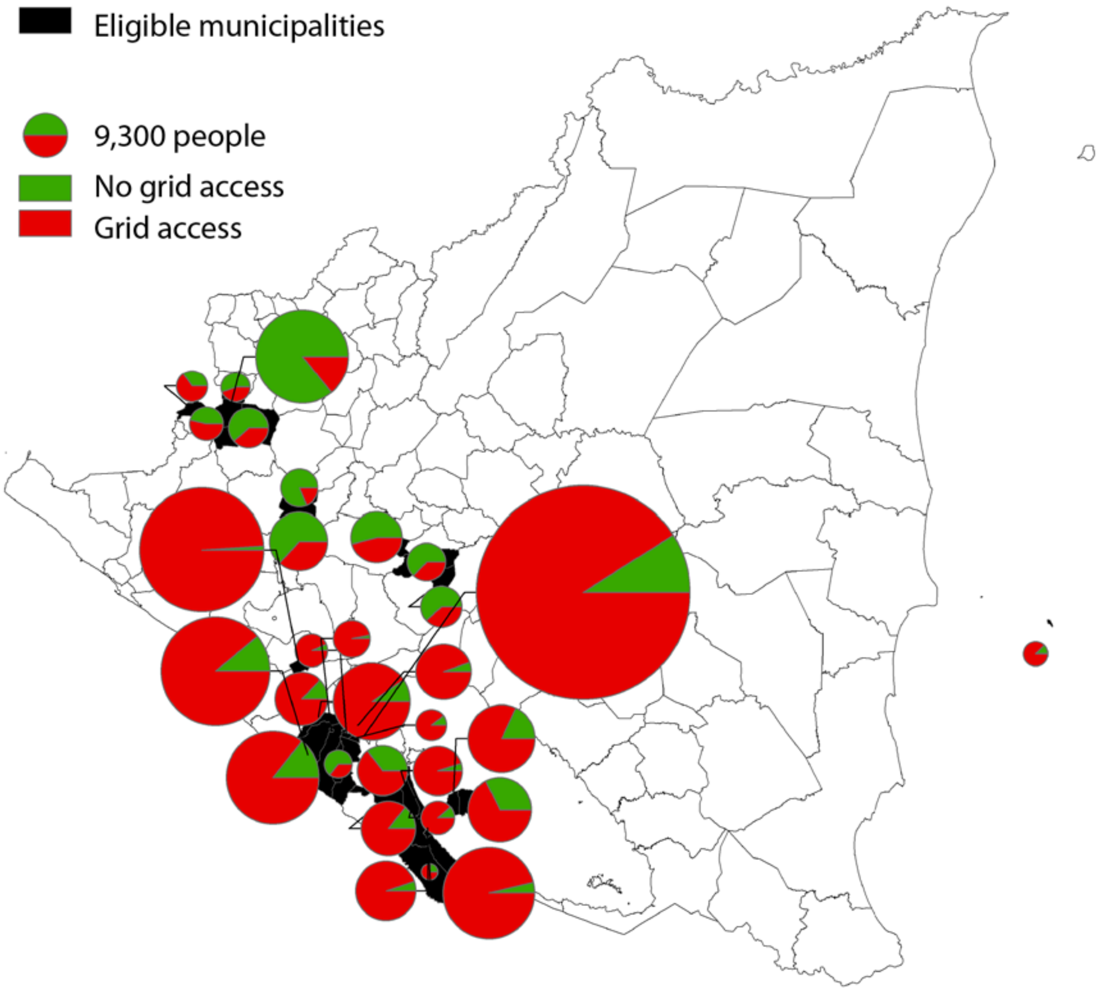


Figure 5-44: The proportions of people who already have access to grid electricity in each of the viable municipalities.

5.3.5.2 Ability to pay

The ability and willingness to pay for the service of access to electricity and cover the ongoing costs of operating and maintaining a SWT is vital to the sustainability of any rural electrification project. Donor funding for the upfront capital costs (equipment, construction materials, system design, site selection and installation) is relatively easy to find, however it is rare to find donors who would be also be willing to cover the cost of maintaining the system after installation, leaving this responsibility to the beneficiary community. Figure 5-41 estimates the O&M costs of a 1kW SWT at $491/yr ($465/yr for easy to access sites and $646 for very remote sites), which when split between 14 households would come to $35/household/yr or $0.09/household/day. The costs are based on the Cuajinicuil case study and Figure 5-6 shows that this figure is likely to double when including the maintenance requirements of the 540W PV panels, battery bank, control panel and micro-grid distribution infrastructure.

However, quantifying the ability of rural communities across the country to find this amount of money on a regular basis proved much more difficult. It was not possible to obtain data on the average incomes of people living in unelectrified rural areas across the country or better, the amount they are currently spending on energy (candles, batteries, kerosene etc.). In the Cuajinicuil case study, each family was spending an average of $8/yr on batteries for torches/radios, petrol for a small generator and kerosene for lighting. After installation of the renewable energy system, a tariff of $15/yr was collected from each household and even this small amount was very difficult for some.

The latest census (INIDE, 2005) contained data on the percentage of households living in poverty and the percentage in extreme poverty in each municipality. Living in extreme poverty was defined by the lack of at least 2 of the 5 basic services (density of people per household, proper lodging, access to water & sanitation, access to education and economic dependency). Although the people living in extreme poverty are in most need of the energy services that a SWT could provide, they are unlikely to be able to pay to maintain the system. What is more, they have other more pressing needs that should be addressed first if any donor or government funding becomes available to them. As a result, the percentage of people living in extreme poverty in each municipality (see Figure 5-28) was also subtracted from the total population of each municipality when calculating the final market size.

> *"In Nicaragua, there is a very low capacity to pay for energy services, even more so because the populations targeted by rural electrification are generally also the poorest."*
> *Roberto Sosa, Project Director, CHF International, November 2012*

5.3.5.3 Results of second filter: market size per municipality

Figure 5-44 shows the results of applying the second (eligible population per municipality) filter to the municipalities that passed through the first (renewable resources municipal level) filter. The tabulated data for each municipality can be found in Appendix N. The market size in each of these 11 municipalities represents 12,949 people, which is equivalent to 2,590 households. Assuming a similar micro-grid infrastructure to the Cuajinicuil case study, this would indicate a market potential of 185

1kW small wind power systems. The eligible regions are concentrated in the north-central highlands and to the south-west of Lake Nicaragua, the only regions with a viable wind resource (apart from Corn Island in the Caribbean Sea). Figure 5-45 shows that all of these municipalities have average levels of access and are clustered into groups of two or three, making the establishment of a service centre in each cluster viable. If it were possible to use the small wind power systems to generate revenue (for example by using the electricity produced to pump water for irrigation or process fruits, as is planned in Cuajinicuil), it is possible that the technology could be applicable for those living in extreme poverty. In this case, the market size would be extended to 31municipalites, 97,574 people, 19,514 households and therefore 1,394 1kW small wind power systems (see Appendix F for full details). Further sales could be gained by supplying SWTs to small businesses. As a result, the figure of 185 1kW SWTs should be seen as conservative.

> *"I would say that small scale wind power is valid in about 5% of cases at a national scale in Nicaragua."*
> *Jaime Muñoz, Director, AsoFenix, November 2012*

> *"There must be good wind and a passionate individual or a capable institution to maintain the system – there needs to be physical access to the system that is cost and time-effective. Technically speaking, I think it could work in limited situations where all the stars align, but I don't see it scaling big."*
> *Mathias Craig, Founder and Director, blueEnergy, November 2012*

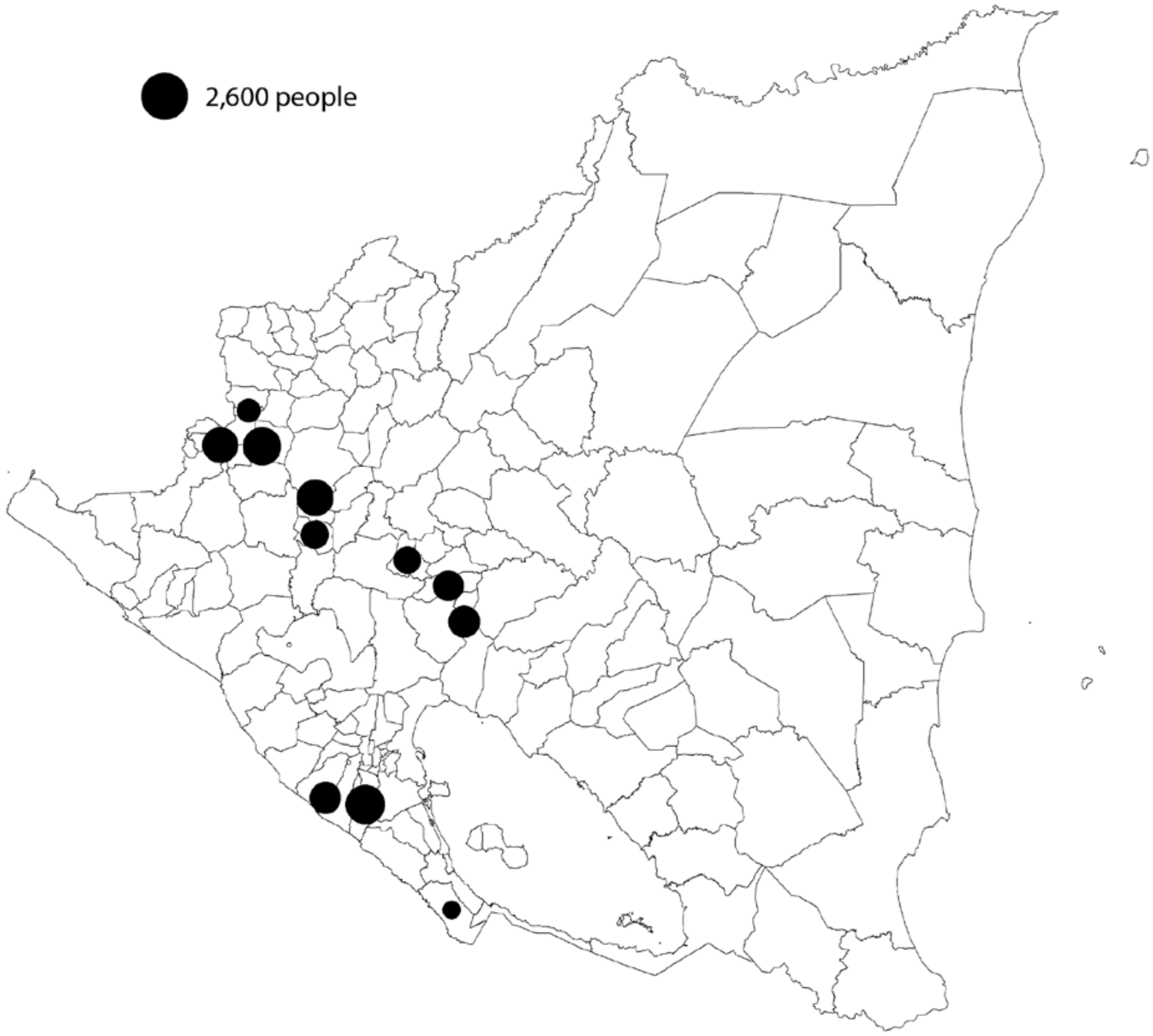


Figure 5-45: Graphical representation of the conclusion of the market study, highlighting the size and distribution of the market for SWTs in Nicaragua.

5.3.6 Evaluation of LGC/GIS methodology

This study has shown that the LGC/GIS methodology can be successfully applied to small wind to give a quantitative estimation of the size and location of the market for small wind. However, some of the assumptions on which the LGC/GIS methodology is based and the procedure itself could be refined to offer a more accurate assessment of the market.

5.3.6.1 Filter 1: renewable resources at the municipal level

The municipalities selected by the chosen methodology were in good agreement with those identified by the wind power experts; however the LGC analysis neglects the fact that hybrid systems with complementary renewable resources are widely acknowledged to provide a more resilient solution for battery charging systems in many different contexts (Lew *et al.*, 1997; Craig, 2007; Oliva, 2008; Ferrer-Martí *et al.*, 2010). It should be extended to include PV-wind hybrids in all municipalities and wind-hydro/PV-hydro hybrids in all municipalities with proven hydro resources. It also neglects the fact that small-scale technologies are complimentary to large scale generation, i.e. even in municipalities with sufficient hydro potential to meet the demand for the entire population, the cost of distributing this power to the remotest parts of these municipalities would become much higher than the cost of installing small-scale isolated systems for each of the remotest communities.

Although the transportation costs for travelling from the manufacturer to the installation site were modelled, the location of the manufacturer also determines the transportation costs for construction materials, appliances and equipment. What is more, in more remote locations there is often a restricted choice, pushing the costs of these items up further, i.e. a length of steel tube for the tower may cost $50 in the capital, but if only a slightly larger and slightly smaller size are available locally at $70 and $40, then for safety reasons the $70 tube must be purchased.

The ENCO wind map shown in Figure 5-3 is significantly different to the SWERA map (Figure 5-21) used in this analysis. As a result, it would be worth repeating the analysis using this wind data to determine the sensitivity of the results to the differing wind data.

The LGCs are based on single data point, the Cuajinicuil case study. As a result, the solar LGC is significantly higher than would be expected if using long-term data for O&M costs. However, the LGC for wind is also likely to be conservative, as the first year after installation typically experiences a higher than average failure rate and manufacturing in higher volumes would increase quality.

5.3.6.2 Filter 2: Determining the market size in each municipality

Whilst the choice of excluding those that already had access to electricity was clearly correct, this could have been extended to exclude those that will soon gain access, as the Nicaraguan government has ambitious plans to expand the national grid under the PNESER programme in the next few years (MEM, 2009). The methodology was also limited by the lack of data with which to model the ability to pay for at least the O&M costs of a small wind power system. The decision to subtract the percentage of the population in extreme poverty from the total market size in that municipality neglects the fact that some of these people may also be connected to the national grid. What is more, those living in extreme poverty are most in need of access to energy. Further research is needed in each of the selected municipalities to identify the viability of tying the small wind systems to traditional productive activities in that region, such as water pumping for irrigation systems. The amount of revenue that these activities could generate could then be added to the amount that people currently spend on energy sources that would become obsolete[89] (batteries, candles, kerosene etc.) and evaluated against the cost of maintenance for a small wind system.

5.3.6.3 Additional factors

Due to insufficient data, although the following factors are known to have a significant impact on the success of small wind rural development projects, it was not possible to model:

[89] Or at least their use would be significantly reduced.

- Willingness to pay for the service of access to electricity.
- Community governance.
- Availability of micro-finance.
- Environmental hazards, such as corrosion and lightning strikes.
- Cultural differences between and within communities.

"There are many technologies available, from the classic diesel generator to renewable energy systems. They are well known, but the beneficiary communities are very diverse, with many social and cultural differences."
José María Blanco, Regional Director, BUN-CA, November 2012

5.4 Strengthening the small wind ecosystem in Nicaragua

Despite its simplistic nature, the GIS/LGC analysis predicts that a small market exists in the central highlands and on the south Pacific coast. However, Figure 5-46 shows that there is little optimism in Nicaragua regarding the future of small wind. This negative opinion can be divided into two distinct categories:

- Issues that are inherent to the technology and/or the local context and cannot be changed.
- Issues that can be addressed by targeted programmes of training and awareness raising.

Figure 5-47 categorises these factors, showing that approximately half of the major barriers identified during this study can be addressed. A similar analysis is presented in Figure 5-48, which lists the critical success factors for small wind in Nicaragua and separates them according to the financial, policy, capacity and environmental dimensions of the small wind ecosystem framework.

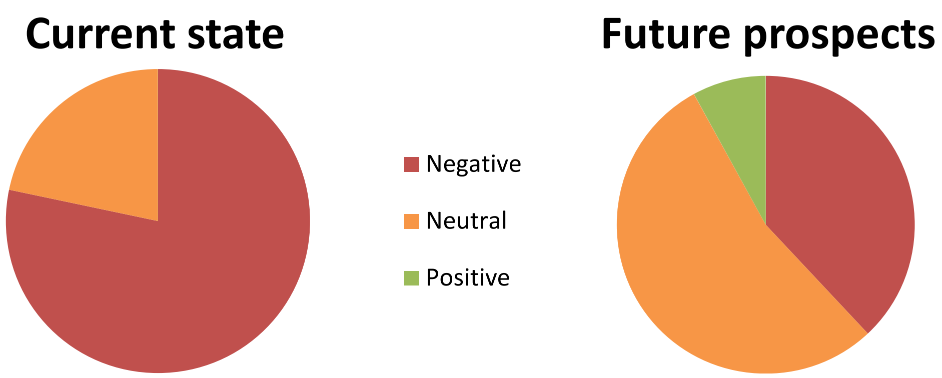


Figure 5-46: Perceptions of the 13 Nicaraguan wind power experts interviewed on a) the current state and b) the future prospects for the small wind sector in Nicaragua.

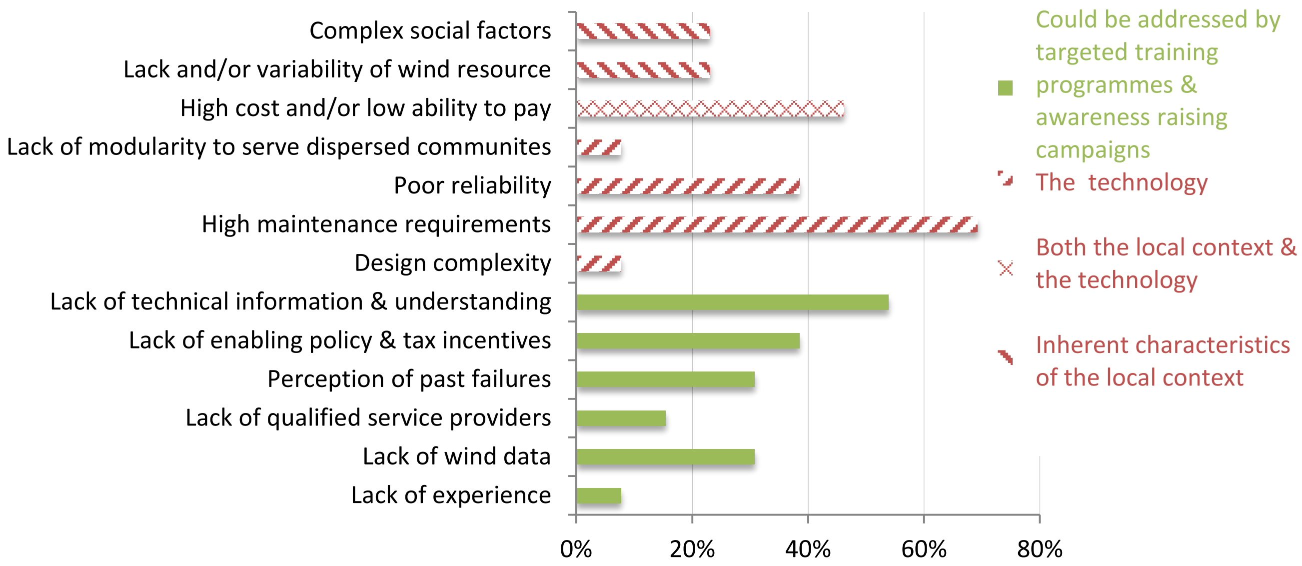


Figure 5-47: Percent of interviewees citing specific factors as major barriers to the development of small wind in Nicaragua.

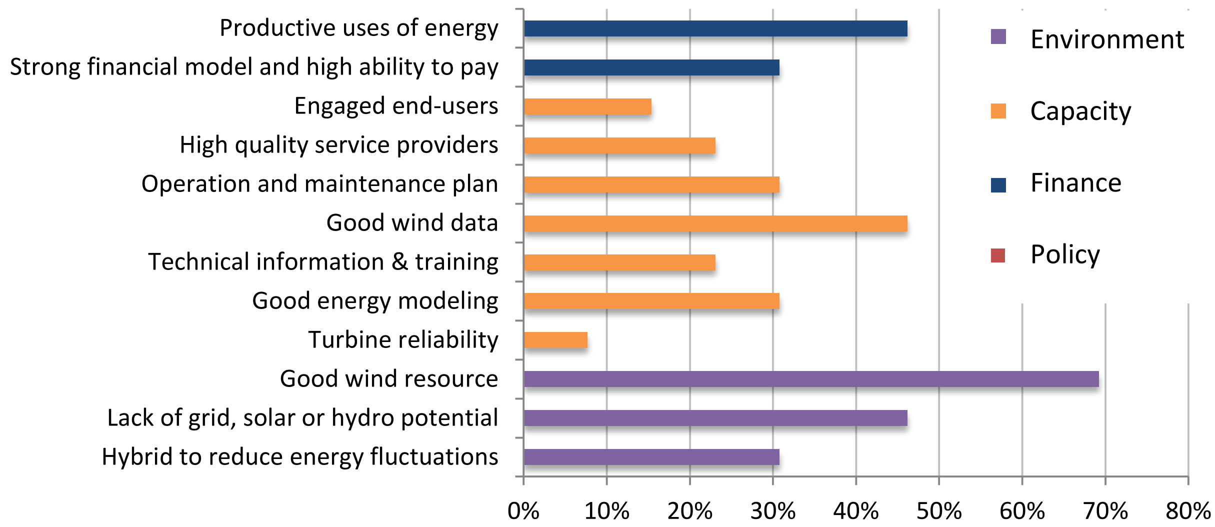


Figure 5-48: Percentage of interviewees citing specific factors as critical to the success of small wind in Nicaragua.

In a similar study of the Kenyan small wind sector, it was found that "*lack of government incentives and out-of-order turbines are the main factors that inhibit confidence in small wind turbines*" (Vanheule, 2012). Figure 5-47 shows that the results of this study are similar, as high maintenance requirements tops the rankings, with poor reliability and perception of past failures not far behind. However, in Nicaragua, both high cost and/or low ability to pay and lack of technical information and understanding rank above lack of enabling policy and tax incentives.

It is possible to address some of these barriers, for example: the lack of enabling policy and tax incentives can be influenced by political lobbying and the lack of technical information and understanding by targeted training programmes and awareness raising. However, some of the barriers are either inherent characteristics of either the local context, (e.g. lack and/or variability of wind resource), or the technology, (e.g. poor reliability). As a result, these barriers will not be able to be overcome, no matter how much effort is put into doing so, i.e. although better wind maps may improve our knowledge of the wind resource, they do not change the wind resource itself and even if thousands of wind turbines are installed and an extensive service network is established, wind turbines will always be less reliable than solar PV.

As a result of this study, a series of recommendations were made that would allow Green Empowerment and the WISIONS Initiative to take concrete steps towards strengthening the small wind power sector in Nicaragua.

5.4.1 Financial recommendations

Ensure access to the lowest price solar panels

Hybrid systems are much more resilient both meteorologically and technologically than either technology alone. Despite the fact that global solar PV prices have dropped significantly in recent years, the technology is still much more expensive in Nicaragua than in many other parts of the world.

Support project-specific wind assessments

The lack of funds for proper wind resource assessment has caused many SWTs to be installed in locations with poor wind resources. A targeted subsidy for wind resource assessment studies conducted at least 1 year prior to projects would greatly reduce this problem.

Select and promote modular solutions that could be financed through micro-finance loans

The modularity of solar home systems is key to its penetration in dispersed, low-load settlements as every household can have its own small solar panel. Whilst technically wind cannot complete in terms of modularity, innovative delivery models drawing on rural micro-financing institutions and mobile pre-paid energy payments can help further expand access to energy from the wind.

Energy based enterprises

Due to its inferior modularity and need for regular access to maintenance services, the use of SWTs for households in very remote areas is not recommended. Donor funds given for rural electrification projects often have a bias towards funding capital expenditures versus on-going costs and often have a finite funding horizon of a year. Because the life-time costs of a solar project are front-loaded, whereas wind projects have more on-going costs due to the increased maintenance requirements, solar is generally a better fit with the financial model of donor funding. This leaves three options: only applying to donors that will allow the inclusion of O&M costs in the initial grant (along with the installation, material and labour costs), only promoting SWTs to people with the ability to pay upfront or create a link to some form of economically productive use of electricity with which to generate sufficient revenue to cover O&M costs.

> *"I think that it would be valid to link small scale wind electricity generation with agricultural processing industry. However, it remains to be seen if the O&M costs can actually be lower than the revenues generated. This is our biggest concern."*
> *Aracely Hernandez, Head of Wind Projects, MEM, November 2012*

If local energy based enterprises require additional power, SWTs could be complementary to existing solar installations. Alternatively, new revenue streams could be created with which to cover the on-going costs of a new PV-wind hybrid system.

> *"Small scale wind could work for creative and proactive families, those with innovative agricultural processes or already with some alternative energy sources."*
> *Susan Kinne, Director, Grupo Fénix (UNI – PFAE), November 2012*

Further research is needed to determine which productive uses of electricity would be most appropriate for each of the regions identified in this study. In particular, productive uses that are seasonally compatible with the wind resource, e.g. irrigation during the dry season. A similar targeted subsidy is recommended to finance socio-economic assessment studies at least 1 year prior to any new pilot projects within these areas.

Pair utility-scale companies with small-scale service providers.

Utility-scale wind power has been an enormous success story in Nicaragua in recent years, with the installed capacity growing from 0 in 2008 to 40MW in 2009, 63 in 2010 and 140MW in 2012. Another 80MW will be installed in 2013. AEI Energy, MesoAmerican Energy, BLUE POWER (Grupo Terra) and ALBA Generación could support local small scale initiatives as part of their CSR (Corporate Social Responsibility) programmes, both financially and technically. For example, by offering technical exchange programmes between their engineers/technicians and small-scale wind power actors (small businesses, NGOs, students) or by sharing their wind resource data.

5.4.2 Capacity recommendations

Conduct an in-depth study of successful SWT rural electrification projects.

Through existing networks, such as WindEmpowerment, a worldwide review of successful small wind rural electrification projects should be conducted in order to select proven designs for SWTS, proven delivery models and identify the ecosystem conditions necessary for the rapid growth in rural electrification with SWTs.

Evaluate the direct contribution that big wind could make to rural electrification

The establishment of larger scale grid-connected hydro projects can create the opportunity for communities in the surrounding area that were previously too far from the national grid to be connected to gain access to electricity. The impact of Nicaragua's new wind farms on electrification rates in the surrounding areas should be studied so that similar impacts can be expected around any potential wind farm sites in the central highlands and south Pacific coast.

Local manufacture is a viable option, but the development of the industry must be fostered in the early stages.

Locally manufactured technology can present significant savings over imported technology, but only if an industry that can produce in reasonable quantities can be established. The costs of producing in low volumes are too high and ensuring the necessary quality is difficult until a significant number of machines have been produced by each manufacturer.

More detailed wind resource assessment in identified high wind areas.

Although the MEM plans to have a wind map of Nicaragua by 2016-2017, it is likely to be designed for utility-scale projects, i.e. with measurements at 50 m, 75 m and 100 m (most SWTs have 10-30m towers). As a result, assessing the wind resource for small-scale wind projects in the areas selected by this market study will require a specific effort in addition to this. The local conditions in each of the identified regions should be studied in coordination with universities and local actors (NGOs, communities, small businesses).

Characterise environmental hazards in identified high wind areas.

In addition to improving the level of knowledge of the wind resource in each region, the severity of environmental hazards should also be studied. Environmental factors have a much bigger impact on wind turbines than solar PV. Lightning strikes and corrosion from the hot humid and highly saline environment that is present in the majority of Nicaragua's coastal regions are the two most common and most costly environmental hazards.

Effective training of motivated and capable individuals is necessary to empower local technicians and improve the sustainability of SWT installations

Sufficiently motivated individuals from within the community must be willing to take on the role of technician (ideally at least three in case one leaves the community and another is busy when a problem occurs). Due to the high maintenance requirements of SWTs, selection of appropriate individuals for this role is of critical importance to the sustainability of SWT installations. When using locally manufactured technology, participation in the construction of the SWT that will be installed in their own community provides the ideal opportunity for this transfer of knowledge. Involvement in the installation of the technology is also an excellent way of transferring knowledge and increasing the communities' sense of ownership of it.

Technology demonstration is necessary to raise awareness of the technology

Establishment of a renewable energy demonstration centre could help raise awareness of the technology and would also be useful for training purposes. Clustering wind projects together would allow communities to share knowledge and expertise, as well as reducing travelling time for engineers if called out for major repairs. It would also help build up awareness of the technology in that area and a rolling demonstration programme could be established – where the technicians of a community about to install a wind turbine visit a community that has recently installed one (much like the '*campesino a campesino*' environmental awareness programme that has already been successfully established for Nicaraguan farmers).

Strengthen the small-scale wind curriculum at technical colleges and universities.

LUX-DEV and the Autonomous Basque Region of Spain[90] have already launched an initiative to improve the theoretical and technical capacities of INATEC of several million dollars to create a small-scale wind curriculum and training.

Improve the technical ability of the power electronics subsector.

The repair of electronic components is very difficult to perform in Nicaragua. Any plan aiming at promoting the use of isolated solar PV and/or small-scale wind systems should take this deficiency into account and plan to build capacity in this area.

Design and implement a training programme for public servants and electricity sector employees.

The lack of knowledge about the technicalities of small-scale wind is widespread in both the public and private electricity sectors:

> *"We lack technical capacity in the private sector."*
> *Aracely Hernandez, Head of Wind Projects, MEM, November 2012*

This could be addressed through dedicated technical training sessions designed to improve their understanding of the technology and how it can be promoted through public policies.

5.4.3 Policy recommendations

Select and demonstrate reliable hybrid solar PV / wind systems.

It is very important to set a positive example of small-scale wind installations in Nicaragua by demonstrating proven system designs. There is a lack of knowledge about which brands are reliable and which combinations of components work well together. As a result, the technology has gained a bad reputation, as many of the current installations are either out of service or have been uninstalled completely.

[90] Project NIC/023.

Promote the use of wind pumps for direct water pumping and irrigation.

There are many water pumping wind turbines in Nicaragua, mostly in the rural areas of the Carazo, Granada and Rivas departments. Most of them are not well maintained, and have gradually been replaced by electric pumps. A similar market study would be required to determine the size of this market. The creation of a successful ecosystem for wind pumps would have a complementary effect on the SWT ecosystem, for example by improving the quality of wind resource data at the low hub heights relevant to small scale technologies.

> *"Wind power has a great future in Nicaragua for direct water pumping and irrigation"*
> *Iris Valle, Technical Specialist, Centro Humboldt, November 2012*

Assist current lobbying for feed-in tariffs.

Although grid-tied systems do not have a direct impact on rural electrification, the legalisation of a feed-in tariff for the national grid with a favourable pricing structure for SWTs would certainly strengthen the SWT ecosystem by improving the enabling environment and increasing the quantity and quality of SWT market actors and supporting services. The Nicaraguan renewable energy association, Renovables, is currently lobbying to obtain such feed-in tariffs for households and small businesses in Nicaragua.

Assist current lobbying for tax exemptions for imported SWTs.

Solar panels and deep cycle batteries are currently exempt from import tax and VAT. If the same were possible for wind turbines, imported turbines would become competitive. Renovables is also currently lobbying to obtain tax exemptions for SWTs that are comparable to those offered for solar PV.

Promote SWTs in areas with a critical mass of potential users by supporting the development of a network of service centres in these areas.

Technologies that require a significant amount of maintenance require a critical mass of potential users in any particular region in order to justify the establishment of an appropriate network of service centres. Cars, bicycles and diesel/petrol generators all require high levels of maintenance and a critical mass of users already exists in most parts of the country. As a result, car mechanics, bicycle repair shops and generator repair workshops can be found all over the country, proving that this model can work in Nicaragua. However, for any private provider to be economically justified to offer those services, a critical mass of potential installation sites is needed in a particular local area. Because of the small size and distributed nature of the locations where small wind is cost-competitive, the cost of offering maintenance services to these limited and scattered opportunities would be too high to justify the establishment of a national network of service centres. However, local initiatives in these pockets of high wind resource could be successful on an ad-hoc, non-replicable, non-scalable basis. In order to be successful in these regions, the development of a local network of service centres should be supported.

5.5 Conclusion

Despite important efforts led under the government's flagship PNESER project since 2011, a significant portion of the Nicaraguan population still do not have access to electricity, particularly those on the Atlantic coast. However, the distribution of the wind resource (high in the central highlands and on the Southern Pacific coast) does not match well with the location of people without access to electricity (mainly in the Northern regions and on the Atlantic Coast). What is more, most of the high wind regions in Nicaragua also have high solar and hydro potential. Small wind is more difficult to install or maintain than solar PV, and the LGC is a lot higher than hydro. The modularity offered by solar PV and the simplicity of assessing the resource makes it much more appropriate for dispersed and remote settlements and much more scalable than small wind. Although utility-scale wind power is a success story in Nicaragua, there is no track record of successful small wind installations. As a result, a significant amount of time and effort would need to be invested to strengthen the small wind ecosystem in Nicaragua through an extended programme of technical training, awareness raising, lobbying, further research and technology demonstration.

This market assessment is a direct application of the SWT ecosystem framework described in Chapter 2 and proves that in order for SWTs to be successful in a new local context, it is absolutely essential to understand the socio-technical system within which they are being introduced. Technology that is simply transplanted into a new location is almost certain to fail, as the enabling environment, supporting services and relevant market actors will not be properly equipped to support it. Leapfrogging a remote unelectrified community from the lowest level of the energy access up to level 3 (AC micro-grid - see Figure 1-4) requires the support of a significant amount of social infrastructure. This is especially true of SWTs due to the high level of technical capacity they require throughout the technology lifecycle, in order to ensure that they are installed on windy sites and are properly supported by the relevant maintenance services. The lack of technical capacity relating to wind power that was found to be hindering many of the actors within the SWT ecosystem in Nicaragua could be addressed by offering technical training to these actors and improving the curriculum at training centres and universities.

To a certain extent, SWTs have been able to 'piggy-back' on the development of the solar industry in Nicaragua, as even though the majority of parts for an SWT can be manufactured locally, batteries, charge controllers and other key components of a wind power system must still be imported (via a supply chain that has already been created by solar distributors). Unfortunately though, this 'piggy-backing' has led to many costly errors, as the wind resource is more difficult to assess than the solar resource and SWTs require much more post-installation support than PV. Targeted awareness raising in windy areas with a critical mass of potential users could help reduce this problem.

The Atlantic coast of Nicaragua was found to be a particularly unfavourable local context for SWTs, as there are many environmental hazards (lightning, corrosion, hurricanes), the low level of existing transportation infrastructure makes gaining access to maintenance services particularly difficult and the wind resource is low, so energy yields are disappointing. The increased level of training offered to community technicians and easier access to the community, coupled with the superior wind resource and fewer environmental hazards made the pilot project in the central highlands much more sustainable.

The lack of information about the wind resource itself was found to be a major barrier to the uptake of SWTs, which should be addressed by improving the quality of wind maps and providing technical and financial support for individual site assessments. The final major barrier was found to be the provision for maintenance services. Currently the only actors offering maintenance services are based in non-windy areas, meaning that those living in windy areas must travel long distances on a regular basis in order to keep their SWTs in service. This could be addressed by offering technical training to Nicaraguan renewable energy equipment suppliers to improve their capacity for performing maintenance on SWTs from their branches in areas identified by this study. The willingness of the community to continue to pay for access to electricity is linked to the value it offers them, which is in turn linked to the quality of the service that the system provides. As SWTs are less reliable than PV, the supply of electricity is more likely to be interrupted when the SWT is awaiting repair and therefore the willingness of the community to pay for this service decreases. This in turn causes the system to spend even more time out of service as the lack of funds prevents a repair from being made, further decreasing the value of the system to the end-users. Consequently, the establishment of this maintenance infrastructure prior to the installation of SWTs is of critical importance.

The post-installation analysis methodology developed during the previous case study was employed to the Cuajinicuil case study and extended to evaluate economic performance and end-user testimony. The addition of this qualitative data from interviews and observations in the community itself was absolutely essential to add the necessary depth to the case study with which to determine the reasons why the technology was able to succeed in this particular local context. The economic data gave further insight into the relative merits of solar PV and SWTs in the context of rural electrification and provided the basis for the quantitative, LGC/GIS based economic model to determine the size and location of the market for SWTs in Nicaragua.

The combination of case study evidence with the interview data from Nicaraguan wind power experts and the LGC/GIS analysis allowed triangulation of key research findings from multiple sources. For example, the fact that the central highlands could be a viable location for SWTs is demonstrated by the success of the Cuajinicuil pilot project, the identification of viable markets in some of these municipalities by the LCoE /GIS methodology and the recommendation of this part of the country by the wind power experts. As a result, although it is impossible to quantify the exact size of the market for small scale wind in Nicaragua, there is a high level of confidence in the overall conclusions of the study, i.e. that there are a few small potential markets in the central highlands and southern Pacific coast.

Chapter 6. Scotland

Figure 6-1: A shattered set of wind turbine blades lies abandoned amongst the heather and rocks that cover the majority of this windswept peninsula

6.1 Introduction

"More and more we feel the need to be on site, and to be there long enough to be able to understand what is going on (we began with a week and are now spending months and even years)."
(Mintzberg, 1979: 587)

The Peru case studies were lacking in depth due to the lack of time spent by the author in the rural communities themselves and therefore the lack of contact with the people who are using the technology every single day. This was addressed in Nicaragua by spending almost a week in two separate rural communities and conducting surveys and interviews with end-users, community technicians and community leaders. However, this was still not enough to fully appreciate the way in which people interacted with the technology on an everyday basis. To really be able to pull apart the socio-technical system that exists in each place and truly understand what the underlying reasons why wind power worked (or did not work) in each local context, a greater understanding of the context itself and how SWTs fitted within it was required.

The author began field work on the Scoraig peninsula in April 2012 to undertake technical performance measurements on the LMSWTs built, installed and maintained by Hugh Piggott in his home community. Such measurements require the installation of a data logger and sensors on the turbine under test (see Figure 6-2) and the collection of data over the course of several months. The resulting information is used to characterise the performance of the turbine in a range of wind conditions and is usually presented in the form of a power curve (see Figure 6-13). A total of 6 machines were monitored, requiring the author to return to Scoraig on multiple occasions over the next year and a half for periods of 1-4 weeks, as shown in Figure 3-7. An example of the technical methodology employed during this process is described in 0.

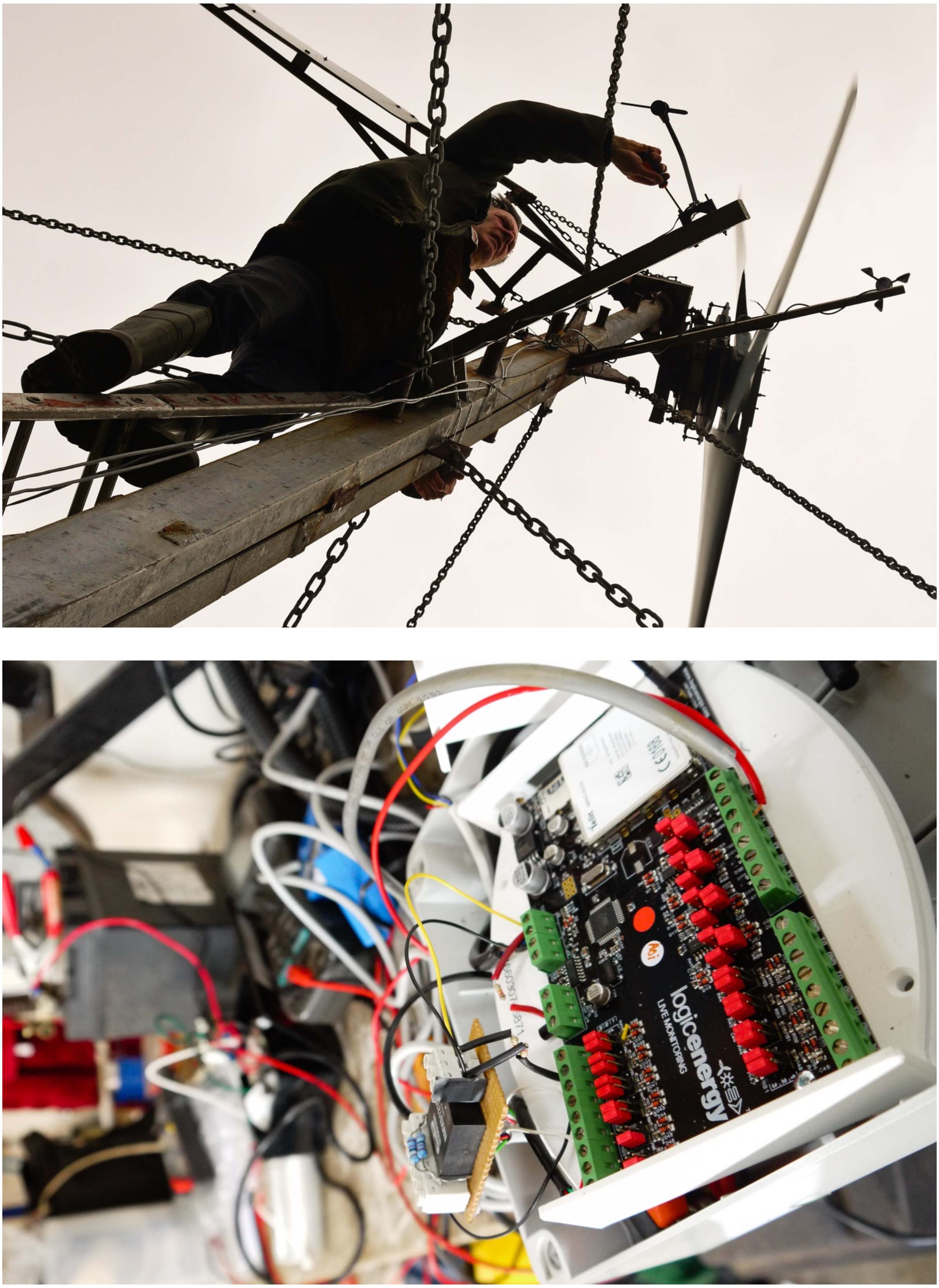


Figure 6-2: a) Hugh Piggott uninstalling wind sensors (wind vane and anemometer) from a 5m diameter machine and b) the data logger under test in Piggott's workshop.

The term 'an accidental ethnography' is probably the most appropriate way to summarise the methodology employed during this chapter, as despite having a very clear plan of the technical performance measurements to be undertaken in the community, it was the participation in the everyday life of the people of Scoraig that provided an unexpectedly fruitful learning opportunity. Conversations at the dinner table about whether there would be enough wind to have a hot shower that night without lighting the stove and observations of the role that many other alternative technologies, such as rainwater harvesters or passive solar building design play in daily life gave valuable insight into the fundamental reasons why SWTs have been such a success in this unique rural community. This led to the realisation that the addition of the rural community of Scoraig as a final case study in this thesis would add significantly to the understanding of the technology and how it can work in a local context that is virtually ideal.

Figure 6-3: A wind power themed bottle of wine to complement the frequently wind power themed conversation at the dinner table.

6.2 Methodology

To gain further insight into the issues uncovered during this 'accidental ethnography', a number of the techniques employed in the previous case studies were also carried out on Scoraig. Three of the energy systems that had been studied for the technical performance measurements were selected for further study, due to both the technical familiarity with these systems as well as with the end-users themselves. A series of interviews were conducted with these end-users to discover more about their experience with SWTs and to collect quantitative data for the post-installation analysis and energy systems modelling of each individual household energy system. The information gained from the end-user interviews was accompanied by invoices issued by Scoraig Wind Electric to the end-users for installation, maintenance and upgrade of their renewable energy systems and personal communication with the community technician, which in this case was Piggott himself. As this data frequently overlapped, it offered the possibility to triangulate findings between the various sources and verify their accuracy against each other.

Figure 6-4 shows the Scoraig peninsula and the locations of the three households selected for individual case studies. Households were not selected at random, as each house on the Scoraig peninsula has a unique energy system, designed specifically for the needs of that household, the resources they have available on site and the amount they are able to pay. Instead, they were chosen because they fitted into certain categories and illustrated these differences most clearly:

1. The Davys moved to Scoraig in 1984 and live very simply. They are willing to put up with high levels of disruption to the energy supply in order to reduce their dependence on fossil fuels and reduce the overall cost of their system.
2. Andy Whisken & Susan McSweeny moved to Scoraig in 2005 when Susan found a job as a teacher at the local primary school. They moved from London, where the availability of energy services is higher than almost anywhere else in the world, so although they have made significant changes to their lifestyle, they have chosen an energy system that prioritises reliability and safety over cost.
3. Lee Brown has the most diverse energy system on Scoraig, with a PV array, an LMSWT, a hydro turbine and a petrol generator all feeding into the domestic battery bank.

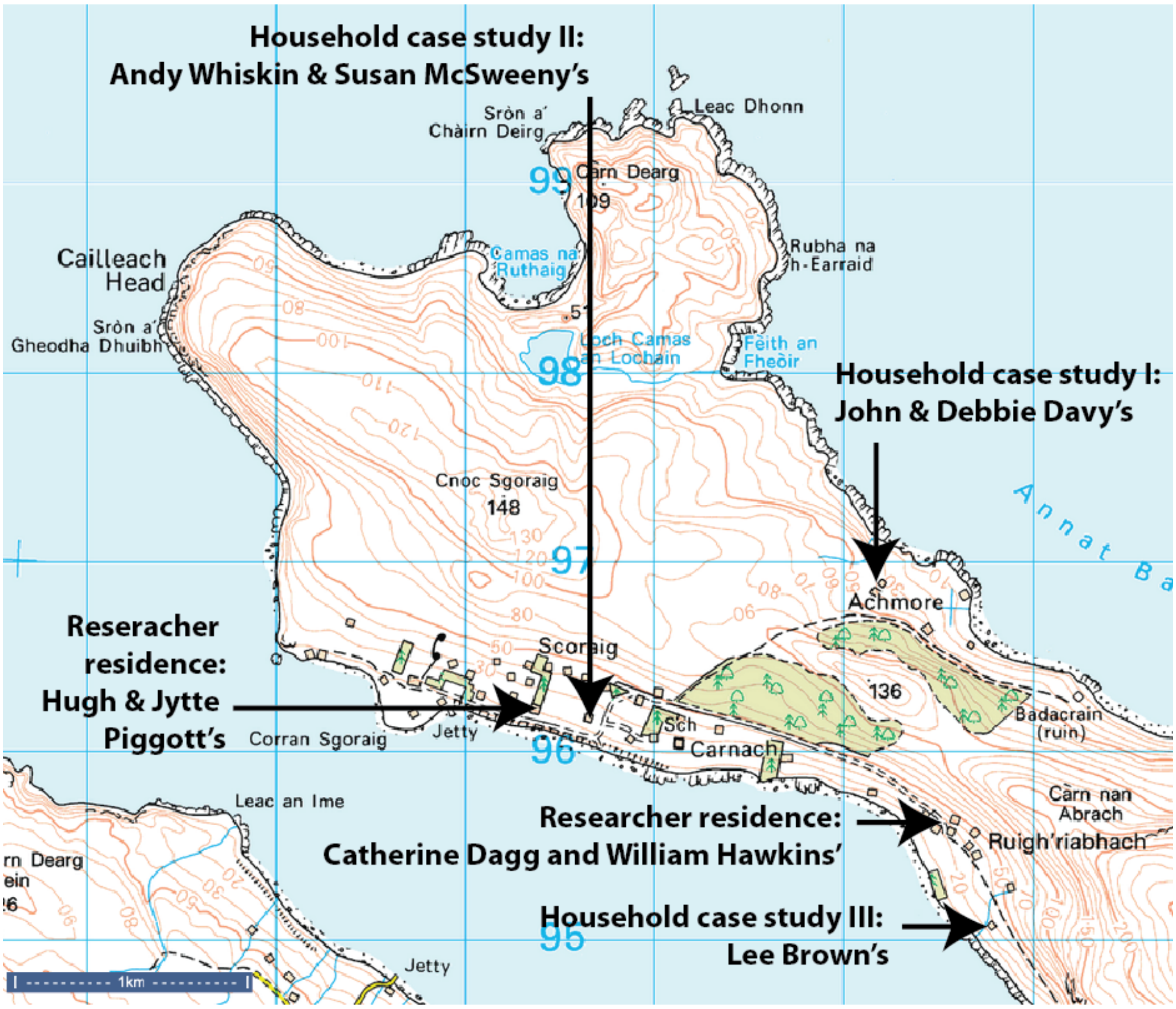


Figure 6-4: Map of the Scoraig peninsula showing the location of the households selected for the three household case studies and those where the author stayed whilst conducting the research. Image adapted from Streetmap.co.uk.

6.2.1 Participant observation

As discussed previously in Chapter 2, the author was treated very much as an insider within Scoraig Wind Electric, giving access to a whole range of opportunities for data collection. Although Piggott makes no secret of his work, (a simple internet search quickly reveals the vast amount of content that he has published on the subject), the ability to chat freely with him, as well as observe the way in which he interacts with the technology he has designed, built and installed, as well as the other end-users was invaluable. In addition to carrying out the power performance testing, the author accompanied and assisted Piggott on a number of maintenance visits (see Figure 6-5), giving valuable insight into the way in which he deals with this key issue and his relationship with each other member of the community. Finally, staying at the Piggott household and observing, as well as participating in, the way in which energy is used on a daily basis gave an even deeper understanding of how SWTs work under virtually optimal conditions.

Figure 6-5: Assisting Hugh Piggott on a maintenance visit.

When working on the Scoraig peninsula, the author stayed with either the Piggott or the Dagg/Hawkins family, both times in a bothy[91] near the family home. The former was connected directly to the family's PV-wind-petrol/diesel energy system whilst the latter had no electricity. In fact, many of the pages of this thesis were written using electricity from the wind turbine shown in Figure 6-6, meaning that the experience of living with limited quantities of electricity helped to shape these very words in more ways than one.

> *"Today I wrote code all day to process the power curve data. I took my laptop up to the house three times to charge it and have to plan the work I do around this. I can't imagine how annoying it must have been for Hugh to carry a heavy car battery over the loch to the shop when he first arrived on Scoraig, just for a few hours of light in the evening from the 12V car bulbs."*
> *Field diary extract, 17th June 2013.*

[91] A small hut/cottage, usually built from stone.

Figure 6-6: The wind turbine that generated the electricity used to write part of this thesis.

During the three months that the author spent on Scoraig, many opportunities to participate in social occasions were available. It is certainly not the case that the author took such opportunities purely to enhance the quality of the research, however, they did provide a greater level of understanding of how the various community members use energy in their daily lives, their attitudes towards energy related issues and an overall understanding of the way that the community functions. In fact, Figure 6-7 shows that it was often the anecdotes picked up during such events that led to new lines of investigation or illustrated various constructs much more clearly than any set of numbers ever could. In order to record these anecdotes and any emerging constructs, a field diary was kept. The diary included both factual statements of what happened, as well as "*unfiltered reflections*" (Yadoo, 2011: 37) on the potential implications. The field diary was complemented with photographs, both of which were thoroughly reviewed during the data analysis process. A sample page from the field diary, along with the accompanying photographs, is shown in Appendix H.

Figure 6-7: A live music gig in the kitchen of the Davy household under the electric light of their recently installed 240V AC lighting system.

6.2.2 Interviews

Interviews with the three families selected for household case studies were conducted to find out more about their particular experience with wind power, as well as to obtain specific quantitative information to perform the post-installation analysis and energy systems modelling. A semi-structured approach, similar to that employed in Nicaragua was used, with a number of set questions planned in advance and used as a checklist to ensure that certain key issues were covered (see 0) The remainder of the interview was unstructured, allowing the conversation to encompass any relevant issues specific to that interviewee. The interviews were conducted in informal settings in which the interviewees would feel comfortable and would not be inconvenienced, usually the interviewee's home. An additional interview was also conducted with Catherine Dagg, an archaeologist and expert in Scoraig history, the findings of which are included in section 6.3. Notes were taken during each interview, summarised immediately afterwards and then reviewed during the data analysis process. All interviews were conducted in June 2013 and unless otherwise stated, all direct quotes in the household case studies were recorded during this period.

6.2.3 Energy systems modelling

In order to understand the technical and economic consequences of the design choices made by each of the three systems under study, each system was modelled in the micro-power optimisation software, HOMER, using a similar methodology to that described in the previous case study. The energy systems modelling technique is limited by the quality of the input data and the fact that the entire process is a simplification of reality. To address this, Figure 6-8 shows that a feedback loop was added to the process described in Chapter 5, in order to validate the results of the analysis before any conclusions were drawn from it.

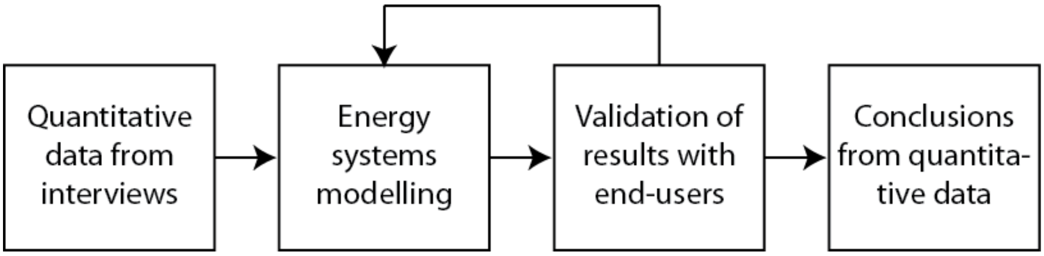


Figure 6-8: The iterative nature of the energy systems modelling process.

6.2.3.1 Energy resources

Figure 6-9 shows the estimated monthly mean wind speeds for each site to be used as input data for the HOMER models. These estimates were made using data from each site that was recorded during the power performance logging and scaled to fit the seasonal trends observed in many years of recorded data from the Piggott household using the procedure described in Appendix Q.

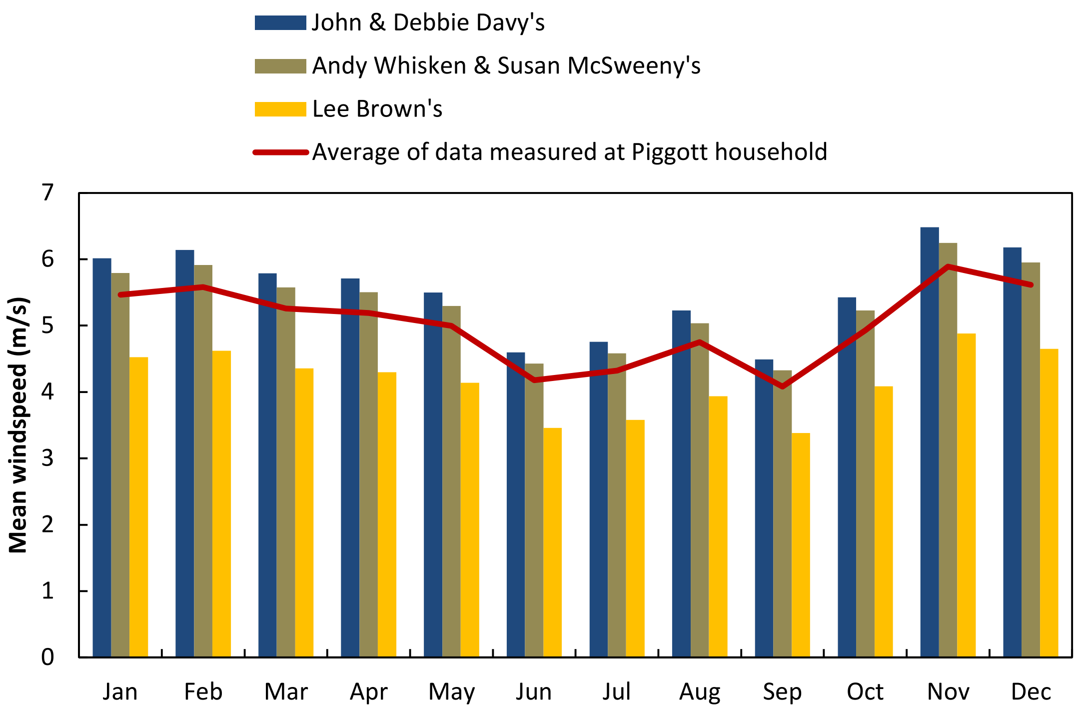


Figure 6-9: HOMER input data based on the seasonal profile of the data measured at the Piggott household and scaled appropriately for each site.

Fortunately, the solar resource is significantly easier to estimate and the NASA (2013) data shown in Figure 6-10 was used for all three sites. Local shading effects could have an influence on the solar resource available at each site, especially at the Davy household on the North side of the peninsula;

however this was considered outside the scope of the study and therefore was not evaluated. All solar panels were assumed to have been mounted at the optimal 58° azimuth. At 2.3kWh/m^2/day, the annual average daily solar radiation is low due to frequent cloud cover and high latitude (58°), which also causes high seasonal variation in the solar resource.

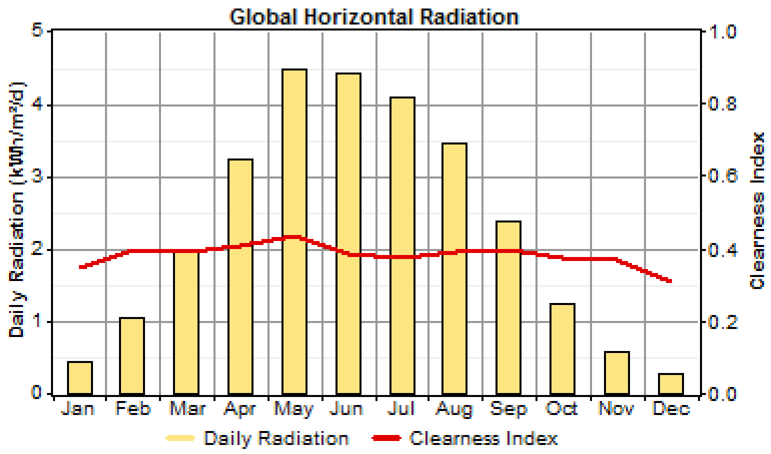


Figure 6-10: Solar resource input data for the Scoraig peninsula. Data source: NASA (2013).

Petrol prices in the UK have always been very high and in early 2013, they were at approximately 2.11$/l (1.35£/l). Hydro resources are scarce in the inhabited parts of the Scoraig peninsula, with just a few houses closest to the mountain having a stream that runs through their property and flows all year round. Figure 6-11 shows the seasonal flow rates of the stream that runs beside the Brown household (household case study III), from which a 10m drop can be exploited for power generation. It was not possible to model the fact that the hydro resource occasionally disappears completely (as reported by Lee Brown, the end-user of the system), either drying up due to lack of rainfall or freezing over in the winter, sometimes for as long as 6 weeks.

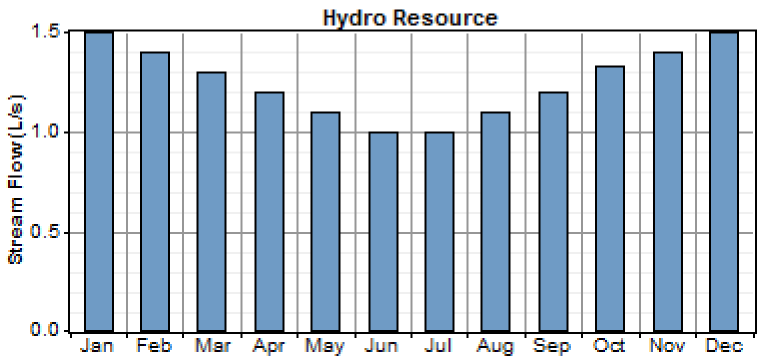


Figure 6-11: Seasonal flow rates in the stream beside Lee Brown's household, used to extract power from a 10m head.

6.2.3.2 Equipment

Figure 6-12 shows how the costs associated with the equipment installed at each site is categorised into the following key elements:

- Power generation – system components that generate power or are required by those that generate power in order to be able to charge the batteries. Split into sub-elements by power source. The costs of components such as the charge controller and dump load that may be associated with multiple power sources and therefore split between sub elements are apportioned according to the rated power of each power source.
- Energy storage – a battery bank stores the variable power input from the power generation equipment to meet the variable power demand from the domestic loads.
- Converter – an inverter converts DC power from the batteries into AC power for domestic loads and may also allow a petrol generator to charge the batteries.

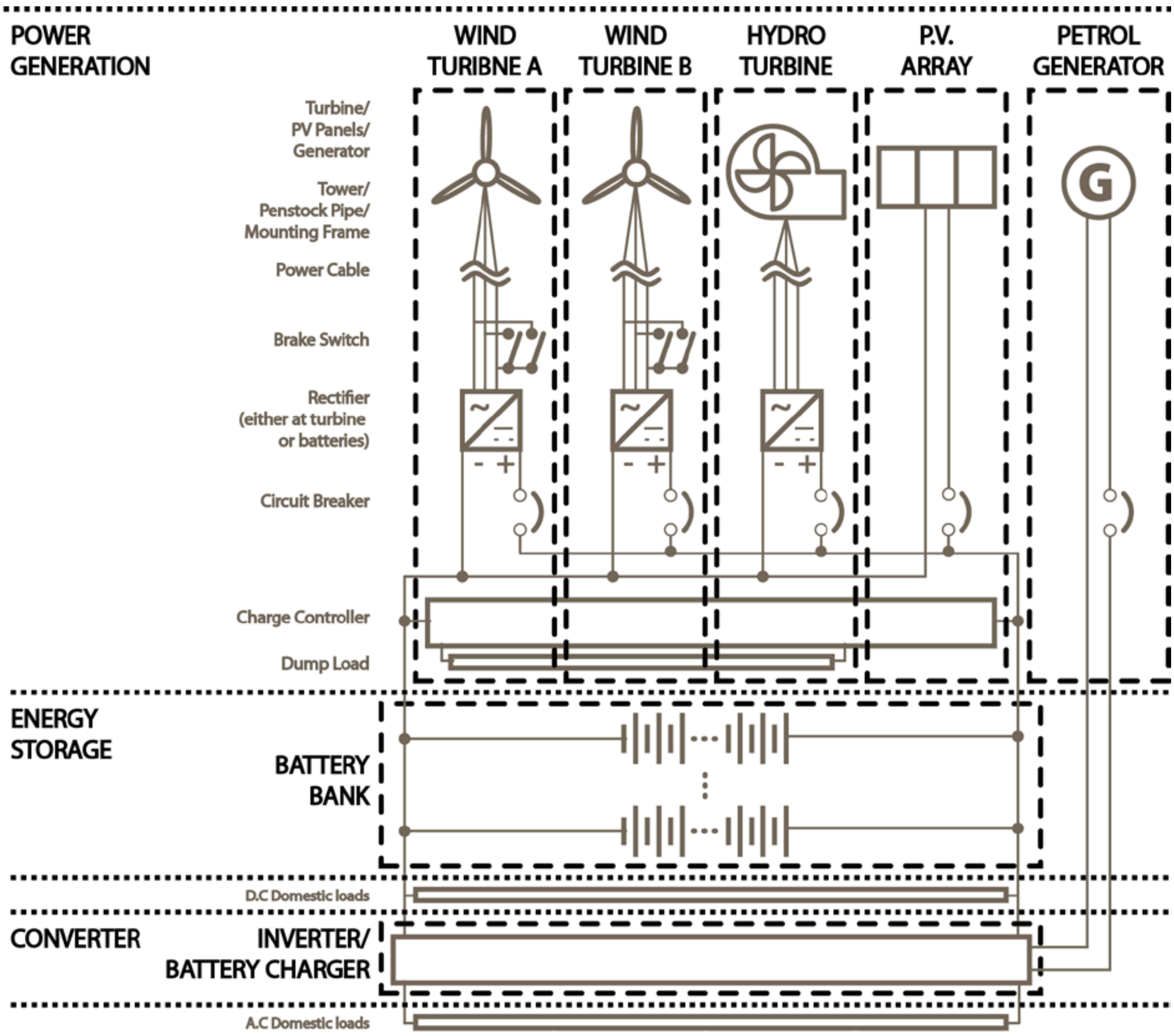


Figure 6-12: Wiring diagram showing the major system components in a hybrid renewable energy system, showing how they are divided into elements within the energy systems modelling.

Each element has an associated capital cost and O&M cost (either annualised or per hour of operation) to cover both preventative and corrective maintenance, as well as a lifetime (in either years or operating hours), after which the entire element is replaced at the original capital cost. Capital costs are made up of the cost of individual system components (rectifier, PV panels, fuses etc.) and the labour required to install them. O&M costs and lifetimes are much more difficult to model, requiring long-term data collection from a large number of systems in similar local contexts to that under study. Data was collected on each failure that had occurred within each of the three energy systems under study, so it was possible to calculate an average annual expenditure on O&M (both parts and labour) for each element within each system. However, as some of the equipment had been installed just a few months before the analysis began, it was decided that this was not an appropriate method for modelling O&M costs. Instead, a standard figure for each element based upon a percentage of capital costs for that particular module was used. These figures are listed in Table 6-1 and are based upon the experience of Hugh Piggott, who has been offering maintenance services for small scale renewable energy systems on the Scoraig peninsula and the surrounding area for over 30 years.

Table 6-1: Standard O&M costs and lifetimes for each element of a hybrid renewable energy system.

Element		*O&M Costs (% of capital costs)*	*Lifetime*
Power generation	Wind turbine (locally manufactured)	15% per year	10 years
	Wind turbine (commercial)	5% per year	15 years
	PV array	0.5% per year	20 years
	Hydro turbine	5% per year	20 years
	Petrol generator	0.05% per hour	2,000 hours
Energy storage	Batteries	5% per year	10 years maximum (dependent on number of cycles)
Converter	Inverter/battery charger	0.5% per year	10 years

Modelling the O&M costs for the wind turbine was particularly difficult, as the lifetime of a SWT is highly dependent on the site. Referring to the particularly turbulent site at Achmore (the Davy household), Piggott explained that:

> *"If you had a Marlec[92], it would last two years on a site like this, but it might last 15 on a caravan park in Oxfordshire underneath an oak tree!"*

Whilst quantifying the effect of wind resource on O&M costs could be done by including a per kWh cost component in addition to the standard annual cost component, incorporating the effect of turbulence would be much more difficult. As a result, a figure of 15% per year for locally manufactured technology and 5% per year for commercial machines was used for all sites. However, these figures

[92] Commercial brand of SWT.

also depend on the amount of maintenance that the user is willing to do themselves. The most independent users on the peninsula have built their own wind turbines and are capable of performing all maintenance themselves with little more than the occasional piece of friendly advice from Piggott himself. On the other extreme, Piggott offers a range of service plans with a fixed annual fee that includes both parts and labour for any preventative or corrective maintenance that may be necessary. Each service plan is bespoke and depends primarily on the complexity and size of the energy system, as well as the preferences of each individual user, e.g. whether they are willing to perform basic preventative maintenance such as topping up the batteries themselves. It is difficult to estimate the effect of these different options on O&M costs and lifetimes, as although Piggott charges for his time, he charges very little (just $16 per hour) and his experience may well save money in the long term by preventing possible future failures from happening or by substituting second hand parts that he may have in his workshop at the time.

Although figures of 10 and 15 years were chosen for the lifetime of locally manufactured and commercial SWTs respectively, these were equally difficult to quantify, particularly for locally manufactured machines, because as Piggott states, "*you can just go on replacing parts forever*." However, there are few machines on Scoraig that have survived longer than this, whilst there are many sites that have been using wind power for many times longer. Deciding on a figure for battery O&M costs was also difficult, as with good care, the only significant cost would be distilled water to top up the electrolyte[93]. However, a figure of 5% per year was chosen, as there is always the risk that the batteries could be left to run dry or accidentally very deeply discharged/overcharged by either a charge controller or inverter failure or by user error. Table 6-2 lists the most important variables used to represent the equipment installed at each of the three sites in the HOMER models.

[93] Estimated at $25 per year for a bank of four 400Ah 6V Rolls 4000 series S-530 deep-cycle lead-acid batteries, retailing at $1,581.

Table 6-2: Input variables for the three renewable energy systems modelled in HOMER.

	Household case study	*I: Davy family*	*II: Whisken/ McSweeny family*	*III: Lee Brown*
SWT A	Model	Piggott 3N	Piggott 2F	Piggott 2.4N
	Rated power	800W	400W	500W
	Hub height	10m	11m	12m
	Capital cost	$2,445	$1,735	$2,040
SWT B	Model		Ampair Hawk	
	Rated power		85W	
	Hub height		5m	
	Capital cost		$1,670	
Hydro turbine	Model			EcoInnovation Hydro Turbine Kit
	Rated power			200W
	Penstock length			100m
	Head			10m
	Flow-rate			1-1.5l/s
	Efficiency			75%
	Capital cost			$1,653
PV	Model	2x 84W Kyocra + 2x 230W REC	7x 84W Kyocera	4x 84W Kyocera
	Rated power	628W	504W	320W
	Capital cost	$1,735	$3,984	$2,060
Pet. gen.	Model		Honda GX200	Honda EM5500CXS
	Rated power		2,800W	5,600W
	Capital cost		$548	$500[94]
Batteries	Model	8x Rolls 4000 series S-530	4x Rolls 4000 series S-530	8x Rolls 4000 series S-530
	Nominal voltage	6V	6V	6V
	System voltage	24V	12V	48V
	Round trip efficiency	85%	85%	85%
	Rated capacity, per battery	400Ah	400Ah	400Ah
	Capital cost	$2,431[95]	$1,581	$3,246
Converter	Model	PulseStar	Studer XPC	Outback VFX3048
	Rated output	800W	1,100W	3,000W
	Efficiency as inverter	90%	90%	90%
	Efficiency as battery charger	n/a	75%	75%

[94] Obtained second hand from a neighbour.
[95] Delivered on a bulk shipment at lower cost.

Household case study	*I: Davy family*	*II: Whisken/ McSweeny family*	*III: Lee Brown*
Capital cost	$0[96]	$1,221	$3,025

Figure 6-13 shows the power curves of the three LMSWTs installed at the households under investigation, whilst Figure 6-14 shows the predicted annual energy yields on different site conditions. The largest machine, the Piggott 3N generates approximately twice as much energy as the smallest machine, the Piggott 2F.

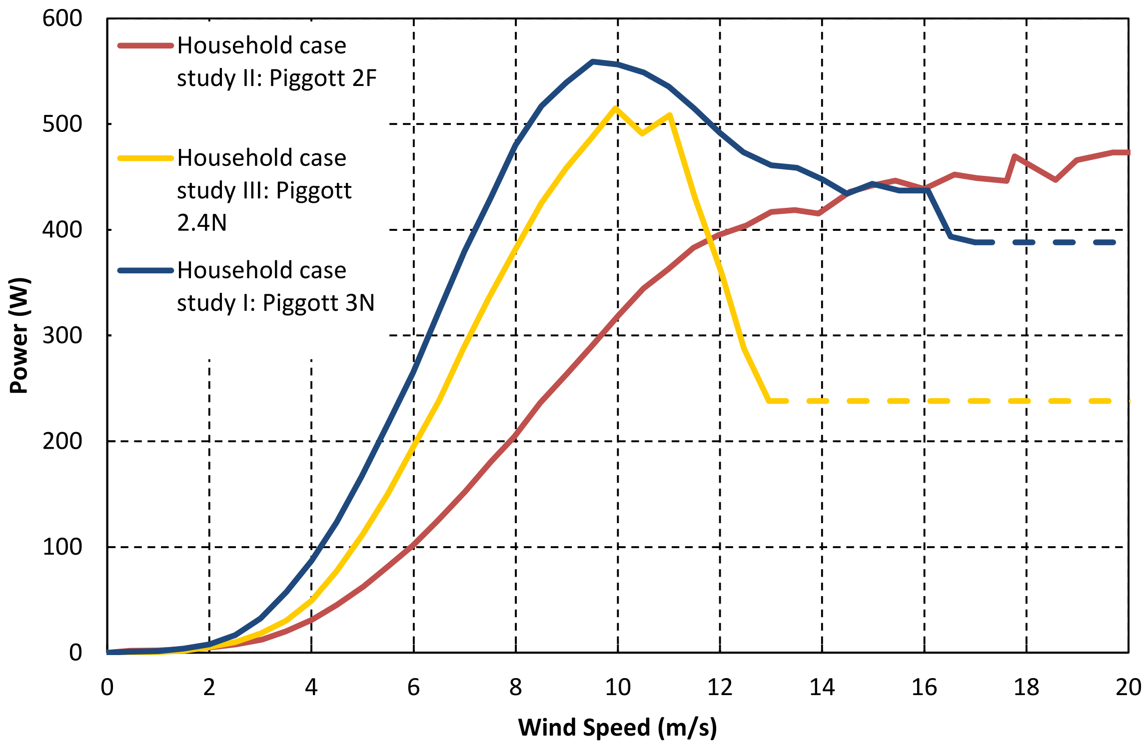


Figure 6-13: Power curves for the three wind turbines investigated during the household case studies. Dashed line signifies extrapolated data due to the lack of high wind data during the measurement period for that particular turbine.

[96] On long term loan, so capital costs effectively $0.

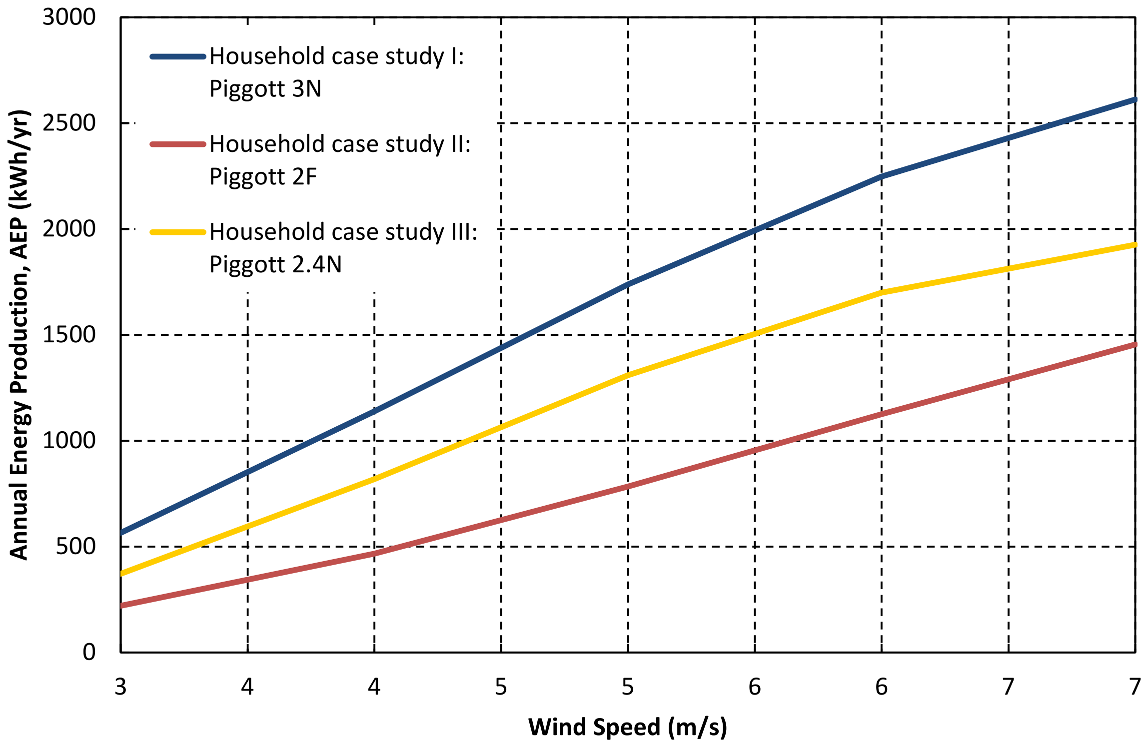


Figure 6-14: AEP (Annual Energy Production) for the three wind turbines investigated during the household case studies.

6.2.3.3 Energy demand

Energy demand was modelled using data obtained from the interviews on the number, type and power ratings of appliances in use at each household. The hours they were typically used throughout the day were also recorded to build up a profile of energy use throughout a typical day. An example is shown below in Figure 6-15. Although energy demand varies throughout the year (more light required in winter, more cooling required in summer etc.), this was simplified in the model by using a typical day throughout. The random variation between days was set at the highest value possible to reflect the changeable weather conditions on the Scoraig peninsula (i.e. the amount of time people spend inside, using electrical appliances). It was also not possible to model the behaviour of the end-users regarding their tailoring of demand to resource availability, e.g. using high power appliances such as electric kettles only when it's windy/sunny.

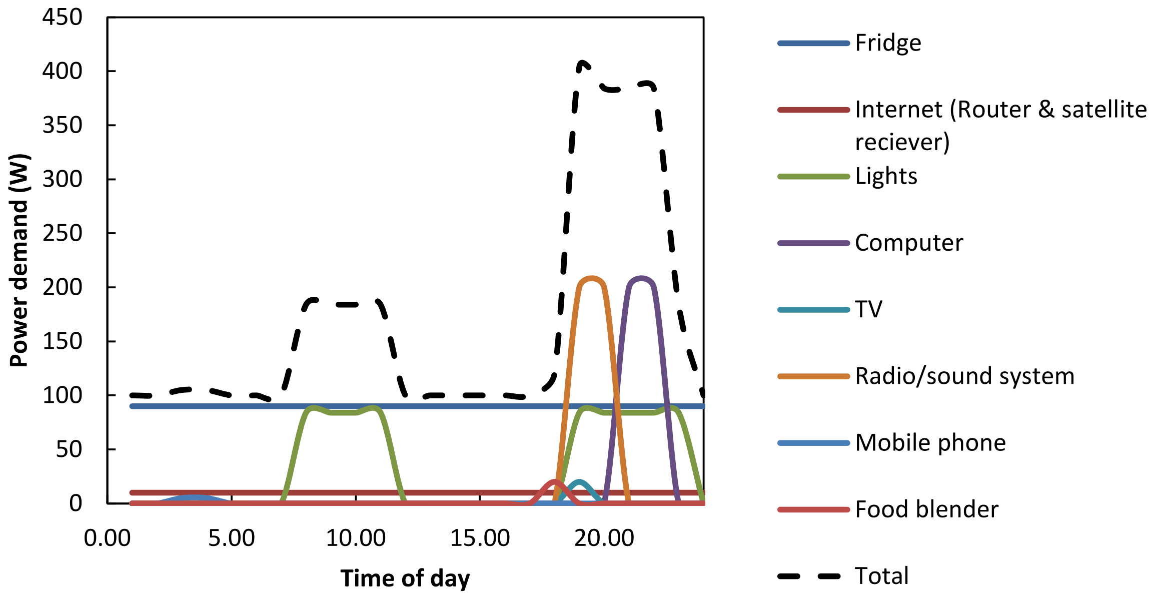


Figure 6-15: Power demand during a typical day at the Davy household (household case study I).

6.2.3.4 Economics

A discount/real interest rate of 10% was used, as recommended by ESMAP (2007) and IRENA (2012). The energy systems were modelled over a 15 year lifespan, as although some of the systems may well be in place for longer than 15 years, it is difficult to predict what will happen beyond this time period. A negative cost is attributed to the salvage value of equipment predicted to survive beyond the lifespan of the system. The system currently in operation at each household is modelled as if all components were installed at the same time and no upgrades were to take place during the lifespan of the system. All prices are quoted in USD, with the conversion rate of 1USD=0.63831GBP used throughout[97]. All costs are inclusive of VAT, which in the UK was 17.5% before 2011 and 20% from 2011 onwards. These rates only apply to replacement parts, upgrades and labour costs, as complete renewable energy systems are subject to a reduced VAT rate of 5%.

[97] Source: xe.com 12/6/13.

6.3 The Scoraig peninsula

Figure 6-16: a) The Scoraig peninsula, as seen from Beinn Ghobhlach, the mountain that separates it from the UK mainland and b) the only overland route that leads around Beinn Ghobhlach.

Located in the Highlands of Scotland, Scoraig is certainly not a typical British community; nor is it even a typical Highlands community. In fact, life on Scoraig is fundamentally different to life almost everywhere else in the UK. Life on Scoraig presents significant challenges to overcome on a daily basis due to the lack of infrastructure and extreme environment.

"We are attacked by a swarm of midges so thick that we both end up coughing from swallowing so many that the only option is to carry the entire wind turbine on the front of the quad bike and work inside as it is also raining"
Field diary extract 7th June 2013

Various waves of settlers have arrived on the Scoraig peninsula since the Iron Age, during which time the majority of the trees were cleared to make space for livestock, leaving the land barren and windswept. In the 18th and 19th centuries the infamous Highland Clearances brought a new wave of settlers - Gaelic peasants who had been evicted from their homes further inland. Whilst the peasants had previously been able to survive on a subsistence lifestyle, producing enough to survive from the small and poor quality crofting[98] land they received on the Scoraig peninsula was almost impossible, forcing many to seek a better life in North America.

By the 1960s, the peninsula had been almost completely abandoned; however there was another wave of settlers ready to repopulate the Scoraig peninsula once again. In contrast to the Gaelic peasants who had arrived 200 years earlier, these people were much more highly educated and had moved to the peninsula of their own free will. Many of these new comers were dissatisfied with the growing dependence of modern civilisation on unsustainable practices, such as continued fossil fuel exploitation in spite of the widely acknowledged environmental consequences. Scoraig has no connection to the National Grid, nor the water mains and neither are there any roads connecting it to the rest of the UK[99]. As a result, the people of Scoraig need to obtain the majority of their own food, water and energy from the peninsula itself.

Figure 6-17: A renewable energy upgrade to one of the original stone crofting cottages.

[98] Crofting is a social system unique to the Scottish Highlands in which the crofter owns or rents a small landholding for the primary purpose of food production.
[99] Access is by boat across Little Loch Broom and there are no scheduled ferries, see Figure 6-18.

Figure 6-18: Awaiting pickup at the end of the UK road network at the Badcaul jetty looking towards the Scoraig peninsula across Little Loch Broom.

6.3.1 The development of wind power on the Scoraig peninsula

Hugh Piggott moved to Scoraig in the mid-70s to live a rural lifestyle, away from the unsustainable urban culture in the rest of the UK. At the time, he had a 12V car battery that he charged up at the shop when he went into town. As the nearest shop is on the other side of Little Loch Broom, it wasn't long before he realised how much more convenient it would be if there were a way to charge it on the peninsula itself. Elsewhere in the Highlands, many others had faced the same dilemma, as they were far from the National Grid that linked the primarily coal based centralised electricity generation infrastructure with the homes of people in England, Wales and the rest of Scotland. Lack of access to electricity and other basic services contributed significantly to the rapid depopulation of the Highlands, as young people were moving south to the cities at a startling rate (Wood, 2004).

The topography and climatic conditions of the Highlands are perfectly suited for hydroelectric power generation and as a result, many game keeping estates built private hydroelectric schemes in the 1890s and 1900s in order to allow the visiting aristocracy to continue to live in the style to which they had become accustomed. These schemes were often then extended to the homes of those working on the estates and then onto the surrounding communities. This distributed form of electricity generation offered remote communities the ability to enter the modern world and live a 20th century lifestyle without having to leave the places where they had grown up (Wood, 2004).

However, the Scoraig peninsula is relatively flat, so its hydroelectric potential is limited. Little Loch Broom is also known as '*The Loch of 1,000 Winds*', revealing the powerful and unpredictable renewable resource that is so abundant in this coastal region. In the 1970s, the oil crisis led to wind power generation taking off in Denmark, California and other environmentally conscious corners of the globe (Khennas *et al.*, 2008), Around this time, Scoraig's new residents also began to harness the strong winds that blows over their homes every single day. Early attempts by Hugh Piggott and other Scoraig residents met with mixed results, with some machines lasting just minutes before they were torn apart by the ferocious winds. However, they continued their experiments and as they learned more about the wind and how to extract power from it, the machines they built became more reliable and capable of generating a significant quantity of electricity.

Figure 6-19: a) Hugh Piggott with one of his earlier machines (photo courtesy of the Piggott family) and b) the workshop in which many such machines were produced.

Before long, neighbours began asking for one of these devices to charge their own batteries and in 1978; Hugh founded Scoraig Wind Electric to keep up with this growing demand. Although it may not have been considered such at the time, Scoraig Wind Electric could now be described as a social enterprise, as in addition to generating enough revenue for Hugh and his family to live on, it also has the aim of providing electricity access on the Scoraig peninsula. Hugh charges very little for the services he provides, instead choosing to ask only what people can afford so that they too can benefit from the energy services that a domestic renewable energy system can provide. In the 1980s, Piggott produced his first guide to building an LMSWT so that people outside of Scoraig could also benefit from this technology (see Figure 6-20). Soon after, he was invited to teach practical courses on wind turbine construction at the Centre for Alternative Technologies in Wales and since the year 2000, he has been teaching people all over the world how to build these machines.

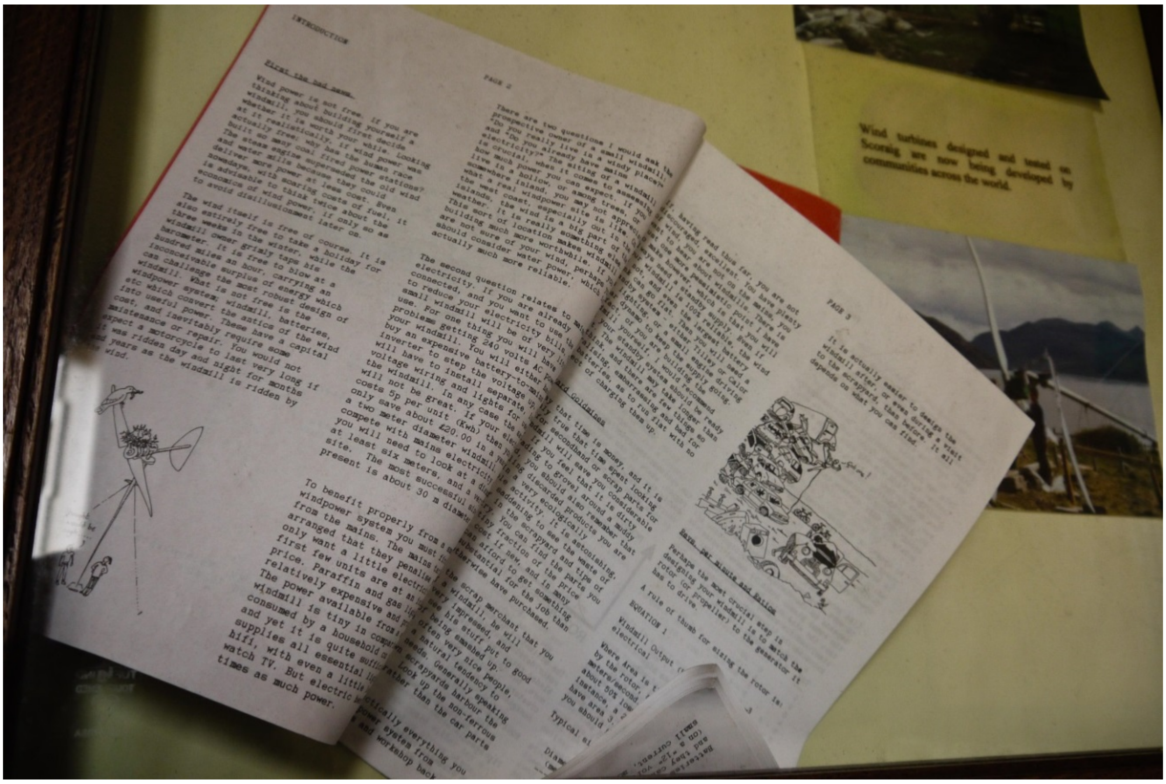


Figure 6-20: One of the first guides to building a SWT produced by Hugh Piggott in the 1980s.

Electricity from the wind has played a vital role in the transformation of the inhabited parts of Scoraig over the last half a century, allowing people to have access to the same energy services that are available in the big cities: electric lighting, the internet, etc. The house that Hugh lives in today is warm, comfortable and equipped with all the conveniences of modern living: they drink the rainwater that falls on the roof (pressurised by an electric compressor), eat the fish from the sea, the animals from the fields and the vegetables from the garden (supplemented by the supermarket when necessary and preserved by an electric refrigerator and freezer) and generate all their own electricity from a combination of wind and solar (with the occasional boost from a diesel generator).

Figure 6-21: Hugh and the Piggott family enjoying some solar energy in front of their comfortable and predominantly wind-powered home.

The creation of a series of sheltered, green and hospitable enclaves on this barren, isolated and windswept peninsula was made possible by the hard work and adoption of sensible, sustainable practices by Hugh, his family and the other members of the community. The relationship between the wind and the trees is one of the best examples of this transformation, as it was the wind that made Scoraig such an inhospitable place for the Gaelic crofters over 50 years ago, whipping across the peninsula from the Atlantic Ocean and scouring the landscape down to the heather. When the newcomers arrived from the sixties onwards, they planted new trees and when they eventually took root they provided not only firewood and materials for building, but also shelter for crops to grow and for people to live in comfort (see Figure 6-22). Today, wind turbines are placed strategically above or away from the trees to harness this powerful source of energy and generate clean, renewable energy for Scoraig's inhabitants.

Figure 6-22: The wind turbines that supply the Piggott household with electricity stand tall above the windswept trees.

6.4 Household case studies

6.4.1 Household case study I: John & Debbie Davy

Figure 6-23: The Davy household with its 3m Piggott turbine on the North side of the Scoraig peninsula.

John and Debbie Davy moved to the Scoraig peninsula in 1984 and settled in Achmore, a small settlement of just a few houses on the North side of the peninsula that had been abandoned since the 1930s. Achmore is even more remote than Scoraig, as not only must you make the crossing across Little Loch Broom, but there is also a forty minute walk up and over the ridge on a track that is only just passable on the Davy's tractor. Until 1989 the only electricity they had access to was a battery radio and a car battery that they would charge at a neighbour's house or on their tractor, in order to be able to power lights in emergencies and more importantly, a record player:

> *"It didn't matter about sitting in the dark or not having any water, but we did have to listen to music"*
> *Debbie Davy, June 2013.*

Today, Debbie works as a teaching assistant at the local school, whilst John works as a dry stone waller, using traditional methods to repair stone walls across the Highlands.

Figure 6-24 illustrates the evolution of the energy system installed at the Davy household. The following paragraphs describe the major events in this timeline and the numbers in brackets link the descriptions to their position on the timeline. The first electricity generating system installed in the

Davys' home was a truck radiator fan held up by a stick that would just about charge their car battery when the wind blew in the right direction (1). Next came a second hand 50W LVM wind turbine, which allowed 12V DC lights to be installed around the house. These are still in place today as a backup in case the inverter fails and the 240V AC lights that were installed just this year go out. The LVM machine gradually seized up (2) and was replaced just a few years later by a second hand 50W Rutland machine. Unfortunately this machine was also not robust enough to withstand the high level of turbulence on the site resulting from the combination of nearby trees, buildings and the long ridge to the South (3).

"The wind does weird things at Achmore: it'll stop suddenly and then slams in from the other direction…you can go out in the middle of the night and it'll be flat calm, you'll be walking and then it'll knock you on the ground."
Debbie Davy, June 2013

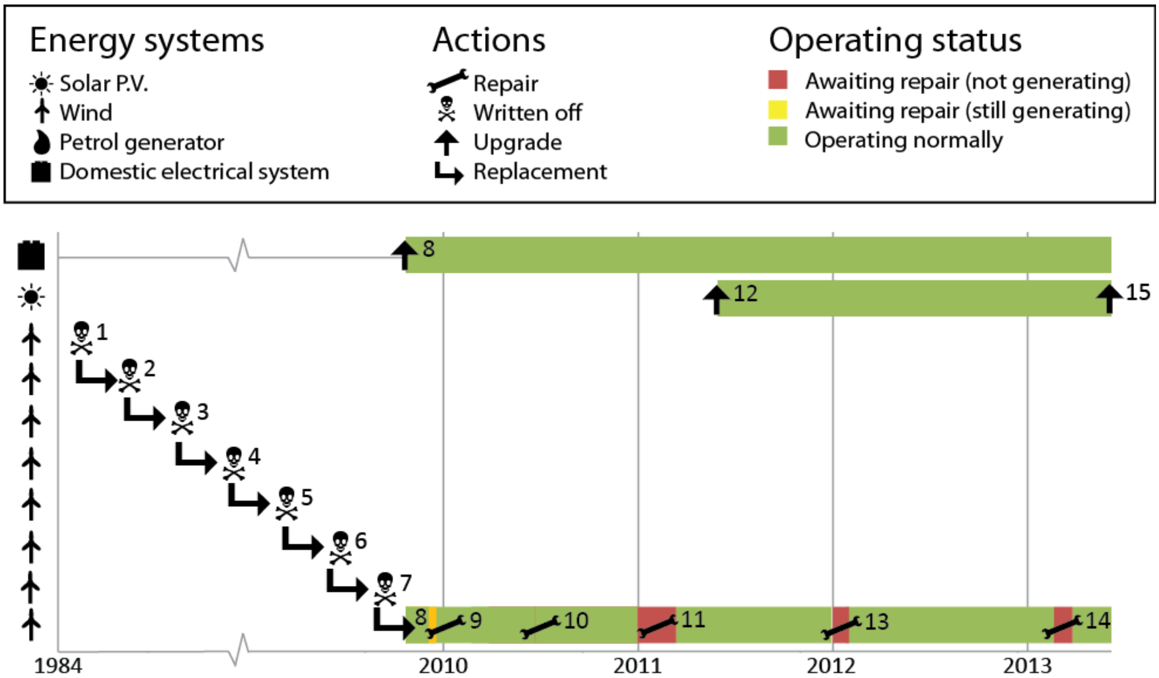


Figure 6-24: Timeline showing the evolution of the Davy's energy system since moving to Scoraig in 1984.

As a result, an identical machine was acquired and the two operated 'one up one down' (4) until they were replaced by a 3m diameter Chinese machine in 1994. This machine destroyed itself spectacularly by hurling its blades towards the house in high winds, leaving a sizeable dent in the newly built porch roof and cutting down a tree! It was resurrected by Piggott numerous times over the next few years by building new sets of blades for it, but was eventually replaced (5) in 2001 by a slightly smaller 2m machine, also imported from China. This second Chinese machine suffered the same fate of repeated blade failures and was replaced four years later (6) by an early AFPM machine designed by Hugh and a precursor to the machines he describes in his recipe book (7). The machine had been installed in

Badrallach[100], but was sold to John and Debbie when the grid arrived. The latest in this long line of self-destructing wind generators is a 3m AFPM machine built on a wind turbine construction course led by Hugh in 2009 and sold to John and Debbie for the price of the materials (8).

Figure 6-25: The 'wind turbine graveyard' outside John and Debbie's home.

"Wind power allowed us to have internet, which allowed Richard to continue writing the code that landed the Phoenix programme on Mars during his PhD…he was sitting in bed in Achmore with three computers and his blanket pulled up to his neck because it was freezing cold!"
Debbie Davy, June 2013

[100] Settlement further up the peninsula at the point where the road ends.

Figure 6-26: The front cover of Science showing the Mars landing that Richard Davy worked on proudly displayed on the wall of the Davy household, made possible by the wind powered satellite internet connection.

In addition to the satellite internet connection, the Davys acquired a fridge a few years ago and as it is only really necessary during the summer, they bought two 84W Kyocera solar panels to run it (12). In fact, the interview with John Davy was conducted whilst he installed a further two PV panels (see Figure 6-28), both rated at 230W and manufactured by REC (15), as the smaller panels were not sufficient to power the fridge alone on calm summer days. The panels came across the loch on a bulk shipment organised by Piggott at a third of the price per watt of the 84W Kyocera panels due to the falling price of solar PV.

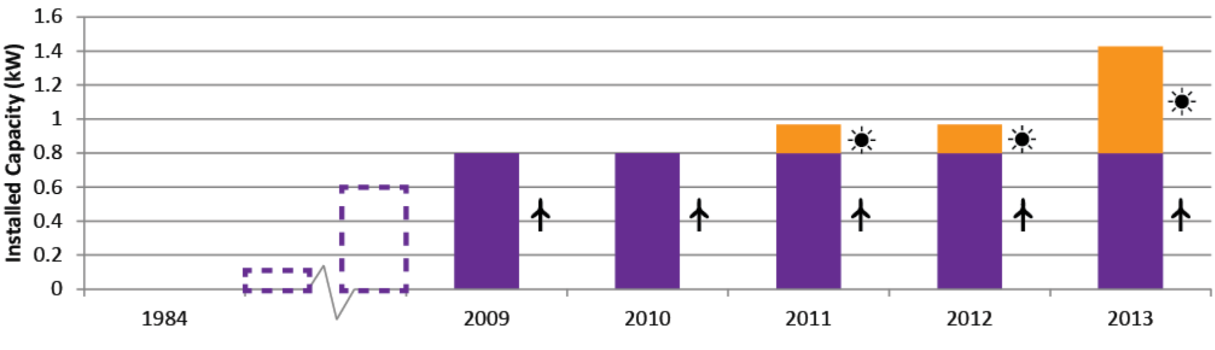


Figure 6-27: Timeline showing the increasing capacity and diversity of the Davy's domestic energy system.

Figure 6-28: John Davy taking advantage of the falling price of PV and expanding the family's solar array.

Figure 6-15 (shown previously) illustrates the power demand during a typical day in the Davy household. Although domestic power demand is much higher than in any of the previous chapters, at 4.61kWh/day (1,679kWh/yr), the modelled demand is modest by UK standards (typically 3,300kWh/yr (Ofgem, 2011)). The fridge draws a constant load throughout the day and demand peaks in the evening, when lights, computers and the sound system are in use. Figure 6-30 shows the results of the HOMER simulation, displaying the flow of energy from conversion to electricity by the PV panels and wind turbine, filling of the batteries and ultimately fulfilling the demand from the domestic loads. The complementarity of the wind and solar power generation is clear: on a seasonal basis, wind generates most in the winter, whilst the solar produces most in the summer. On a daily basis, wind can produce throughout the night, whilst solar offers more predictability. Although power shortages can occur throughout the year, they are most likely in the summer months when the wind resource is lowest. This demonstrates that although the rated power of the wind and solar systems is similar (800W vs. 628W), the system is highly dependent on the wind power component due to the superior quality of the resource available in this location.

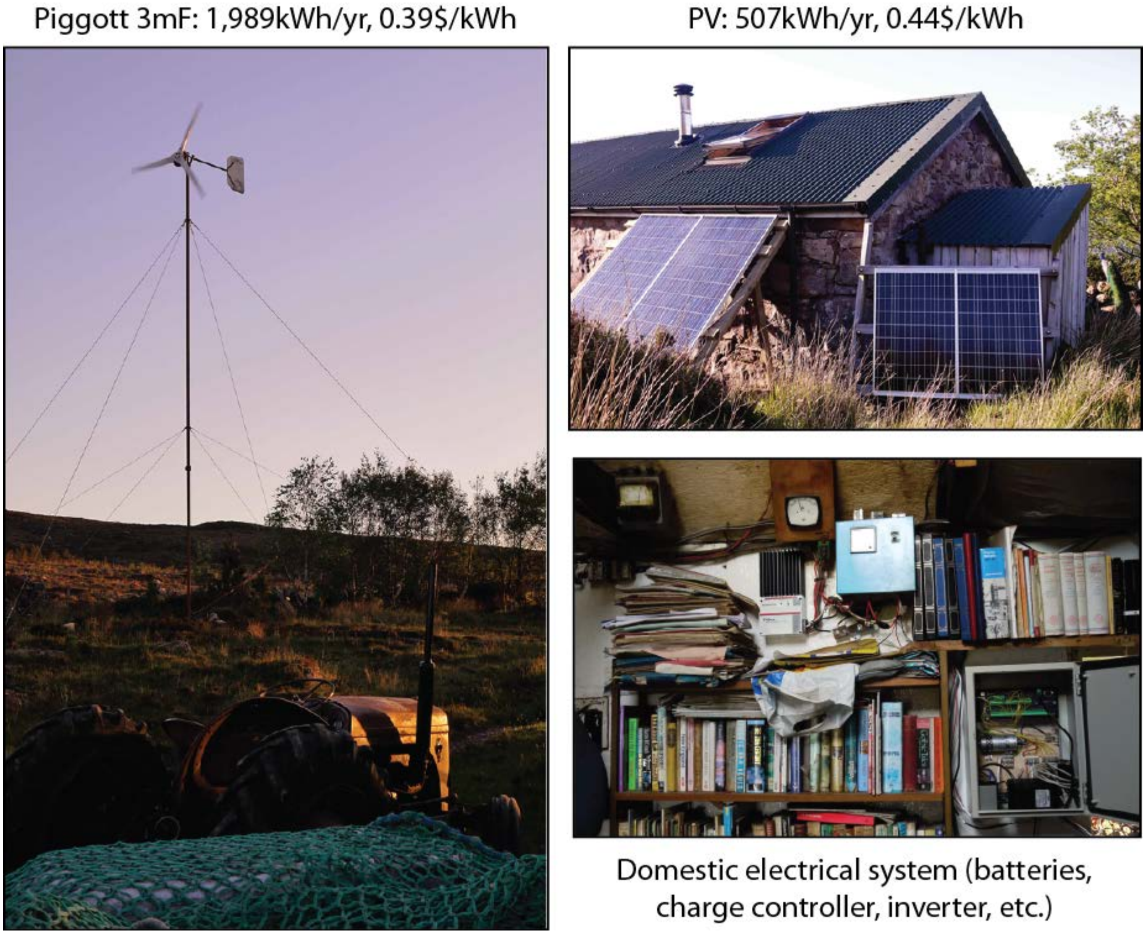


Figure 6-29: The power generation equipment currently installed at the Davy household.

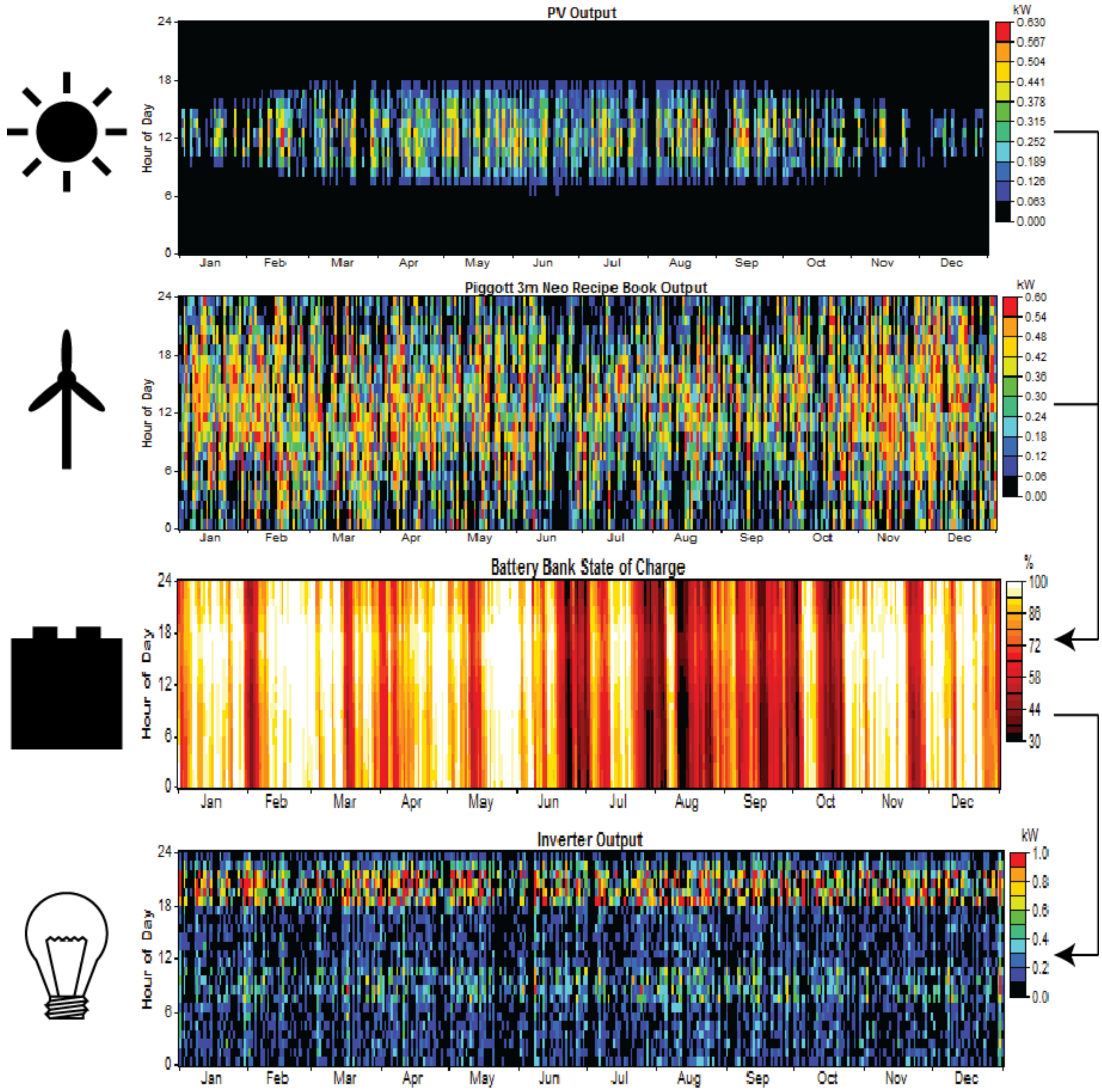


Figure 6-30: Hourly energy flow throughout the Davy's household energy system throughout the day (y-axis) and across the seasons (x-axis).

Given that the Davys run a 100% renewable energy system, matching their demand to the availability of the renewable resources that feed the batteries reduces the overall cost of the system significantly. Just like all the other houses on Scoraig, John and Debbie's house features the familiar battery voltage and incoming power meters in the living room, where it can easily be seen (see Figure 6-31).

> *"You make a lot of compromises to live off-grid; to live this life, but it's worth it…I can live without stuff to keep the costs down."*
> *Debbie Davy, June 2013.*

Fortunately, the HOMER simulation predicts that with their recent PV upgrade, just 3% (58kWh/yr) of the electric load will now go unserved each year, as opposed to 9% (162kWh/yr) with just the original two 84W PV panels. Of course, this does not include the periods when the whole energy system is offline awaiting repair. In these situations, Debbie demonstrates that they are prepared to go even further than most by putting up without power for extended periods when failures occur: “I just get used to sitting in the dark.”

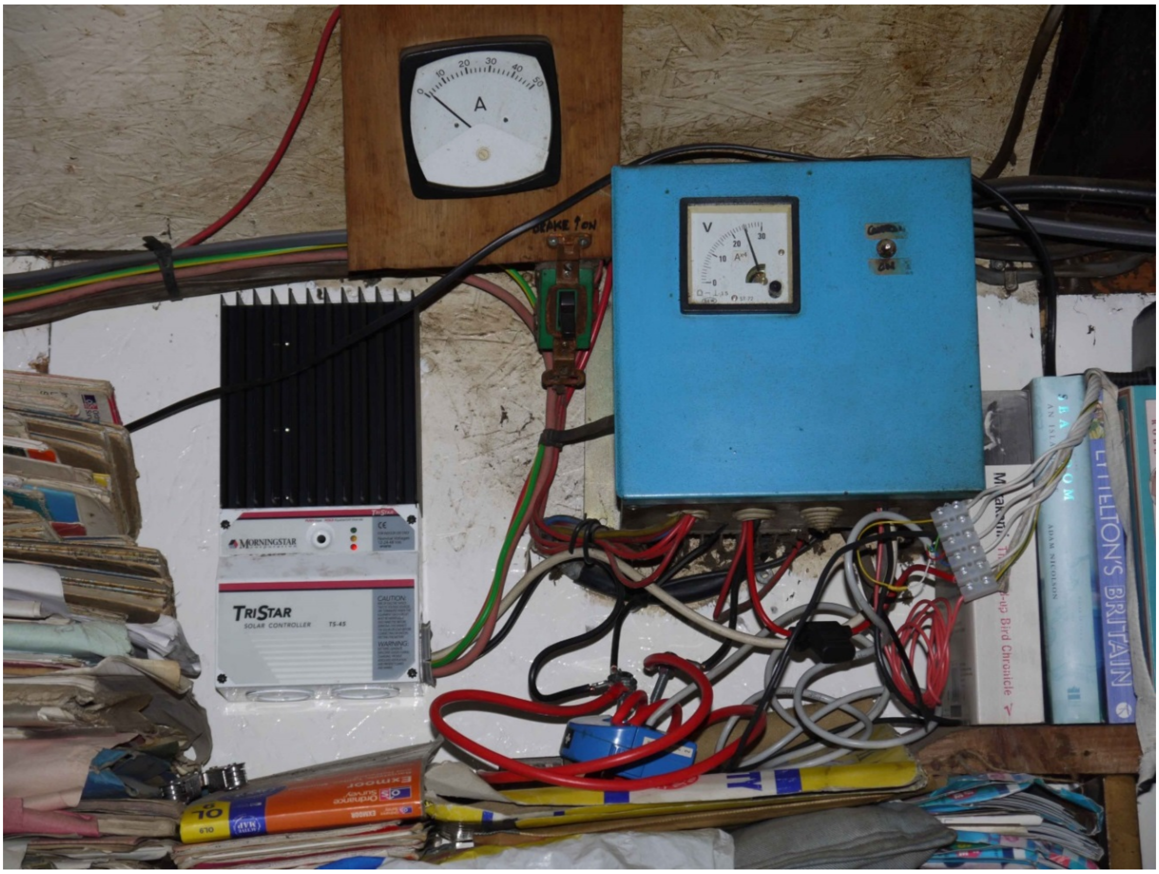


Figure 6-31: Nestled between the books and the charge controller in the corner of the Davy’s living room is the voltmeter indicating battery state of charge and ammeter displaying power coming in from the wind turbine.

To date, the solar system has not experienced any failures, in part due to John’s careful siting of the panels – on the South East corner of the building and low to the ground. Although this may sacrifice some of the energy yield due to shading effects at the beginning and end of the day, it protects them from the flying debris that the wind whips up on the North and West of the house, as well as from any stray pieces of wind turbine! However, the same cannot be said for the Piggott 3N machine that is currently powering the Davy household, as just like its predecessors it has suffered multiple failures. It began with a dump load failure shortly after installation (9); however the turbine was able to continue generating power. The next failure occurred later that year, when the main stud on alternator broke, but looseness in the turbine motion was identified by John Davy, who replaced the stud himself using materials that he already had available before any major damage occurred. Unfortunately the subsequent failure was rather more serious, as the tail hit the blades (11), smashing them to pieces (see Figure 6-32). This left the Davys without power for 7 weeks in the depths of winter, as at that time, they had no backup power generation.

Figure 6-32: What's left of the blades after colliding with the tail in 2011.

The next disaster occurred a year later, when metal fatigue caused the yaw bearing to snap the top of the tower off, leaving the turbine hanging precariously from the power cable, but only smashing one blade (13). Little more than another year had gone by when the latest wind power catastrophe occurred during the first stages of the power performance measurement campaign. Figure 6-33 shows the result of strong winds gusting up to 37m/s, which caused the tower to rock back and forth due to incorrectly positioned guy wires, ultimately bending the tower in half like a paperclip (14). Once again, the turbine was left hanging from the power cable, sparing it from more serious damage. The blade that hit the ground was repaired and a new tower was built.

Figure 6-33: "By the standards of our windmills, which usually helicopter off the tower and destroy themselves, this was nothing!" Debbie Davy, June 2013. Image courtesy of Hugh Piggott.

All of the major failures have occurred during winter storms, when any weakness in the machine will be repeatedly exploited by the full force of the wind until a catastrophic failure occurs. It illustrates the fact that wind turbine O&M costs are not only proportional to the time spent in operation, but also to the site conditions, specifically the frequency of extreme winds and level of turbulence. Figure 6-34 shows the breakdown of these O&M costs, clearly showing the huge expense incurred by the Davys each year, just to keep the wind power system in operation. In fact, the O&M costs total an average of $345 per year, almost exactly 15% of the installed cost of the wind power system ($2,302).

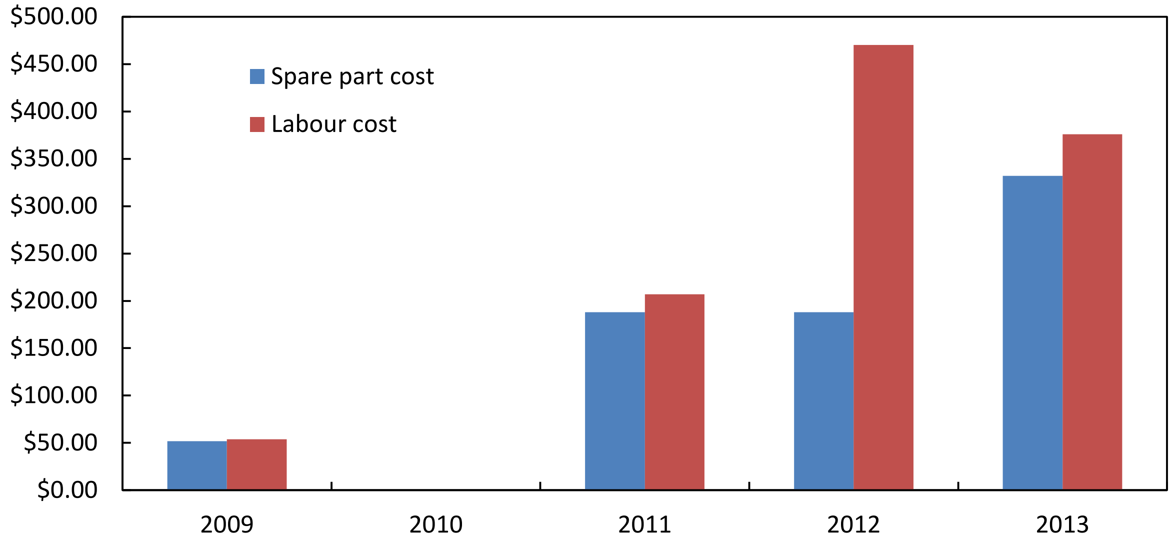


Figure 6-34: Breakdown of the O&M costs incurred by the Davy household for their wind power system.

Despite the many failures, John Davy points out that "*in terms of things that break down all the time, it's no more irritating than a car or a computer*," and that by providing access to the required maintenance services, "*Hugh's done a pretty good job of keeping us supplied with cheap power*". In spite of the high number of failures, it appears that the choice of locally manufactured technology coupled with the accessibility of affordable maintenance services (just $16 per hour) has allowed the Davys to live an unexpectedly high quality of life, considering their low income and remote location. To test this hypothesis, an alternative system was modelled in HOMER, in which their latest wind turbine, a Piggott 3N was replaced by a comparable brand new commercial SWT, the Bergey XL.1. Table 6-3 shows the parameters used in this model and the outputs from the HOMER model. All other parameters are identical to those previously described for the Davy household.

Table 6-3: Comparison of the Piggott 3N with the Bergey XL.1, as modelled in HOMER.

		Piggott 3N	*Bergey XL.1*
Capital costs	Wind turbine	$1,080	$4,595
	Tower	$368	$368
	PV	$1,644	$1,644
	Electrical system	$3,263	$3,263
Installation costs		$252	$252
Delivery costs		0% ($0)	10% ($460)
O&M costs (per year)		15% ($367)	5% ($321)
Lifespan		10 years	15 years
Rotor diameter		3m	2.5m
Rated power		800W	1,000W
RAEY		1,739kWh/yr	1,935kWh/yr
AEY at Davy household		1,989kWh/yr	2,375kWh/yr
Capacity factor		28.4%	27.1%
LGC (all electricity produced by turbine)		0.39$/kWh	0.49$/kWh
LCoE (cost of meeting demand with PV/wind hybrid)		0.95$/kWh	1.23$/kWh
Excess electricity		553kWh/yr	943kWh/yr
Unmet electric load		60kWh/yr	70kWh/yr

Debbie notes that "*the batteries are the most expensive thing we've ever bought*." At $2,430, they were certainly expensive, however the Bergey XL.1 retails for $4,595. They paid just $1,080[101] for the Piggott 3N, however the fact that it is manufactured locally using basic tools, materials and techniques, rather than in a factory with hi-tech machinery, high quality materials and advanced techniques, could mean that it is more likely to fail. To reflect this, as mentioned previously, the O&M costs of the locally manufactured machine were modelled at 15% of the capital costs per year, whilst those of the commercial machine were set at 5%. Figure 6-35 shows that the lifecycle costs of the locally manufactured machine are more evenly distributed throughout the system lifetime, which has the advantage of giving the Davys time to build up the necessary capital rather than having to pay almost all of it upfront.

[101] Cost of materials only, as the machine was built on a wind turbine construction course hosted by Piggott. Price likely to double if labour during construction included.

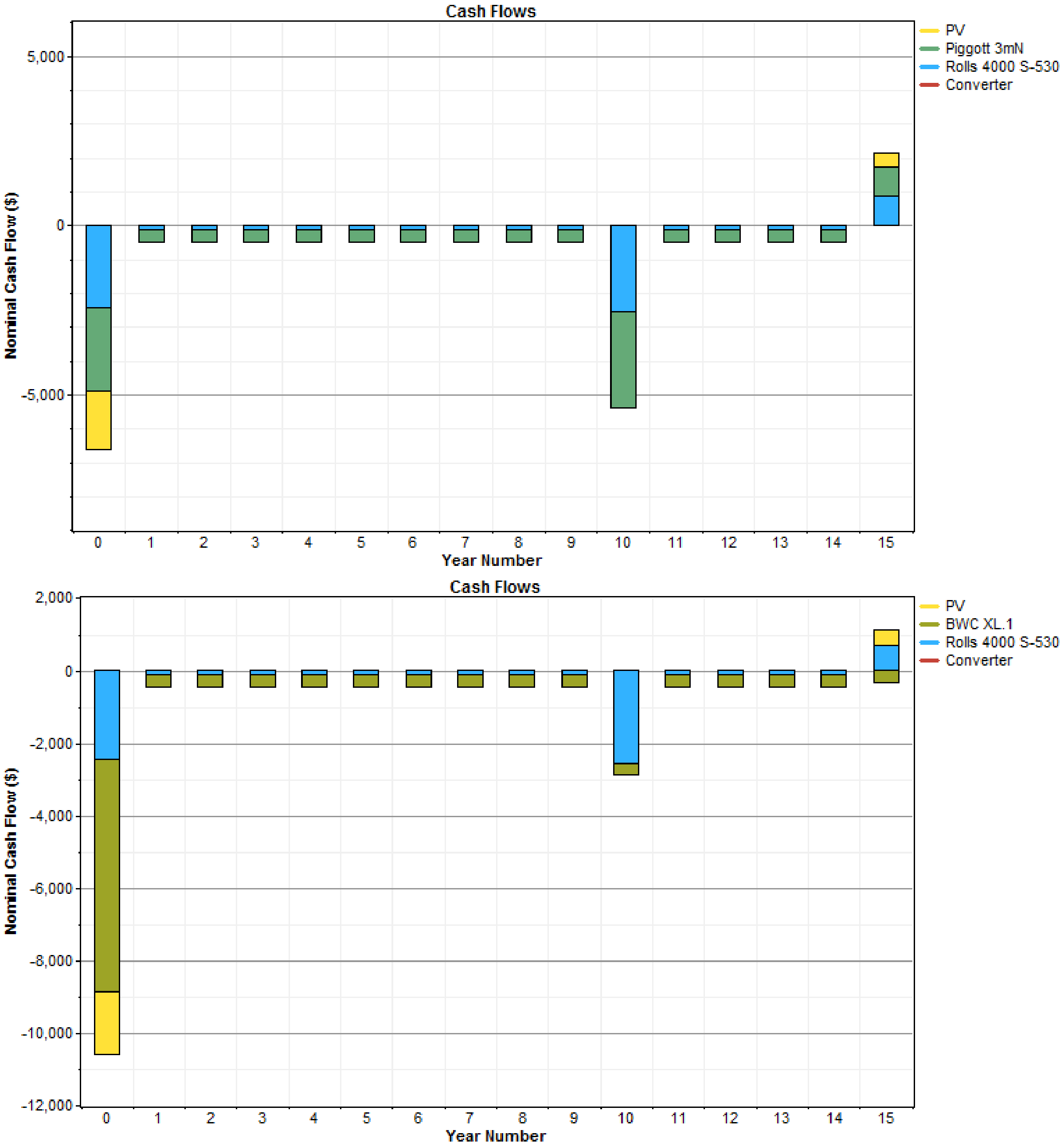


Figure 6-35: Nominal cash flow for a) the Davy's energy system and b) an identical system with the Piggott 3N replaced by a Bergey XL.1.

Figure 6-36 compares the net present costs of the two systems, clearly showing that despite its higher O&M costs and shorter lifespan, the locally manufactured turbine represents better value over the 15 year expected lifetime of the energy system. The installation costs of either wind power system ($252) add significantly to the upfront capital costs, as does the siting of the turbine, location of the guy anchors, assembly of the turbine components and other more complex tasks that require Piggott's specialist knowledge. The tower ($226), guys ($143), armoured power cable ($267) and electrical system components such as the rectifier, brake switch, dump load and charge controller ($477) also add significantly to the cost. In contrast, the installation of the solar system is easy enough that the Davy's were capable of doing it all themselves, simply building a mounting frame from scrap wood (see

Figure 6-28) and connecting the panels up to the batteries/charge controller with left over standard electrical cabling, as the distance was much smaller and almost completely inside. In fact, the only significant upfront capital expenditure for the solar system on top of the panels themselves was the charge controller ($91). What is more, the O&M costs are negligible, as there is very little that can go wrong.

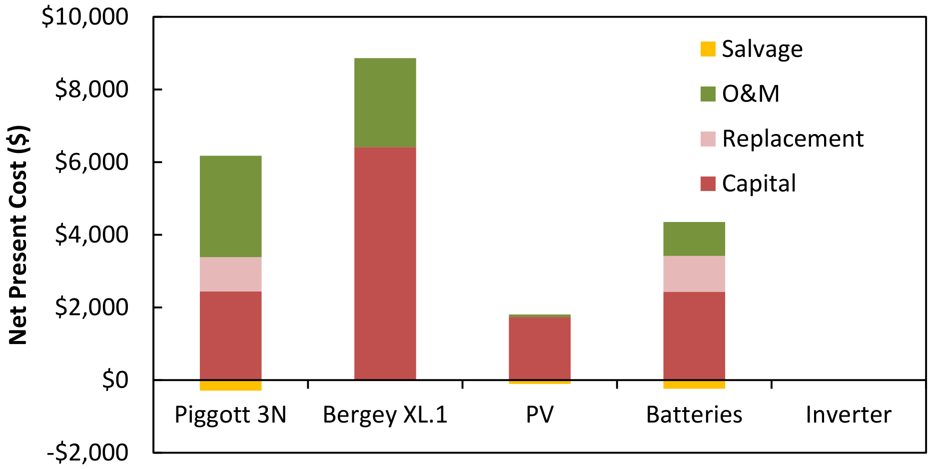


Figure 6-36: Net present cost broken down by component[102] of the energy system components installed at the Davy household and the commercial Bergey XL.1.

Despite being of similar size (Piggott 3N: 3m diameter, Bergey XL.1: 2.5m) the performance of the two machines is very different. Figure 6-37 shows how the bigger locally manufactured machine performs better at lower wind speeds, whilst the smaller commercial machine performs better at higher wind speeds. The Bergey XL.1 actually exceeds its rated power of 1kW, whilst the Piggott 3N never actually reaches its rated power of 800W[103]. Whilst this may be seen as disappointing for the Piggott turbine, in fact both wind turbines operate using a furling system, which limits the turbine output during high winds, and the Piggott 3N has been set at a more conservative value, turning the rotor out of the wind at 8m/s, as opposed to 12m/s. The benefit of doing so is that it increases durability, as the faster the machine spins, the quicker its parts will wear out. The Piggott turbine therefore sacrifices peak power for reliable operation, something that is especially important in remote, turbulent and windy sites, such as Achmore.

[102] The 800W Pulsestar inverter was given to the Davys on long term loan, so has been given a value of $0 in the HOMER model.

[103] The power curve is based on 10 min averages, so both machines will actually produce instantaneous peaks much higher than the values shown on the power curve. During the test period, the Piggott 3N was observed to produce more than 800 watts, however as these readings came from an invalid measurement sector, they were not included in the final power curve. The difference is likely to be due to a leaning tower, which can cause significant asymmetry in the performance of a furling system.

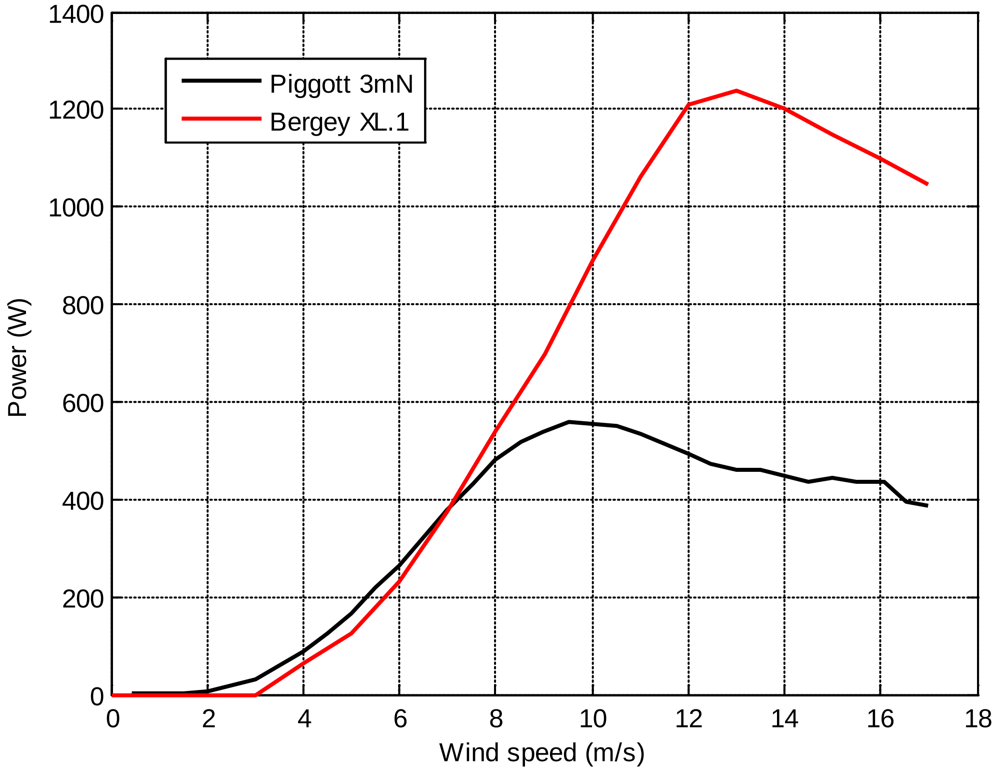


Figure 6-37: Power curves of the locally manufactured Piggott 3N and commercial Bergey XL.1.

What is more, the increased energy yield generated by the Bergey XL.1 is largely wasted, as most of the extra power is generated when the batteries are already full. Although the Bergey XL.1 produces 386kWh (19%) more than the Piggott 3N, 943kWh are sent to the dump load when the batteries are full (as opposed to 553kWh for the Piggott 3N). Interestingly, due to its poor performance in low winds, when the batteries are likely to be empty, it is actually the Bergey which leaves a greater proportion of the load unmet (70kWh, as opposed to 60kWh with the Piggott turbine). So whilst Figure 6-38 suggests that the Bergey XL.1 performs better on windy sites such as the Davy household (5.53m/s annual mean wind speed) due to its higher energy yields, Figure 6-40 demonstrates that the output of the Piggott 3N is much more evenly spread throughout the day and across the seasons. In fact, Figure 6-39 reveals that their ability to fill the batteries is almost identical and Figure 6-41 shows that whilst the average power production by the Bergey XL.1 in the most windy month, November, is 43% greater than the Piggott 3N, in the least windy month, September, it is actually 2% lower.

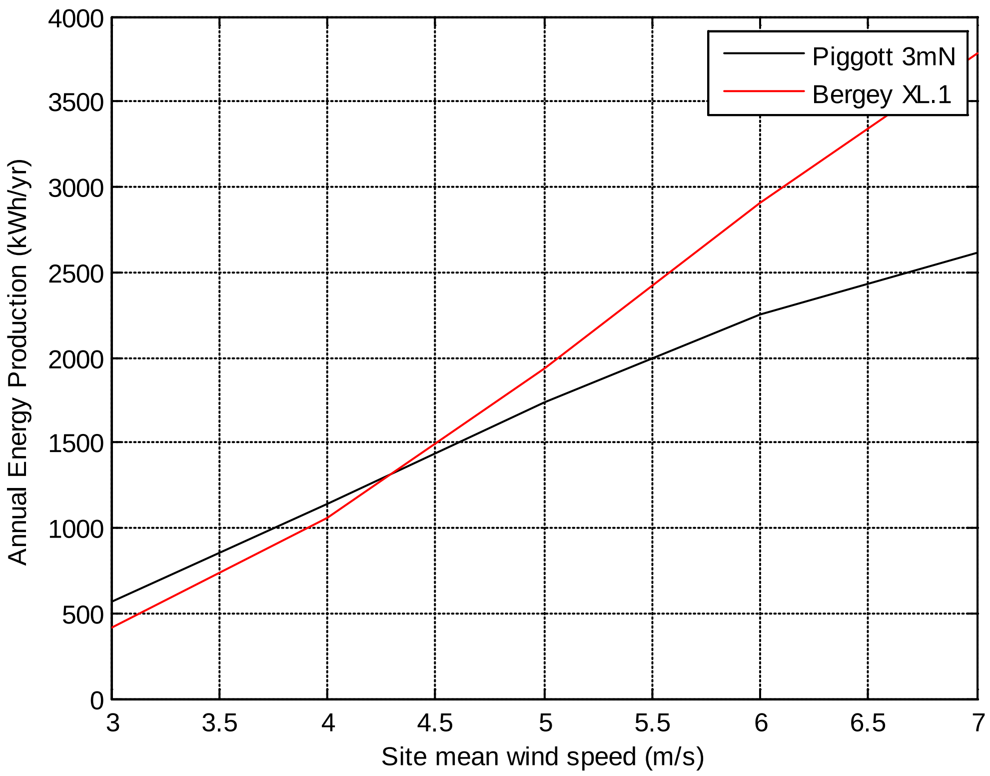


Figure 6-38: Annual Energy Production (AEP) for the locally manufactured and commercial turbines.

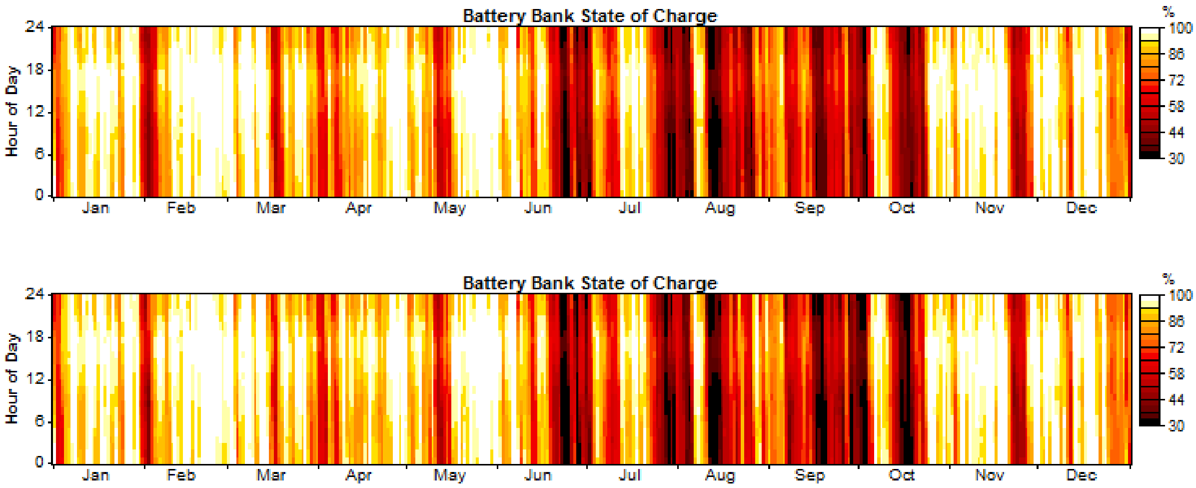
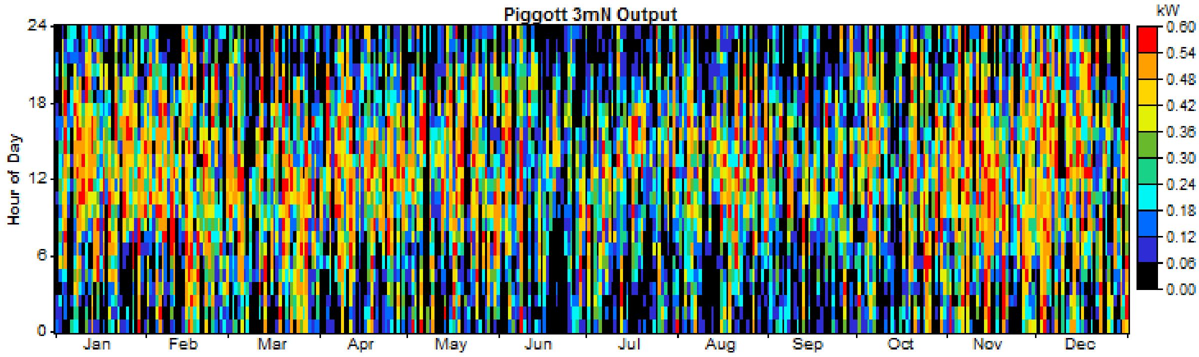


Figure 6-39: Battery bank state of charge throughout the year for a) the Piggott 3N and b) the Bergey XL.1.



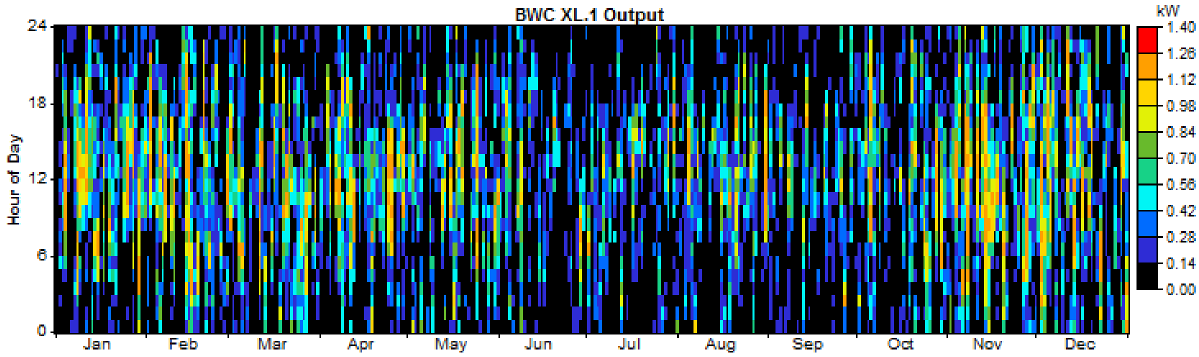


Figure 6-40: Hourly average power output throughout the year for a) the Piggott 3N and b) Bergey XL.1.

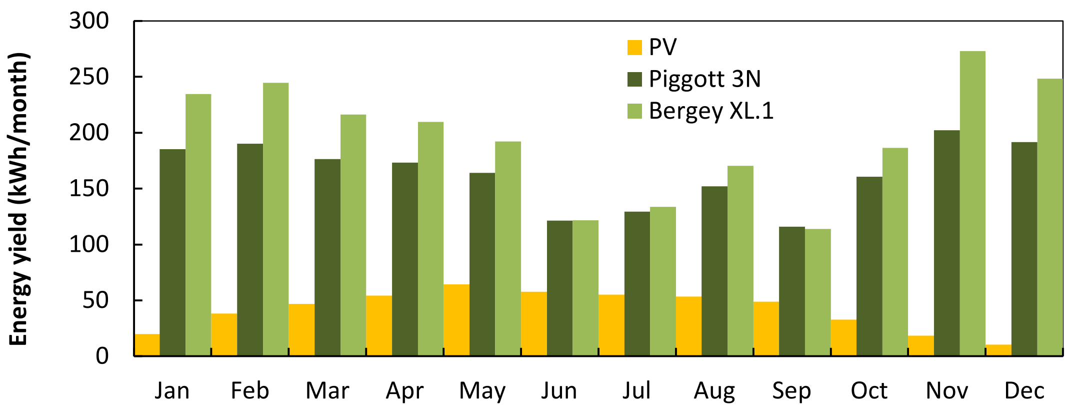


Figure 6-41: Monthly average power output for a) the Piggott 3N and b) the Bergey XL.1.

When considering the cost of producing each kWh of electricity from the wind turbines alone, at 0.39$/kWh, the LGC of the Piggott turbine is significantly lower than that of the Bergey (0.49$/kWh) primarily due to its lower upfront cost. What is more, its more consistent power output makes it more compatible with the patterns of use of an off-grid system. Therefore when considering the cost of meeting end-user demand with this PV-wind hybrid system, the Piggott turbine is clearly the most economic SWT, producing electricity with an LCoE of just 0.95$/kWh, as opposed to 1.23$kWh with the Bergey. However, this of course assumes that no value is attributed to the heat produced by the dump loads that contribute towards heating the Davys' water, as well as their living room. This excess heat is mainly produced during the cold winter months, when demand for it is greatest, suggesting that the Bergey may actually be more appropriate for this specific context than previously thought.

Interestingly, the use of electric light for weaving, paperwork and other indoor tasks is the only productive use of the electricity provided by the renewable energy system. Indeed, the Davy's incomes are very modest by UK standards and Debbie Davy states that: "*we've never got any money and Hugh always gives us a cheap deal*." This illustrates both the flexibility with which these ad-hoc energy solutions are created by Piggott for his fellow community members and the fact that Piggott is willing to subsidise poorer members of the community so that everybody can have access to electricity. Each installation is different: tailor made to the renewable resources available on each site and balanced between demand, reliability and willingness to pay. The Davys have a good, if turbulent wind resource, no hydro resource and a poor solar resource as they are on a North facing slope at high latitude. They have little money, but are prepared to put up with things breaking down and cut back their electricity usage on calm and cloudy days. As a result, Hugh has been able to offer them a range of second hand machines for very low prices and give them a significant discount on the maintenance by prioritizing other jobs over theirs.

When asked why small scale wind power has been such a success on Scoraig, John Davy quickly and concisely replied: "*Hugh*." Adding later that he "*wouldn't be motivated enough to take Hugh's recipe book and put it all together*" himself as it's still "*too much of an unknown*." Despite the fact that there are many people on Scoraig who are skilled enough to maintain their own wind power systems, the dependence of the majority of these machines on Hugh was illustrated further when John stated that if Hugh disappeared tomorrow, you'd "*hear a lot more generators*" on Scoraig. Commenting on the implications of this statement on the replicability of the small wind systems installed on Scoraig in a developing country context, John estimates that "*you could find 1 person in 100 capable of doing what Hugh does; the question is whether they would have the motivation to actually get the work done*."

6.4.2 Household case study II: Andy Whisken and Susan McSweeny

Figure 6-42: The Whisken/McSweeny household, with their two SWTs, the Piggott 2F (far left) and the Ampair Hawk (centre left).

Andy Whisken and Susan McSweeny came to Scoraig from South East England to experience life in the Highlands, arriving on Scoraig almost by accident. Unlike many who came to Scoraig and then tried to make a living, Susan was looking for teaching jobs in the Highlands and found work in the local primary school. They moved to Scoraig in 2005 and shortly after, Andy began working with John Davy as a dry stone waller. Just as the Davy's energy system evolved with their needs, ability to pay and technological developments in wider society, the development of Andy and Susan's energy system during the last 9 years is shown in Figure 6-43 (again, it is referred to in the following section with the bracketed numbers). At first they used tilly lamps for light and ran a second hand 600W petrol generator to charge a small caravan leisure battery when needed (1), but it wasn't long before they purchased their first solar panel, an 84W Kyocera (2). Within a year, the single panel had become an array of 4 (3) and a new 4x225Ah 12V battery bank was installed in the house. A new Honda GX200 2.8kW petrol generator was wired into the upgraded charge controller to top up the batteries on overcast days as a replacement for the 600W petrol generator which was no longer functioning (4). The solar array continued expanding, eventually totalling 7 panels (5). In contrast to many other Scoraig residents, they had chosen solar over wind initially because "*it was easy…with solar you could install it all yourself*." They also were not sure how long they would be staying on Scoraig, so the panels offered a more portable solution and they wanted a reliable energy supply (finding a broken Ampair Hawk lying on the ground out the back of their house when they moved in was enough to put them off of wind power initially).

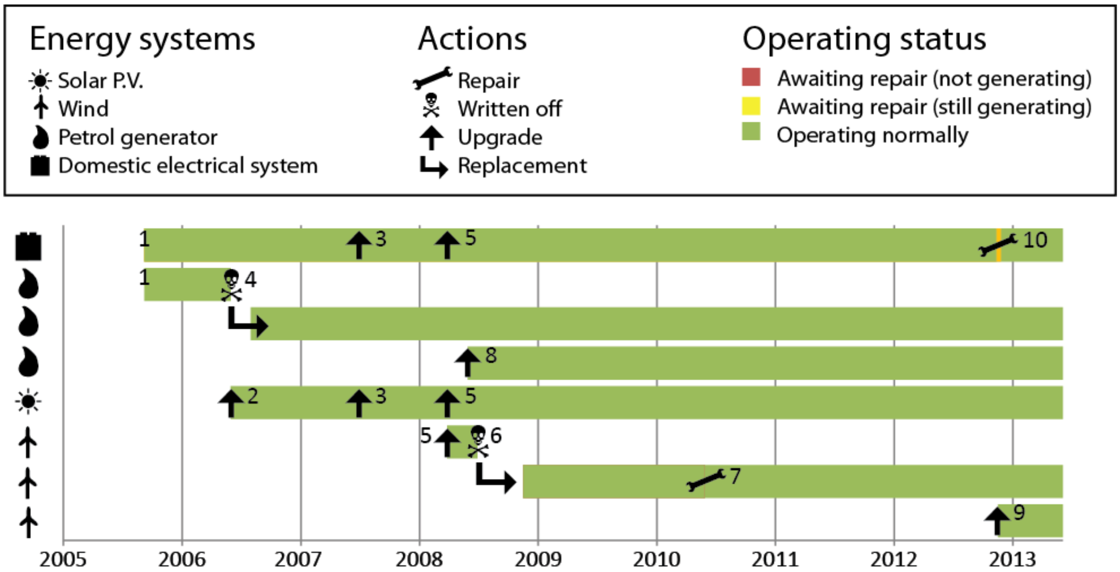


Figure 6-43: Timeline showing the evolution of the energy system installed at Andy & Susan's home since they moved to Scoraig in 2005.

However, they soon gave in and in 2008 they acquired their first wind turbine, a Wren LE-300 that Hugh had been given to test by the manufacturer (5). Although they were very impressed with the performance, after just a few months "*it literally exploded*!" (6). Debris was strewn everywhere, most of it in such small pieces that it was never found, apart from a few blade fragments and some magnets that were "*stuck to the roof*!" This didn't put them off wind power though, as it was quickly replaced by a brand new Ampair Hawk, which despite having found a broken model in their garden when they arrived on Scoraig, had gained a reputation across the rest of the peninsula as a solid, reliable machine. At this point, they "*just wanted something that wasn't going to blow up*!" Although it doesn't produce as much power (85W maximum as opposed to the Wren's 170W), the reputation for reliable operation is deserved as this machine is still in operation today without any maintenance, except for the replacement of a guy shackle, which Andy was able to do himself (8).

Wind turbines are usually considered noisy and visually intrusive due to the fact that they must be placed high above the ground and away from obstacles. However, both these factors have hidden benefits in terms of O&M for off-grid systems. Well trained users learn to recognise the sights and sounds of normal operation and are often able to identify potential problems and take appropriate action before a failure occurs. Andy and Susan pass both turbines every day and they can even see the Ampair Hawk from the kitchen window (see Figure 6-44). The failure of the guy shackle left the turbine suspended by just three guy wires; if the wind had changed direction before Andy had spotted the missing guy wire then the tower would have tipped over and smashed the turbine to pieces.

Figure 6-44: a) Both turbines are located directly in front of Andy and Susan's house and b) the Ampair Hawk can even be seen from the kitchen window.

Andy and Susan's power demands have always been very low, as they have always purchased appliances with the lowest possible power demand, such as 1.2W 12V LED lights and a 'AAA' rated freezer[104], however their power demand continued to grow (see Figure 6-45). In 2008 they purchased a 5.6kW Honda EM 550CXS petrol generator to run a washing machine and power tools directly (9). They found themselves switching on the generators more and more, which led them to upgrade the system once again in 2012 by adding another, larger wind turbine, a Piggott 2F[105] (8). The machine was produced in Ireland on a course taught by Hugh and just like John and Debbie's latest machine, was

[104] Highest level of energy efficiency in the current UK energy efficiency ratings for appliances.
[105] 2m diameter, 400W rated power, 777kWh/yr RAEY.

sold to them for just the price of the materials. This required significant upgrading of many of the other system components, including the addition of a bathroom heater to act as a dump load and convert the excess electricity on windy days into heat for this cold, north facing room.

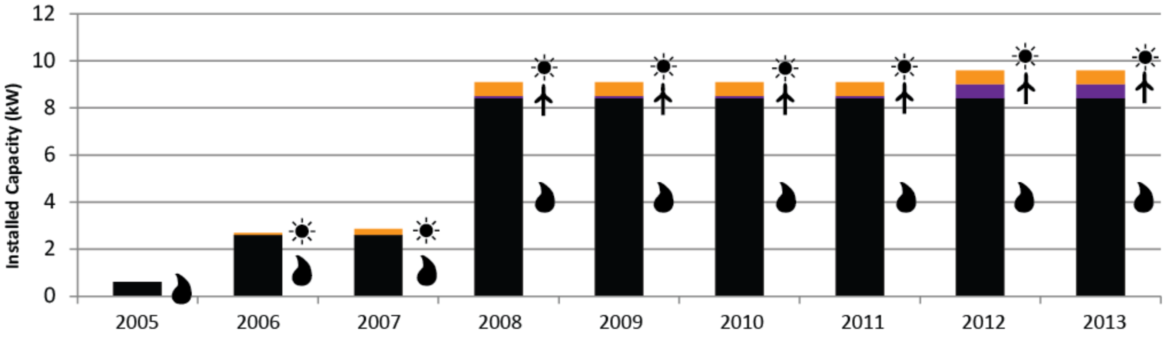


Figure 6-45: The continually expanding power generation capacity to keep pace with the rising demand for electricity at the Whisken/McSweeny household.

Just like the Davys, Andy and Susan are extremely adept at adapting their electricity use according to the availability of renewable resources. In their home, the all important battery voltage meter is located in the kitchen/dining room (see Figure 6-46), the most frequently used room in the house. When the battery voltage meter settles below 12.5V, Andy and Susan turn off their appliances and manually start the generator to prevent damage to the batteries from discharging them too deeply. To model this behaviour in HOMER, the generator was set on a cycle charging dispatch strategy, starting the generator when the battery state of charge stabilises below 75% (roughly 12.5V)[106] and charging them back up to 75%. It can be seen from Figure 6-47 that under these conditions, the generator is started 13 times per year.

[106] Below 75% state of charge and batteries have stopped discharging - this prevents the generator from constantly starting and stopping and allows the batteries to be discharged deeply occasionally, which is necessary for them to reach their expected lifetime.

Figure 6-46: The battery voltage meter (and ammeters from the PV and wind turbines) neatly displayed in Andy and Susan's kitchen.

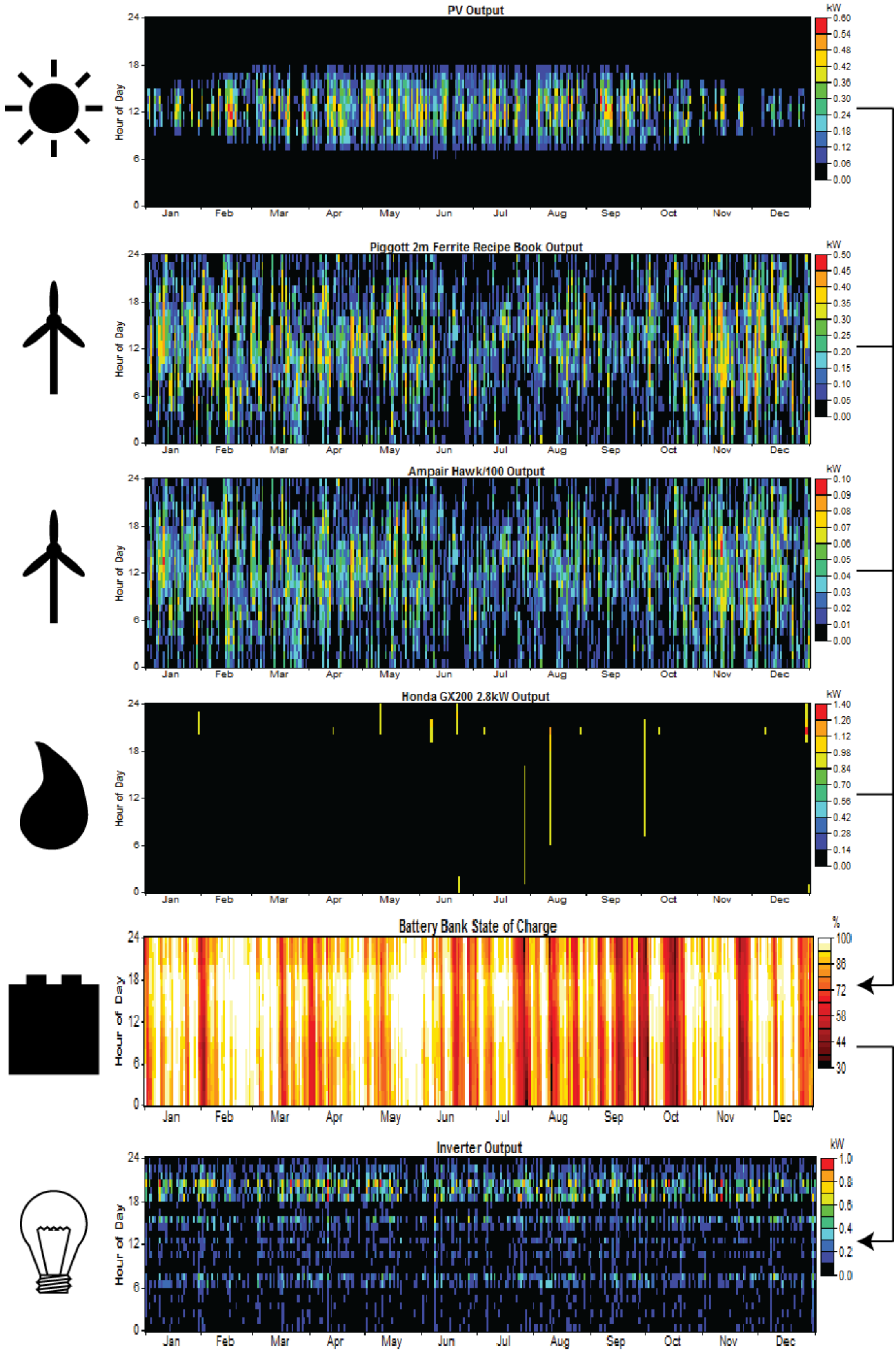


Figure 6-47: Plots of hourly output throughout the day (y-axis) and across the year (x-axis) of the various power generation technologies installed at Andy and Susan's house, compared to the battery state of charge and inverter power draw.

Leaving the batteries in this almost constantly full state effectively reduced their capacity to a quarter of the rated value and what is more, despite carefully avoiding deeply discharging the batteries, Andy and Susan had neglected to top up the batteries with distilled water. Coupled with the fact that the dump loads installed at the time weren't able to cope with all the power from the new wind turbine caused the voltage to frequently rise above 15V, quickly gassing off the distilled water and causing them to boil dry (10). At $1,581, the cost of a new battery bank was high, however unlike the case studies in Nicaragua, Andy and Susan had put aside enough money to cover such eventualities and they were soon replaced. However, this does demonstrate that even with the highest levels of user awareness, lead acid batteries are extremely delicate and will often fail prematurely due to misuse.

Although Andy and Susan have a wider variety of appliances than the Davys, with the exception of the washing machine and power tools which are run directly off of the 5.8kW generator, they use very little energy due to their careful choice of energy efficient appliances. Figure 6-48 shows the power demand during a typical day in the Whisken/McSweeny household, with a 'AAA' rated freezer drawing a constant load throughout the day, the electric kettle creates short spikes in demand throughout the day (the full magnitude of which are not properly represented by this model due to its hourly resolution) and peak demand occurring in the evenings when the lights are switched on and computers are plugged in. Average daily demand has been estimated at a very modest 2.33kWh/day, putting annual demand at 850kWh/yr.

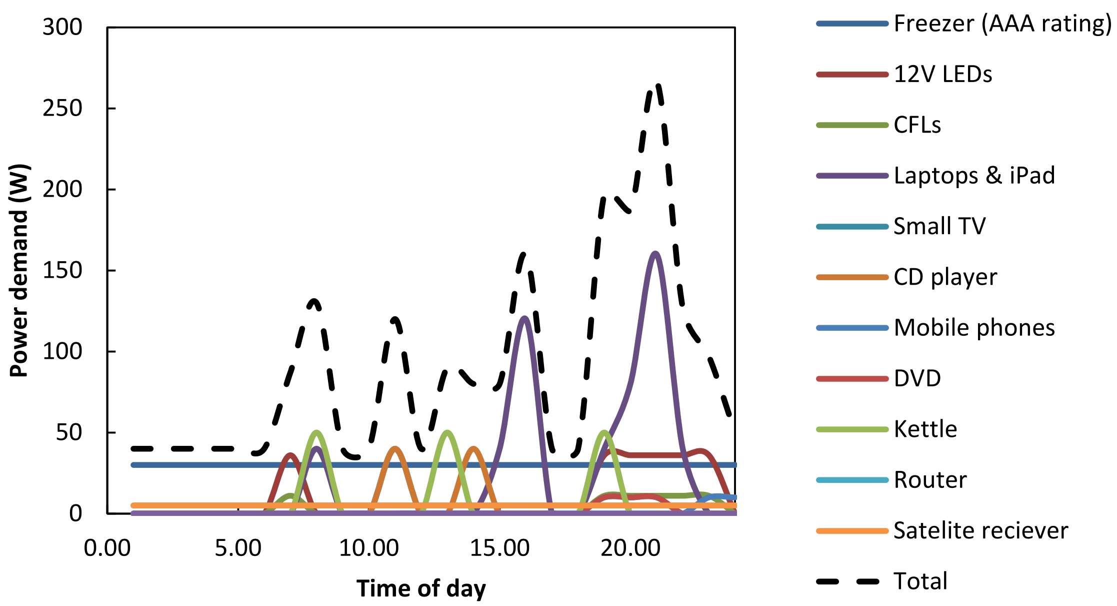


Figure 6-48: Average daily power demand at Andy and Susan's house. Washing machine not included as it is run directly from the 5.8kW petrol generator.

In order to create a safer environment for their son, Andy and Susan have chosen to create a far more conventional energy system than many of the ad-hoc electrical installations in other Scoraig homes, buying almost all of their components and appliances brand new. When they arrived they replaced the car headlamps that were "*hanging from the ceiling*" and light switches that "*sparked every time you flicked them*" with 1.2W 12V LED bulbs and conventional household wiring, even going as far as completely re-digging the house earth[107].

For Andy and Susan, reliability and safety are more important than low cost. A SWT has been able to offer them this security because of the easy access to maintenance services offered by their neighbour, Hugh Piggott. Although they're not interested in maintaining the turbine themselves, they are very satisfied with its performance, which produces much more electricity than they need: "*sometimes it dumps all day…we can turn on every electrical device we've got and it still dumps*!" 33% (515kWh/yr) of the energy their system produces is sent to the dump loads, which in this case is a series of heaters located in the battery bank (wasted energy) and a 300W bathroom heater (useful energy, which is most available in the winter when demand is highest). Figure 6-49 shows that with this increased wind power capacity, the 2.8kW petrol generator is rarely needed, burning just 31.7litres/yr and contributing 62.4kWh/yr, primarily in the summer months when the wind resource is lowest.

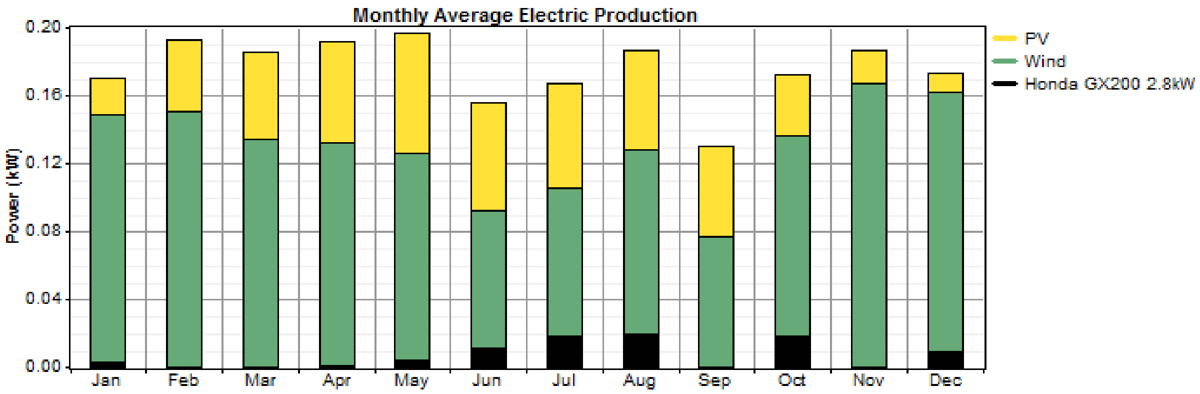


Figure 6-49: Monthly average power generation for the PV/wind/petrol hybrid system.

The Piggott 2F also has much better performance in low winds than the Ampair Hawk, illustrated by the fact that swallows perch on the blades of the big turbine on calm days and "*fall off as it starts to spin*" under their tiny weight due to its extremely low start-up torque. The low energy appliances they have purchased take little from the batteries and with a little discipline in matching their use to the availability of the wind and solar resources whilst having the generator for backup, this system has allowed them to live in a very similar lifestyle to that which they had become accustomed in London.

Unfortunately, this level of dependability comes at a cost. To meet the Whisken/McSweeny family's power demand of 2.33kWh/day, Figure 6-50 shows that the net present cost of the entire system comes in at $15,854, putting the LCoE up at 2.45$/kWh. As seen previously, the majority of the net present cost of the Piggott turbine is embedded in the O&M and replacement costs, whilst the net

[107] The house earth failed a test performed by a qualified electrician during the certification process required to be able to sell the house at a later date.

present cost of the PV is primarily made up of the purchase price of the panels. The generator has relatively low O&M costs, but despite running for just 72 hours per year, the fuel costs make up almost half of its net present cost. The batteries also have a significant O&M cost component, due to the need to purchase distilled water[108] and more importantly, the risk that the batteries could fail before their expected lifespan, as happened here at the end of 2012.

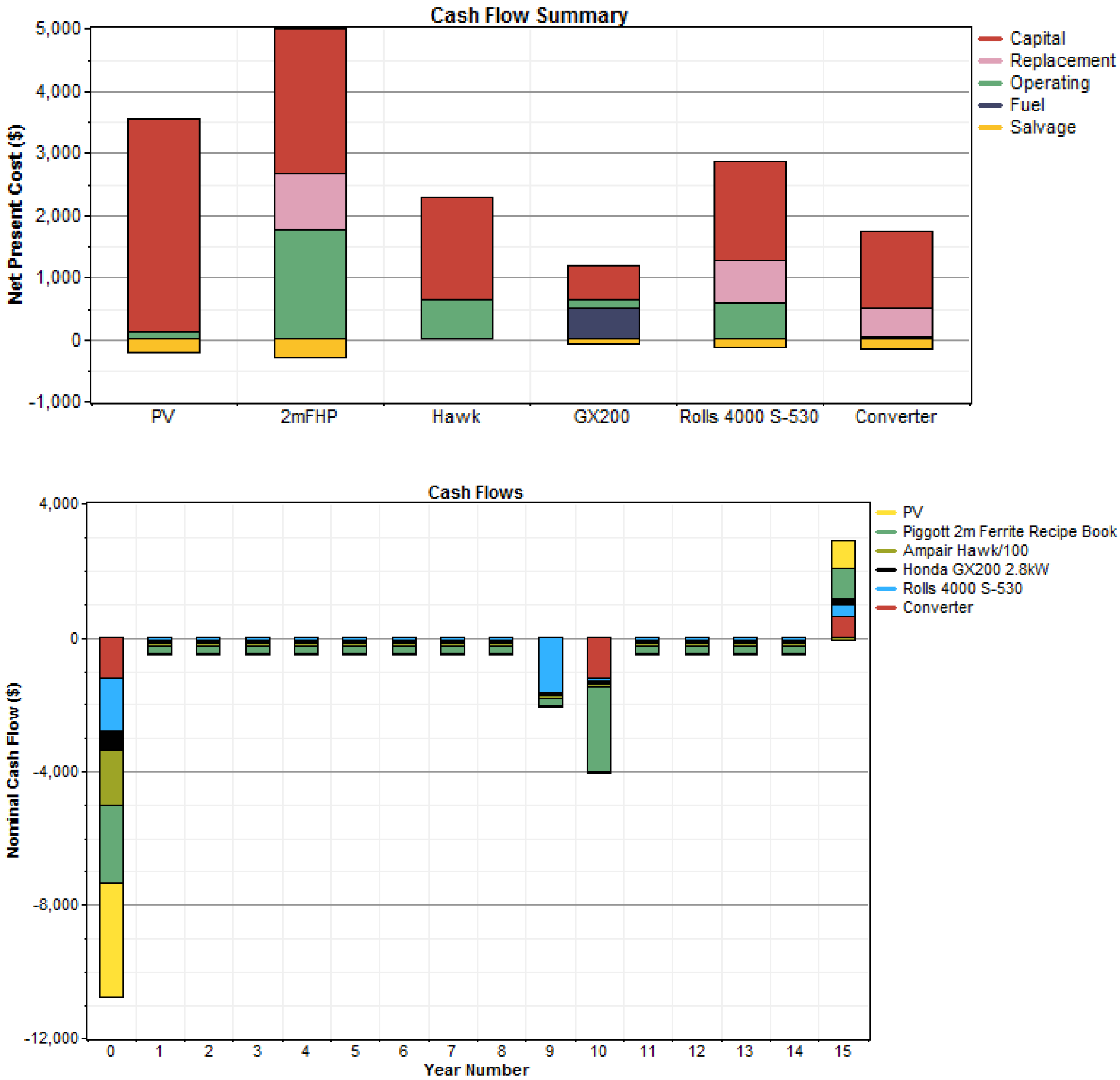


Figure 6-50: Breakdown of a) the net present costs and b) the nominal cash flow for the various components of the Whisken/McSweeny energy system.

With regard to the individual power generation equipment, Figure 6-51 shows that with an LGC of 0.69$/kWh, the Piggott 2F generates electricity most economically. Despite its high O&M costs (349$/yr, 15% of initial purchase costs), its energy yield is over double that of the PV array and over five times that of the Ampair Hawk. Due to its high initial purchase costs, the PV array follows with an

[108] Estimated at around $15 per year.

LGC of 1.09$/kWh and high fuel prices push the petrol generator's LGC up to 1.70$/kWh[109]. However, at 1.76$/kWh it is the Ampair Hawk that generates the most costly electricity, as its initial purchase and therefore also O&M costs are high, given its limited power generation capacity.

Figure 6-51: Annual energy production and LCoE for each of the power generation technologies installed at the Whisken/McSweeny household.

To determine the optimum configuration of power generation equipment to meet the power demand at the Whisken/McSweeny household, an optimisation was performed using HOMER. The maximum annual capacity shortage was set at 15% to simulate Andy and Susan's willingness to adapt their demand to the availability of the renewable resources. The 84W PV panels were allowed to vary in number from 0-100, the 0.4kW Piggott 2F and 0.1kW Ampair Hawk wind turbines from 0-5 and the

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109 Petrol generator LGC based upon a fixed generation cost of 1.02$/hr with 72 hrs/yr of operation and a marginal generation cost of 0.53$/kWh.

2.8kW Honda GX200 petrol generator from 0-1. To cope with the increased variability of the purely renewable systems, the number of battery strings[110] was allowed to vary from 0-10. The costs were scaled linearly and all other parameters were kept the same.

Of the 33,000 possible system configurations, those that met the 15% maximum annual capacity shortage constraint were ranked by total net present cost and sorted into categories (wind, PV-wind, PV, PV-petrol, wind-petrol, PV-wind-petrol and petrol). Table 6-4 shows the most economical solution for each category, clearly showing that a PV-wind hybrid would be able to meet the demand with the lowest net present cost. The complementarity of the two renewable resources and their ability to keep the batteries topped up throughout the year is clearly demonstrated, as either a purely wind or purely PV system would have been significantly more costly (22% or 33% respectively).

Table 6-4: Results of the HOMER optimisation, showing the optimum solution for each category of energy system as determined by the total net present cost

Power generation technology	*PV*	*Piggott 2F*	*Ampair Hawk*	*Honda GX200*	*Rolls 4000 S-530*	*Total NPC ($)*	*LCoE ($/kWh)*	*Capacity Shortage (%)*	*Excess electricity (%)*
Capacity per unit	*0.084kW*	*0.4kW*	*0.1kW*	*2.8kW*	*400Ah*				
	2	1	0	0	4	10,982	1.92	-12%	13%
	0	1	2	0	4	13,397	2.33	-8%	24%
	5	1	0	1	4	14,545	2.25	0%	23%
	0	1	0	1	8	14,593	2.26	0%	7%
	18	0	0	0	8	16,818	3.00	-13%	25%
	12	0	0	1	8	17,698	2.74	0%	6%
	0	0	0	1	8	20,580	3.18	0%	0%

Whilst adding a generator offers the convenience of dispatchable power, Figure 6-52 shows that it significantly raises the cost of the system, so much so that if the generator were to be used as the sole power source, the net present cost of the system would almost double. However, the major benefit of having a generator that is not recognised by this simulation is the ability to lift the batteries out of a critically low state of charge during calm and overcast days. Figure 6-52 shows that the purely renewable systems leave the batteries in a critically low state for long periods of time (most of the summer for the wind systems and most of the winter for the solar systems). Leaving lead acid batteries in such a low state of charge for so long is likely to significantly lower their capacity, as sulphate crystals begin to build up on the negative plates, permanently blocking the flow of charge.

[110] 1 string = 2 x 6V Rolls 4000 S-530 400Ah batteries.

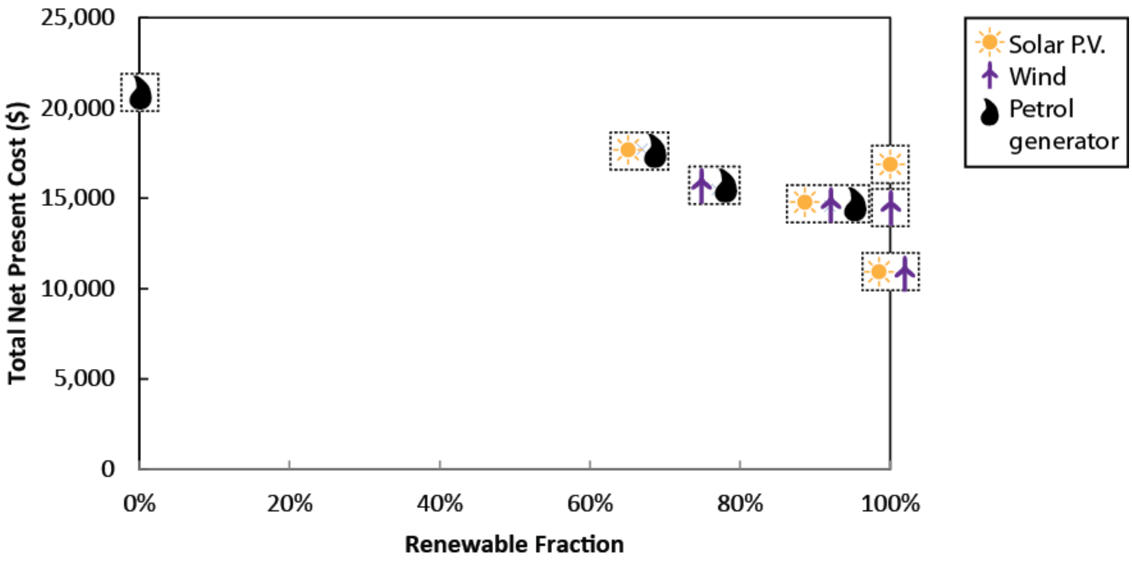

Figure 6-52: Results of the HOMER optimisation, showing the relationship between the proportion of renewable generation and the total net present cost.

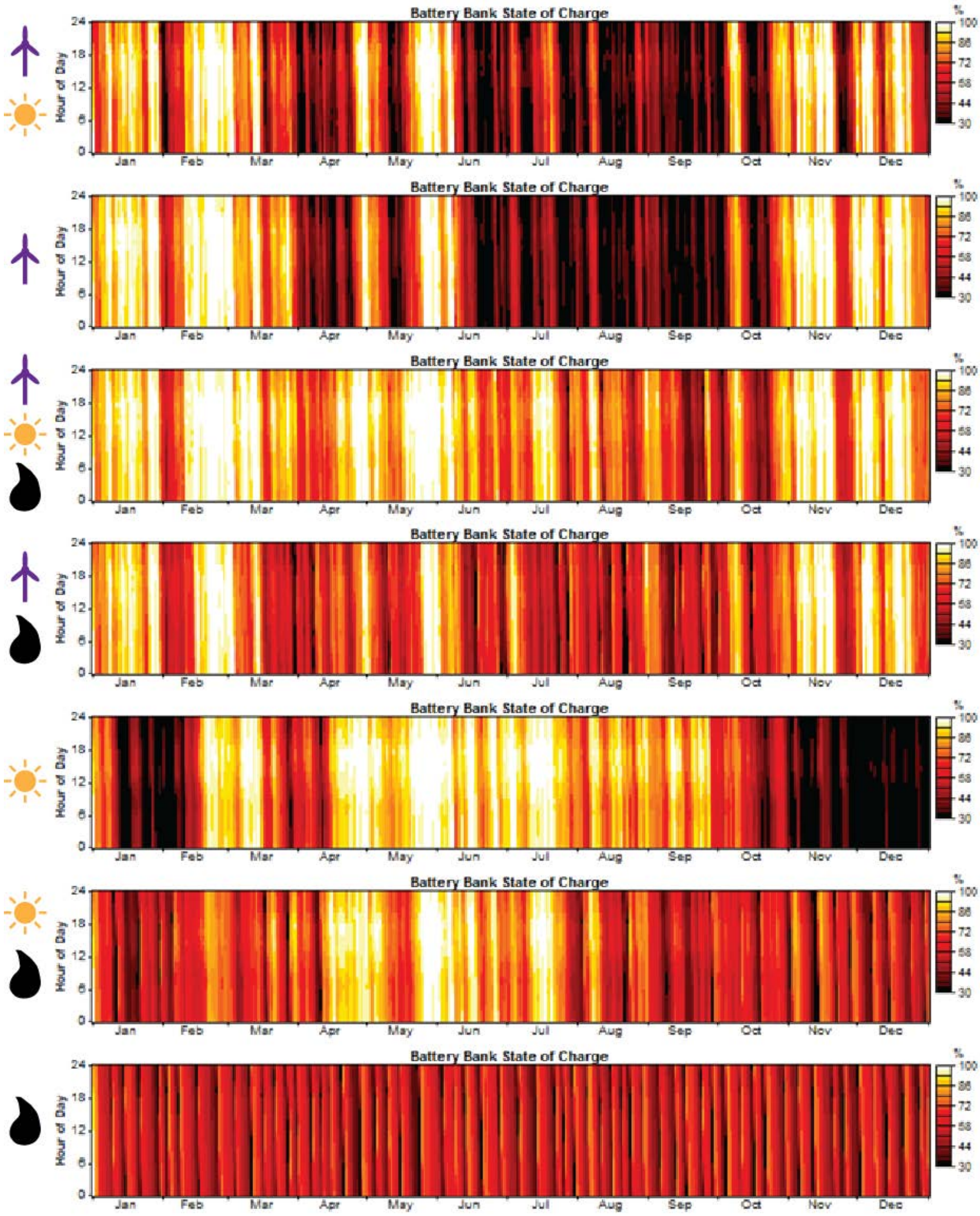

Figure 6-53: Battery bank state of charge for the most economical solutions of each energy systems category.

Interestingly, the model predicts that the PV-wind-petrol hybrid energy system installed at the Whisken/McSweeny household is quite far off optimal. Table 6-4 shows that renewable generation from five PV panels (as opposed to 7) and the Piggott 2F (without the Ampair Hawk) topped up by dispatchable power from the Honda GX200 would be able to meet current demand with a 13% lower NPC. One of the biggest advantages of solar PV is its modularity, i.e. the generating capacity can be tailored to fit demand by adding and subtracting panels, with an approximately linear cost increase.

Another important feature that is not taken into account by the model is resilience. Having multiple smaller generators is inherently more resilient than having a single larger generator, as each failure that occurs with the larger generator will leave the end-user without electricity. It is very unlikely that all the smaller generators will fail at the same time and as a result, the system will almost always be generating a small amount of power.

6.4.3 Household case study III: Lee Brown

After experimenting with cheap Chinese petrol generators, one of which lasted just a few hours (1), Lee Brown arranged for Hugh to install a renewable energy system in 2007 (Figure 6-54). A significant block of high trees creates shelter around the house and reduces the annual mean wind speed to 4.2m/s (as opposed to 5.3m/s at Andy & Susan's and 5.5m/s at John & Debbie's). However, a small stream runs through the property, one of the few watercourses on the Scoraig peninsula that flows throughout the year. As a result, it was decided to install a PV-hydro-diesel hybrid renewable energy system (2), as just like wind, the hydro resource is greatest in the winter. A resource assessment of the stream predicted a 20m head and 2-3litres/s flow, a small but viable resource if an appropriate turbine could be found to exploit it. An EcoInnovation Hydro Turbine Kit was identified and imported from New Zealand at a cost of $1,653, plus an additional $176 for shipping and $313 for UK import duty.

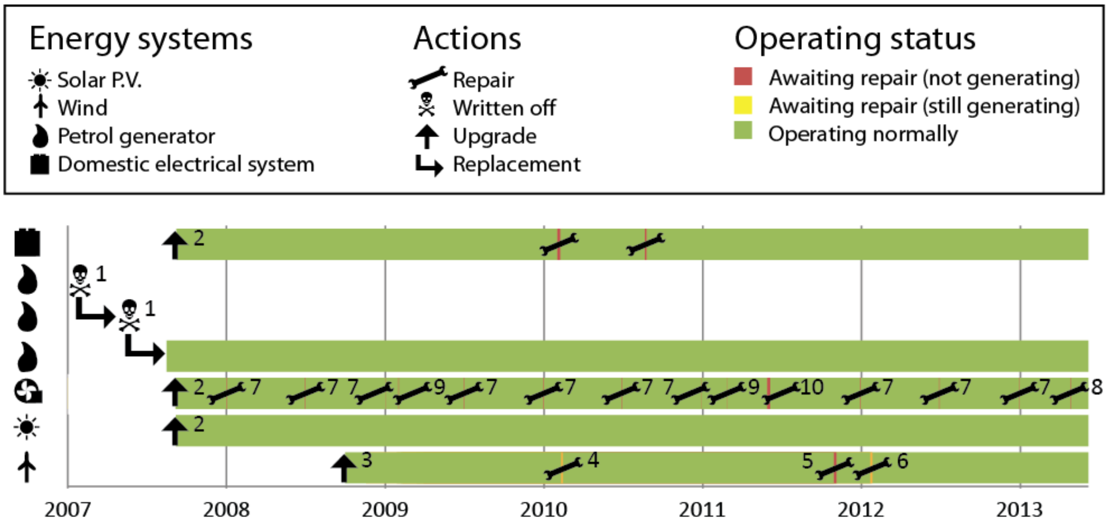

Figure 6-54: Timeline showing the chronology of events relating to Lee Brown's domestic energy system.

Unfortunately due to the lack of hydro resource, the hydro system did not perform as well as expected, with a recently acquired Honda EM5500CXS 5.8kW diesel generator[111] meeting the majority of the demand. Instead of the predicted 2-3litres/s flow rate and 20m head, in reality, the flow rate is closer to 1-1.5litres/s and the head is around 10m. This left the generator to produce 1,731kWh/yr instead of just 561kWh/yr. Figure 6-55 a) and b) show the resulting difference in power production between the design (0.2-0.4kW) and actual (0.07-0.11kW) operating conditions. As a result, a Piggott

[111] Obtained second hand for free from a neighbour.

2.4N[112] was added to the site the next year (3), greatly increasing the energy yield and reducing the load on the generator down to 797kWh, as illustrated by Figure 6-55c).

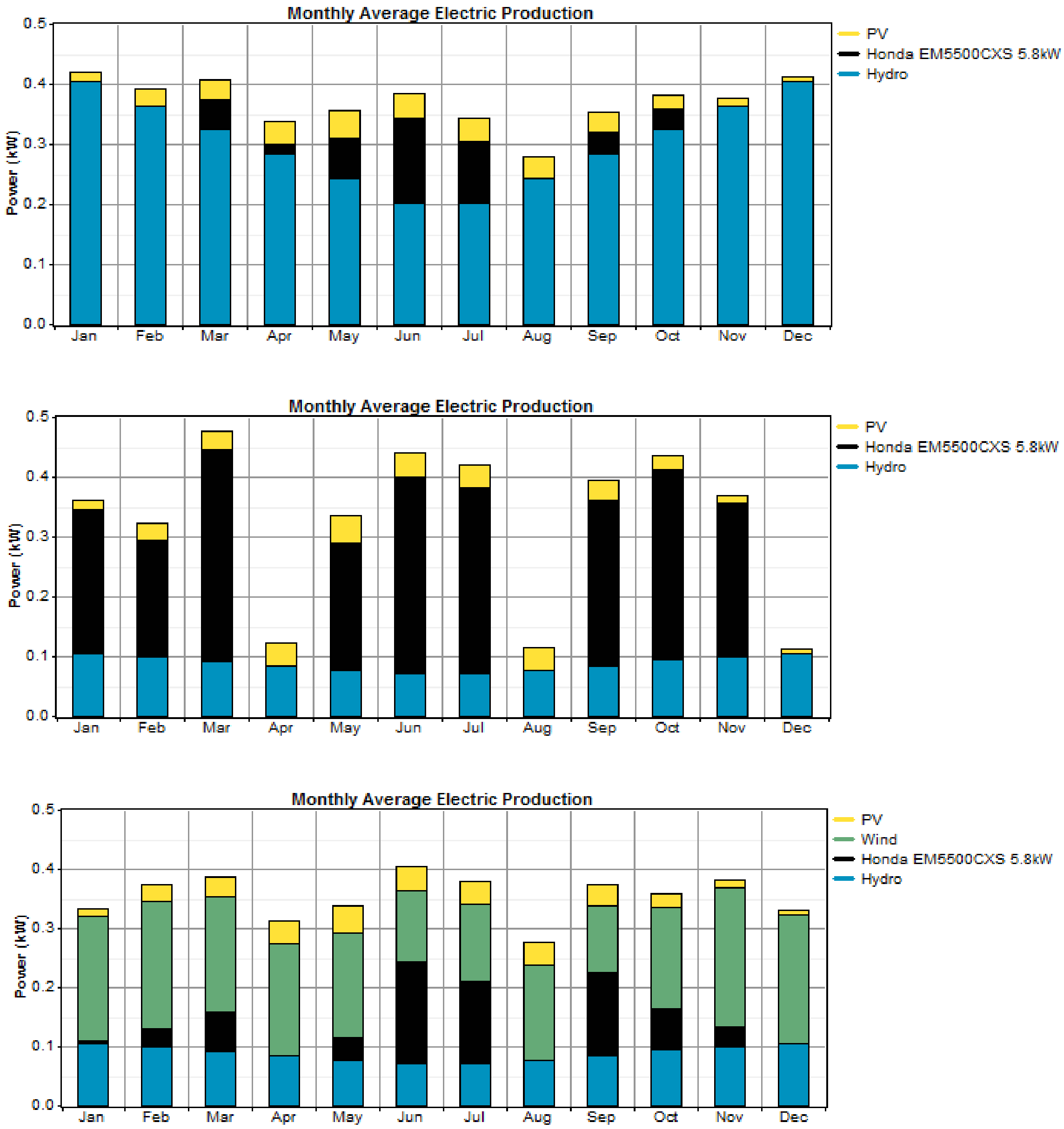

Figure 6-55: Monthly average electricity production in the PV-hydro- diesel energy system a) as designed b) as reported by Lee Brown and c) after the addition of the Piggott 2.4N wind turbine.

The impact on the LCoE is also dramatic, with the original PV-hydro- diesel hybrid designed to supply power at 1.26$/kWh, but actually producing at 2.66$/kWh before being reduced to 1.82$/kWh with the addition of the wind turbine. Figure 6-56 compares the LGC of each power generation technology in the PV-wind-hydro-diesel hybrid system, showing that despite the increase from a very competitive design value of 0.11$/kWh up to 0.39$/kWh, hydro remains the most cost effective power source. However, at 0.41$/kWh the Piggott 2.4N follows is only marginally more expensive per kWh. As

[112] 2.4m diameter, 700W rated power, 1,309 kWh/yr RAEY.

expected, the generator is the most expensive due to the high price of fuel, with the PV almost as high due to high capital costs.

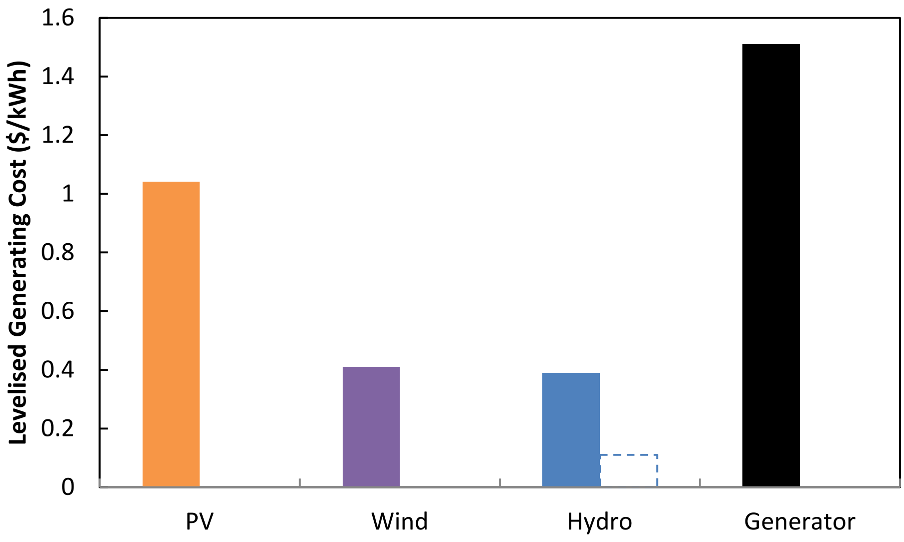

Figure 6-56: Cost of producing each kWh by power generation source. Design value for hydro is shown with a dashed line. Generator LGC is based upon 284 hours of operation per year at a fixed generation cost of 1.79$/hr and production of 725 kWh/yr at a marginal cost of 0.53$/kWh.

At 5.43kWh/day (see Figure 6-57), daily demand at the Brown household is significantly higher than either of the other households; however, the house is only inhabited for approximately 9 months every year. Unfortunately, this pattern of use is not so compatible with renewable energy systems, as they continue to generate power whether or not it is being used and once the batteries are full, it is all sent to the dump loads. As a result, Figure 6-58 shows that although 2,613kWh/yr are generated from renewable sources (255kWh/yr from solar, 1,561kWh/yr from wind and 797kWh/yr from hydro) and only 1,650kWh/yr are required, the model predicts that the generator is run for 284 hours per year to produce the 508kWh required to meet the shortfall during the 9 months in which the house is inhabited. However in reality, this is not the case as Lee Brown's energy demand responds to the availability of renewable resources, primarily the wind, i.e. high power appliances are only used on windy days to prevent the generator from being run so often.

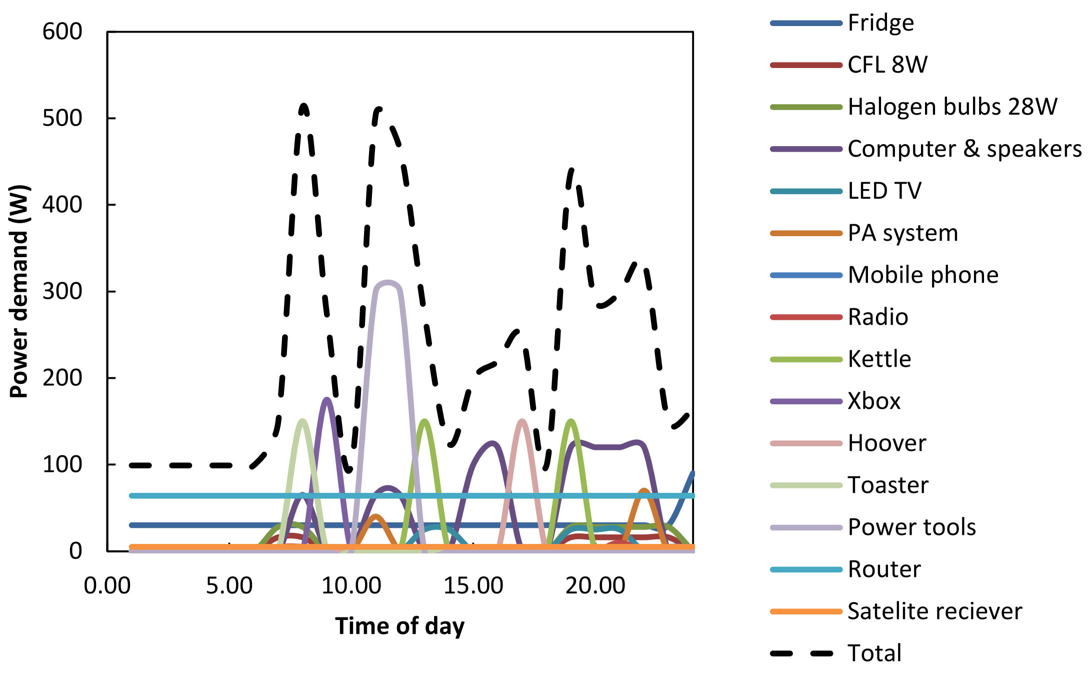

Figure 6-57: Demand during a typical day at the Brown household[113].

Figure 6-58 also shows that each resource adds something different to the energy system. The wind turbine provides the bulk of the power, but it is unpredictable and significantly weaker in the summer. In general, hydro is more predictable, generating some energy almost all the time, however there are times when the stream either dries up or freezes over completely for a number of weeks. Solar generates the least, but it fills the gap in the summer, when both wind and hydro are at their lowest. However, in order to meet the relatively high demand when the house is occupied, the diesel generator's ability to provide power whenever the batteries start getting low justifies its relatively high unit cost because not only does it allow demand to be met, but it also prevents the batteries from sitting at a critically low state of charge for long periods of time and causing irreversible damage.

[113] It should be noted that not all of these appliances are used every day. As a result, their average monthly usage was converted to a daily figure for inclusion in this diagram.

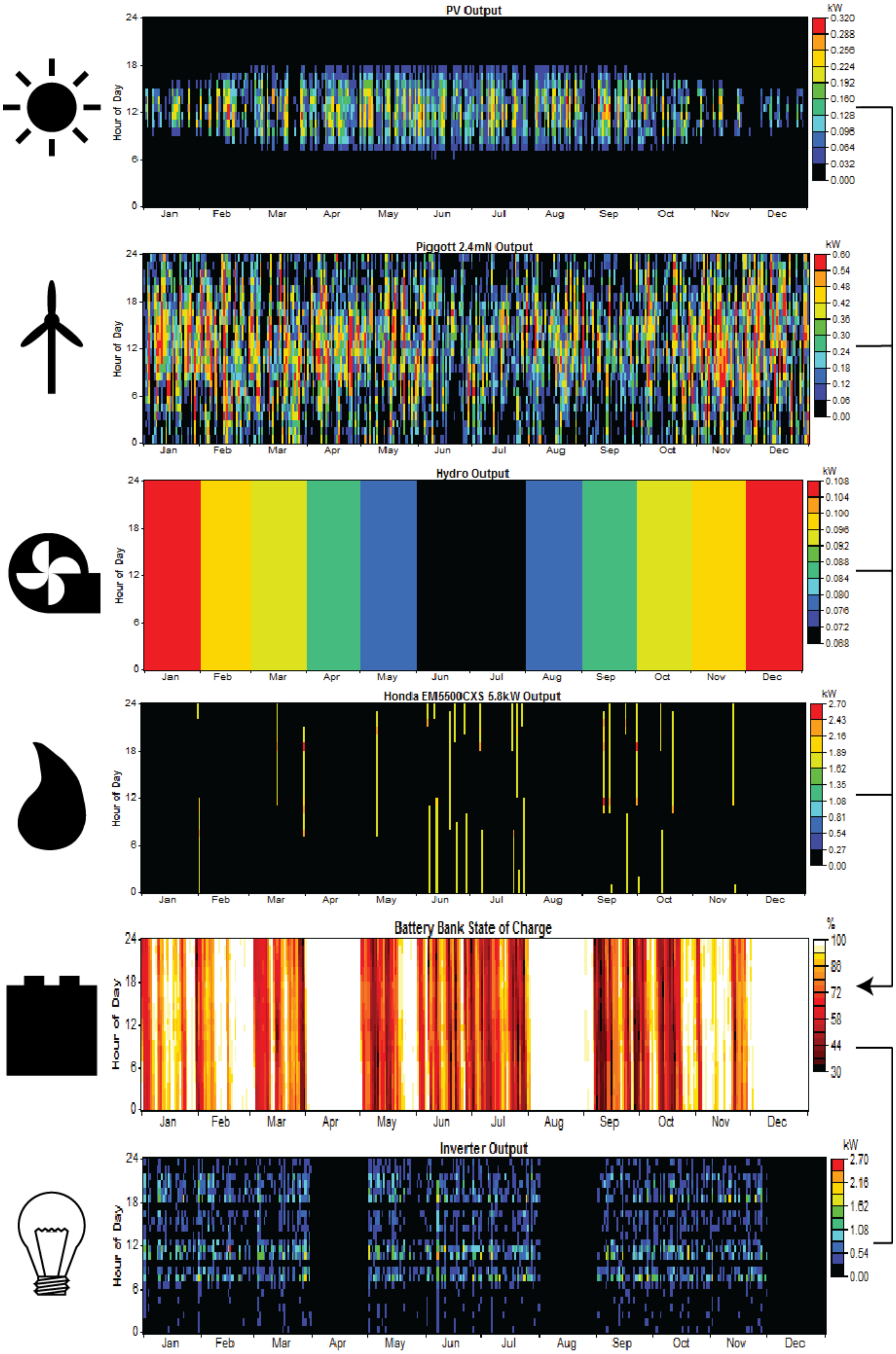

Figure 6-58: Daily and seasonal energy flow through the PV-wind-hydro-diesel hybrid installed at the Brown household.

In terms of reliability, the PV has not yet experienced any failures, the only issue being the continuing growth of the trees, which are now shading the panels at the beginnings and ends of the day. The diesel generator has also operated successfully with only preventative maintenance, such as changing the oil, required to keep it in operation. In contrast, the Chinese bearing used experimentally in the wind turbine required replacement with the standard car wheel bearing[114] when it failed after just one year (4). The following year, the yaw bearing got stuck when Lee was away, so a neighbour lowered the turbine to prevent it from being damaged in high winds as it would not have been able to furl away from the oncoming wind and protect itself (5). A simple re-greasing was enough to put the yaw bearing back in operation; however when it began shorting out and stopping at low speeds, the generator had to be completely disassembled to repair corroded magnets (6). Routine preventative maintenance including reconstruction of blade leading edges and repainting was also performed at this time.

The hydro turbine (Figure 6-59) has required even more frequent maintenance due to stones washing down the pipe and blocking the flow around twice a year (7). In fact, just a few weeks before the interview was conducted, an eel was washed down the penstock and ended up with its head extruded through the inlet nozzle (8)! Fortunately, correcting this failure is simply a case of detaching the nozzle, removing the offending item and reattaching the nozzle. However, to maximise power output, the nozzle must also be manually changed to suit the flow conditions. As this must be done around 10 times per year and the hydro turbine is located around 100m from the house and 20m downhill, Lee pointed out that "*hydro is a pain when the drop is a long way away.*"

[114] The recipe book states that a car bearing should be used; however every machine that Piggott builds is slightly different according to the materials available at the time of manufacture and any new design ideas, such as the incorporation of a Chinese bearing as a potentially cheaper alternative.

Figure 6-59: 200W EcoInnovation hydro turbine installed at the Brown residence.

The bearings have also required replacement twice, but as this is also relatively simple, Lee was able to order a spare part on the internet for $75 and fit it himself (9). However, when the machine ground to a halt due to an extremely high resistance in the stator, it either needed rewiring or replacing. Rewiring is a complex task that requires specialist tools and knowledge. Luckily, the manufacturer just happened to be visiting Hugh one week after the failure occurred, so was able to rewire the stator and get the machine back into service (10)! This demonstrates the problems with relying on imported technology as, given that the turbine was manufactured on the other side of the world, the alternative would have been to order a replacement stator, rather than pay the postage both ways and spend a significant amount of time with the system out of service

With regard to the cost distribution across the lifespan of the energy system, Figure 6-60 shows that the hydro turbine sits somewhere between the wind and solar system, with the majority of the net present cost made up by the initial purchase costs, but still significant recurring costs to cover O&M. With regard to the diesel generator, its higher level of usage and the fact that it was obtained second hand mean that its initial purchase costs are almost negligible in comparison with its fuel and operating costs.

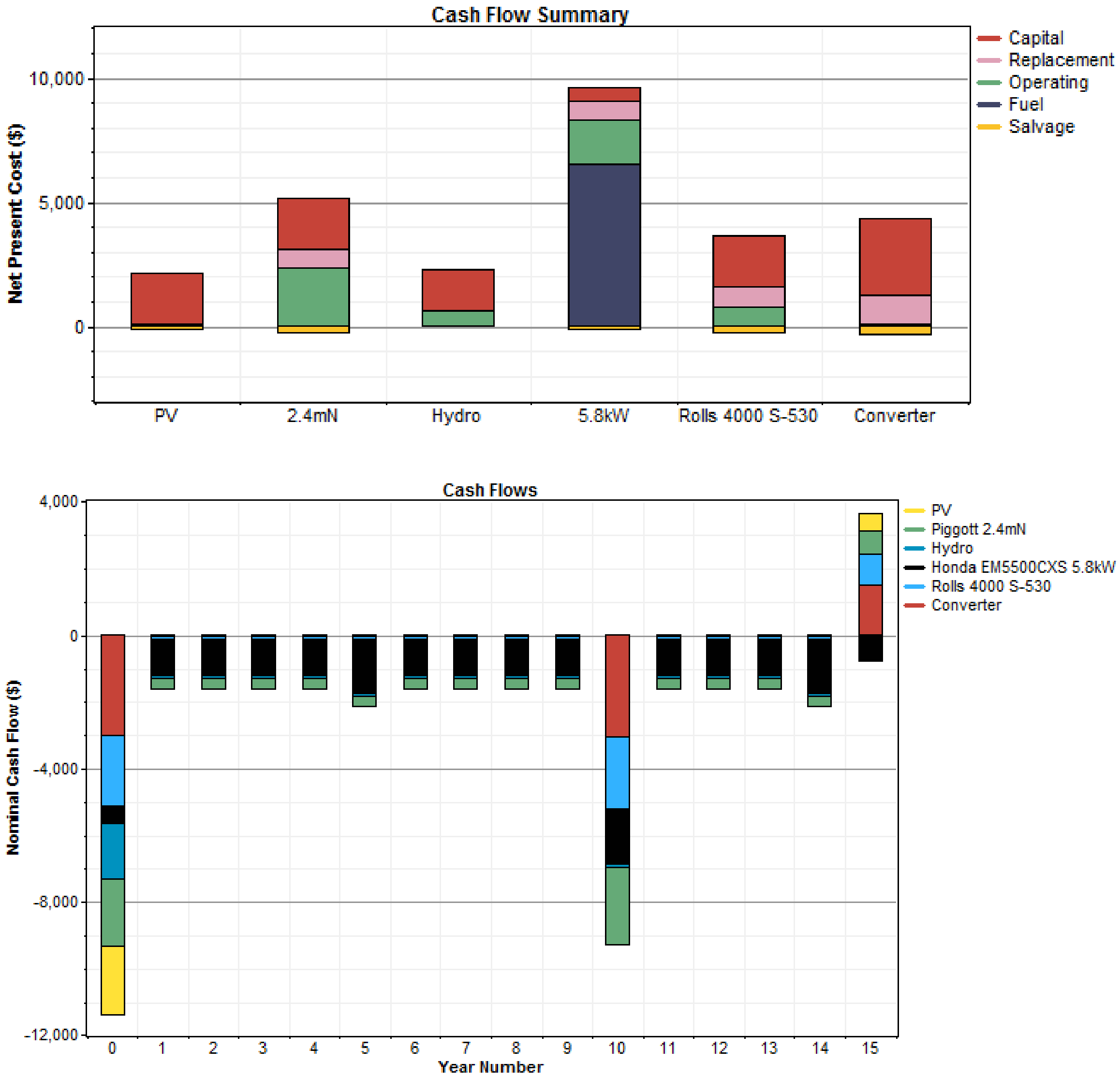

Figure 6-60: a) Net present cost and b) nominal cash flow for the Brown energy system.

6.5 Why has wind power been so successful on Scoraig?

Hugh has a degree in mathematics and experimental psychology from Cambridge University and many other Scoraig residents are also highly educated. It therefore comes as no surprise that the solutions that these highly educated free-thinkers have come up with to improve their standards of living without damaging the environment in this remote corner of the UK are just as useful for remote communities in developing countries. The experience gained by living with the technology they have developed during every single day of the year has been invaluable in ironing out any design flaws and ensuring that the product has evolved into something that adequately met the needs of people on Scoraig. Hugh has lived on the electricity produced by his wind turbines for over 30 years and as a direct result of this, the machines that he has developed are truly appropriate for the local context. They are made from materials that can easily be obtained on Scoraig, require the use of tools and techniques already available on Scoraig, are optimised for the wind distribution on Scoraig and to meet the needs of the people on Scoraig. The environmental conditions on the peninsula are close to ideal for these machines, as the incidence of lightning strikes is low (see Figure 5-20), whilst the corrosion caused by the highly saline coastal environment and any overheating issues are regulated by the cold climate.

What is more, the innovative solutions that other Scoraigers have come up with have played a pivotal role in the success of wind power on Scoraig. After all, it is not electricity that people want, it is the energy services that it is capable of providing them with that make it such a sought after commodity. The first wind turbines developed on Scoraig produced small amounts of power that was fed into a 12V battery, whilst most electrical appliances are designed to run on the 240V AC mains supply with little regard to the amount of energy they consume. The use of 12V automotive parts such as car headlamps for domestic lighting systems allowed many people on Scoraig to exploit the most fundamental application of electricity and replace the dangerous and inefficient open-flame lamps that have burnt down a number of houses on Scoraig, just as they continue to do in developing countries around the world today.

Even today, commercial washing machines remain one of the most difficult appliances to run on Scoraig due to their high power demand and the need for a high quality inverter. However, particularly innovative solutions such as Alan Beavitt's use of a car windscreen wiper motor to spin a metal barrel back and forth, creating a low power washing machine that has operated successfully for the past 30 years, as well as a whole workshop of power tools (see Figure 6-61). Alan Beavitt worked as a physicist before coming to Scoraig and his scientific training has given him the ability to develop novel ways of accomplishing things that are often taken for granted in the "*push button society*" (William Hawkins) by making efficient use of the limited resources available on the peninsula.

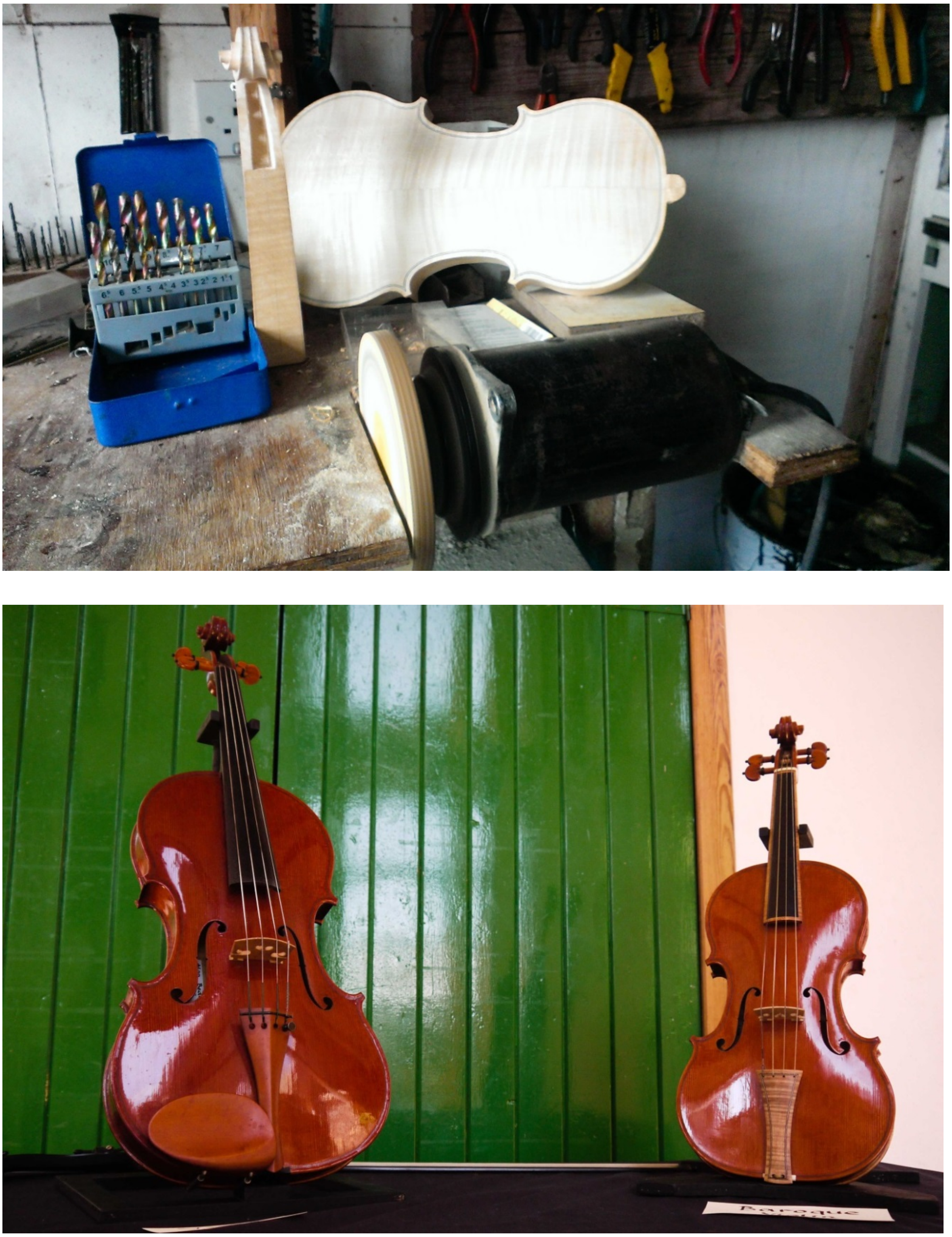

Figure 6-61: a) Alan Beavitt's 12V sanding/grinding disc made from a re-used car window winding motor and b) a selection of the high quality violins that it has allowed him to produce.

This term, the "*push button society*" refers to the ability of those living in grid connected households where an unlimited amount of electricity is available at the push of a button. In fact, the willingness of many Scoraigers to adapt their lives around the availability of renewable electricity is another key factor that makes harnessing electricity from the unpredictable wind resource using unreliable SWTs a viable option here. Whilst staying at the Dagg/Hawkins household on Scoraig, daily life was dictated by the battery voltage monitor, appropriately positioned in the living room. For example, if it read below 13V, water would be boiled on the hob rather than with the electric kettle.

In fact, the weather forecast would frequently be consulted before deciding whether to use the washing machine or not, as even if it was windy and/or sunny at that particular moment in time, if the next few days were set to be calm and/or overcast then the batteries would not be refilled and therefore it would make sense to wait. Both the ability to monitor the amount of energy coming into and stored within the system, as well as the willingness of the end-user to change their behaviour based upon this information have also had a significant impact on the success of SWT technology on Scoraig. Meters such as those shown in Figure 6-46 are fitted as standard in almost every renewable energy system on Scoraig. They offer the end-user real time information on the power coming in from each renewable source, the energy stored in the batteries and often even more. They are installed in whichever room is in most frequent use, so that the user does not have to go out of their way to find out the information and can stay up to date with what is happening in their energy system and plan their activities around it.

Unlike Cuajinicuil, El Alumbre, Monkey Point or the other rural communities mentioned during this thesis, the fundamental characteristic that differentiates Scoraig is that the vast majority of the community's residents have chosen to live there. Most have moved there because they appreciate the rural lifestyle and because of the value that they place on environmental protection. As a result, they are much more open to the prospect of using alternative technologies such as LMSWTs and are willing to reduce their needs in order to lower their environmental impact. In fact, many Scoraig residents also use other alternative technologies, such as solar thermal water heating or rainwater harvesting, illustrating the fact that their willingness and ability to adapt their lives to accommodate a range of alternative technologies is much higher than average. In contrast, although many of the members of the rural communities in developing countries were also aware of the environmental benefits of renewable energy, their primary motivation has been to gain access to electricity in whatever way possible. Although renewable energy can often provide the most economical solution, it can also require a certain level of commitment to environmental protection in order to put up with what is still very much an experimental technology.

The concentration of technical knowledge in just a few individuals is a concern, as at some point Hugh will not be able to continue to maintain the wind power systems installed on the peninsula and although there are a significant amount of people who have the skills to be able to do so, the question is whether they would have the motivation to provide such a high level of service for such an affordable price. This may then tip the balance and make PV the technology of choice due to its simplicity, or even petrol/diesel generators due to the widespread availability of maintenance services and low upfront cost. Whilst many people around the UK know how to build an LMSWT due to the success of Hugh's recipe book, the nearest organisation offering maintenance services (V3 Power) are based in Nottingham, meaning that obtaining anything other than technical advice or spare parts by mail order would be impractical.

Strict planning regulations in the UK add significantly to the initial capital costs of a wind power system[115] and often limit the size and location of such installations. Regulations surrounding solar and pico-hydro are less strict, as the technology is less visible. In developing countries, such regulations often do not exist, whilst on the Scoraig peninsula due to its remote location and liberal attitudes, there is a 'gentlemen's agreement' with the local planning authority that they will not ask for the usual permits as long as nothing obviously dangerous occurs. The author is unaware of any serious wind turbine related injuries on Scoraig, however the potential certainly exists. Users readily acknowledge the dangers, with Andy Whisken saying that "*it makes some horrendous noises when you're under it and its windy*" and a neighbour mentioning that "*when there's a gale, I always duck when I'm walking along the track beside a windmill*." Fortunately the risk to wildlife seems minimal (see Figure 6-62); with Debbie Davy pointing out that she has "*only ever found 1 dead bird under the turbine, but 4 against the greenhouse*."

[115] Obtaining planning permission alone can cost more than the materials to build a small LMSWT.

Figure 6-62: A small bird lies dead after an altercation with the school window.

As the community technician, there is no doubt that Piggott's vast experience from 30 years of designing, building and installing LMSWTs on Scoraig has given him more than enough knowledge with which to be able to maintain these machines. However, there is a huge range of abilities among the end-users as, although almost everybody would have been involved with the installation of their SWT, most have not been involved with the manufacture. To cater for this, Piggott offers a range of maintenance services depending on the abilities and willingness of each end-user to perform each of the tasks themselves. This ranges from friendly advice over the phone every few years, up to a full service plan that covers all parts and labour. It is typically those that have built independently or at least participated in the construction of their LMSWT that are the most independent in terms of maintenance, having acquired a much greater skill set during the construction. However, even for those that have had no involvement in the construction of the machine, familiarity with the technology through machines installed at neighbouring houses (as occurred in Inner Mongolia) and helpful instruction from Piggott coupled with the high levels of education and practical know-how mean that the majority of Scoraig residents are more than capable of performing at least basic maintenance on their SWT.

Lee Brown highlights two important points when he stated that "*when you're living here, you're always keeping an eye on other people's wind turbines*," as it was a neighbour who spotted that his turbine was stuck whilst he was away and lowered it to prevent potentially serious damage. The first is that once the technology is established in a particular place, then the assistance offered by neighbours becomes a valuable source of maintenance services that is often much quicker than going through the official channels. The second is that the fact that wind turbines are so prominently displayed above the skyline makes observing their operation part of daily life, enabling end-users to hear any strange noises or see and odd behaviour that may indicate a failure that is about to occur and enable appropriate action to be taken to prevent it.

Despite the frequent informal social events held on the Scoraig peninsula and the seemingly close relationship between community members, Debbie Davy describes her dislike for the word '*community*', as to her it implies that "*the same people end up doing all the work..*" A neighbour added that "we're not an intentional community, we're an ad-hoc collection of people who sometimes come together to do things." This helps to explain why despite the various discussions about possible community energy schemes[116] that have happened over the years, the community have always rejected these proposals in favour of the small scale, isolated solutions they currently have in place. However, regardless of this, Hugh recognises that "*some people are certainly unsatisfied with the quantity and quality of electricity available on the peninsula*," the majority have always voted against these proposals, in part because they wouldn't want overhead cables or what would now be a very expensive connection fee, but mainly because they are happy with the independence they have and the control it gives them over their personal environmental impact.

The fact that every single energy system installed on the Scoraig peninsula is different is another key reason why LMSWTs have been so successful here. Unlike in El Alumbre in Peru, where each household received exactly the same wind power system, each energy system on Scoraig is tailor made to suit the individual household's current and predicted future energy demand, the renewable resources available on site, the availability of commercial and locally manufactured equipment at the time, the end-user's ability to pay and any other requirements or preferences that the end-user may have. This is testament to Piggott's comprehensive technical knowledge, as well as his understanding of the needs of the end-users, as he himself is an end-user. In addition to this, his personal drive to

[116] The most viable schemes would either have been to extend the grid from 3 miles further back up the peninsula or to develop the hydro resource running off the mountain. Scoraig was even offered a grid connection for just $150 back in the 1970s under the EC grant scheme for grid extension.

continually optimise both the technology and each individual system ensures that it continues to evolve to meet the changing needs of the end-user as closely as possible.

> *"Electricity has always been a hobby of mine…I would get books on electricity out from the library and read them for pleasure"*
> *Hugh Piggott, June 2013*

What is more, the fact that he is a member of the community means that he is able to charge a price that is affordable to the end-users as his expenditures are likely to be similar to theirs. It also means that he is likely to run into them regularly and any issues with the system can be discussed informally. Even more importantly though, it means that he is able to perform any maintenance quickly (even the furthest house in the community is only 40 minutes' walk away and he keeps a variety of spare parts at his workshop) and cheaply (due to his low labour and virtually zero transportation costs). Finally, the small amount of money that is earned by Scoraig Wind Electric is kept within the community, boosting the local economy.

Figure A-23 in Appendix R shows that apart from the hydro turbine with its continual stone clogging problem, the LMSWTs experienced failures most often, on average every 202 days. The fact is that wind turbines are unreliable and dangerous, but so are many other technologies that are in common use across society today. The car is a great example, as many people are killed in car crashes and they require regular maintenance to keep them in service. People live with the risks and inconvenience because driving a car is so much quicker than walking. People understand the risks and take appropriate action to minimise them, for example just as people avoiding crossing roads when the cars are going very fast, people on Scoraig avoid going near their wind turbines during high winds. To address the need for regular maintenance, an extensive service network has been set up across the world to offer access to spare parts, tools and the relevant expertise required to repair punctured tyres, change dirty engine oil etc. Such a service network was created in Inner Mongolia to keep the hundreds of thousands of household wind generators in operation there and the services offered by Piggott through Scoraig Wind Electric offer the same support to the SWTs on Scoraig.

In fact, with regard to availability (Figure A-23c in Appendix R), all of the figures are impressively high (95-100%), which shows that the socio-technical system keeping these machines in operation is working effectively, i.e. between the community technician (Hugh Piggott) and the end-users, there is enough knowledge and access to the required tools and spare parts to keep the energy systems in operation for the vast majority of the time. Due to the fact that all three systems are hybrids, the only people to have gone without power for any significant amount of time are John & Debbie Davy before they purchased their first solar panels.

Figure 6-63 compares the LCoE of each of the hybrid energy systems from each of the household case studies. At just under 1$/kWh, the Davys' energy system is the most economical, sacrificing reliability and convenience for cost. They also have the largest LMSWT and recently purchased the majority of their solar array at a very low price. Both the Whisken/McSweenys and Lee Brown prefer a reliable supply of electricity and have opted for a wider range of power generation equipment that will ensure they always have power when they need it. The Whisken/McSweeny family rely on two smaller wind turbines and a significant amount of solar PV, which together with the occasional generator use pushes up their LCoE above 2.50$/kWh. Lee Brown is able to exploit the small stream that runs through his property to generate very cheap hydroelectricity, however extensive use of the generator and the fact that he is not resident on Scoraig to make use of the renewable energy that is available for much of the year push up the overall LCoE of his PV-wind-hydro-diesel hybrid energy system.

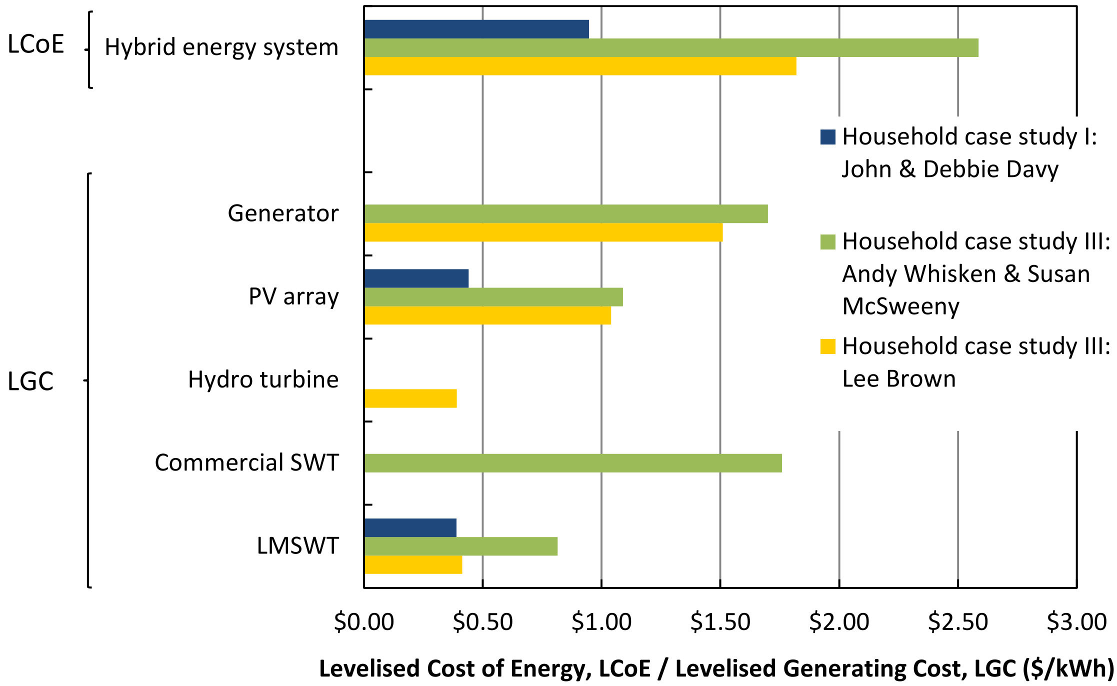

Figure 6-63: LCoE of the hybrid energy systems and LGC of each power generation technologies installed in each household case study.

The use of laptops, washing machines and other modern appliances has pushed energy demand up to a much higher level than when Piggott first arrived on the Scoraig peninsula over thirty years ago. As a result, generating electricity on Scoraig has become even more important, as ferrying sufficient diesel across the loch would be prohibitively expensive and time consuming. Whilst Hugh began with a single turbine with a rotor diameter of around a metre, he now has two machines, the biggest of which has a diameter of over 5m. This shows that in the right context, SWTs can be a flexible solution to rural electrification, keeping pace with growing demand.

6.6 Evaluation of methodology

The additional time spent in the community itself gave a much deeper understanding of the role that wind power plays in this rural community. The level of trust that the author was able to build up within the community gave access to a much greater amount of information from a much wider range of sources. This was further aided by the commonality in language and cultural heritage between the author and the participants, which in turn facilitated the development of the methodological techniques first employed in the Peru and Nicaragua case studies. For example, the iterative nature of the energy systems modelling in this case study ensured that the results matched much more closely with reality than was the case in Nicaragua, where the data had simply been collected and entered into the model, without verifying the results of the model with the end-users themselves. Now that these techniques have been developed, it would be beneficial to apply them in the previous case studies, in order to improve the quality of the data collected there.

6.7 Conclusion

SWTs have been supplying the Scoraig peninsula with electricity for over 30 years. They have played a critical role in transforming this barren, windswept peninsula into a thriving community with a standard of living very similar to that in the rest of the United Kingdom. Similar challenges face many communities in less developed countries and as a result studying Hugh Piggott's home community has given valuable insight into why the technology has been so successful in this particular local context and whether it is possible for it to achieve such success in other parts of the world.

Favourable environmental conditions

Firstly, the environmental conditions on the Scoraig peninsula are almost perfect: there is a low frequency of lightning strikes and due to the cold climate, a low risk of corrosion and overheating. The wind resource is excellent; however this does mean that failures are more likely as the frequency of extreme winds is increased. The terrain is complex, although the peninsula is relatively flat and surrounded by the sea, where the wind is unobstructed, making individual site assessment relatively easy. The wind resource is highest in the winter, when excess power can be used to heat water or living spaces during the cold weather.

Hybrid systems for increased resilience

Due to its Northern latitude and frequent cloud cover, the solar resource is low and almost non-existent in the winter, however the falling price of PV has made it a great complement for SWTs in a hybrid system, as it can keep the batteries topped up during the calm summer months. Whilst LMSWTs can be built in a large range of sizes to match the energy demand of a particular house, they are not as modular as solar panels (the LGC of a single solar panel is close to that of a larger array, whilst the LGC of a small SWT is much greater than that of a large SWT), which can be added and subtracted from an array much more easily to cope with changing demand.

Almost all the household energy systems on Scoraig today are hybrid systems, as they offer increased resilience both meteorologically (cloudy, calm or dry spells) and technologically (when a failure puts a particular piece of power generation equipment out of service), which allows the energy system to continue to provide the end-user with at least a small quantity of electricity almost 100% of the time. Running a generator is expensive, but offers the convenience of dispatchable power to meet demand when renewable resources are low and can also increase battery life by preventing batteries from being left at a critically low state of charge for prolonged periods and risking permanent damage.

Whilst the seasonal availability of the wind and hydro resources are identical on Scoraig (both peak in the winter), the greater geographical availability of the wind resource means that the two are complementary, as hydro offers cheap and predictable power where a suitable site exists, whilst wind offers almost limitless possibilities for expansion to meet growing demand. The hydro resource also has the disadvantage that it can disappear completely for over a month if the stream dries up or freezes over, whilst calm spells don't typically last longer than a week and the sun shines every single day (even if it is through the clouds and for only a few hours in the winter). The fact is that Scottish weather is notoriously unpredictable, so as Table 6-5 demonstrates, diversity of supply is extremely important, as a hybrid of as many different power sources as possible is best placed to keep the batteries consistently full. Whilst a range of smaller power generation technologies may have higher capital costs than a single larger technology of comparable rated power, the greater diversity that they offer can significantly reduce battery bank size. As the battery bank is often the single most expensive component of an off-grid system, the total system costs of a diverse system are often lower.

Table 6-5: Each technology offers something different to a hybrid energy system on Scoraig.

Technology	*Wind*	*Solar*	*Hydro*	*Petrol/diesel*
Longest duration with negligible resource	1 week	1 day	1 month	Dispatchable
Season of lowest resource	Winter	Summer	Winter	Dispatchable
Geographical availability of resource	Almost anywhere	Almost anywhere	Limited sites only	Anywhere
Quality of resource (where available)	High	Low	High	High
Ease of assessing resource	Low	High	Medium	Dispatchable
Predictability	Low	Medium	High	Dispatchable
Fuel costs	None	None	None	Expensive
LGC	Average	Expensive (but falling)	Cheap	Poor
Technical reliability	Low	High	Medium	Medium
Ease of installation	Low	High	Medium	High
Potential for local manufacture	High	Low	High	Low

Access to affordable and convenient maintenance services

The fact is that wind turbines are unreliable pieces of equipment and they are going to fail probably at least once a year. They do not come with 20 year guarantees like solar panels; however, there are many other equally unreliable pieces of technology in widespread use today, such as the car or the computer. The key to mitigating this unreliability is making the necessary technical knowledge, tools and spare parts available, so that when a failure occurs, the machine can quickly and cheaply be put back into operation. The further somebody must travel to obtain of any of these three key ingredients, the longer they must wait and the more they will have to pay to fix their machine and therefore the value that it offers them reduces. As a result, relying on imported technology causes significant problems when it fails, as spare parts (and often also specialist tools and knowledge) are difficult and expensive to acquire.

On Scoraig, SWTs are supported by the maintenance services offered by the world's foremost expert and original designer of the Piggott turbine, Hugh Piggott. Not only does he have the technical knowledge to solve almost any problem, he also has a workshop full of tools and spare parts, so that he can quickly and cheaply repair any machine that fails. What is more, he has the motivation to do. Electricity is a hobby for Hugh and he is completely committed to keeping his neighbours supplied with (mostly) renewable electricity, despite the fact that he could easily earn ten times more working elsewhere. Additionally, now that SWTs have become well established on Scoraig, neighbours can offer each other technical advice, making basic maintenance services even more widely available and reducing the community's dependence on Piggott (therefore increasing the resilience of the community energy supply).

This combination of motivation and capacity is very rare, yet absolutely fundamental to the success of off-grid community electrification projects, regardless of the context. This may explain why there are few successful examples of such projects in the UK and why so many projects in developing countries are not successful. Yadoo *et al.* (2011: 6405) studied another radical Scottish community, the Isle of Eigg, and highlighted the fact that if such projects are to become more widespread, there is a need for "*facilitation and guidance from an external agency*" to offer the "*strong leadership*" required to initiate and manage community renewable energy projects.

Hugh Piggott is an exceptional person and there are few cases from a developing countries context where such an individual has been able to have such a transformative effect on the community energy supply without outside assistance (e.g. Kamkwamba (2009)), as the challenge is much greater due to the lower levels of education, the less developed transportation infrastructure etc. However, it is possible to find people with the same motivation to serve their community and with the right level of external support to empower them with the relevant technical and organisational skills (see section 5.2.2.4), it is possible for communities in less developed countries to follow a similar pathway, in which they are able to take control of their own energy supply and manage a sustainable energy system that can adapt to the changing needs of the community and add significant value to the daily lives of the people who live there. Of course, the empowerment process has a significant cost (in terms of programmes design, identification of suitably motivated individuals, technical and organisational training and ongoing support), however this is justified by the increased value offered to the community by having an energy system that is much better suited to meeting their needs, both at the moment of installation and in years to come.

Empowered and proactive end-users

Wind turbines are often considered an eye sore, however the fact that SWTs are so prominently displayed above the landscape allows end-users to keep an eye on their turbine and those of neighbours, allowing minor problems to be identified and addressed before a failure occurs. There are significant safety risks associated with wind turbines, however familiarity with the technology on Scoraig has allowed people to make common sense judgements to minimise them, for example by not walking near them during high winds when they are most likely to fail.

Manufacturing a wind turbine locally offers the possibility for the end-user to participate in its construction. On Scoraig, not only has the community technician (Piggott) designed, organised and participated in the manufacture of all of the LMSWTs, but many end-users have either built independently or participated in the construction of their LMSWT. These users typically show the highest level of independence in terms of their ability to perform maintenance themselves, due to the skills they have acquired during this practical learning opportunity.

The level of cohesion between community members also has a major influence on the success of community renewable energy projects (Yadoo *et al.*, 2011). Whilst Scoraig is certainly not the most close-knit community, many of the inhabitants share the common goal of wanting to live a rural lifestyle in an environmentally friendly way and as a result, are motivated to work together to achieve this goal. As a member of the community, Piggott understands the internal conflicts within the community and is able to manage these so that they do not hinder the development of the renewable energy systems he installs. In a developing countries context, Yadoo *et al.* (2011: 6405) recommends the use of an "*external mobiliser*" to fulfil this role by engaging with the community from an early stage.

Flexibility of system design and maintenance services

Not all users are interested in maintaining their own SWT and Piggott recognises this by offering a range of bespoke maintenance services that cater for everything from occasional friendly advice up to a complete service plan covering everything from keeping the batteries topped up with distilled water to replacing a broken set of blades. Furthermore, Piggott's ability to plan each energy system around the renewable resources available on that particular site, the energy demand of that particular household, their willingness to pay, preference for reliability, currently available technology and other important factors ensures that each system is optimised for each individual household. This is in contrast to the energy systems studied in the previous chapters, in particular in Chapter 4, where each community (WindAid) or each household (Soluciones Prácticas) was given exactly the same SWT, regardless of any of the above criteria.

Responding to feedback and co-creation of innovative energy solutions

The design of renewable energy systems is complex, as whilst it is possible to measure the performance of various technologies under controlled conditions, each site is different, and therefore actual energy system performance is very difficult to predict. What is more, the way that end-users draw power from the system is inseparably tied to the availability of that power. Therefore fine tuning of the system after installation is critical in ensuring that each energy system evolves into something that is capable of meeting the needs of the end-users. In fact these are not static, they change as children leave home, new appliances are bought, more money is saved etc. Having local technical knowledge available to upgrade and fine-tune each individual energy system is absolutely vital.

Piggott's personal motivation to continue developing not just the energy systems on Scoraig, but LMSWT technology itself ensures that it continues to meet the changing needs of the end-users. LMSWTs have been designed on Scoraig for Scoraig. The fact that the technology has been continually refined here over 30 years has enabled it to evolve into something that is capable of meeting the needs of the community using the resources available within the community and on a budget appropriate for the community. In fact, many end-users have also played an active role in not only in the evolution of the technology, but also by finding innovative ways to gain access to the desired energy services by coming up with novel machines that can use limited quantities of electricity. Familiarity with other alternative technologies and their willingness to adapt their behaviour around the availability of energy also play a major role in the acceptance of SWT technology on Scoraig.

Whilst this process may have taken place over 30 years on Scoraig, the sharing of knowledge can greatly accelerate this process. The WindEmpowerment association bridges the geographical gap between its members by providing a global platform for knowledge sharing, allowing the lessons learned from one country to be employed in another before the same mistakes are made. On a more local level, Scoraig is an exceptional community in the context of the UK, it is likely that if there were other similar communities in the surrounding area, then knowledge could have been shared much more easily, thus accelerating the development of the renewable energy solutions employed on the peninsula. Consequently, clustering pilot projects together makes sense in a development context, as it facilitates the sharing of knowledge, tools and spare parts between communities. The successful '*campesino a campesino*' (farmer to farmer) programme has had great success in Nicaragua by getting rural people together to share advice with their peers on environmental awareness. Such a programme has the potential to greatly accelerate the development of community renewable energy projects in a specific local area.

Live feedback on system performance

The availability of information about incoming power and battery state of charge from displays in the main living area of the house and predictions of energy yields over the next few days from weather forecasts allow people to plan their energy use and manage the energy system much more effectively. Lead-acid batteries are one of the most delicate components of an off-grid renewable energy system, as there is little indication that damage has occurred until it is too late. They are also one of the most expensive components to replace. Such displays help prevent damage and ensure that they reach their full potential in terms of both capacity and lifetime, meaning that their small additional cost is fully justified. However, even with the most sophisticated feedback devices currently available, it is inevitable that some batteries will still fail to reach their expected lifespan due to misuse.

Favourable economics

Finally, the requirement for significant amounts of upfront capital has been a major barrier to the uptake of PV technology. LMSWTs have moderate capital costs, but higher O&M costs, meaning that the cost of wind power is spread more evenly over the lifetime of the system. Unfortunately, in a development context, aid projects are often financed with upfront donor capital and the need to plan for recurring O&M costs is often overlooked, meaning that the machines soon fall into disrepair indefinitely. A much higher proportion of the net present cost of an LMSWT is embedded in labour, so producing the machines as locally as possible makes them more affordable. In a development context, foreign labour is the most expensive[117] (i.e. imported machines), national labour is cheaper (i.e. produced in a nearby city), but local labour is the cheapest (i.e. manufactured within the community). Piggott charges very little for his time and is able to do so because he lives on Scoraig, so his personal expenses are on par with the rest of the community. This is an argument that has already been recognised as one of the key drivers for a successful utility-scale wind industry (Lewis and Wiser, 2007).

Local is key

To conclude: locally manufactured SWTs work best when the technology is properly established on a local level. Labour costs are minimised, maintenance services are widely available for when things go wrong and awareness of the capabilities and limitations of the technology spreads so that end-users can understand how to make the most of this new technology. Piggott's incredible drive to continue developing the technology and adapting each and every energy system to meet the needs of each individual household show that having a capable and motivated community technician must be the cornerstone of any rural electrification initiative based on locally manufactured SWT technology.

[117] Although mass-produced machines from China arguably have a lower embedded labour costs due to the combination of efficient production techniques with low labour costs, however, delivery and import taxes still raise the price significantly.

Chapter 7. Discussion

7.1 Introduction

In this chapter, the evidence collected from each case study is compared to give an overall view of SWTs as a technology for rural electrification. Firstly, the generic factors that are inherent to SWT technology are discussed and contextualised by making comparisons to the other popular technological options for decentralised rural electrification: solar PV, micro-hydro and petrol/diesel generators. Secondly, the ecosystem framework is used to compare the place specific factors that are inherent to each case.

7.2 SWTs as a technology for rural electrification

In order to properly evaluate SWTs as a technology for rural electrification, it is necessary to know how they compare to other technologies commonly employed for small scale power generation. This research has highlighted these differences (and similarities) by continually comparing and contrasting SWTs with the possible alternatives in each local context. As these are generic characteristics that are inherent to the technology itself, it is absolutely essential to have a full appreciation of them in order to make an assessment of whether SWTs will be appropriate for a new local context. The following section is structured according to the eight stages of the technology lifecycle, as outlined in Figure 2-3.

7.2.1 Manufacture

Table 7-1: Contextualisation of SWTs as a technology for rural electrification at the manufacturing/acquisition stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Availability of prefabricated technology in remote locations	Low	Average	Average		High	
Potential for local manufacture	High[118]	Low[119]	High[120]		Low	
Upfront capital ($/W)	Medium	High[121]	Low		Low	
Complexity of controller	Average	Simple	Complex		Average	
Susceptibility to environmental hazards	High[122]	Low[123]	Low[124]		Low	

"Building a low cost turbine that's going to survive any length of time is really difficult."

(Craig, 2013)

[118] Batteries & control system usually imported, but turbine & tower can be manufactured locally.
[119] Only mounting rack usually manufactured locally.
[120] Batteries & control system usually imported, but civil works must be manufactured locally & can use off the shelf pump/motor as turbine/generator.
[121] Falling rapidly.
[122] e.g. turbulence, corrosive (hot, humid, highly saline) environments and lightning strikes all cause significant damage.
[123] e.g. extreme heat levels reduce life.
[124] e.g. siltation in water can wear turbine blades.

Piggott's (2013) *A Wind Turbine Recipe Book* describes the technical processes involved in manufacturing a SWT using readily available materials and only basic tools and techniques. Despite this, evidence from the case studies has shown that it is still not possible to simply 'copy and paste' LMSWTs from one local context to another. Manufacturing SWTs of sufficient quality also requires the development of a significant amount of local capacity, as well as adaptation to face the environmental hazards present in each particular place. The major challenges include: identification of appropriate supply chains for the best price and quality construction materials, establishment of a suitable workshop and the training (and retention) of workshop technicians. As a result, there is a significant barrier to overcome in terms of scale as it is also difficult to achieve the necessary quality standards and offer the required maintenance services when producing just a few machines.

> *"If you're trying to create employment locally, [local manufacture] is worth it."*
> *(Craig, 2013)*

It is without doubt that one of the greatest advantages of local manufacture is the fact that it creates jobs in developing countries. However, it is worth considering exactly where these jobs are created. In Peru, Inner Mongolia and Nicaragua, the turbines were manufactured in cities (often hundreds of kilometres from the installation sites) whilst in Scotland they were manufactured in the community itself. As a result, a much higher proportion of the money paid by community members for their SWTs was fed back into the local economy. Of course, the price of the materials and the electrical system components still leaves the local economy as these must still be purchased from external suppliers. It should also be noted that whilst it is possible to manufacture a controller for a wind power system locally, they are more complicated than solar PV controllers and serious damage can occur to other system components if they do not function correctly. However, unlike solar PV, the majority of the materials for an LMSWT can be purchased from a nearby town, meaning that this portion of the initial purchase costs still stays within the regional economy.

The alternative to manufacturing SWTs locally is to import mass-produced technology. Even if imported technology could be shown to be more efficient, more reliable and have a longer lifespan than LMSWTs, a failure will eventually occur. The following key issues then arise: will there be sufficient local technical knowledge to perform the repair and how long will it take/how much will it cost to send a spare part from overseas? Evidence from the Scotland case study has also shown that commercial technology is often optimised for best performance at rated power (which is more marketable) rather than in low winds (which is more useful for battery charging systems, as calm periods can last up to a week and the batteries are often filled quickly during periods of high winds, meaning that much of the extra energy is often wasted).

Ultimately, the decision as to whether to manufacture SWTs locally or to import must be made independently for each local context as there are many place-specific factors that influence the decision, for example:

- The availability of maintenance services for imported technology in that particular country and more importantly, that particular region. The ability of local manufacture to facilitate the development of these maintenance services will be discussed later on in this chapter.
- The import taxes in that particular country.
- The shipping costs to get the equipment into that particular country and then into that particular region.
- The wind regime in that particular region – locally manufactured technology can be better adapted to low wind regions (4-5m/s annual mean wind speed).
- The planned scale of manufacture – at low volume, costs are high and it is difficult to ensure the necessary quality with local manufacture.
- The external environment – corrosive environments push up the cost of locally manufactured technology (metal parts galvanized, stainless steel instead of mild steel bolts etc.), whereas some commercial turbines are designed specifically for marine environments and have these features as standard.
- The capacity and willingness of communities to perform maintenance – locally manufactured machines require more preventative maintenance (greasing bearings, repainting blades etc.) and regularly sending engineers out to remote communities quickly becomes expensive.

7.2.2 Site selection

Table 7-2: Contextualisation of SWTs as a technology for rural electrification at the site selection stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Resource assessment	Complex[125]	Simple[126]	Average[127]		None	
Confidence in power prediction	Low	High	Medium		High	
Global compatibility of resource with settlements	Poor[128]	Good[129]	Poor[130]		Transportable fuel	
Local compatibility of resource with settlements	Poor[131]	Good[132]	Poor[133]		Transportable fuel	
Modularity	Average	High	Low		Average	

[125] Many site visits required to find most appropriate location and record data at hub height for at least 1 year.
[126] Desk study usually sufficient.
[127] Some site visits required to measure head and flow rate in various seasons.
[128] Most communities are not in windy areas.
[129] Every community has at least some solar resource.
[130] Both elevation drop and sufficient precipitation necessary.
[131] Most buildings are in areas of low wind resource, i.e. forested valleys rather than bare hilltops.
[132] Solar resource at demand points equal to that of the surrounding area.
[133] Most communities are not near a suitable water course.

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Transporting materials to site	Difficult	Easy	Difficult		Easy	
Susceptibility to environmental hazards	High[122]	Low[123]	Low[124]		Low	
Training requirement	High[134]	Low	High		Average	

On a global scale, neither the wind nor hydro resources correlate well with the location of people without access to electricity (see Appendix A). In contrast, the solar resource is highest around the equator, particularly in Africa, where there is the highest concentration of people living without electricity. In fact, many of the regions where there are good wind resources also have significant environmental hazards (lightning strikes, corrosion, etc.). Consequently, the number of regions where wind power is a viable technology for rural electrification and therefore the global potential for the technology is much lower than for solar PV.

Evidence from the Peru case study has shown that the wind resource tends to be much more variable than the solar resource, requiring more data collection and analysis to be able to obtain an accurate prediction of the resource. Whereas almost every household has an unshaded area where a solar panel could be mounted, few households are near the points of high wind resource, which are normally located at the tops of hills (see Figure 4-13). Not only this, but the relationship between wind speed and power is cubic. The implication of this is that only a small difference in wind speed has a significant impact on the energy yield of a turbine, whereas a small difference in solar radiation has a negligible impact on power generation (see Figure 5-43).

Working at small scales presents some challenges for site selection that do not exist at larger scales. For both solar and wind, sites with a better resource can be selected for utility-scale developments, due to the greater distances that the power can be transmitted. There are also some significant differences between the solar and wind resources that make working at small scales much more difficult for wind turbines. Whilst a small solar panel installed next to a large solar array will have an identical solar resource (apart from shading from trees etc. which is arguably more likely for small scale systems), the energy yield of a SWT at a typical hub height of 10-20m is likely to be less than half of what would be expected if the same turbine would be placed on top of a utility-scale 80-100m tower on the same site (Gipe, 2004). What is more, trees and buildings create turbulence, sheltering SWTs from what little wind resource there is in the surrounding area and causing fatigue loading that shortens their life.

[134] System must be switched off in lightning storms, lowered/braked for high winds and observed daily to check for faults.

Both the Peruvian and Nicaraguan case studies have demonstrated that there is lack of sufficient wind resource mapping, especially relating to low hub heights and higher resolutions that are relevant to small scale projects. Individual site assessment is often too costly for small scale projects, meaning that the energy yield at many sites has been disappointing. Small wind requires more detailed mapping, that is more difficult to do (due to the influence of local obstructions such as trees and buildings) and therefore more costly. Unfortunately, the small wind industry has a lower ability to pay than the big utilities, who in a development context are almost always backed by foreign capital from multinational wind farm developers (Lewis and Wiser, 2007).

An individual resource assessment is always conducted for wind farms, as the benefits far outweigh the costs; however an accurate assessment of the wind resource at each proposed SWT site is much less likely to occur. A wind resource assessment is much more difficult, yet much more important than for solar (where the power produced is linearly proportional to the resource), as even a relatively small difference in the average wind speed at a given site can have a huge effect on the actual energy yield. Unfortunately, wind measurement is not usually an economically viable option for the installation of a single SWT, as logging data at hub height for a full year can increase capital costs by 15% at the 1kW scale (see Figure 5-6) and even more at even smaller scales.

Another issue highlighted by the case study work is that on local level, people do not generally tend to live in windy areas. In Peru, the community of El Alumbre was located in a valley, where the wind resource was much lower. The wind resource is typically highest on the tops of hills; however there are few communities that have chosen to live in such inconvenient places, as finding water and carrying heavy items into to the community can be unnecessarily difficult. In Scotland, end-users planted trees around their houses to create shelter for their homes; however it also created shelter for their SWTs. As the trees grew, so did the SWT towers, pushing the cost of the system up with them. SWTs must be installed within a few hundred meters of where the power will be used, meaning that even if there are no trees around, they will almost always be in the shelter of a building at some point.

Wind is also less well suited to reach the most remote (and often poorest) communities than solar PV: a heavy tower and generator must be transported to the installation site, multiple visits must be made for training and resource assessment (both of which are more demanding than solar PV) and SWTs are less modular (meaning that they are less able to serve dispersed communities or isolated households). Not only is this due to the fact that power output scales with the square of a wind turbine's radius, but as discussed previously, the smaller the wind turbines are, the more likely they are to be installed in locations with a poor wind resource, i.e. on low towers (to reduce upfront costs), in the shelter of trees or buildings (which are relatively much larger in comparison to the SWT) and without a proper resource assessment (again, to lower initial capital costs).

7.2.3 System design

Table 7-3: Contextualisation of SWTs as technology for rural electrification at the system design stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Confidence in power prediction	Low	High	Medium		High	
Local compatibility of resource with settlements	Poor[131]	Good[132]	Poor[133]		Good	
24h operation	No	No	Yes		Yes	
Longest duration with negligible resource	<1 week	<1 day	1 season		Dispatchable	
Modularity	Average	High	Low		Average	
Complexity of controller	Average	Simple	Complex		Average	
Dump load	Yes	No	Yes		No	
Brake switch	Yes	No	Yes		No	
Inverter required for AC?	Yes	Yes	Yes	No	Yes	*No*
O&M ($/W)	High	Low	Medium		Medium	

Due to the variability in the wind resource, in off-grid applications SWTs are almost always used to charge batteries and commonly form part of a hybrid system with solar PV (see sections 5.2.2 and 6.4). The wind and solar resources often peak at different times on a short-term timescale (i.e. wind generates at night and cloudy days are often windy days), however the solar resource is much more predictable. As a result, solar PV was found to be an almost essential complement to SWTs in order to smooth out the variability in the wind resource, as it can be very calm for up to a week. However, the complementarity of the two resources on a seasonal basis is specific to each local context: in Nicaragua, both the solar and wind resources peaked in the dry season, whilst in Scotland, the wind and solar resources peaked in opposite seasons. The energy systems modelling conducted in Scotland found that a PV-wind hybrid system was 22% cheaper than a wind only system and 53% cheaper than a PV only system.

The hydro resource is much more cost effective and should always be chosen in preference to wind, however the case studies in Nicaragua and Scotland highlighted the fact that small scale wind-hydro hybrids have significant potential in regions with a limited hydro recourse, i.e. just a few small streams or streams that run dry at least once a year. In such regions, wind can offer almost limitless possibilities for expanding power generation capacity, whilst hydro offers cheap and dependable power. The fluctuations in the hydro resource occur over weeks/months, whilst the wind resource fluctuates at every scale, from one second to one year. As a result, when the resources peak in opposite seasons (as they did in Nicaragua), wind-hydro hybrids make a very attractive combination.

The Scotland case study also illustrated the fact that petrol/diesel generators do still have a role to play, as the dispatchable power that they offer can save batteries from permanent damage when discharged deeply in seasons of little renewable power generation. Batteries are often the most expensive components of a renewable energy system, so the increased capital expenditure of a small petrol/diesel generator and occasional fuel costs can be justified in the long term. In addition to offering convenience to regular users of renewable power systems, dispatchable power is also necessary for certain critical loads, such as medical centres with vaccine fridges that must be kept cool or operating theatres with lights that must stay on (Dulas, 2013).

The design of a small wind power system is more complex than a comparable solar power system. Even if a wind resource assessment is conducted, confidence in energy yield predictions is likely to be lower. The electrical system for a SWT requires a controller capable of operating in diversion mode, a dump load and a brake switch, whereas a PV panel requires only a simple controller that is capable of disconnecting the panels when the battery is full (Piggott, 2000). Hydroelectric systems that produce AC may have an even more complex controller; however they eliminate the need for batteries and an inverter, two of the most expensive components (Harvey, 1993). What is more, system designers such as Ferrer-Martí *et al.* (2011) rarely take into account the relatively high O&M costs of SWTs when planning electrification projects, which can present the technology in an unfairly favourable light.

The modular nature of solar PV, makes it ideal for dispersed communities, where each household has a very low power demand and interconnection is not viable, as the cost of 1kWh from a 50W solar panel is similar to 1kWh from a 5kW solar array. In contrast, a 5kW wind turbine will produce much cheaper power than a 50W wind turbine, making wind more appropriate for higher power applications such as agriculture (irrigation, agricultural processing equipment), small businesses (power tools, fridges/freezers), community services (lighting and computers for schools or health centres, water pumping etc.) or a micro-grid to supply multiple households. Such applications can provide an anchor load, which can provide financial justification for rural electrification projects. The cost and risk involved with extending such a system to nearby houses is minimal compared to building a dedicated system purely for the households.

7.2.4 Installation

Table 7-4: Contextualisation of SWTs as a technology for rural electrification at the installation stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Modularity	Average	High	Low		Average	
Transporting materials to site	Difficult	Easy	Difficult		Easy	
Civil works	Average[135]	Simple[136]	Complex[137]		None[138]	

The modularity of solar PV makes its installation significantly easier, as not only can the energy system be broken down into individual panels (which are easier to transport and do not require the use of specialist machinery[139]), but the installation can also take place over an extended period of time. This allows power generation to begin as soon as the first panel arrives, whereas wind power systems require the transportation of not only the turbine, but also the tower and guy ropes, as well as the construction of the anchor points, before any power can be produced. However, this is significantly easier than hydro, where significant civil engineering works are required to channel the water down into the turbine. Nevertheless, these civil works do provide an opportunity for the community to contribute labour to the project, when they may be unable to contribute financially. This '*sweat equity*' also has the potential to increase the community's sense of ownership of the project and build local capacity for O&M, although the degree to which this is achieved depends heavily on the value that project is able to offer to the community (Hirmer and Cruickshank, 2014).

7.2.5 Operation

Table 7-5: Contextualisation of SWTs as a technology for rural electrification at the operation stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Training requirement	High[134]	Low	High		Average	
Fuel costs	None	None	None		High	
Susceptibility to environmental hazards	High[122]	Low[123]	Low[124]		Low	
Visibility	High	Average	Low		Average	

[135] Tower & foundations. Separate power house for larger systems.
[136] Mounting PV panels. Separate power house for larger systems.
[137] Forebay tank, Penstock, Separate power house for larger systems.
[138] Separate power house for larger systems.
[139] Larger SWTs require cranes to assemble the tower and larger hydro-generators may need to be helicoptered into particularly remote sites.

All three case studies have shown that weather is a huge problem for SWTs - lightning storms and high winds can destroy them if the user does not protect them. In a remote community there is often no warning that a storm is going to occur, however the Scotland case study has shown that access to weather forecasts via the internet or the radio can offer invaluable assistance to the end-users by alerting them of incoming storms. It also provides a valuable opportunity to plan the activities of the next few days according to how much wind is predicted, i.e. how much extra power there will be.

The fact that SWTs are located in prominent positions on top of tall towers gives them a significant advantage – they are very easy for operators to observe on a daily basis to check for faults. Whilst solar panels are often prominently displayed on top of a building or a pole, they show no visible signs of operation (Louineua, 2008). Hydro generators are often located far away from the community itself, as they are tied to wherever a suitable watercourse exists (Harvey, 1993).

7.2.6 Maintenance

Table 7-6: Contextualisation of SWTs as a technology for rural electrification at the manufacturing/acquisition stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Availability in remote locations	Low	Average	Average		High	
Potential for local manufacture	High[118]	Low[119]	High[120]		Low	
Modularity	Average	High	Low		Average	
Complexity of controller	Average	Simple	Complex		Average	
Transporting materials to site	Difficult	Easy	Difficult		Easy	
Training requirement	High	Low	High		Average	
Community technician	Essential	Optional	Essential		Optional	
Susceptibility to environmental hazards	High[122]	Low[123]	Low[124]		Low	
O&M ($/W)	High	Low	Medium		Medium	

Evidence from all the case studies has shown that wind turbines have higher maintenance requirements than the other technological options for decentralised rural electrification. However, this fact is often neglected and has led to many of the SWTs installed in remote communities falling into disrepair indefinitely due to lack of adequate support after the installation has taken place. Access to the relevant tools, technical knowledge and spare parts on a local level (see section 2.4) can empower communities and create a sustainable solution.

It is clear to see why a mechanical technology with many moving parts (SWTs) has higher maintenance requirements than a solid-state electrical device (PV). However, when comparing with the two other mechanical technologies, micro-hydro and petrol/diesel generators the distinction is less obvious. The frequency of failures is likely to be higher for SWTs due to the fact that they are, by design, exposed to the full force of the weather. The variable nature of the wind resource subjects them to dynamic loading that frequently leads to fatigue failures of critical components. By exposing a SWT to the wind, it is also vulnerable to higher levels of corrosion from the rain (and salt spray in coastal locations), to overheating and thermal fatigue from the heat of the sun and to lightning strikes. In fact it is remarkable that SWTs survive for as long as they do under these conditions - there are few other electrical machines that would be as comfortable as they are sitting on top of a tall tower waiting for the weather to tear them to pieces.

What is more, after a failure has occurred, it is relatively easy to perform maintenance on a petrol/diesel or hydro generator, as they are normally kept inside. However, a SWT is at the top of a tall tower that must first be lowered and if the weather is bad, carried inside (if it is even possible to lower the tower at all due to the safety risks presented by lowering the tower in high winds).

Due to the relatively low power density of the wind resource, SWTs are physically much bigger than hydro or diesel/petrol generators of equivalent rated power. As a result, it is much more difficult to carry them to a service centre when a more specialist repair must be performed. The solar resource is of comparably low power density; however a solar array can be easily disassembled into lightweight, people-sized modules.

It is possible to manufacture wind turbines locally and because of the increased maintenance requirements, it is much more worthwhile to do so. Machines that are to be installed far from where they are manufactured need to be very reliable, as the supply of spare parts is difficult. Less reliable machines need to be installed in places where spare parts, tools and technical knowledge are readily available, ideally close to the manufacturer. As a result, both the importation of high quality machines or the local manufacture of less reliable SWTs can work, however installing poor quality machines in remote places without any provision for maintenance services is sure to end in failure.

In Scoraig, the manufacturer is located in the community itself, eliminating the long and expensive supply chains seen in Peru and Nicaragua. The cost of the labour involved at all stages of the technology life cycle is much more likely to be affordable to the end-users if the labour comes from the community itself. This is particularly important for maintenance, as an engineer from the city expects higher wages and the cost of their travel out to the remote community must also be covered. Because of the distances involved, this often means that the engineer would take a number of days to do what could be done by a local technician in under an hour, increasing the labour costs even further and pushing the costs of maintaining a SWT out of the reach of many rural communities. The argument for local maintenance services is strengthened even further when considering the fact that the high maintenance requirements of SWTs mean that there is a higher potential for feeding money back into the local economy by creating local jobs. This in turn can increase the value of the project to the community as a whole and therefore build a lasting sense of ownership of the technology.

The issue with providing maintenance services locally is that the level of education among potential community technicians is typically very low. Empowering these people with the skills with which to be able to maintain a SWT is not an easy process, however the case study evidence has shown that practical learning opportunities hold the key. Whilst these people may have had little formal education, their practical skills are highly developed. As a result, Table 7-7 shows how practical learning opportunities such as training courses at demonstration centres or seeing the technology in action at a neighbouring house/community or involvement in the installation of a SWT are key ways to transfer knowledge. What is more, the case studies in Nicaragua and Scotland have shown that local manufacture offers the unique opportunity to involve community members in the construction, as well as the installation of a SWT.

Table 7-7: Empowerment of community technicians through practical learning opportunities.

Country	Community	Implementing organisation	Practical learning opportunities	Abilities of community technician
Inner Mongolia	Various households	IMS&TC	Participation in installation, training course at RE demo. centre, SWTs at neighbouring houses	Preventative maintenance, basic & some advanced corrective maintenance, upgrade
Case study I: Peru	El Alumbre	Soluciones Prácticas	Participation in installation, training course at RE demo. centre	Preventative maintenance, basic & some advanced corrective maintenance
	El Olivo/Paranchique/La Florida	WindAid	Participation in installation	None
Case study II: Nicaragua	Monkey Point	blueEnergy	Participation in installation, training course at RE demo. centre	Preventative maintenance & basic corrective maintenance
	Cuajinicuil	blueEnergy/Aso Fenix	Participation in installation & construction, training course at RE demo. centre	Preventative maintenance, basic & some advanced corrective maintenance, upgrade, installation
Case study III: Scotland	Scoraig	Scoraig Wind Electric	Leading installation & construction, running training courses at RE demo. centre, conducting research	All stages of the technology lifecycle

In situations when it is not practical to construct SWTs in the community in which they will be installed, a network of service centres is needed to bridge the gap between the manufacturer and the community. Such networks have allowed cars, bicycles and petrol/diesel generators to spread all over the world. The fact that this network was so extensive in Inner Mongolia allowed the technology to spread all over the region, regardless of where the manufacture of the machines took place. What is more, the fact that motor vehicles were common amongst herdsmen meant that a similar maintenance infrastructure already existed and that many people already had technical knowledge of the key components (bearings, generators and DC electricity). Deliberately targeting regions where the SWT maintenance infrastructure can 'piggy-back' on other technologies in this way is recommended.

In the early stages of establishing SWTs in a new area, the evidence from Nicaragua and Scotland has shown the importance of working with particularly creative and proactive communities, who are familiar with alternative technologies and are willing to adapt their lives accordingly. For community electrification projects, the ability of either the community or an individual within the community to organise the end-users and collect funds and then to carry out maintenance is essential and the identification of suitably motivated individuals has been shown to be of critical importance in establishing ownership of the project and therefore ensuring its longevity. Whilst the contribution that communities make to the maintenance fund can be seen as an indication of the value that they place on the technology, ensuring that sufficient funds are available is also a difficult issue, as many rural communities have little or no disposable income. In such cases, finding productive uses of electricity that match with the seasonal availability of the wind resource is essential.

7.2.7 Upgrade/disposal/reuse

Table 7-8: Contextualisation of SWTs as a technology for rural electrification at the manufacturing/acquisition stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Availability in remote locations	Low	Average	Average		High	
Potential for local manufacture	High[118]	Low[119]	High[120]		Low	
Modularity	Average	High	Low		Average	
Complexity of controller	Average	Simple	Complex		Average	
Transporting materials to site	Difficult	Easy	Difficult		Easy	
Civil works	Average[135]	Simple[136]	Complex[137]		None[138]	
Training requirement	High[134]	Low	High		Average	
Upfront capital ($/W)	Medium	High	Low		Low	
Potential for reuse	High	Average	High		Low	

The issues surrounding the upgrade/disposal/reuse stage are very similar to those surrounding maintenance, installation and system design, i.e. adequate supply chains need to be in place to get the new equipment to the community and technical knowledge is needed to plan extensions to the existing power generation capabilities. Solar PV is the simplest upgrade to add to a system as it is modular and easy to install, meaning that it is realistic to assume that many community technicians may be able to plan and carry out the upgrading of their own renewable energy systems using solar PV. However, both SWTs and micro-hydro are significantly more complex and therefore almost all communities will be reliant on their equipment supplier to plan and carry out an upgrade with these technologies. Due to the large amounts of civil works required, the potential for reusing parts of obsolete SWTs is quite high. What is more, the case study work in Scotland (Chapter 6) has shown that the lifetime of LMSWTs can be greatly extended, as individual parts can continually be replaced with new or second hand components when necessary.

7.2.8 Research

Table 7-9: Contextualisation of SWTs as a technology for rural electrification at the research stage of the technology lifecycle,

	Wind	*Solar PV*	*Micro-hydro*		*Diesel/petrol*	
	Battery	*Battery*	*Battery*	*Direct*	*Battery*	*Direct*
Ease of collecting data on power performance	Difficult	Easy	Average		Easy	
Potential for local manufacture	High[118]	Low[119]	High[120]		Low	

The fact that SWTs can be manufactured locally opens the door for user feedback from each particular local context to be incorporated into changes in the design. This is a much smaller feedback loop than exists for solar PV, which from the point of view of not just the end-users, but also the whole ecosystem of market actors within a particular local context, is essential a 'black box' technology.

7.3 The SWT ecosystem framework

The concept of seeing this network of actors as an ecosystem was originally adapted from management theory into the world of energy access by Practical Action (2012), however this thesis has focussed this framework onto finding the ecosystem conditions necessary to promote rapid growth in access to energy services through SWTs. Figure 2-2 illustrates the key components of this SWT ecosystem and the following section presents a cross-case comparison of the evidence presented throughout this thesis (summarised in Table 7-10).

Table 7-10: Comparison of the SWT ecosystem in each case study.

		Inner Mongolia	*Case Study I Peru*		*Case Study II Nicaragua*		*Case Study III Scotland*
	Key actor	IMS&TC	WindAid	Soluciones Prácticas	blueEnergy	blueEnergy /AsoFenix	Scoraig Wind Electric
	Community	Household Wind Generators	Various	El Alumbre	Monkey Point	Cuajinicuil	Scoraig
Enabling environment	Environment	High & evenly distributed wind resource, few hazards.	Highly variable wind resource, few hazards. High altitude.		Low wind resource, many hazards. Solar peaks in same season, no hydro.	Highly variable wind resource, few hazards. Solar peaks in same season, hydro in opposite.	High & evenly distributed wind resource, few hazards. Solar peaks in opposite season, hydro in same.
	Policy	Strong institutional support for over 20 years.	SWTs included in latest rural elec. strategy.		SWTs not included in latest rural elec. strategy.		Strong institutional support in recent years.
	Capacity	Regional wind resource assessment sufficient due to simple terrain. High wind power awareness level.	Good wind data available. Low wind power awareness level.		Good wind data available. Low wind power awareness level.		Good wind data available + operating experience from neighbouring sites. High wind power awareness level.
	Finance	End users with sufficient capital.	International volunteers fund pilot projects.	International donors fund pilot projects.	International donors fund pilot projects.	International donors fund pilot projects.	End users with sufficient capital.
Supporting services		Strong collaborations with many universities. Easy access by motorbike.	Collaboration with some universities. Poor transport infrastructure.	Strong collaborations with many universities. Poor transport infrastructure.	Collaboration with universities. Poor transport infrastructure.	Collaboration with universities & average transport infrastructure.	Strong collaboration with many universities & good transport infrastructure.

	Inner Mongolia	*Case Study I Peru*		*Case Study II Nicaragua*		*Case Study III Scotland*
Market actors	Many manufacturers, demo/training centres & well established service network.	No service or demo/training centres.	Service & demo/training centres near communities.	Service & demo/training centres, but far from communities.	Service & demo/training centres near communities planned.	Piggott performs all roles from within the community.
Community, enterprise & end-users	Empowered end-users. Feedback collected by service centres.	Community technician unable to perform O&M. Feedback collected by NGO & open-source Piggott design.	Empowered community technician & end-users. Feedback collected by NGO & open-source Piggott design.	Community technician able to perform only basic O&M. Feedback collected by NGO & open-source Piggott design.	Empowered community technician & end-users. Feedback collected by NGO & open-source Piggott design.	Empowered community technician & end-users. Feedback collected on a daily basis & open-source Piggott design.
Scale	100,000+ SWTs. Sustainable.	10+ SWTs. Not yet sustainable	<100 SWTs. Not yet sustainable.	10+ SWTs. Not sustainable.	1 SWT in new context. Pilot project sustainable.	100+ SWTs. Sustainable.

7.3.1 Enabling environment

The enabling environment is analogous to the natural environment in natural ecosystems. It describes a particular local context in terms of its suitability for SWTs and is divided into four dimensions: finance, capacity, policy and environment.

7.3.1.1 Environment

The wind resource itself is the most fundamental environmental characteristic of each local context, however proper assessments are often not carried out until after SWTs have been installed to determine why energy yields have been disappointing. The wind resource is more difficult to predict than the solar resource, yet predicting it is far more important for system design. The topography has a huge influence on the wind resource, with simple, flat, unobstructed terrain, such as the plains of Inner Mongolia, the most favourable for SWTs. In complex terrain, such as the high peaks of the Peruvian Andes, the spatial variation of the wind resource is extremely high, making individual household SWTs impractical. However, such topographical features (hills and ridges) can provide opportunities for '*micro-siting*' (Piggott, 2000). In such situations, even though it will add significantly to the amount of planning and upfront capital required, it is absolutely essential that an individual resource assessment is carried out for each new site, as the risk of disappointing energy yields is high.

In Nicaragua and Peru, the magnitude of the wind resource varies an incredible amount across the country and doesn't necessarily correspond to the spatial distribution of people without access to electricity. The need to generate revenue with which to pay for the high O&M costs of SWTs can be met by using the generated electricity to improve existing productive activities. As many of the rural poor are subsistence farmers, areas where the wind resource peaks in the dry season provide a key revenue generating opportunity in the form of irrigation (Practical Action, 2012).

The case studies in Nicaragua have shown that the combination of heat and humidity characteristic of tropical climates can create an incredibly corrosive environment when combined with high salinity in coastal locations. Lightning strikes can also cause serious damage to SWTs, which are often the highest point in the surrounding area. In such places, the ability of the community to repair the machines autonomously is absolutely vital; otherwise the cost of maintaining such machines quickly spirals out of control.

> *"[SWTs are] an extra option when the other technologies aren't viable"*
> *(Craig, 2013)*

The viability of other renewable resources in a particular place is also extremely important in determining the viability of wind power. Solar PV is simpler and micro-hydro is more cost-effective than wind, so SWTs should not be employed if either of these technologies is capable of meeting demand throughout the year for an affordable price. Evidence from Scoraig has shown that the falling price of solar PV has actually increased the viability of solar PV in this local context. In Northwest Scotland, the solar resource drops to almost nothing during the short winter days, making PV-only systems unviable. However, the wind resource is significantly lower in the summer, making PV-wind hybrid systems the topology of choice in that particular place.

7.3.1.2 Capacity

Wind power awareness level

Yadoo (2011: 181) stated that there is a need for "*widespread awareness of the range of off-grid electrification options and their respective advantages and disadvantages*." However, the case study work in Nicaragua has shown that there is often a lack of knowledge about wind power at all levels that is significantly inhibiting its growth: most rural communities are unaware that it is even an option, suppliers are unclear on how to select a site, install and maintain SWTs and policy makers are unaware of how to identify viable regions for the technology and support its development in these places. Almost every aspect of wind power is more complicated than solar PV - as a result, the technology requires a much greater support network. The international association, WindEmpowerment, has a critical role to play in providing technical knowledge and experience of what works and what doesn't in different local contexts to the various actors around the world who are currently battling with wind-based rural electrification, as well as those who work in viable regions but are not even aware that it is an option.

Energy data availability

The Peru and Nicaragua case studies illustrate the fact that whilst government ministries in many developing countries have made significant efforts to improve the availability of wind resource data, this is often targeted towards utility-scale development. Whilst this data is still relevant to small scale wind projects, it is not as useful as data created specifically for small wind projects, i.e. high resolution wind maps at 10-20m hub height with anemometry points in the regions where small wind is most viable.

7.3.1.3 Policy

Policy has a significant role to play in supporting the development of the SWT ecosystem in each local context, particularly when attempting to establish an industry based on local manufacture. In Inner Mongolia, the government agency, the IMS&TC fostered the development of such an industry by first identifying Inner Mongolia as a region with good wind, where local resource assessment would not be necessary due to the simple terrain, and then supporting the development of the technology, demonstrating it to end users and then collecting feedback from them (Batchelor *et al.*, 1999). This political support continued for over twenty years, allowing SWTs to grow from the demonstration stage (similar to the projects studied in Peru and Nicaragua) to widespread adoption (Batchelor *et al.*, 1999).. Although it has not been demonstrated through the case studies included in this thesis, the development of product quality standards is also expected to be a particularly important role for governments to play, as recent work in Kenya has shown that the production of poor quality machines by a variety of informal manufacturers has diminished the reputation of the technology as a whole (Vanheule, 2012). Evidence from Nicaragua and Scotland has shown that favourable policies towards grid-connected SWTs can have the knock-on effect of strengthening the ecosystem for their off-grid counterparts.

7.3.1.4 Finance

The analysis of lifecycle costs presented in both the Nicaragua and Scotland case studies has shown that the falling price of solar PV has led to a cost per watt close to that of a SWT. What is more, the O&M costs are much higher and the expected lifetime is much shorter for SWTs. However on a good site, a SWT will produce more energy and consequently, the LCoE will often be lower, especially if using locally manufactured technology.

The fact that the costs of wind power are much more evenly distributed throughout the lifetime of the system means that it is not well suited to the donor model, as most donors seek to fund upfront capital expenditures and are reluctant to fund on-going costs such as O&M (Ferrer-Martí *et al.*, 2011). As a result, evidence from both the Peru and Nicaragua case studies has shown that many donor funded SWT installations are now out of service due to the lack of funds with which to pay for repairs. Donors often fund SWT projects with the aim of freeing rural communities from dependence on foreign fuel imports; however in many cases such projects have merely replaced this dependency with a dependency on spare parts for SWT. Unfortunately, whilst the distribution network for fossil fuels is very well established, the SWT spare part supply chain is often weak and unreliable. As a result, many communities who have supposedly benefited from donated SWTs are in fact worse off than they were before, as each time a failure occurs they are faced with a big bill to pay and no electricity to generate revenue until it is paid. What is more, there is no guarantee as to how long the system will work for before the next failure occurs and the next big bill arrives. In contrast, the fluctuations in petrol/diesel prices seem relatively insignificant.

However, it appears that SWTs are more appropriate for a commercial model, in which the end-users purchase a SWT with their own funds (the same model that has allowed small diesel/petrol generators to reach many remote settlements). In both Inner Mongolia and Scotland, where SWTs have successfully been providing access to energy services for over 30 years, the fact that the lifecycle costs were spread more evenly over the lifetime of the system made a SWT more attractive than PV, as the initial capital cost was therefore low enough for end-users to be able to purchase a SWT without any form of loan. In Inner Mongolia, herdsmen had animals that they could sell at market, whilst in Scotland; income levels were already sufficiently high.

However, in many other developing country contexts, the lack of access to capital for this initial purchase is a significant barrier, albeit a smaller barrier than for a similar sized solar PV system. As a result, innovative financing mechanisms are needed, such as pay-as-you-go solutions, where a private company finances the installation and maintenance and generates revenue over the lifetime of the system through the collection of funds for each kWh that the end-users consume (Rolffs *et al.*, 2014). An alternative strategy is to use the electricity to generate revenue, with which to pay back the initial capital costs, cover O&M costs and make a profit. This would involve linking the SWT to existing productive activities or creating a new micro-enterprise. Designing the system around an anchor load (e.g. irrigation, agricultural processing) can offer financial sustainability to a SWT installation, as the extension of a micro-grid to nearby houses carries only a small additional cost. However the case study in Cuajinicuil, Nicaragua illustrates that if there are problems with this anchor load (in this case, delays in digging the well from which to draw water for irrigation), then the whole system suffers due to the lack of capital with which to purchase spare parts.

The energy systems modelling conducted in Scotland has shown that provided that sufficient local technical knowledge and access to the relevant tools and spare parts are available, then locally manufactured technology can offer savings of more than 20% on the NPC of a commercial system. What is more, Figure 6-36 shows that the costs of an LMSWT are distributed even more regularly throughout the lifespan of the energy system than an imported SWT. This is due to both the higher retail price of mass-produced technology and the addition of import taxes of 10-20% and shipping charges of a similar amount. It should be noted that the modularity offered by solar PV offers a similar option for reducing upfront costs, i.e. a smaller number of panels can be purchased and further panels can be added throughout the lifetime of the system as more funds become available.

7.3.2 Supporting services

In all the case studies, collaborations with local universities and research institutions have offered significant benefits, most notably, technical improvements to the design and enhanced capacity for wind resource assessment. They also have a significant role to play in training future engineers, social scientists and policy makers with skills that are relevant to wind power. Utility-scale wind farm developers also have the potential to provide both technical and financial support to SWT initiatives through the sharing of wind data, secondment of trained personnel and allocation of funds through corporate social responsibility schemes. Consumer and industry associations, such as *Renovables* in Nicaragua draw together the market actors in a particular region and give them a voice to lobby for policy changes. Internationally, the *WindEmpowerment* association facilitates the sharing of knowledge between actors in different countries, sharing experience of what works and what doesn't across the globe.

The state of the existing national grid infrastructure in a particular location also has a number of implications for rural SWTs. The Nicaraguan example has shown that it is not just the location of the current electricity grid that is important, but also where it will soon be extended to that will govern whether or not SWTs should be promoted in a particular region. Electricity is needed to produce them and although it is possible to produce them using the electricity from a SWT (as is the case on Scoraig); it is much easier to do so using grid electricity, especially when producing at scale. As a result, this means that most manufacturers are located in areas far away from the rural communities where the SWTs will be installed, leading to the long and problematic supply chains seen in Nicaragua. The lack of existing transportation infrastructure in remote regions creates significant challenges for the exchange of equipment, tools and spare parts and is addressed in different ways by the various market actors.

7.3.3 Market actors

Due to the lack of ecosystem members in Peru and Nicaragua, NGOs have taken on the roles of many different market actors. For example, blueEnergy manufactured SWTs on the Caribbean coast of Nicaragua, but also supplied the technology to the communities, offered maintenance services and established a training and demonstration centre. Whilst this shortened the supply chain between actors, a long supply chain still existed between the NGO and the community. Soluciones Prácticas bridged this gap by offering maintenance services from its regional office just a few hours from the communities it served (as opposed to almost a full day's travel from the manufacturer). In Inner Mongolia, the establishment of a service network allowed SWTs to spread throughout the entire region, regardless of where the manufacturers were located. In Scoraig, all of these market actors (apart from the construction materials supplier) were located in the community itself, eliminating the need to transfer knowledge, tools, spare parts or equipment between them.

The two contrasting models show that both centralised and decentralised manufacture of SWTs can work, as long as they are properly supported. In the case of centralised manufacture, this requires a network of service centres to allow the transport of equipment, tools and spare parts out to the communities, whilst in the case of decentralised manufacture, the transport of construction materials and equipment out to the community is the major challenge. In both cases, the empowerment of rural communities with technical knowledge is essential; however the challenge is even greater for decentralised manufacture.

The centralised manufacture approach holds the promise of reaching supply chain maturity, with the fabled benefits of economies of scale, standardisation and widespread adoption. However, evidence from Peru and Nicaragua has shown that there is a significant hurdle to overcome at the beginning, where the end-users are far away from the manufacturer and the low volume production of poor quality SWTs creates a false economy, where maintenance costs spiral out of control. In contrast, whilst the decentralised, '*small is beautiful*' approach promoted by Schumacher (1973), is difficult to replicate, as its success hinges so much on the technical ability and motivation of the entrepreneur who is producing the SWTs for their community. They must be willing to fulfil every single stage in the technology lifecycle (see Figure 2-3) and run the risk of becoming the '*jack-of-all-trades*', but master of none.

7.3.4 Community, enterprise & household

In community electrification projects, the community technician is the single most important actor in each individual project. The empowerment of the community technician is absolutely essential to the sustainability of SWT-based rural electrification initiatives. It is far more important than for solar PV, as the level of technical knowledge required to operate, maintain and upgrade SWTs is much higher. Evidence from Peru and Nicaragua has shown that the consequence of low levels of knowledge transfer to the community technician results in numerous lengthy journeys to and from the community on the part of equipment supplier and/or long periods without electricity for the community. With their unique knowledge of the community they live in, empowered community technicians can also help adapt the technology so that it best meets the needs of the community and create links to existing productive activities with which the SWT can generate revenue to sustain its high O&M costs. Both the Cuajinicuil case study in Nicaragua and the Scoraig case study show that empowered community technicians can really drive a project forward and make wind power work for their own community.

Empowering community technicians is not an easy process and requires a concerted effort by a number of different actors: the equipment supplier can involve future community technicians in the installation of SWTs in their community, training centres can provide specialist courses on SWT O&M, manufacturers can offer the chance to participate in the construction of a SWT and service centres can offer technical support at a local level for particularly difficult issues. When the technology becomes established in a particular area, then the role of neighbouring houses/communities in transferring technical knowledge to new users becomes significant. The Inner Mongolian experience shows that when employing individual household SWTs, the end-users themselves are able to take on the role of performing O&M (supported by neighbours and the network of service centres), a finding that was replicated in Scotland. This shows that despite the high level of technical knowledge required, it is possible for somebody from every household to operate and maintain a SWT, even in places with relatively poor levels of education.

7.4 Conclusion

The cross-case analysis conducted in this chapter has shown that the most important issues relating to SWTs as a technology for rural electrification are the variability in the wind resource, the lack of modularity, high maintenance requirements and the high level of technical knowledge required at every stage of the technology lifecycle. Each local context is different and exactly how SWTs are supported by an ecosystem of actors is different in each place. However, the most important roles within this network are supporting the assessment of the wind resource (identification of windy areas, technical & financial support for individual site assessments), empowering of community technicians/end-users (practical training courses, participation in the installation/construction, local support from a service centre) and raising the level of awareness about the advantages and disadvantages of SWTs (technical training for all market actors and supporting services).

Chapter 8. Conclusion

8.1 Introduction

This PhD sought to identify the factors that affect the viability of SWTs as a technology for rural electrification across a variety of local contexts. Case study research in Peru, Nicaragua and Scotland has shown that the differences between local contexts have a greater influence on the success of SWTs than their closet equivalent, solar PV. Firstly, the following key factors show that the range of environments in which SWTs can be successfully employed is more limited:

- *Highly variable resource*: the wind resource has a much greater spatial variation than the solar resource, yet power production is cubically proportional to the wind resource and only linearly proportional to the solar resource. Fewer places have a sufficient wind resource for SWTs and determining where these places are is more difficult than for solar PV. Scaling up SWTs is therefore problematic anywhere other than across vast, windy, flat plains with few obstructions (i.e. where individual site assessment is unnecessary).
- *Lack of modularity*: the greater modularity of solar PV allows it to reach further into the most remote and dispersed communities than SWTs (however, the simpler the terrain, the more modular SWTs become, as smaller turbines can be employed on a wider range of sites in a given area).
- *Susceptibility to environmental hazards*: lightning strikes, corrosion, hurricanes, etc. all affect SWTs more than solar PV or even micro-hydro.

This research has also investigated how communities access the technical knowledge, equipment, tools, spare parts and capital needed to maintain an effective energy system. One of the central findings is that, contrary to initial expectations, a key factor in the sustainability of SWTs was the robustness of this social infrastructure. The following factors were found to be most important:

- *High maintenance requirements*: this necessitates the support of a service network, which can only be established in regions with a critical mass of potential SWT users (which is often limited by the high spatial variation in the resource). As a result, SWTs are not recommended in the most remote areas, unless service centres (or better, decentralised manufacturing manufacturing) can be established in these remote communities themselves. The empowerment of the community technician, who is responsible for the day to day O&M of the systems installed in their community, is key in achieving sustainable wind based electrification.
- *High level of technical knowledge required*: SWTs require more technical knowledge and therefore more support at almost every stage of the technology lifecycle in order to reduce the risks involved with identifying sites with sufficient wind resource, manufacturing SWTs of sufficient quality, etc.
- *Financing*: solar PV fits well with donor financing (high upfront capital, low O&M), however SWTs fit better with a commercial model (using the electricity for revenue generation), as more power can be generated per watt, but O&M costs are high. The falling price of solar PV

means that the price per watt it is now comparable to SWTs, however on a good wind site (>5m/s) SWTs have a higher capacity factor and therefore a lower unit cost ($/kWh).

The direct consequence of this is that SWTs cannot be seen as a technology that can simply be '*copied and pasted*' from one local context to another; they must be seen as locally embedded socio-technical systems. Each local context is different and requires proper evaluation of the wind resource, settlement patterns, the potential for establishing a service network, the level of existing capacity relating to wind power and all of the other critical factors identified in Chapter 2. Moreover, the way that the social and the technical factors interact is also unique to each local context.

8.2 SWTs as socio-technical systems: the ecosystem perspective

This PhD sought to examine and understand more about how and why the factors that affect the viability of SWT vary between places. To address this, the thesis explored the implications of looking at SWTs as existing within an ecosystem (Practical Action, 2012; Practical Action, 2013), which is comprised of both social and technical components. Just as people depend on the electricity that SWTs produce, SWTs depend on people to manufacture, select a site for, design a system around, install, operate, maintain, upgrade and conduct research to improve them. Without an ecosystem of actors that are capable of supporting them, SWTs cannot provide a sustainable solution for rural electrification. The ecosystem perspective allows appreciation of the fact that it is not simply the influence of each component that governs the overall sustainability of the system, but also the interaction between these components. For example, the case study in Nicaragua has shown that the high frequency of lightning strikes was one of the key reasons why wind-based rural electrification on the Caribbean coast of Nicaragua failed. It could therefore be reasonably assumed that any other place in the world that has frequent lightning storms is not appropriate for SWTs. However, this simplistic viewpoint neglects the fact that it was the combination of this technical component with other components (both social and technical, some of which are generic and some of which are specific to the Caribbean coast of Nicaragua) that make this an inappropriate local context for SWTs. In other local contexts, where performing maintenance is easier (better transportation infrastructure, more motivated community technicians etc.) and the wind resource is better (which increases the value of the technology to the community) then the problem of lightning strikes could have been overcome by performing more frequent repairs.

The original contribution to knowledge made by this thesis is the presentation of a distinctive analysis of the factors that enable and constrain the effectiveness of SWTs as a tool for rural electrification through the study of a number of specific cases and by comparison to the technological alternatives for decentralised rural electrification. Whilst a significant body of literature exists with regard to the technical optimisation of SWTs for rural electrification (Freere, 2010; Ghimire *et al.*, 2010; Latoufis and Kotsampopoulos, 2010; Mishnaevsky Jr *et al.*, 2011) and some social science literature has also been published (Vanheule, 2012), little published work is available that encompasses both the social and the technical to offer a holistic viewpoint on what makes the technology appropriate (or not) for each local context. With case studies in Peru, Nicaragua and Scotland, this PhD has contributed new empirical material, which has been used to develop a conceptual framework (Chapter 2) that brings together the social and technical. Throughout the thesis the two have co-evolved, with the data building the framework and the framework directing data collection and analysis. This has resulted in theory that is firmly grounded in reality (Eisenhardt, 1989).

8.3 Summary of case studies

The following section summarises the research conducted in each case study, highlighting what was learned in each place and tying this into the broader aims of the thesis. As mentioned previously, the fact that the framework was developed throughout the course of the research means that the methods employed and the data collected in each place are a reflection of both the experience of the author at that time, as well as the issues that are relevant to that particular place. A multidisciplinary mixed methods approach was employed and the range of methodologies employed became broader, yet each technique became sharper, as the research progressed. This allowed the findings of each case study to dig deeper and deeper, reaching closer and closer to the fundamental reasons why SWTs were working (or not) in each particular place. The complementarity of the methodologies offered triangulation of the key findings where they overlapped, adding further weight to the constructs developed. When they did not, they offered the opportunity to fill in the gaps left by each individual technique. What is more, the author's unique position as an engineer, as well as a social scientist, offered the opportunity to become part of the socio-technical system under study, giving access to and a greater understanding of both its social and technical components.

The major drawback to this approach was that the data analysis was much more difficult, as the evidence available to assess each case was different. Furthermore, the author did not begin the research as a social scientist. The learning of new skills, methodologies and epistemologies occurred throughout the research, resulting in a gradual transition from engineer to multidisciplinary researcher. As a result, the quality of the evidence from the first case studies was also lower and only limited conclusions could be drawn from them. This meant that the influence of factors found to be critical in the final case study could not always be verified with the previous cases. As Eisenhardt (1989) warned, the incredible volume of data generated from case study work made taking an overall perspective extremely difficult. Distilling what really mattered in each place and developing an overall theory that was simple enough to be useful to readers of the research was an incredibly challenging task.

Doing so was a highly iterative process that involved the continual validation of the new parts of the framework by cross-checking the constructs emerging from one case with evidence from the other cases. Fortunately, the multidisciplinary mixed-methods approach offered the ability to see the evidence through many difference '*lenses*' and ensured that a wider evidence base was available to test any new constructs that began to emerge. This process continued throughout the course of the research and ended only when the marginal improvement to the framework from further revision of the case study evidence became negligible. Even now, the framework cannot be considered complete, as even at this addition of evidence from subsequent cases would likely result in the revision of the resulting theory in some way.

8.3.1 Peru

In the first case study, the delivery models employed by two separate NGOs in the Northern Peruvian Andes were compared. The post-installation record of the SWTs installed by each organisation was used to evaluate the performance of the delivery models they had employed. It was found that the strategy for providing access to maintenance services had the biggest effect on the sustainability of the SWTs installed in this local context. Due to the poor transportation infrastructure in this region, empowering a community technician to be able to perform maintenance themselves was found to greatly increase the amount of time that SWTs spend in operation and therefore the overall sustainability of such installations. SWTs require a high level of maintenance and sending engineers out to these remote communities every time a failure occurs is impractical[140]. Technical training for a designated community technician, who is supported by a service centre in the local area, is therefore considered to be an essential component of sustainability in particularly remote communities.

8.3.2 Nicaragua

The lack of qualitative data obtained in the rural communities themselves significantly restricted the conclusions that could be drawn from the case study work conducted in Peru. As a result, detailed ethnographic work was conducted in Nicaragua in two separate rural communities on opposite sides of the country. Qualitative data collection tools offered the opportunity to fill in gaps left by the predominantly quantitative approach adopted in Peru, enabling the author to gain a much more complete picture of what had happened to each individual SWT since it had been installed. On the Caribbean coast of Nicaragua, many SWTs have now been replaced by solar panels, due to the combination of poor wind resources with significant environmental hazards, which led to frequent failures. A lack of access to maintenance services in this remote region meant that the majority have spent the more time out of service than operational. Although significant efforts had been made to empower community technicians, most communities could only be reached by a long and expensive boat ride and the lack of wind resources significantly reduced the value that the technology provided to the community, as the amount of energy actually produced by the SWTs was too small to be worth making these regular journeys to obtain spare parts.

A subsequent pilot project in which an identical SWT was installed in the central highlands was found to be much more successful, showing that the context in which a SWT is installed is as important as the technology itself. In the central highlands, the wind resource is superior, there are fewer environmental hazards, the existing transportation infrastructure is much better (just 3 hours by road to the capital) and an even higher level of training ensured that the community technicians were

[140] At least one journey per turbine per year is expected, which often involves a multi-day trip to perform a task that may take just a few hours, purely because of the length of the journey.

capable of performing all but the most complicated maintenance operations themselves. However, the lack of access to capital with which to pay for spare parts still hindered the project due to the difficulties in establishing economically productive uses for the energy generated by the SWT.

Assuming that this problem could be addressed, the question was then: *how scalable was the technology across Nicaragua*? A methodology by which to evaluate the size of the potential market for SWTs was developed that recognised the fact that many of the factors that affect the viability of SWTs are place specific. It was found that although Nicaragua has world class wind resources, they are not located in the same parts of the country as the people without access to electricity. Although a small market was found to exist in the central highlands and south Pacific coast, the wind resource in the former has a high spatial variation due to the topography and grid electrification had already reached most people in the latter.

The ecosystem framework was used to determine the state of the SWT ecosystem in Nicaragua and provide constructive advice on how best to strengthen it with targeted interventions. Promoting SWTs through energy based enterprises in the regions with a critical mass of potential users to enable the cost-effective provision of maintenance services was found to be the most viable pathway for action.

8.3.3 Scotland

The final case study took place in the home community of world renowned SWT expert, Hugh Piggott. This case study saw the addition of participant observation to the mixed methods post-installation analysis techniques employed in the previous case studies. This gave valuable insight into the role that wind power plays in everyday life in this remote community, where SWTs have been supplying electricity for over 30 years. The favourable environmental conditions (including a high wind resource), use of hybrid systems to smooth out the variability in the wind, favourable economics, and the empowered and proactive end-users that were willing to adapt their lives around the wind were all found to be critical success factors. However, the key to the success of SWTs in this remote community was the fact that as the community technician, Hugh Piggott, was able to offer affordable, convenient and flexible maintenance services (as well as site selection, system design and installation) due to the fact that he lives and works in the community itself. This not only eliminated almost all of the supply chain issues[141] seen in the previous cases, but also allowed Piggott to respond rapidly to feedback from the end-users, ensuring that the SWTs he is responsible for continually evolve to meet their needs.

8.4 Why are so many SWTs out of service and what can be done about it?

This research has shown that SWTs are much more difficult to work with than solar PV. The resource is more difficult to assess (leading to SWTs installed on sites with no wind), transporting the

[141] Construction materials and equipment (batteries, inverters etc.) still had to be transported to Scoraig in the first place.

equipment is more difficult (making obtaining spare parts difficult) and performing maintenance is more problematic (meaning that significant effort must be made to empower community technicians). Lack of understanding of the technology and failure to establish the technology at a local level has resulted in SWTs all over the world falling into disrepair. SWTs require a high level of technical knowledge at almost every stage of the technology lifecycle, yet this knowledge is often simply not available. As a result, the technology is frequently employed in inappropriate locations, with insufficient support after installation. Consequently, in addition to the empowerment of community technicians, the empowerment of market actors and their supporting services through appropriate technical training is also seen as a prerequisite for successful wind-based rural electrification.

SWTs require significantly more maintenance than solar PV, but no more than cars, bicycles or many other products that are in common use around the world today. There is a popular misconception that the energy from a SWT is cheap or even free. In fact it is very expensive, as the cost of maintenance soon inflates the lifecycle costs[142], especially when there are large distances between the supplier/manufacturer and the communities they serve. If adequate provision is not made to offer access to maintenance services, then the dependence of communities on expensive diesel/petrol for generators is simply replaced by a dependence on bespoke spare parts that are often only available from a single organisation and are even more expensive, as they are manufactured in low volumes. Whilst manufacturing SWTs in rural communities is difficult and often impractical in a development context, providing maintenance services locally was found to be a critical factor with regard to sustainability. Training community technicians, who are supported by a nearby service centre reduces costs, reduces downtime and reduces the administrative demand on the original installer, who is often reluctantly responsible for providing maintenance services. What is more, it builds capacity, creates jobs and feeds money back into the remote communities that the SWTs were designed to empower. The identification and empowerment of sufficiently motivated individuals to provide these mainteance services is absolutely vital to the success of community electrification projects.

The wind resource itself is fundamentally less appropriate for rural electrification than the solar resource. It is more difficult to assess, yet an accurate assessment is more important for system design. It is more variable on both short and long-term timescales and has a greater spatial variation at local, regional, national and international scales. What is more, the global distribution of people without access to electricity matches the global distribution of the solar resource much more closely than the wind resource. Just like the hydro resource, the wind resource is extremely site specific and the high level of technical knowledge needed to successfully identify suitable sites has resulted in the installation of many SWTs in places that simply are not windy enough. It is easy to fall into the trap of thinking that almost anywhere is a suitable site for a SWT, as everywhere has at least some wind, whilst a site without a stream is clearly not suitable for hydroelectric power generation. It is the cubic

[142] Estimated at around 5-5% of capital costs per year with a 10-15 year lifetime, as opposed to just 0.5% and a 20 year lifetime for PV. Both are site dependent, but the SWT costs are extremely variable.

dependence of power on wind speed that makes SWTs installed on a site with less than 4m/s annual mean wind speed uneconomic compared to the other current technological solutions for decentralised rural elctrification. Unfortunately, most potential SWT sites around the world fall into this category, as buildings and trees block the wind, yet they are inherently linked to human settlement. The tops of hills are where the best wind resources can be found, however few people live in such inconvenient places and in many countries, even hilltops lack sufficient wind resource as if there is no wind at higher altitudes, adding a few tens of meters to the elevation of an SWT will still result in disapppointing energy yields.

As demonstrated in Inner Mongolia (where SWTs provide power to hundreds of thousands of households) vast flat plains with few obstructions are ideal, as individual resource assessents are unnecessary. In complex terrain (such as the Peruvian Andes or the central highlands of Nicaragua), where the wind resource varies wildly, a full resource assessment using an anemometer and datalogger must be conducted prior to installing a SWT in a new location, even though it will add signiificantly to the initial costs of the project. Experience from Scoraig has shown that once wind power is established in a rural community then the actual energy yields of existing SWTs can be used to estimate the resource available for neighbouring houses.

8.5 The future of SWTs for rural development

The combination of the high maintenance requirements with these fundamental problems with the wind resource itself implies that wind does not have the same potential for rural electrification as solar PV. The high spatial variation of the resource makes it difficult to reach the critical mass required in any given region to justify the establishment of a service network and higher volume manufacturing. However, comparing the global renewable resource maps with the global distribution of people without access to electricity in Appendix A shows that there are some regions of high wind resource where solar and hydro resources are not able to meet demand throughout the year, the most notable of which is Patagonia, the dry, cold and windy southern tip of Latin America. It is in niche locations such as this where SWTs can play the biggest role in bringing energy services to remote communities. In places such as Somalia, where the wind resource is excellent but the solar resource is high all year round, the potential for higher energy yields with larger machines[143] means that SWTs may still have an important role to play in providing affordable power to small businesses. Such a model can create an 'anchor load', which can be leveraged to create a local micro-grid in which neighbouring households are connected for a marginal extra cost.

Table 8-1 lists the critical success factors for SWTs by describing the ideal conditions for the dissemination of SWTs. It is not envisaged that any single local context will ever embody all of these characteristics, however it does provide a guide for policy makers wanting to determine if SWTs could be a viable technology in their local context and if so, how to support their dissemination. The

[143] SWT power production scales with the square of the radius, whilst the costs increase linearly.

environmental factors listed in Table 8-1 allow the identification of regions where SWTs have potential, which can also be guided by the decision support tree shown in Figure 8-1. In these regions, a market assessment should be conducted to determine how scalable the technology is and the current state of the SWT ecosystem. Targeted interventions can then be made to strengthen the ecosystem and create the market conditions in which SWTs can thrive.

Table 8-1: Ideal conditions for SWTs (the most critical factors are shown in italics).

	Environment	∗ *High wind resource (>4m/s monthly average throughout the year) in the regions where most people lack access to electricity.*
	Environment	∗ *Lack of environmental hazards (low frequency of dangerously high winds and lightning strikes and cool, inert environment to prevent corrosion, overheating or contamination with dust/sand).*
	Environment	∗ *Solar or hydro resources that peak in the opposite season to the wind resource and cannot provide sufficient power generation throughout the year.*
	Environment	∗ *Flat plains with no trees or other obstructions (to cause turbulence, reduce wind speeds and necessitate individual site assessment).*
	Environment	• Wind resource that peaks in the same season as traditional productive activities, e.g. dry season for farmers in need of irrigation.
	Environment	• High air density (cold, low altitude) for maximum power extraction and cooling of the generator.
Enabling environment	Finance	∗ *If there is insufficient access to capital, the potential for establishing energy based enterprises should be high and/or innovative financing models such as pay-as-you-go energy metering should be available.*
Enabling environment	Finance	∗ *Targeted subsidies for providing maintenance services or wind resource assessment can be effective*
Enabling environment	Capacity	∗ *High level of awareness of SWTs and understanding of the technical advantages and disadvantages.*
Enabling environment	Capacity	∗ *Freely available high quality wind maps (validated with anemometry in the areas where SWTs are most viable, of high resolution and relevant to low hub heights).*
Enabling environment	Policy	∗ *A realistic evaluation of the national potential for SWTs and a plan for how to achieve this potential, which forms part of national rural electrification strategy.*
Enabling environment	Policy	∗ *In complex terrain, individual wind studies should be supported for each new location.*
Enabling environment	Policy	∗ *Strong and consistent institutional support to foster the development of a strong SWT ecosystem, in particular the social infrastructure required for maintenance.*
Enabling environment	Policy	• Product quality standards that ensure consumer confidence, but don't unnecessarily hinder manufacturers.
Enabling environment	Policy	• Government endorsement to build trust in SWTs.
Enabling environment	Policy	• Tax exemptions for imported SWTs, wind pumps, power electronics and batteries.
Enabling environment	Policy	• Favourable feed-in tariff to encourage grid-tied SWTs.

Supporting services	* *Good transportation infrastructure that facilitates easy access to installation sites.* * *Consumer and industry associations that share knowledge between SWT market actors and give them a voice in the policy arena.* • Universities that are willing to collaborate with SWT market actors in specific research projects, as well as offering wind power related training. • Utility-scale wind farm developers willing to support SWT market actors with funds and experience. • Grid electricity available in a nearby town/city (if manufacturing centrally).
Market actors	* *A variety of training and demonstration centres that can raise awareness of SWTs and empower community technicians/end-users.* * *A network of service centres capable of bridging the gap between the supplier/manufacturer and the community by offering technical support for SWTs at a local level.* • A variety of construction material suppliers offering products relevant to SWTs (if manufacturing locally). • A variety of SWT manufacturers offering a range of products that are well matched to local needs. • A variety of SWT suppliers with regional branches in all areas where SWTs are viable, offering support for site selection and system design, as well as installation.
Community	* *High level of technical knowledge available at a local level.* * *Highly motivated individuals to take on the role of community technician.* * *End-users with sufficient capital to pay for O&M costs or a willingness to use the electricity to generate sufficient revenue.* • End-users that are willing to adapt their behaviour around the availability of the wind resource.

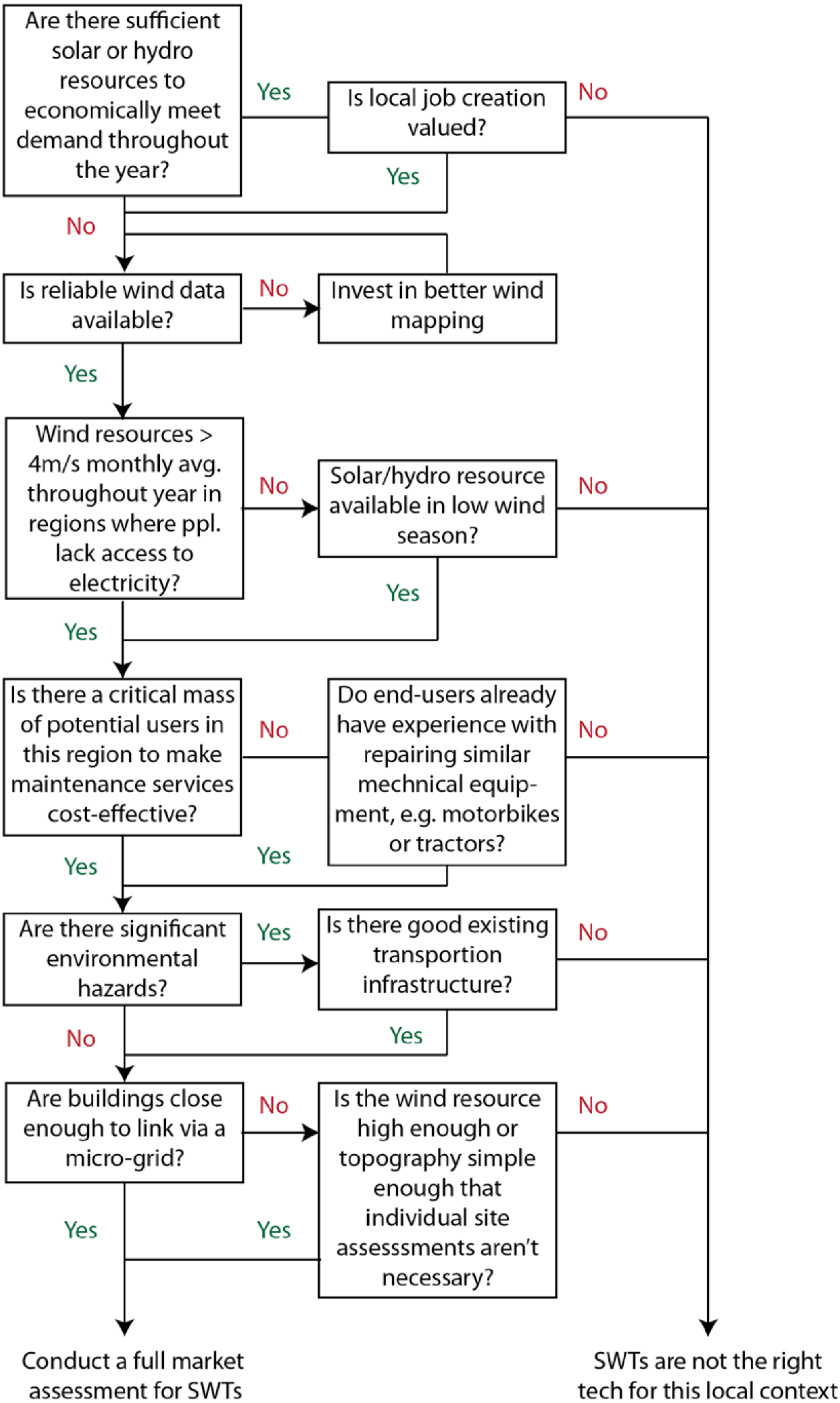

Figure 8-1: Decision support tree for the identification of viable regions for SWTs.

8.5.1 Implications in support for SWTs

Strong and stable support is required to foster the development of a SWT ecosystem, as each local context presents new challenges and new manufacturers require a certain amount of experience before they are able to produce reliable machines. This research has identified the following key areas in which support for SWTs should be targeted in order to maximise impact:

- *Maintenance*: SWTs require a high level of maintenance, which therefore requires a high level of support. Financially, this fits best with a business model (as opposed to a donor model, where upfront costs are donated), where the energy produced is used to generate revenue that can pay for the ongoing costs of O&M. Local capacity to perform maintenance must also be created by training community technicians and establishing a service network to bridge the gap between the manufacturer/supplier and the community itself, which offers the opportunity to create jobs and build capacity in rural areas. Areas with high levels of environmental hazards (lightning, corrosion, hurricanes etc.) should be avoided unless a strong support network can be put in place for maintenance.
- *Wind resource assessment*: The wind resource varies much more than the solar resource in both space and time. Assessing it is more difficult, yet more important for power production, which is proportional to the cube of the wind velocity. At the national scale, identifying windy areas where a critical mass of potential users exists in order to establish a service network is vital. Flat plains with few obstructions are ideal, as individual site assessment is unnecessary. In complex terrain, a proper wind resource assessment should be supported for each new location to avoid disappointment.
- *Technical training*: Wind is fundamentally more technical than solar and therefore more technical training is required at every stage of the technology life cycle. Targeted training for key actors in the SWT ecosystem to ensure that they are fully aware of how the technology works and how it should be employed is essential, especially for the community technician.
- *Local manufacture vs. importing*: Imported SWTs are often not appropriate for rural electrification, as they are designed for peak performance (which is more marketable) rather than continuity of supply (which is more useful for battery charging systems). Local manufacture offers the potential for local job creation, a lower cost solution (in terms of both initial capital and lifecycle cost) and a stronger supply chain for spare parts. However, as mentioned previously, producing in low volumes is expensive, time consuming and challenging to produce machines of sufficient quality.
- *Feedback*: Designing and manufacturing a SWT requires a high level of technical knowledge. Gaining sufficient manufacturing experience to be able to manufacture a reliable SWT require the collection of feedback from end-users to ensure the continual redesign of the product to best meet their needs.

8.6 Future work

The following section offers recommendations for work that could be conducted to enhance and extend the body of work described within this thesis:

Additional cases

The addition of further cases would verify or extend the current theory, raising the level of generalizability of the findings. In addition to studying the technology in further local contexts, there are a number of key issues that have not yet been fully investigated. Particularly interesting cases of which the author is aware include:

- Patagonia, as neither the solar or wind resources are capable of meeting demand throughout the year, yet the wind resource is exceptionally high. There are already over 1,500 SWTs operating in the province of Chubut (Mattio, 2013), however there is little published literature on how this was achieved. There are currently 18 SWT manufacturers in Argentina (Martín, 2013) and regional authorities such as INTI[144] and CREE[145] are playing a very similar role to the IMS&TC in Inner Mongolia, however the true potential of the technology across the whole country is unknown.
- Bolivia, where Practical Action have used imported SWTs in community electrification projects with a very similar delivery model to that employed by the same organisation in their projects involving LMSWTs in the Peruvian Andes (Ferrer-Martí *et al.*, 2011).
- South Africa, as the Broad Based Black Economic Empowerment (BBBEE) offers a political mechanism by which labour in poor communities is highly valued, potentially making the local manufacture of SWTs more viable.
- Kenya, where distributed informal manufacturing has allowed SWTs to spread rapidly across the country, but the market is now being undermined by the poor reliability of these machines due to the lack of quality control (Vanheule, 2012).
- Palestine, where COMET-ME[146] have been using pay-as-you-go metering as an innovative financing mechanism to enable end-users with particularly low incomes to gain access to electricity from a SWT.

Expanding the framework to other decentralised technologies

The framework could also be extended to other decentralised energy generation technologies, such as solar PV or micro-hydro. There is also the possibility that it could even be extended to decentralised technologies in other fields, such as water and sanitation.

[144] National Technological Institute (Instituto Nacional de Tecnología Industrial).
[145] Regional Centre for Wind Energy (Centro Regional de Energía Eólica, Chubut).
[146] Community Energy Technology in the Middle East.

Continued development of the methodologies used for case study data collection and analysis

The development of the methodologies used to analyse each case should continue to offer more accurate, more efficient and more complete toolkit for data collection and analysis. Specifically, the following developments are recommended:

- Extension of the energy systems modelling to include a greater range of variables in the sensitivity analysis. For example, Figure 4-14 shows that there is significant inter-annual in mean wind speeds, however a sensitivity analysis was not conducted on the wind speeds used as inputs for the energy systems modelling in the Scoraig chapter. Varying the hourly rate paid to the community technicians for the time spent on O&M would demonstrate how much income an individual could realistically earn from this job without making the technology economically uncompetitive with solar PV.
- The market assessment methodology requires further development to improve both its accuracy and its usability, which could be gained through its application in further cases. Specifically, the ecosystem perspective lacks quantitative gauges by which to assess the health of a given ecosystem. Practical Action (2012; 2013) describe a range of indicators for ecosystem health for generic energy access technologies and a similar range of indicators could be developed for SWTs. Further improvements are discussed in detail in section 5.3.6.
- Extension of the post-installation dataset would increase confidence in the ability of this technique to accurately measure the post-installation performance of SWTs and therefore offer the ability to pinpoint the critical factors in the sustainability of the rural electrification initiatives under study. This could be done by revisiting the SWTs described in this thesis, as it will now be possible to collect data from many more hours of turbine operation. Further SWTs could also be added, either from the cases described in this thesis (which would increase confidence in the findings in these particular places) or from new cases (which would broaden the range of local contexts).
- Section 4.6 discusses the fact that in the first case study, the post-installation analysis technique measured only the technological availability of a particular SWT. Dataloggers could be used to measure power production throughout the year, i.e. both meteorological and technological availability combined. In fact, in the later cases (Chapters 5 and 6), the utilisation (whether sufficient energy is available when the users require it) is measured qualitatively through the interviews with end-users and participant observation. However, energy yield and even utilisation are both intermediary variables - the ultimate measure is the impact that a particular SWT has had on the development of the community in which it was installed. Again, this was measured qualitatively using the techniques described previously, however quantitative gauges such as those proposed by Ferrer-Marti *et al.* (2012) or Yadoo (2011), or even a more structured qualitative measure such as that proposed by Lillo *et al.* (2014) would give a more rigorous evaluation of this variable and give a much clearer means for comparison between cases.

Revisiting earlier cases

The fact that new techniques were added throughout the course of this research (and will continue to be added) implies that it would be valuable to return to the earlier cases and apply the full range of methodologies (where applicable). This would allow the comparison of identical data across all cases, which would enhance the generalizability of the resulting theory. For example, visiting the community of El Alumbre in Peru would allow verification of the secondary data obtained from Soluciones Prácticas on the post-installation performance of the SWTs installed in the community by interviewing the community technicians, as well as the end-users themselves. What is more, the collection of economic data from Peru would enable energy systems modelling to be carried out (as in Chapters 5 and 6), and Chapter 6 has shown that further insight could also be gained here using participant observation. In fact, the case studies have shown that the longer a researcher spends in a particular place, the more they discover about how people interact with the technology and the role it plays in their daily lives. If time were not a restricted resource, then spending at least three months in each community under investigation would be highly recommended, however the there is a practical dilemma between depth and breadth, i.e. which is more important, understanding each context completely or studying a variety of contexts to look for patterns?

Global market assessment

A global market assessment for SWTs is needed to determine regions where the technology could contribute to the electrification of rural areas. The recent development of powerful tools such as IRENA's *Global Atlas for Renewable Energy* (2013) that collate datasets on wind and solar resources and allow them to be superimposed onto GIS layers containing other relevant information (such as elevation, population density and electricity grids) make conducting such a study much simpler. In each of the regions identified by the global study, a more detailed market assessment should then be conducted in each of these regions using the methodology outlined in Chapter 5.

Access to technical knowledge

This work has highlighted the fact that SWTs require very high levels of technical knowledge. The role of knowledge sharing networks such as the WindEmpowerment association is seen as absolutely critical in making this knowledge available to anybody that is working with (or is considering working with) SWTs for rural electrification. To improve capacity for providing maintenance services, a technical and business focussed handbook for actors wishing to offer such services could be developed, which also describes successful techniques for community technician training. Such handbooks already exist for other renewable energy technologies (Louineua, 2008), and provide a useful reference for newcomers to the field.

Facilitate wind resource assessments

Difficulty in assessing the wind resource has been found to be one of the major barriers facing the technology, which could be addressed by offering technical training on the subject for all actors that perform site selection for SWTs, developing better wind maps that are more widely available and more relevant to small wind, e.g. IRENA (2013), and the development of simpler and more widely available datalogging and anemometry kits to enable on-site verification of wind resources.

Quantification of the socio-economic benefits of local manufacture

This thesis has focussed on NPC and unit costs of electricity (LCoE, LGC) as means of economic comparison between technological options and between cases. However, this places no emphasis on where this money is spent. Adelmann (2013) argues that moving a larger part of the value chain over to developing countries by assembling PV systems locally is absolutely key to their wider economic development. Clearly LMSWTs offer a much greater potential for shifting the value chain, however exactly how far has yet to be quantified both in terms of the number of jobs created and the percentage of the NPC. In fact, the increased maintenance requirements of SWTs necessitates that part of the value chain be shifted right out to rural areas, where job creation is valued even higher than in urban centres.

Lifecycle Analysis (LCA)

SWTs are often described as a 'low-carbon technology'; however such a description assumes that the carbon emissions during the operational stage of the lifecycle are minimal. However, Taverner-Wood (2011) found that the embedded carbon in the materials required to build a 1.8m Piggott turbine (202kgCO_2) was comparable to the carbon emissions from the installation journey alone (169gCO_2). This turbine was installed in Northwest Scotland, 400km from where it was manufactured, however most Piggott turbines used in rural development projects are installed much further away. What is more, regular journeys to and from the site are required for resource assessment, community training and maintenance, as well as installation. It would be interesting to investigate under what conditions they could still be considered a 'low-carbon technology', i.e. at what point does it become more environmentally friendly to pour the fuel straight into a diesel/petrol generator rather than into the tank of the vehicle used to travel between the manufacturer and the installation site?

References

3TIER (2011). Global Wind, Solar and Hydro Resource Maps.

Acharya, P. (2010). A Case Study of the Usability of 50W Rutland Wind Turbine Replaced with Timber Blades. International Workshop on Small Wind Energy for Developing Countries. Pokhara, Nepal.

Acharya, P., R. Sinha, R. Sharma, P. Ghimire and P. Freere (2009). Design and Construction Issues of Small Wind Turbines for Rural Applications. Bhattidanda, Dhulikhel, Nepal, Kathmandu Alternative Power and Energy Group (KAPEG).

Adams, L. L. (1999). "The mascot researcher: Identity, power, and knowledge in fieldwork." Journal of Contemporary Ethnography **28** (4): 331–363.

Adelmann, P. (2013). Value Chain of Pico PV Systems. Global Conference on Rural Energy Access: A Nexus Approach to Sustainable Development and Poverty Eradication. Addis Ababa, Ethiopia, United Nations.

Adler, P. and P. Adler (1987). Membership roles in field research. Newbury Park, CA, Sage.

African Windpower (2007). AWP3.7 Wind Generator - Owners Manual Version 1.1. Harare, Zimbabwe.

Barley, C. D., D. J. Lew and L. T. Flowers (1997). The Design of Wind/PV Hybrids for Households in Inner Mongolia. American Wind Energy Association Windpower. Austin, Texas, USA.

Batchelor, S., N. Scott, L. Daoqi and Bagen (1999). Evaluating the Impact of Wind Generators in Inner Mongolia - Project Technical Report. Reading, UK, DfID, Gamos Ltd.

Bennett, C., M. Gleditsch and P. Carvalho Neves (2011). Assessment of the role of wind turbines in blueEnergy's portfolio. Bluefields, Nicaragua, blueEnergy.

Better Generation. (2013). "BetterGeneration.co.uk." Retrieved 23rd April, 2013, from http://www.bettergeneration.co.uk/.

Bhowmick, N. (2011). The women of India's Barefoot College bring light to remote villages. The Guardian - Global Development.

Bloomberg, B.-F. (2012). Climatescope 2012 Report.

blueEnergy (2009). Technical Report - 12' Turbine Final Design. Bluefields, Nicaragua.

blueEnergy (2011). Condición del equipo instalado en la comunidad de Pearl Lagoon. Bluefields, Nicaragua.

Bradsher, K. (2009). China Tightens Grip on Rare Minerals. The New York Times.

Casillas, C. (2012). Rural electrification, climate change, and local economies: Facilitating communication in development policy and practice on Nicaragua's Atlantic Coast.

CEPAL (2011). Estadisticas del subsector electrico - L1088.

Chávez, S. G., J. C. Baldera and T. S. Campos (2008). Diseño Y Construcción De Un Aerogenerador De 500 W Con Imanes Permanentes Para Pequeñas Demandas Electricas De Zonas Rurales. Lima, Perú, Soluciones Prácticas.

Chiroque, J. (2011). Resultados micro aerogeneradores para electrificación rural: Caso de El Alumbre, Alto Perú Cajamarca (Soluciones Prácticas - Perú). Simposio internacional de energia eólica de pequeña escala. Lima, Peru.

Chiroque, J. and C. Dávila (2008). Microaerogenerador IT-PE-100 Para Electrificación Rural. Lima, Perú, Soluciones Prácticas.

Chiroque, J., T. Sánchez and C. Dávila (2008). Microaerogeneradores de 100 y 500 W. Modelos IT-PE-100 y SP -500. Lima, Peru, Soluciones Prácticas.

Corbyn, S. and J. L. Buckle (2009). "The Space Between." International Journal of Qualitative Methods **8**(1).

Craig, M. (2007). Bringing Light to the Edge of the World: blueEnergy's Adventures Building Micro Wind Turbines on the Caribbean Coast of Nicaragua. Google TechTalk. Mountain View, California, USA.
Craig, M. (2013). Aplicaciones de Energía Limpia para las Américas (no solar): energía eólica, micro-hidroeléctrica, y el biogás. Solar Energy International.
Cross, J. (2012). History, Science and Society. LCEDN Inaugural Conference: Low Carbon Energy for Development: Past Experiences and Future Challenges. Loughborough, UK.
de Laet, M. and A. Mol (2000). "The Zimbabwe Bush Pump: Mechanics of a Fluid Technology." Social Studies of Science **30**(2): 225-263.
Developing Renewables (2008). Compilation and Analysis of 74 Renewable Energy Case Studies in Emerging and Developing Countries. Amsterdam, Developing Renewables.
DGER. (2011). "Electrificación Rural en El Perú." Retrieved 5th November 2013, 2013, from http://webcache.googleusercontent.com/search?q=cache:http://www.osinerg.gob.pe/newweb/uploads/Publico/II_Foro_Regional/7.Logros%2520y%2520Perpestivas%2520de%2520la%2520Electrificacion%2520Rural%2520en%2520el%2520Peru.ppt.
DGER. (2013). "Ministerio de Energía y Minas, Dirección General de Electrificación Rural." Retrieved 17th May, 2013, from http://dger.minem.gob.pe/default.aspx.
Dreyer, A. (2010). Lightning Protection study, National Lightning Protection Institute.
Dulas. (2013). "Dulas - Inspiring Renewable Energy." Retrieved 2013, 11th November, from http://www.dulas.org.uk/.
EGG-energy. (2013). "When darkness falls." Retrieved 15th November, 2013, from www.egg-energy.com.
Eisenhardt, K. (1989). "Building Theories from Case Study Research." The Academy of Management Review **14**(4).
ENCO. (2013). "Wind Map of Nicaragua." Retrieved 14th November, 2013, from http://www.encocentam.com/index.php?option=com_content&view=article&id=20&Itemid=13&lang=en.
Ergun, A. and A. Erdemir (2009). "Negotiating Insider and Outsider Identities in the Field: "Insider" in a Foreign Land; "Outsider" in One's Own Land." Field Methods **22**(1): 16-38.
ESMAP (2007). Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies. Washington DC, Energy Sector Management Assistance Program (ESMAP).
Ferrer-Martí, L. (2009). Metodología para la ubicación de aerogeneradores y diseño de microrredes en proyectos eólicos. Evaluación de recursos, diseño, Instalación y gestión de sistemas eólicos de pequeña escala. Cajamarca, Perú.
Ferrer-Martí, L., B. Domenech, W. Canedo, C. Reza, M. Tellez, M. Dominguez, L. Perone and J. Salinas (2011). Sustainable Growth and Applications in Renewable Energy. Experiences of Community Wind Electrification Projects in Bolivia: Evaluation and Improvements for Future Projects. D. M. Nayeripour.
Ferrer-Martí, L., A. Garwood, J. Chiroque, R. Escobar, J. Coello and M. Castro (2010). "A Community Small-Scale Wind Generation Project in Peru." Wind Engineering **34**(3).
Ferrer-Martí, L., A. Garwood, J. Chiroque, B. Ramirez, O. Marcelo, M. Garfí and E. Velo (2012). "Evaluating and comparing three community small-scale wind electrification projects." Renewable and Sustainable Energy Reviews **16**(7): 5379-5390.
Ferrer-Martí, L., R. Pastor, G. Capó and E. Velo (2011). "Optimizing microwind rural electrification projects. A case study in Peru." Journal of Global Optimization: 1-17.
Ferrer-Martí, L., J. Sempere, O. Marcelo, A. Garwood, J. Chiroque and B. Ramirez (2010). El Alumbre, Campo Alegre and Alto Peru: Evaluating and Comparing three Community Small-Scale Wind Generation Project. International Workshop on Small Wind Energy for Developing Countries. Pokhara, Nepal.
Flavin, C. and M. H. Aeck (2005). Energy for Development: The Potential Role of Renewable Energy in Meeting the Millennium Development Goals, Worldwatch Institute.

Freere, P. (2010). Analysis of Nepali Timber for Wind Turbine Blades. International Workshop on Small Wind Energy for Developing Countries. Pokhara, Nepal.
Ghimire, P., R. Sharma, C. Lamichhane, P. Freere, R. Sinha and P. Acharya (2010). "Kathmandu Alternative Power and Energy Group: Our Experience in Promotion of Low Cost Wind Energy Technology in Nepal." Wind Engineering **34**(3): 313-324.
Gipe, P. (2004). Wind Power: Renewable Energy for Home, Farm, and Business. White River Junction, VT, Chelsea Green Publishing Co.
Glaser, B. and A. Strauss (1967). The discovery of grounded theory: strategies of qualitative research. London, Wiedenfeld and Nicholson.
Globeleq Mesoamerica Energy (2012). Wind power in Central America.
GNESD (2006). Poverty Reduction - Can Renewable Energy Make a Real Difference, Global Network on Energy for Sustainable Development (GNESD).
Gurung, A., A. Kumar Ghimeray and S. H. A. Hassan (2012). "The prospects of renewable energy technologies for rural electrification: A review from Nepal." Energy Policy **40**(0): 374-380.
Harvey, A. (1993). Micro-hydro Design Manual: A Guide to Small-scale Water Power Schemes: Guide to Small-scale Water Schemes. Rugby, UK, ITDG Publishing.
Herzfeld, M. (1997). Cultural intimacy: Social poetics in the nation-state. New York, Routledge.
Hirmer, S. and H. Cruickshank (2014). "The user-value of rural electrification: An analysis and adoption of existing models and theories." Renewable and Sustainable Energy Reviews **34**(0): 145-154.
Hosman, N. (2012). Performance Analysis and Improvement of a Small Locally Produced Wind Turbine for Developing Countries. Master of Science, TU Delft.
Iansiti, M. and R. Levien (2004). "Strategy as ecology." Harvard Business Review **March 2004**.
IEA (2010). World Energy Outlook. Paris, International Energy Agency (IEA).
IEA (2013). Rural Electrification with PV Hybrid Systems: Overview and Recommendations for Further Deployment, IEA Photovoltaic Power Systems Programme. **Report IEA-PVPS T9-13:2013**.
IEC (2005). Wind Turbines. Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines.
INIDE (2005). VIII Censo de Población y IV de Vivienda, Instituto Nacional de Información para el Desarrollo (INIDE).
IRENA (2012). Solar Power. Renewable Energy Technologies: Cost Analysis Series. Abu Dhabi, International Renewable Energy Agency.
IRENA (2012). Wind Power. Renewable Energy Technologies: Cost Analysis Series. Abu Dhabi, International Renewable Energy Agency.
IRENA. (2013). "Global Atlas for Renewable Energy." from http://irena.masdar.ac.ae/.
Kahneman, D. and A. Tversky (1973). "On the psychology of prediction." Psychological Review **80**: 237-251.
Kamkwamba, W. (2009). The Boy Who Harnessed the Wind. New York, USA, William Morrow.
Khennas, S., S. Dunnett and H. Piggott (2008). Small Wind Systems for Rural Energy Services. Rugby, UK, Practical Action Publishing.
Latoufis, K. and P. Kotsampopoulos (2010). Design, Construction and Simulation of a Small Scale Axial Flux Wind Turbine for Appropriate Technology Applications. International Workshop on Small Scale Wind Energy for Developing Countries. Pokhra, Nepal.
Leary, J., R. Howell, A. While, J. Chiroque, K. VerKamp and C. Pinedo (2012). Post-installation analysis of locally manufactured small wind turbines: Case studies in Peru. 2012 IEEE Third International Conference on Sustainable Energy Technologies (ICSET).
Leary, J., A. While and R. Howell (2012). "Locally manufactured wind power technology for sustainable rural electrification." Energy Policy **43**(0): 173-183.

Lew, D., C. Barley and F. LT (1997). Hybrid Wind/Photovoltaic Systems for Households in Inner Mongolia. International Conference on Village Electrifcation through Renewable Energy. New Delhi.
Lew, D. J. (2000). "Alternatives to coal and candles: wind power in China." Energy Policy **28**: 271-286.
Lewis, J. I. and R. H. Wiser (2007). "Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms." Energy Policy **35**(3): 1844-1857.
Lillo, P., L. Ferrer-Martí, A. Boni and A. Fernández-Baldor (2014). "Evaluating the management model of off-grid renewable energy electrification projects in Peru using the Human Development apprach." Energy Policy **In Press**.
Little, M. and D. Corbyn (2008). EWB/SIBAT Design Guides. Philippines, Available from RE-Innovation.co.uk.
Louineua, J.-P. (2008). A practical guide to solar photovoltaic systems for technicians - sizing, installation and maintenance. Rugby, UK, Practical Action Publishing.
Marandin, L., M. Craig, C. Casillas and J. Sumanik-Leary (2013). Market Assessment for Small Scale Wind Turbines in Nicaragua 2012-13. Managua, Green Empowerment.
Martín, G. (2013). Experienciaen el ensayo de desempeño de aerogeneradores de baja potencia en Argentina, lecciones replicables a otros países de América Latina. II Simposio de Energía Eólica de Pequeña Escala. Lima, Peru.
Mattio, H. F. (2013). Programa de electrificación para la población rural dospersa de la provincia del Chubul, por medio de sistemas eólicas domiciliarios. II Simposio Internacional de Energía Eólica de Pequeña Escala. Lima, Peru.
MEM (2003). Atlas de Energía Solar del Perú. Lima, Perú, Ministerio de Energía y Minas, Dirección General de Electrificación Rural.
MEM (2008). Atlas Eólico del Perú. Lima, Perú, Ministerio de Energía y Minas, Dirección General de Electrificación Rural.
MEM (2009). Plan Estratégico Del Sector Energético De Nicaragua: 2007 - 2017. Ministry of Energy and Mines. Managua, Nicarauga.
MEM (2012). Plan Nacional de Electrificación Rural. Ministerio de Energía y Minas. Lima, Perú.
Meteosim Truewind S.L. Latin Bridge Business S.A. (2008). "Atlas Eólico del Perú." Retrieved 27th March, 2012, from http://dger.minem.gob.pe/atlaseolico/PeruViento.html
MicroEnergy International, PlaNet Finance Deutschland and UP Micro Loans (2006). Fact Sheet "The Potential of Linking Microfinance & Energy Supply".
Miles, M. and A. M. Huberman (1984). Qualitative Data Analysis. Beverly Hills, CA, Sage Publications.
Mintzberg, H. (1979). "An Emerging Strategy of "Direct" Research." Administrative Science Quarterly **24**(4): 582-589.
Mishnaevsky Jr, L., P. Freere, R. Sharma, P. Brøndsted, H. Qing, J. I. Bech, R. Sinha, P. Acharya and R. Evans (2009). "Strength and Reliability of Wood for the Components of Low-cost Wind Turbines: Computational and Experimental Analysis and Applications." Wind Engineering **33**(2): 183-196.
Mishnaevsky Jr, L., P. Freere, R. Sinha, P. Acharya, R. Shrestha and P. Manandhar (2011). "Small wind turbines with timber blades for developing countries: Materials choice, development, installation and experiences." Renewable Energy **36**(8): 2128-2138.
Mostert, W. (2007). Unlocking potential, reducing risk: renewable energy policies for Nicaragua. Washington DC, World Bank.
Naples, N. A. (1996). "A feminist revisiting the insider/outsider debate: The "outsider phenomenon" in rural Iowa." Qualitative Sociology **19**(1): 83-106.
NASA. (2013). "Surface meteorology and Solar Energy: A renewable energy resource web site (release 6.0)." from https://eosweb.larc.nasa.gov/.

Neves, P. (2011). Lecciones técnicas en fabricación y mantenimiento de turbinas tipo Hugh Piggott (blueEnergy - Nicaragua). Simposio internacional de energia eólica de pequeña escala. Lima, Peru.

Nieuwenhout, F. D. J., A. van Dijk, P. E. Lasschuit, G. van Roekel, V. A. P. van Dijk, D. Hirsch, H. Arriaza, M. Hankins, B. D. Sharma and H. Wade (2001). "Experience with solar home systems in developing countries: a review." Progress in Photovoltaics: Research and Applications **9**(6): 455-474.

Nisbett, R. and L. Ross (1980). Human inference: strategies and shortcomings of social judgement. Englewood Cliffs, NJ, Prentice-Hall.

NREL (2006). Central America Wind Energy Resource Assessment.

O'Toole, J. (2010). Estudio de viento para Cuajinicuil, blueEnergy (informe interna).

O'Toole, J. (2010). Taller de Turbinas Eólicas, blueEnergy (Informe Interna).

Ofgem. (2011). "Typical domestic energy consumption figures." Retrieved 13th November, 2012, from https://www.ofgem.gov.uk/ofgem-publications/64026/domestic-energy-consump-fig-fs.pdf.

Oliva, R. B. (2008). "Simulation and measurement procedures for effective isolated wind and hybrid system development in south Patagonia." Energy for Sustainable Development **12**(2): 17-26.

Pettigrew, A. (1988). Longitudinal field research on change: theory and practice. National Science Foundation Conference on Longitudinal Research Methods in Organizations. Austin, Texas.

Piggott, H. (2000). Windpower Workshop. Machynlleth, UK, Centre for Alternative Technology Publications.

Piggott, H. (2009). A Wind Turbine Recipe Book. Scoraig, Scotland, Scoraig Wind Electric.

Piggott, H. (2013). A Wind Turbine Recipe Book. Scoraig, Scotland, Scoraig Wind Electric.

Pinedo Lujan, C. F. (2011). Experiencias en la implementación de aerogeneradores (WindAid - Perú). Simposio internacional de energia eólica de pequeña escala. Lima, Peru.

Practical Action (2010). Poor People's Energy Outlook 2010: Energy for Households. Rugby, UK, Practical Action.

Practical Action. (2011). "PracticalAction.org." Retrieved 18th August, 2011, from http://practicalaction.org/.

Practical Action (2012). Poor People's Energy Outlook 2012: Energy for Earning a Living. Rugby, UK, Practical Action.

Practical Action (2013). Poor People's Energy Outlook 2013: Energy for Comunity Services. Rugby, UK, Practical Action.

Ranaboldo, M., L. Ferrer-Martí and E. Velo (2013). "Micro-scale wind resource assessment for off-grid electrification projects in rural communities. A case study in Peru." International Journal of Green Energy.

Reyes, G. (2011). Experiencia con pequeñas turbinas de fabricación local para comunidades (AsoFenix - Nicaragua). Simposio internacional de energia eólica de pequeña escala. Lima, Peru.

Rolffs, P., R. Byrne and D. Ockwell (2014). Financing Sustainable Energy for All: Pay-as-you-go vs. traditional solar finance approaches in Kenya, STEPS centre.

Rose, P. (1985). Writing on women: Essays in a renaissance. Middletown, CT, Wesleyan University Press.

Sánchez, T., J. E. Chiroque and S. Ramírez (2002). Evaluación Y Caracterizacion De Un Aerogenerador De 100w. Lima, Perú, Soluciones Prácticas.

Schumacher, E. F. (1973). Small Is Beautiful: A Study of Economics as if People Mattered, Blond & Briggs Ltd.

Scott, N. and S. Batchelor (1999). "Small wind generators - Their impact on people." Boiling Point(43).

Sharma, R., R. Sinha, P. Acharya, L. M. Jr. and P. Freere (2008). Comparison of Test Results of Various Available Nepalese Timbers for Small Wind Turbine Applications. ISES-AP - 3rd International Solar Energy Society Conference – Asia Pacific Region (ISES-AP-08). Sydney Convention & Exhibition Centre.

Sharman, D. (2009). Geting Real About Small Wind. Renewable Energy Focus. **November/December 2009**.

Sinha, R. (2010). Natural Materials and Coatings for Low Cost Wind Turbines for Developing Countries: Summary of Studies. International Workshop on Small Wind Energy for Developing Countries. Pokhara, Nepal.

Soluciones Practicas. (2013). "SolucionesPracticas.org.pe." Retrieved March 3rd, 2011, from http://www.solucionespracticas.org.pe/.

Sumanik-Leary, J., L. Marandin, M. Craig, C. Casillas, A. While and R. Howell (2013). Participatory Manufacture of Small Wind Turbines: A Case Study in Nicaragua. Engineers Without Borders and Enginners Against Poverty present: Going Global. Imperial College, London.

Sumanik-Leary, J., H. Piggott, R. Howell and A. While (2012). Power curve measurements of locally manufactured small wind turbines. 8th PhD Seminar on Wind Energy in Europe. ETH Zurich, Switzerland.

Sumanik-Leary, J., H. Piggott, R. Howell and A. While (2013). Locally manufactured small wind turbines - how do they compare to commercial machines? 9th PhD Seminar on Wind Energy in Europe. Uppsala University Campus Gotland, Sweden.

Sumanik-Leary, J., K. Silwal, T. Wastling and K. Latoufis (2014). Comparison of locally manufactured AFPM generator technologies for wind applications and field testing of small wind turbines. Athens, Greece, DERri (Distributed Energy Resources Research Infrastructures).

SWERA. (2008). "Wind atlas of Nicaragua." Retrieved 14th November, 2013, from http://maps.nrel.gov/swera.

Taverner-Wood, H. (2011). Applications of micro wind: how non-accredited turbines can fulfil user requirements, School of Engineering and Electronics, The University of Edinburgh.

Trochim, W. M. K. (2006). "Research Methods Knowledge Base: Deduction & Induction." Retrieved 4th November, 2013, from http://www.socialresearchmethods.net/kb/dedind.php.

UNDP (2006). Energy for Sustainable Development: Linkages, Impacts and Indicators, United Nations Development Programme (UNDP).

US DoE (2011). Establishing an In-House Wind Maintenance Program, US Department of Energy, Energy Efficiency & Renewable, Energy Wind and Water Power Program.

Vanheule, L. (2012). Small Wind Turbines in Kenya - An Analysis with Strategic Niche Management. Sustainable Energy Technology Master's, Delft University of Technology.

Walker, G., P. Devine-Wright, S. Hunter, H. High and B. Evans (2010). "Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy." Energy Policy **38**(6): 2655-2663.

Watson, G., B. Maboyi, D. Matirekwe, H. Piggott, O. Smyth and N. Murgatroyd (1999). "A wind turbine battery charger for Africa." Renewable Energy **16**(1–4): 934-939.

Wilkins, G. (2002). Technology Transfer for Renewable Energy, Overcoming Barriers in Developing Countries. London, UK, The Royal Institute of International Affairs Sustainable Development Programme.

Wind Empowerment. (2013). "WindEmpowerment.org." Retrieved 26th March, 2013.

WindAid (2011). Brochure WindAid. Trujillo, Peru.

Wood, E. (2004). The Hydro Boys: Pioneers of Renewable Energy. UK, Luath Press Ltd.

World Bank (2008). RETToolkit: A Resource for Renewable Energy Development.

Xiliang, Z., L. Gan, G. Shuhua and L. Wenqiang (1999). Wind energy technology development and diffusion: A case study of Inner Mongolia, China. Oslo, Norway, Center for International Climate and Environmental Research (Oslo, Norway) and Institute for Techno-economics and Energy Systems Analysis (Tsinghua University, Beijing, China).

Yadoo, A. (2011). Delivery Models for Decentralised Rural Electrification: Case Studies in Nepal, Peru and Kenya. Doctor of Philosophy, Cambridge University.

Yadoo, A., A. Gormally and H. Cruickshank (2011). "Low-carbon off-grid electrification for rural areas in the United Kingdom: Lessons from the developing world." Energy Policy **39**(10): 6400-6407.

Yin, R. (1981). "The case study crisis: some answers." Administrative Science Quarterly **26**: 58-65.

Yin, R. (1984). Case study research. Beverly Hills, CA, Sage Publications.

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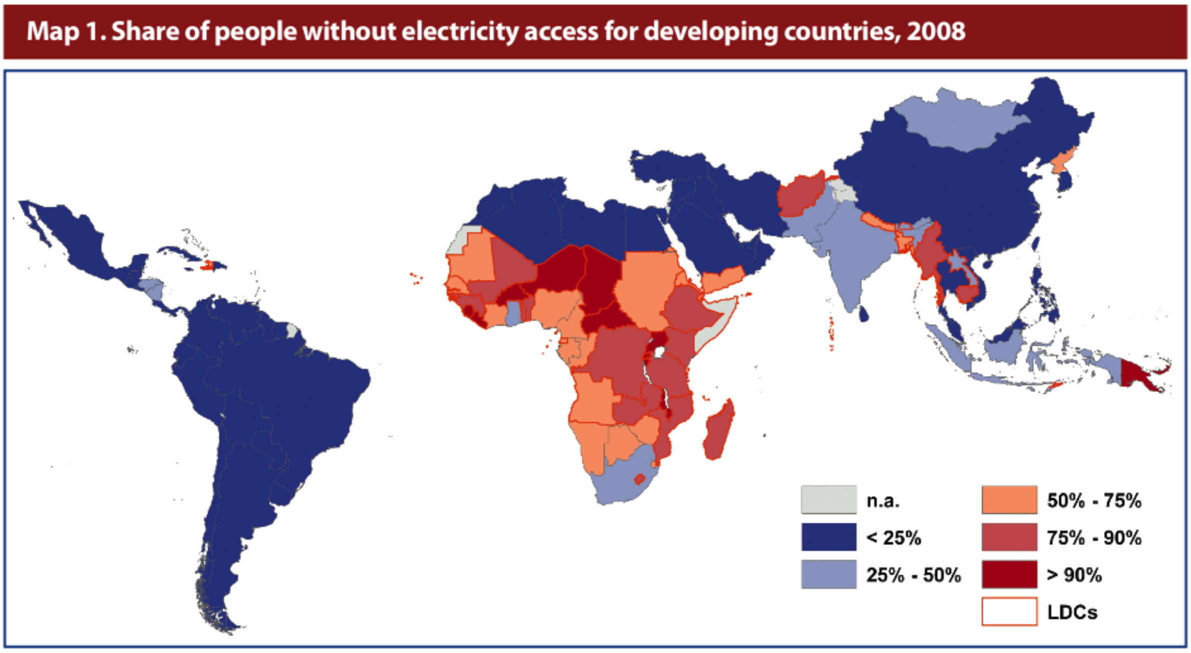
Appendices

Appendix A. Global distribution of renewable resources



N.A. = not available.

Notes: Based on UNDP's classification of developing countries and the UN's classification of LDCs. Some of the small countries and island states are not visible in the map. For a complete list of countries, see Appendix 2. The designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations or UNDP concerning the legal status of any country, territory, city or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

Figure A-1: Global distribution of people without access to electricity (EGG-energy, 2013).

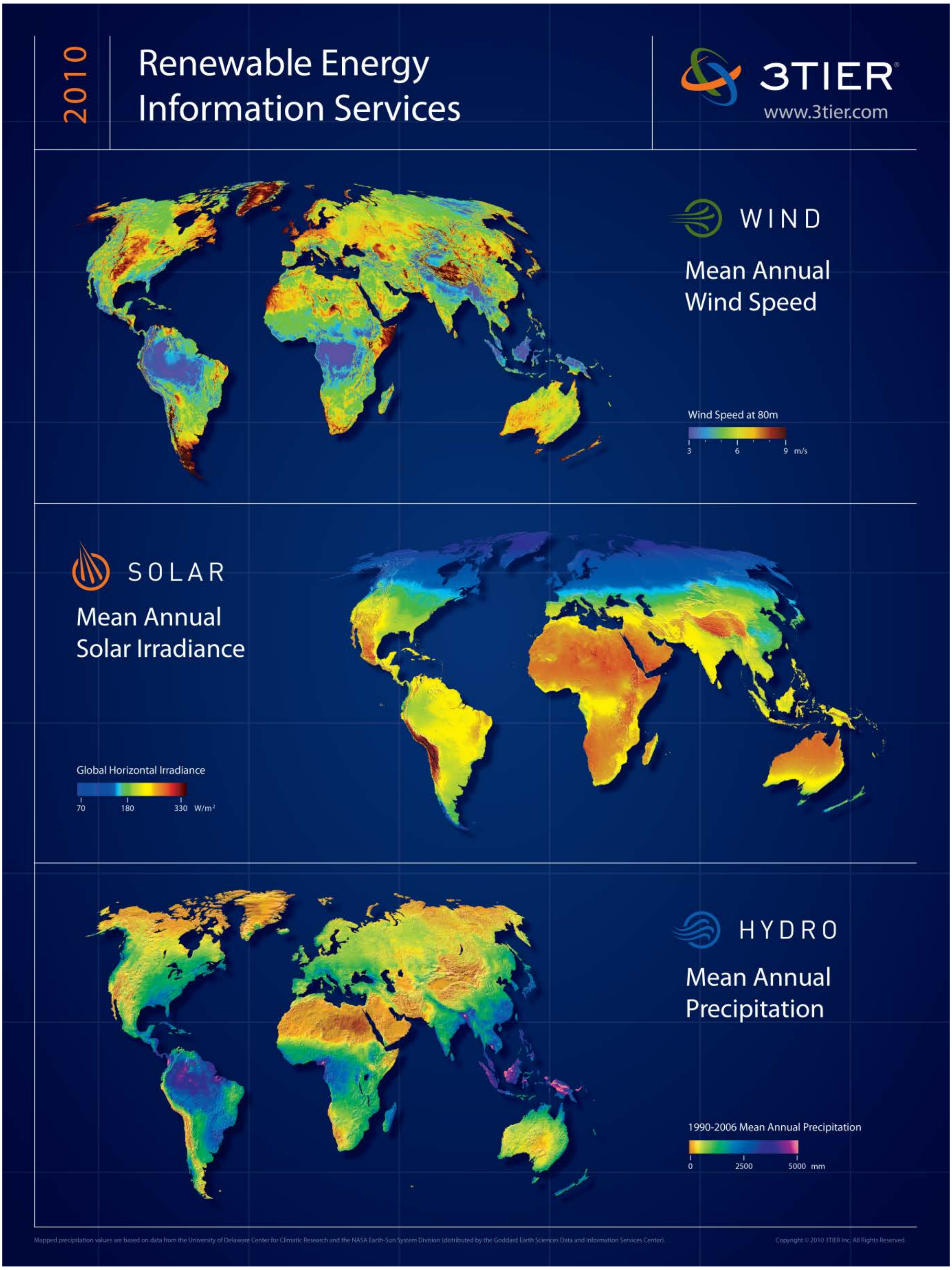


Figure A-2: Global renewable resources map (3TIER, 2011).

Appendix B. Beaufort scale

Table A-1: The Beaufort scale for observational wind measurements (Khennas et al., 2008).

Implications for power generation	*Beaufort number*	*Description*	*Wind Speed (m/s)*	*Observations*
Useless	0	Calm	0	Tree leaves do not move; smoke rises vertically
	1	Light Air	1-1.5	Tree leaves do not move; smoke drifts slowly
	2	Slight Breeze	2-3	Tree leaves rustle; flags wave slightly
Useful	3	Gentle Breeze	3-5.5	Leaves and twigs in constant motion; light flags extended
	4	Moderate Breeze	6-8	Small branches move; flags flap
	5	Fresh Breeze	8.5-10	Small trees sway; flags flap and ripple
Overspeed protection system in operation	6	Strong Breeze	11-14	Large branches sway; flags beat and pop
	7	Moderate Gale	14.5-17	Whole trees sway
	8	Fresh Gale	17.5-20	Twigs break off trees
	9	Strong Gale	21-24	Branches break off trees; shingles blown from roof
Damage possible	10	Whole Gale	24.5-28	Some trees blown down; damage to buildings
	11	Storm	29-32	Widespread damage to trees and buildings
Damage likely	12	Hurricane	33+	Severe and extensive damage

Appendix C. Technical specifications of the LMSWTs studied during this research

Table A-2 compares the technical specification of the LMSWTs under investigation during this thesis. Figure A-3 compares the power curves of these machines, however it should be noted that these power curves were measured by the manufacturer using low cost measurement equipment and whilst some may have used the international standard (IEC-61400-12-1) as a guide during the testing procedure, none of the results were produced in an officially certified testing centre. As a result, these curves should be used as a rough guide only. Figure A-5 shows the power curve for the blueEnergy BD4 with the expected error introduced during the measurement process, as calculated by the manufacturer (blueEnergy, 2009). However, even if the power curves were measured according to IEC-61400-12-1, the actual power produced by a SWT on a real site is likely to vary significantly due to a variety of factors (see the glossary of terms at the beginning of this document for a more detailed explanation).

Table A-2: Comparison of the LMSWTs studied during this thesis.

Case study	*I Inner Mongolia*	*II Peru*			*III Nicara-gua*	*IV Scotland*		
Manufac-turer	SLMF[147]	Soluciones Prácticas		WindAid	blueEnergy	Scoraig Wind Electric		
Turbine	FD2-100	IT-PE-100	SP-500	WindAid 2.5kW	bE12ft	Piggott 2F	Piggott 2.4N	Piggott 3N
Applications	Domestic	Domestic	Com. services[148]	Com. services[149]	Com. services[150]	Domestic	Domestic	Domestic
RAEY	549 kWh/yr	519 kWh/yr	1,855 kWh/yr	4,877 kWh/yr	2,444 kWh/yr	777 kWh/yr	1,309 kWh/yr	1,734 kWh/yr
Rated power	100W @6m/s	100W @7m/s	500W @ 8m/s	2,500W @10m/s	1,000W @12m/s	400W @13m/s	700 @13m/s	800 @13m/s
Diameter		1.7m	3m	4m	3.6m	2m	2.4m	3m
Blade material	Pressed sheet metal	GFRP[151]	GFRP[151]	GFRP[151] & CFRP[152]	Wood carving	Wood carving	Wood carving	Wood carving
Generator topology	Radial flux	Axial flux	Axial flux	Axial flux	Axial flux	Axial flux	Axial flux	Axial flux

[147] Shangdu Livestock Machinery Factory.
[148] Community services - School/health centre.
[149] Community services - School/health centre & battery charging centre.
[150] Community services - Community mini-grids & battery charging centre.
[151] Glass Fibre Reinforced Plastic.
[152] Carbon Fibre Reinforced Plastic.

Case study	*I* *Inner Mongolia*	*II* *Peru*			*III* *Nicaragua*	*IV* *Scotland*		
Overspeed protection	Furling	Furling	Furling	Furling	Furling	Furling	Furling	Furling
Tower	Tilt-up guyed	Tilt-up guyed 7-10m	Tilt-up guyed 7-10m	Tilt-up guyed 9m	Tilt-up guyed 18-30m	Tilt-up guyed 6-12m	Tilt-up guyed 6-12m	Tilt-up guyed 6-12m
Retail price	$137[153]	$974	$2,737	$6,298				
Turbine cost					$2,585[154]		£500[154]	£600[154]
Tower cost					$2,083[154]			
Data source	(Batchelor et al., 1999)	(Chiroque et al., 2008)	(Chiroque et al., 2008)	(WindAid, 2011)	(blueEnergy, 2009)	(Piggott, 2013)	(Piggott, 2013)	(Piggott, 2013)

[153] Unclear whether this includes the price of the tower.
[154] Cost of materials only.

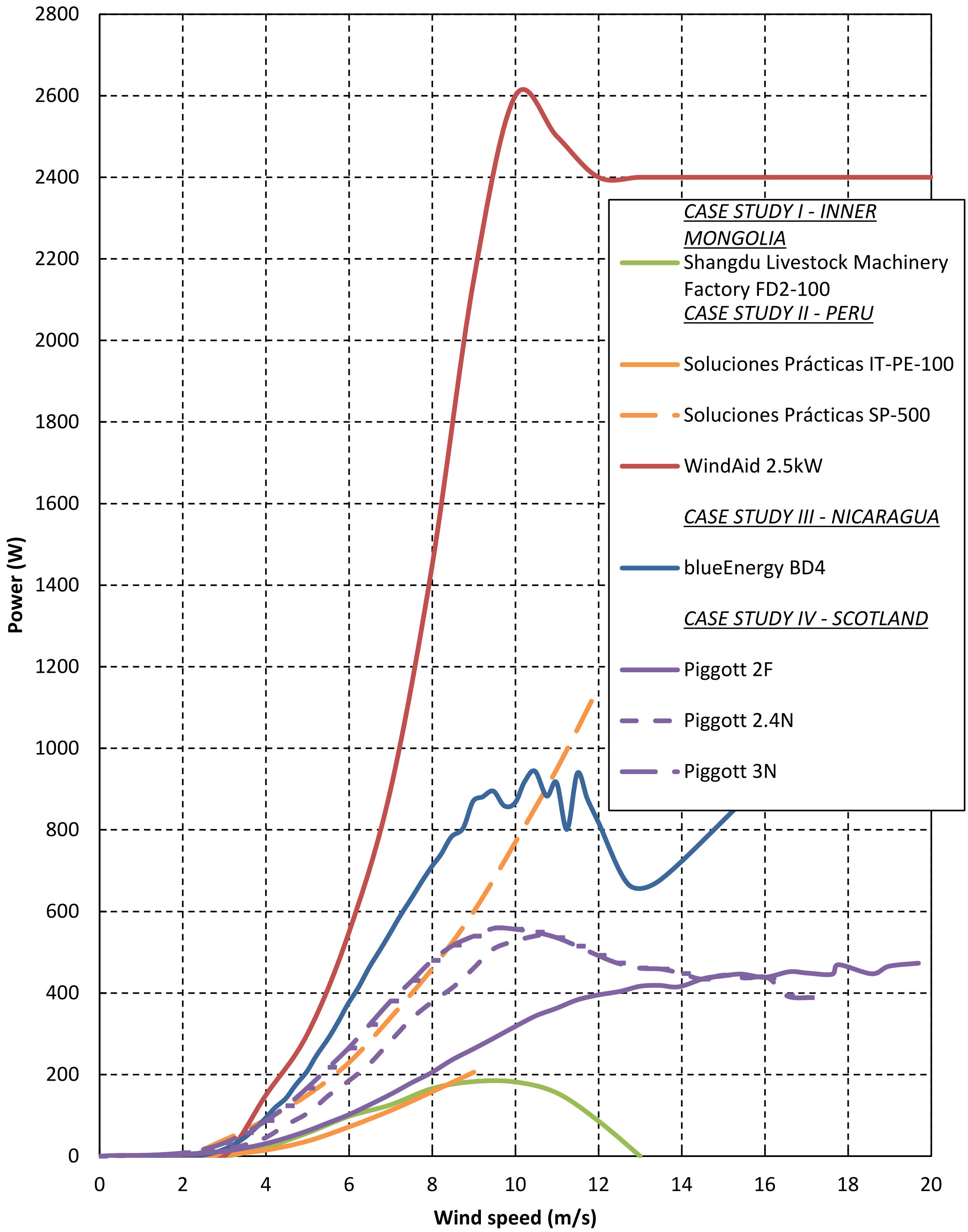


Figure A-3: Power curves for the LMSWTs studied during this thesis. All data provided by the respective manufactures (see Table A-2), except the Piggott 2F, 2.4N and 3N which were measured during the course of this research according to the procedure outlined in (Sumanik-Leary et al., 2012).

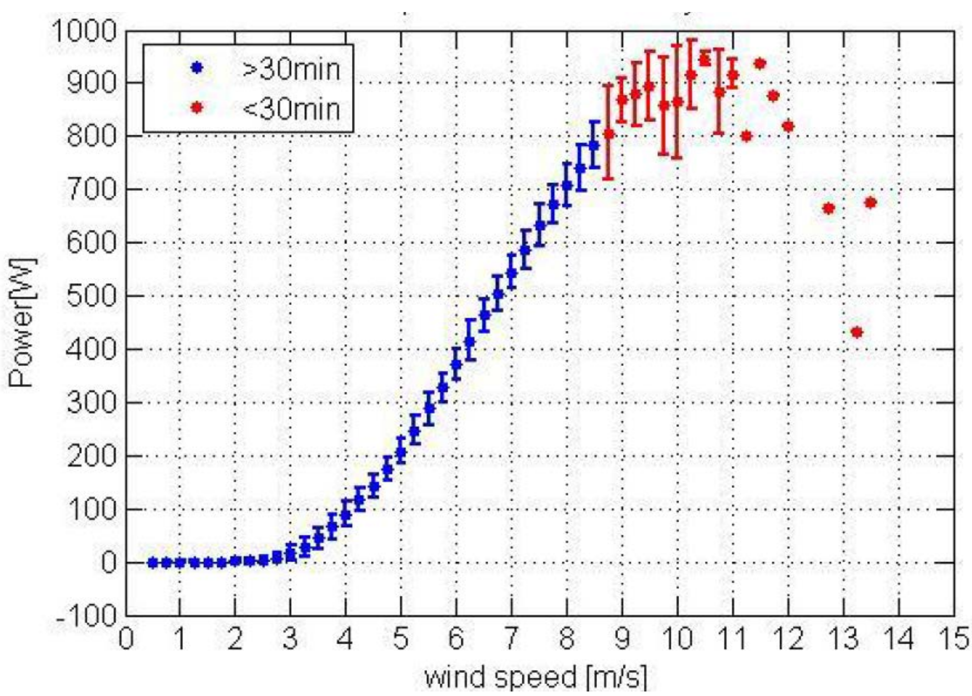


Figure A-4: Measured power curve for blueEnergy BD4, with error bars (blueEnergy, 2009).

Appendix D. SWT electrical system diagram

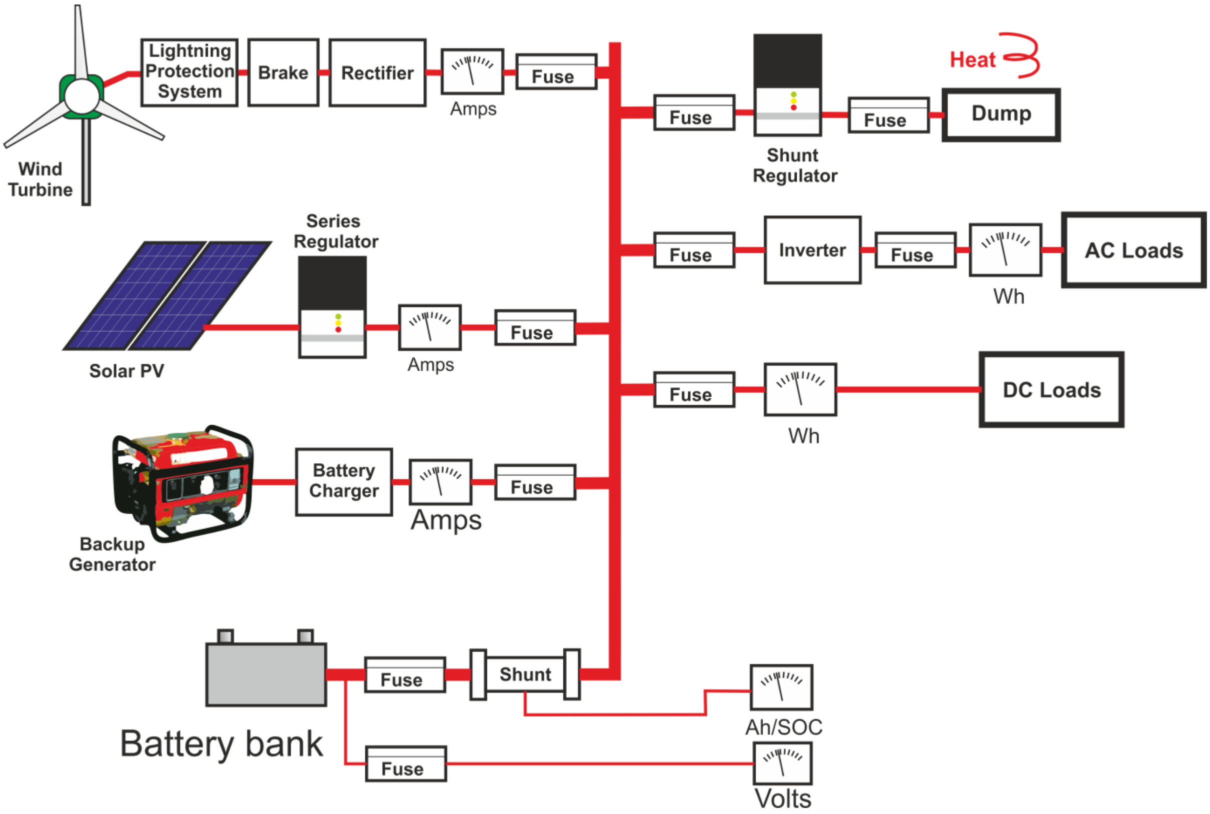


Figure A-5: Layout of a typical wind-solar-petrol hybrid electrical system (Little and Corbyn, 2008).

Appendix E. Tools required to maintain the 1kW SWT installed in Cuajinicuil, Nicaragua

Table A-3: Tools required to maintain the 1kW SWT installed in Cuajinicuil, Nicaragua.

Tool	*Quantity*	*Units*	*Price (US$)*	*Sub-Total*	*With admin. costs*	
Tools for the whole PV-wind hybrid system						
Digital multimeter	1	U	$30.00	$30.00	$39.00	
Hydrometer	1	U	$5.00	$5.00	$6.50	
Wire brush	1	U	$5.00	$5.00	$6.50	
Wire cutters	1	U	$10.00	$10.00	$13.00	
Adjustable spanner	1	U	$5.00	$5.00	$6.50	
19mm spanner	2	U	$5.00	$10.00	$13.00	
Latex gloves	2	Pair	$5.00	$10.00	$13.00	
Soldering iron	1	U	$9.00	$9.00	$11.70	
Solder	1	Roll	$10.00	$10.00	$13.00	
Flat head screwdrivers	2	U	$5.00	$10.00	$13.00	
Cross head screwdrivers	2	U	$5.00	$10.00	$13.00	
Deionised water for batteries	4	Lts	$4.00	$16.00	$20.80	
						$169.00
Tools for the SWT only						
Pulleys	2	U	$50.00	$100.00	$130.00	
½” nylon cord	65	M	$0.50	$32.50	$42.25	
Grease	1	Lbs	$10.00	$10.00	$13.00	
Specialist tools[155]	1		$77.00	$77.00	$100.10	
						$285.35
Total				**$349.50**	**$454.35**	

[155] Jacking screws for removing the rotor discs and other custom tolos.

Appendix F. Wind resource assessment costs from Cuajinicuil case study

Table A-4: Wind resource assessment costs from Cuajinicuil case study.

Materials	*Details*	*Quantity*	*Price (one off)*	*Price (long term)*
Large tube	2 1/2'', 6m, galvanized	2	$211.60	$21.16
Large tube	1'', 6m, galvanized	1	$65.00	$6.50
Guy wires	1/4'', 7x7 or 7x19, galvanized	84	$63.00	$6.30
Cable grips	1/8'	40	$15.00	$1.50
Angle iron	2'' x 2'', 6m	1	$40.00	$4.00
Cable ties	1/8''	8	$15.00	$1.50
Bar	10mm, 6m	2	$15.00	$1.50
Mounting bar	3/8''	4	$20.00	$2.00
Anemometer		1	On loan	$30.00
Wind vane		1	On loan	$20.00
Datalogger		1	On loan	$50.00
Memory card	1G	1	On loan	$3.00
Battery	12V, 7Ah, sealed	1	$25.00	$2.50
Solar panel	12V, 5W	1	$50.00	$5.00
Charge controller	5A, Phocos	1	$35.00	$3.50
Box	waterproof	1	$30.00	$3.00
Cable	various		$30.00	$3.00
Consumables		1	$50.00	$5.00
Tower manufacture	1 engineer day	1	$20.00	$2.00
Transportation for tower	Bluefields-Managua	1	$20.83	$2.08
Trip to pick up data	1 engineer day	4	$330.00	$330.00
Installation trip	2 engineer days		$115.00	$115.00
Unistallation trip	1 engineer day	1	$82.50	$82.50
Admin. Costs: 50% labour, 30% materials		1	$215.63	$316.21
	TOTAL		$1,712.31	$1,017.26

Assumptions:

- Long term price assumes the same equipment is reused at 10 different sites.
- One off price is the actual price paid by AsoFenix and blueEnergy for the wind study in Cuajinicuil.

Appendix G. WindEmpowerment member organisations

Figure A-6: The global distribution of WindEmpowerment's 39 member organisations.

Table A-5: The 39 WindEmpowerment member organisations (Wind Empowerment, 2013).

Member organisation	*Country*
500rpm	Argentina
access:energy	Kenya
AJA Mali	Mali
blueEnergy	Nicaragua (France/US)
Comet Me	Palestine
Craftskills East Africa	Kenya
Eirbyte	Ireland
Energizar	Argentina
Engineers Without Borders UK	UK
Eolocal	Argentina
ÉolSénégal	Senegal
Green Empowerment	US
Green Step	Cameroon
i-love-windpower Mali	Mali
i-love-windpower Tanzania	Tanzania
imecofarm	Ireland
Instituto Denuar	Mexico

KAPEG	Nepal
Kartong project	Gambia
MinVayu	India
Nea Guinea Collective	Greece
Otherpower	USA
Renewable World	UK
RIWIK	Kenya
RURERG NTUA	Greece
SamSaara	Estonia
Scoraig Wind Electric	UK
Sibat	Philippines
Solarmad	Madagascar
The AT Center Korea	Korea
The Clean Energy Company	Mozambique
Ti'éole	France
Tripalium	France
UPC	Spain
V3 Power	UK
WindAid Institute	Peru
Windenergy4ever	Netherlands
WindGEn Power	Kenya
Windmission	Denmark
WISIONS/The Wuppertal Institute	Germany

Appendix H. Sample field diary extract

The following extract if taken from the field diary that was kept throughout this research. Two days of data from the fieldwork conducted on the Scoraig peninsula in Northwest Scotland are shown. Similar records were kept during the field work in Peru and Nicaragua.

17th June 2013

Today I wrote code all day to process the power curve data. I took my laptop up to the house three times to charge it and have to plan the work I do around this. I can't imagine how annoying it must have been for Hugh to carry a heavy car battery over the loch to the shop when he first arrived on Scoraig, just for a few hours of light in the evening from the 12V car bulbs.

As it is almost midsummer and therefore light almost all day long, the only thing I really miss electricity for are charging my laptop and phone, as well as getting instant hot water. Oh and the internet too!

Figure A-7: The bothy that I stayed in during my trip to Scoraig in May/June 2013. The bothy had no electricity, but I was able to charge my laptop and phone at the house (in the trees the background).

Informal conversation with William Hawkins over dinner:

- Scoraig was offered a grid connection in the 1970s for a few hundred pounds per household through EC grants for grid extension.

- “*Some people on Scoraig are certainly unsatisfied with the quality and quantity of electricity available*” from the small scale, off-grid systems.
- Washing machines are one of the most difficult appliances to run on an off-grid system, as they need a good inverter and often have a heating element built in so they have a high power demand. At William and Cathy’s house, they have a top-loading washing machine to reduce power demand by filling it with hot water from the hot tap, which is heated by the Rayburn, solar thermal or dumped power from the PV-wind hybrid system.

18th June 2013

Repair job at Athini’s

I accompany Hugh to repair Athini’s SWT, which has been behaving strangely for some time now.

Syptoms (as reported to Hugh by Athini):

- SWT stopping for no reason.
- SWT not always following widn direction.

Hugh suspects an intermittent short inside tower and dry yaw bearing.

Action:

- Take the turbine down.

Figure A-8: a) Lowering Athini's SWT for maintenance and b) resting the turbine on the ground for inspection.

- Regrease yaw bearing.

Figure A-9: Re-greasing the yaw bearing to enable it to follow the wind more easily.

- Pull out cable
    - Find broken insulation in a few different places.
    - Could have taped up the insulation, but Hugh says its probably better to replace the wire as its very twisted and quite worn in many different places.

Figure A-10: The twisted power cable from inside the tower that was shorting out and stopping the turbine intermittently.

Athini pays Hugh on a service plan (although there is no formal agreement), but is normally behind on payments. The turbine was on the brake for about six months, as Hugh was not prioritising the repair until the payments were up to date. Athini was using a petrol generator as a replacement, which broke this week. She then asked Hugh to fix it, but decided he would rather just fix the wind turbine instead!

Athini's SWT is a 5 year old machine, which is a recipe book design with AWP (African Wind Power) blades, as the original wooden blades fell off when the stainless steel mounting studs suffered a fatigue failure.

Not many people on Scoraig on service contracts:

- Aggie: £100/yr
- Secondary school: £300/yr (includes everything, even battery maintenance)
- Athini: £200/yr
- Chris and Anna: £250/yr

Prices vary depending on the size of the machine, the complexity of the system and the amount of maintenance that each user is willing/capable of performing themselves.

Independent

William & Bev - will only ever come to Hugh for spare parts if absolutely necessary

Lawrence Glass

John & Debbie

Andy & Susan - Installed own PV, but happy for Hugh to take care of SWTs

Malcom Olson - Won't even do battery maintenance

Dependent

Appendix I. Interview questions for NGO staff in Peru

The following questions were used to guide the interviews conducted with NGO staff in Peru:

- What is your role within the organisation?
- How many SWTs has your organisation installed?
- Why did you choose to manufacture SWTs locally?
- What issues have arisen with the local manufacture approach?
- Do you think imported SWTs have a role to play in rural electrification?
- Could you comment on the reliability of the SWTs you have installed?
- How do you ensure that the SWTs you install are correctly operated and maintained?
- Who is responsible for the O&M of an SWT installed in a rural community?
    - What training is offered to this person/people?
- What are your standard O&M procedures?
    - How well do you think these procedures are followed?
- If a failure occurs, how does a spare part reach the community?
    - How long does it take to reach each community? Which modes of transport are used?
- What training is offered to the end-users of the small wind systems?
- Who pays for the O&M costs of the system?

Appendix J. Survey design, sampling and questions in Cuajinicuil, Nicaragua

The following questions were used to gather information from the end-users of the renewable energy systems installed in the Nicaraguan community of Cuajinicuil. The survey was designed together with members of the implementing NGO, AsoFenix, who offered guidance on what information had already been collected from the community and how best to phrase the questions given the cultural norms and local dialect of the community. The aim of the survey was to determine the opinions of each household on their renewable energy system, the delivery model and the social change that the project has had (if any) in the community.

Due to the small size of the community (just 18 households), the entire community was included in the sample. Questions in italics were asked to all households, whilst the additional questions were used to find out further information from certain households. The households for extended questioning were selected through discussion with the implementing NGO and community leaders on which households were most likely to be most receptive to extended questioning and/or had interesting stories to tell (e.g. the household who's power cable was stolen). The questions were originally in Spanish, but have been translated here by the author. The questions were printed out and answers were recorded as notes on these printed pages before being written up into a central database.

Survey questions:

- *Type of energy:*
  a) solar home system; b) PV-wind hybrid mini-grid
- *How many people live here?*
- *How many people are still studying?*
  - *How many people managed to finish:*
    a) no formal levels; b) primary; c) secondary; d) university education.
- *What can you do with the energy that you couldn't do before?*
  a) watch TV; b) listen to music; c) study/read; d) charge mobile phone; e) productive activities, e.g. ………….. ; f) social activities, e.g. ………….. ; g) cook in the early morning/late evening ; h) other ……………
- *In your opinion, is the energy system you have in your home now better than the energy source you were using before (diesel generator/kerosene lamps)?*
  - In your opinion, is there an energy source that would be even better?
- Does the current system always produce enough energy? If not, how often does this happen and does it happen at specific times of year?
- *Has the health of your family changed due to the reduction in use of kerosene lamps at home?*
- *How would you rate the work of the committee that runs the energy system?*
  a) good; b) ok; c) bad.

- *How would you rate the work of the technicians that maintain the energy system?*
  a) good; b) ok; c) bad.
- Is there any way that you would like to participate further in the project?
- *How do you rate the tariff that you are paying for electricity supply?*
  a) high; b) appropriate; c) low.
- Which appliances do you have in your home, how powerful are they and how many hours per day do you use them? Which is the most important to you (second, third….)?

No. & type of appliance (make & model)	***Power rating (W)***	***Hours of user per day***	***Ranking of importance***
…	…	…	…

  - Are there any additional appliances would you like to own?
- How often do technical issues occur with the energy system?
  - Do you wait long for them to be fixed?
- Do you think that the energy system is easy and safe to use?
- Do you do any maintenance to the equipment installed in your home?
  - [solar home systems only] How do you look after the battery?
- Who do you think has benefitted most from the project?
- Do you have any other comments/opinions on the project?

Appendix K. Interview questions used in Cuajinicuil, Nicaragua

The following questions were used to guide the semi-structured interviews conducted in the Nicaraguan community of Cuajinicuil. In depth interviews were conducted with both the organising committee and the community technicians, with some questions asked to both groups and others designed specifically for one group. The interviews were designed to determine the opinions of each group on the renewable energy systems installed in the community, the delivery model and the social change that the project has had (if any) in the community. The interviews were conducted together with members of the implementing NGO, AsoFenix, and were recorded and transcribed on return from the field. The questions were originally in Spanish, but have been translated here by the author.

Questions for both the organising committee and community technicians:

- Who managed to finish:
  a) no formal levels; b) primary; c) secondary; d) university education?
- What do you use energy for in the community?
- What is your vision for the energy system?
  - How are you going to achieve it?
- Does the system provide enough energy for the needs of the users?
- Do you keep accounting records?
- Who pays for the maintenance of the system?
- Is there a preventative maintenance programme? If so, what does it consist of?
- In your opinion, are the users happy with the level of service offered by the technicians?
- Regarding the management model, have you encountered any problems? If so, how did you resolve them?
- Do you think the energy systems are easy and safe to use?
  a) solar home systems; b) PV-wind micro-grid.
- Do members of the community actively participate in the project? If not, why?

Interview questions for organising committee members only:

- Has anything been vandalised or stolen from the system? If so, why and what action did you take?
- Since the installation of the energy system:
- Has education and/or health in the community improved?
- Have women's burden's decreased?
- How often do you (the organising committee) meet? Can other members of the community participate in meetings too?
- How do you select members of the organising committee?

Questions for the community technicians only:

- Does the system produce as much energy as expected?
- Do you keep a maintenance diary?
- Was the experience of manufacturing your own turbine useful?
- Which spare parts and tools are kept in the community?
- What happens if you need a specific spare/tool and its not available in the community?
- Which type of failures are you able to repair? Which can you not?
- What type of knowledge are you missing that would enable you to carry our your work better?
- What do you think of the work of the management committee?
- Could you tell me about any failures that have occurred with the system?

When did the failure occur?	***How long was the system down for?***	***Which component failed?***	***How did it fail?***	***Why did it fail?***	***Where did a spare part come from?***	***How much did it cost?***	***How many hours did you need to fix it?***	***Any other comments?***

Appendix L. Interview design, sampling and questions used for wind power experts in Nicaragua

Table A-4 lists the various actors from the small scale wind power ecosystem in Nicaragua who were interviewed between October 22nd and November 10th 2012. A semi-structured approach was used in all of the interviews to allow interviewees the freedom to convey their own personal experience with SWTs, whilst at the same time capturing their views on critical issues relating to the potential of the technology in Nicaragua. The following questions were used to guide the semi-structured interviews and were accompanied by specific questions that were relevant to each participant's expertise:

- In your opinion, what is the biggest barrier facing small scale wind energy in Nicaragua?
- What potential do you foresee for SWTs as a technical solution for the electrification of isolated rural communities in Nicaragua?
  - Under what conditions would you recommend the use of such systems?
  - In which areas of Nicaragua?

The questions were originally in Spanish, but have been translated here by the author. The list of interviewees was collated by Marandin, as his seven years' experience with the Nicaraguan NGO, blueEnergy, had already allowed him to establish an extensive network of contacts in the rural electrification sector that had specific knowledge or experience with SWTs. For more information on how experts were engaged, please see section 3.8.2.1.

Table A-6: List of interviews conducted and the background to each interviewee.

	Institution	*Interview-ee*	*Title/Role*	*Relevant experience*
NGOs	ASOFENIX	Jaime Muñoz	Director	Practical experience with small-scale community turbine installed in Cuajinicuil (see case study).
	blueEnergy	Mathias Craig	CEO	Local manufacturing and capacity building for small-scale wind over 7 years on Caribbean Coast. Stopped manufacturing in 2011.
	BUN-CA	José María Blanco	Regional Director	Broad overview of rural electrification challenges in Central America.
	Centro Humboldt	Iris Valle	Technical Specialist	Insights of possible community wind projects.
	CHF International	Roberto Sosa	Project Director	Overview of the realities of economic development in Nicaragua. Personal experience with difficulties of owning a SWT.
Renewable energy suppliers	ECAMI, SA	Max Lacayo	Sales Manager	Installed about 20 small-scale wind systems in Nicaragua, but have witnessed decline in interest in the last years.
	ENCO, SA	Tim Coone	Director	Wind resource mapping of Nicaragua led by ENCO in partnership with MeteoSat. Perspective on the wind market, mostly utility and commercial uses.

	Institution	*Interview-ee*	*Title/Role*	*Relevant experience*
	SUNI SOLAR, SA	Douglas González	Director of Operations	Installing small-scale renewables for 13 years, mainly solar PV and about 10 to 15 small wind power installations.
	TecnoSol, S.A.	Lesther Ortiz	Sales Manager	Solar installer with very little experience with wind power - the systems they stock don't sell.
Government	MEM (Ministerio de Energía y Minas)	Aracely Hernandez	Head of Wind Projects	Overview of current government efforts to improve the wind resource mapping and context of wind energy in Nicaragua.
	PRONICARAGUA	Manuel Madriz	Energy Specialist	General presentation of the energy sector in Nicaragua.
Academia	Grupo Fénix (UNI - PFAE)	Susan Kinne	Director	Over 20 years teaching about renewable energy and community development at the UNI.
	UNI (Universidad Nacional de Ingeniería)	Jeronimo Zeas	Head of Wind Studies Department	General presentation of wind power technical issues, and the lack of information about the technology.

Appendix M. Data sources used for LGC/GIS methodology in Nicaragua

Table A-7: Most important maps, data sets and reports used in this study.

Data	Source	Year	Comments
Wind data and map	SWERA	2012	NASA and NREL reference
Wind data and map	ENCO, S.A.	2010	International wind measurement company
Solar data and map	SWERA	2012	NASA and NREL reference
Hydropower data and map	MEM, Asociación Renovables	2012	Based on official information in Nicaragua
Political map of Nicaragua	Authors	2012	Based on official information in Nicaragua
Population census data	INIDE	2005	Official information in Nicaragua
Electric transmission and distribution lines data and map	Authors	2012	Based on official information in Nicaragua
Map of road network	Authors	2012	Based on official information in Nicaragua
Tariffs, Power sector figures	CEPAL[156], MEM	2011	Official information in Nicaragua
LCoE worldwide figures	IPCC, IRENA[157]	2012	International agencies
Solar and small wind technology prices	Quotes from local and international vendors	2012	Quotes

[156] Economic Commission for Latin America and the Caribbean (Comisión Económico para America Látina y el Caribe).
[157] International Renewable Energy Agency.

Table A-8: Key variables used to assess the LGC of rural electrification options in Nicaragua

Variable	Value	Comments	Data source
Supply chain costs	For imported goods: 10% transport 10% import tax 10% VAT Administration costs: 30% for materials 50% for labour	Solar & deep cycle batteries tax exempt. See Figure 5-34 for full details	Interviews, quotes.
Installation costs	Dependent on: capacity of system difficulty of accessing site	Modelled from Cuajinicuil case study (section VI) and verified by IRENA Model	IPCC SRREN Full Report 2012 IRENA Renewable Energy Technologies: Cost Analysis Series 2012 data Lafise BANCENTRO Renewable Energy projects Department
Existing transportation infrastructure	Classified by population density: Poor access = < 25 ppl/km2 Average access = 25 - 100 ppl/km2 Good access = > 100 ppl/km2		INIDE 2005 poverty census
Economic parameters	Cost of capital/real interest rate: 8% Discount rate: 12%	Standard rate in 2012	Nicaraguan banks, ARECA Market Report
O&M costs	Dependent on: capacity of system & difficulty of accessing site		Cuajinicuil case study. Verified by interviews.
Ability to pay	% population living in extreme poverty	Deemed to be unable to pay for electricity from a wind power system	INIDE 2005 poverty census
Access to electricity	% population with access to grid or ENEL diesel mini-grids		INIDE 2005 poverty census
System lifetime	25 years	This is the period over which the lifetime costs are calculated. Many system components, such as the batteries or the wind turbine will need to be replaced one or more times during this period.	

Appendix N. Results of LGC/GIS filter (assuming that productive uses can be found to pay for maintenance costs)

Table A-9: Results of LGC/GIS filter (assuming that productive uses can be found to pay for maintenance costs).

Department	*Municipality*	*Level of access*	*Annual mean wind speed (m/s)*	*1kW Wind LCoE*	*1kW Solar LCoE*	*Total pop.*	*Grid access*	*Market size*
Carazo	Santa Teresa	AVERAGE	5	0.61	0.70	16891	65%	5969
Esteli	San Juan de Limay	AVERAGE	4.5	0.72	0.74	13463	38%	8292
Esteli	San Nicolas	AVERAGE	6	0.48	0.73	6768	19%	5509
Madriz	San Jose de Cusmapa	AVERAGE	5.5	0.53	0.71	7072	14%	6088
Carazo	La Conquista	AVERAGE	5	0.61	0.70	3777	36%	2423
Boaco	Santa Lucia	AVERAGE	4.5	0.72	0.75	8254	38%	5079
Boaco	San Jose de los Remates	AVERAGE	4.5	0.72	0.75	7650	37%	4812
Leon	Santa Rosa del Pe√±on	AVERAGE	5	0.61	0.69	9529	37%	6027
Matagalpa	Terrabona	AVERAGE	4.5	0.72	0.74	12740	46%	6881
Madriz	Las Sabanas	AVERAGE	5.5	0.53	0.70	4136	45%	2281
Rivas	San Juan del Sur	AVERAGE	6	0.48	0.73	14741	77%	3407
Rivas	Altagracia	AVERAGE	4.5	0.72	0.72	19955	68%	6474
Carazo	Diriamba	GOOD	5	0.58	0.69	57542	89%	6355
Carazo	Jinotepe	GOOD	4.5	0.68	0.70	42109	86%	6056
Chinandega	San Francisco del Norte	AVERAGE	5	0.61	0.69	6758	54%	3124
Carazo	San Marcos	GOOD	5	0.58	0.70	29019	90%	2784
Rivas	Belen	AVERAGE	5	0.61	0.70	14428	86%	2078
Granada	Diriomo	GOOD	4.5	0.68	0.70	22352	91%	2035
Managua	El Crucero	AVERAGE	5	0.61	0.68	13656	87%	1758
Rivas	Moyogalpa	GOOD	5	0.58	0.70	9729	82%	1730
Chinandega	San Pedro del Norte	AVERAGE	5	0.61	0.69	4719	65%	1641
Rivas	Rivas	GOOD	5.5	0.51	0.69	41080	96%	1583
Masaya	Niquinihomo	GOOD	4.5	0.68	0.69	14847	94%	838
Managua	Ciudad Sandino	GOOD	4.5	0.68	0.69	75083	99%	837
RAAS	Corn Island	GOOD	4.5	0.68	0.85	6626	88%	826
Rivas	Buenos Aires	GOOD	5.5	0.51	0.69	5420	89%	616

Department	*Municipality*	*Level of access*	*Annual mean wind speed (m/s)*	*1kW Wind LCoE*	*1kW Solar LCoE*	*Total pop.*	*Grid access*	*Market size*
Rivas	Potosi	AVERAGE	5	0.61	0.70	11904	95%	602
Carazo	La Paz de Carazo	GOOD	4.5	0.68	0.70	4657	89%	491
Rivas	San Jorge	GOOD	6	0.46	0.69	8024	95%	429
Carazo	El Rosario	GOOD	4.5	0.68	0.71	5317	94%	330
Carazo	Dolores	GOOD	5	0.58	0.69	6761	97%	224

Table A-10: Tabulated data for the final selection of municipalities where SWTs could be viable (assuming that only those who are not in extreme poverty could afford an SWT).

Department	*Municipality*	*Level of access*	*Mean wind speed (m/s)*	*Wind LGC ($/kWh)*	*Solar LGC ($/kWh)*	*Total pop.*	*Grid access*	*Extreme poverty*	***Market size (ppl)***
Carazo	Santa Teresa	AVERAGE	5	0.61	0.70	16891	65%	25%	**1830**
Estelí	San Juan de Limay	AVERAGE	4.5	0.72	0.74	13463	38%	49%	**1722**
Estelí	San Nicolas	AVERAGE	6	0.48	0.73	6768	19%	58%	**1591**
Madriz	San Jose de Cusmapa	AVERAGE	5.5	0.53	0.71	7072	14%	65%	**1519**
Carazo	La Conquista	AVERAGE	5	0.61	0.70	3777	36%	33%	**1187**
Boaco	Santa Lucia	AVERAGE	4.5	0.72	0.75	8254	38%	47%	**1175**
Boaco	San José de los Remates	AVERAGE	4.5	0.72	0.75	7650	37%	48%	**1132**
Leon	Santa Rosa del Peon	AVERAGE	5	0.61	0.69	9529	37%	54%	**929**
Matagalpa	Terrabona	AVERAGE	4.5	0.72	0.74	12740	46%	47%	**842**
Madriz	Las Sabanas	AVERAGE	5.5	0.53	0.70	4136	45%	39%	**651**
Rivas	San Juan del Sur	AVERAGE	6	0.48	0.73	14741	77%	21%	**370**

Appendix O. Sample of power performance measurements conducted in Scoraig

Methodology

The international standard for power curve testing of small wind turbines, as described in IEC-61400-12-1 (IEC, 2005) was used as a guide during the design of the measurement procedure to ensure the highest degree of accuracy possible given the available time and resources.

Site selection

The selected site was chosen as it is on the far Western tip of the Scoraig peninsula, with no trees nearby and therefore almost completely exposed to the wind coming directly off of the Atlantic Ocean. The house to which the turbine provides electricity is the only building nearby. As it is located 50m South-South-West at a level 10m below the base of the wind turbine tower, it was deemed to have negligible effect on the flow at hub height.

Figure A-11 shows that the predominant wind direction during the monitoring period was North-Easterly, with occasional high winds also coming from the South-West. Figure A-12 shows the frequency distribution of wind speeds recorded during the test period, which had a mean of 4.97m/s.

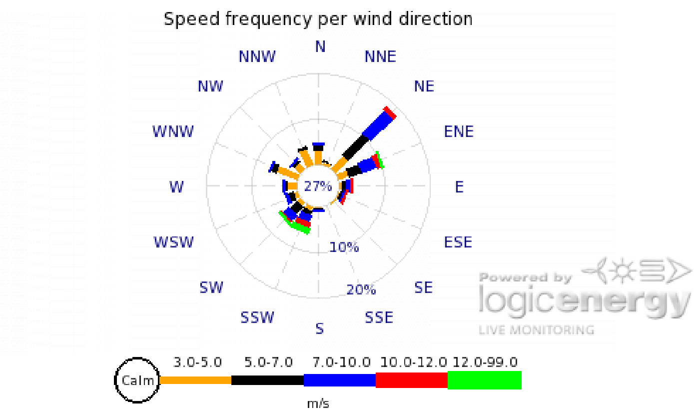


Figure A-11: Wind rose for the Glasshouse test site during the measurement period.

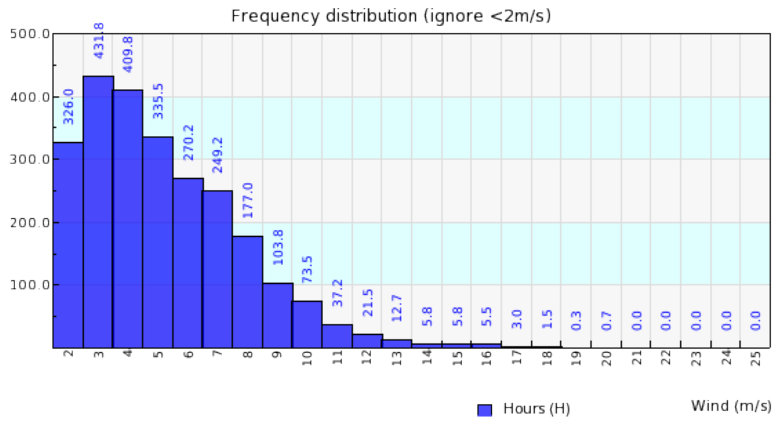


Figure A-12: Wind speed frequency distribution for the Glasshouse test site during the measurement period.

Technical specification of wind turbine

The Glasshouse wind turbine, shown in Figure A-13, is a 1.8m diameter machine built to the specifications of Piggott's (2009) *A Wind Turbine Recipe Book* in 2008. The relevant technical information is presented below in Table 2-1. The only major modification to the design of the machine is the fact that it contains two magnet rotor discs, instead of just one, as described by Piggott (2009). This is a result of a manufacturing error, in which the stator was cast too thick. As a result, flux density in the stator was too low (even when the air gap between the rotor and the stator was reduced to the minimum possible without compromising mechanical reliability) and the cut in speed of the machine would therefore have been excessively high. To rectify this problem, a second rotor disc was manufactured and installed on the other side of the stator, as is normally done for larger machines.

Table A-11: Technical specifications of the Glasshouse wind turbine.

Blades	
Number	*3*
Profile	*Based on Aquila*
Material	*Wood (Siberian Larch)*
Generator	
Generator topology	*Axial flux permanent magnet (AFPM)*
Permanent magnet material	*Neodymium-iron-boron (NdFeB)*
Nominal voltage	*12V*
Rotor disc material	*Steel, polyester/fiberglass*
Stator material	*Polyester*
No. coils	*6*
No. poles	*8*
Resistance	*0.412Ω*

Tower	
Height	*7.7m*
Type	*Tilt-up guyed*
Material	*Tubular steel*
Electrical System	
Battery type	*4x450Ah Rolls S-600 6V*
Battery configuration	*12V - 2 series pairs paralleled*
Charge controller	*Tristar 45 in diversion mode*
Inverter	*Studer Joker 800W*

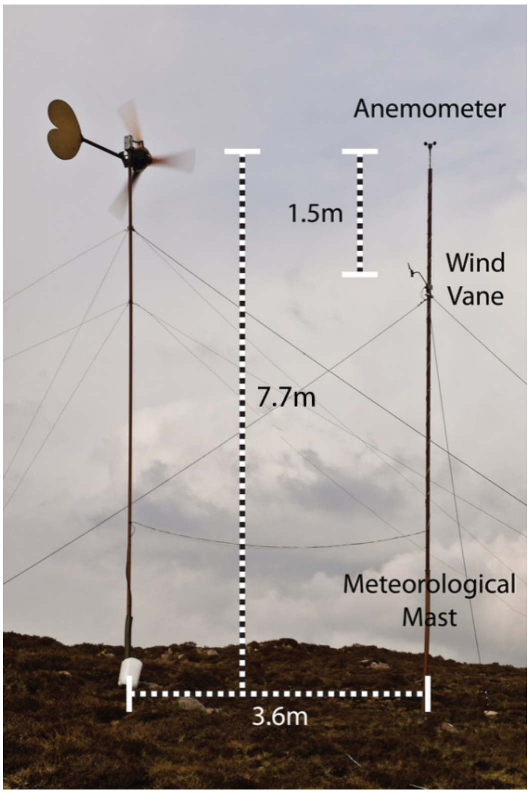


Figure A-13: Photograph of the meteorological mast showing its proximity to the wind turbine.

Technical specification of data logging system

The variables listed in Table A-10 were measured and recorded by the Logic Energy LeNet data logger. All variables were measured at a frequency of 1Hz and averaged over a 10 minute period. The averaged data was transmitted every 10 minutes via the GSM network and stored on the Logic Energy server.

Table A-12: Technical specifications of the data logging equipment.

Variable	*Sensor*
Wind speed	*NRG Max40*
Wind direction	*Davis Pro-D*
Temperature	*Zener diode*
Rotational speed	*AC frequency*
Current	*LEM-HT-200-SBD hall effect probe*
Voltage	*Data logger powered directly from Glasshouse battery bank*

The relative positions of the wind measurement instruments and the wind turbine are shown in Figure A-13. The anemometer is located 2 rotor diameters (3.6m) from the wind turbine tower and at hub height, as required by IEC61400-12-1.

Figure A-14 shows the layout of the sensing equipment used to record the data. Excluding the anemometer and wind vane, all sensors were located in a waterproof housing beside the battery bank at the Glasshouse. Signals were transmitted to the data logger from the wind turbine tower (frequency) and meteorological mast (wind speed and direction) using a 12-core armoured telecom cable.

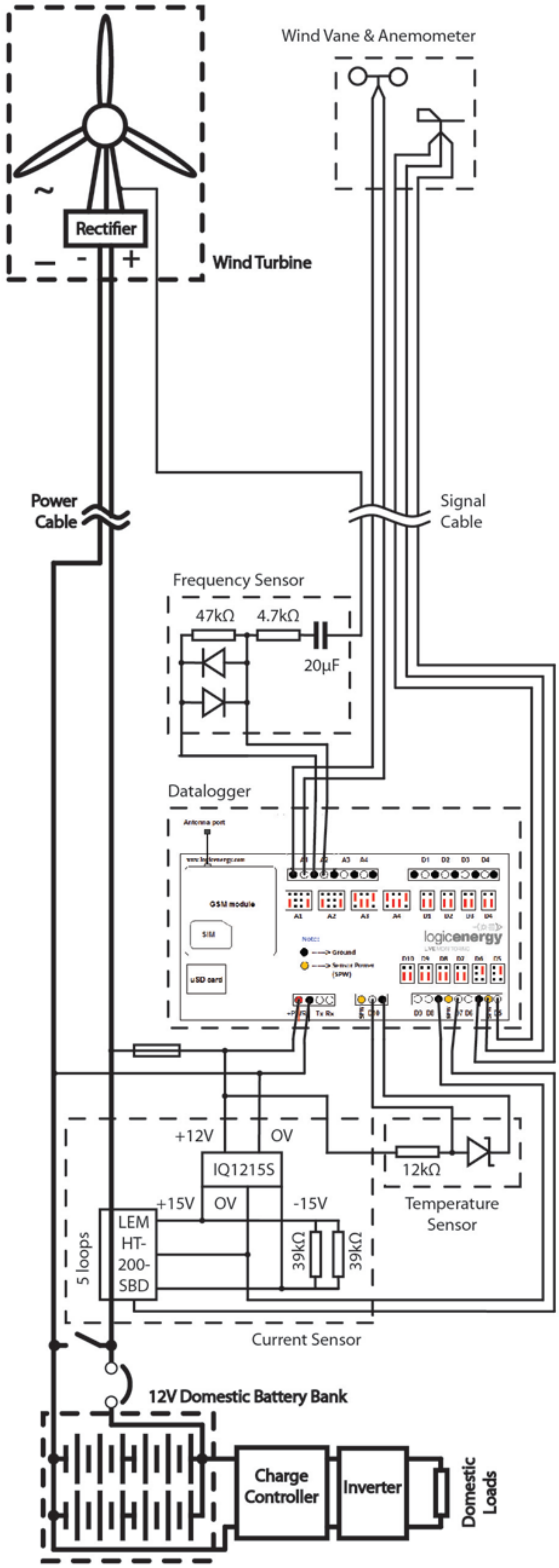


Figure A-14: Wiring diagram of the data logging equipment installed on the Glasshouse wind turbine. LeNET image courtesy of Logic Energy.

Data processing

To remove erroneous data recorded when the anemometer is in the wake of the wind turbine, all data from the sector 298.5-19.5° was removed (as recommended by IEC61400-12-1 and illustrated in Figure A-15), leaving a total of 13,438 samples. However, in contrary to the requirements of the standard, data from when the wind turbine was downstream of the anemometer was not excluded as it can clearly be seen in Figure A-16 that the profile of the anemometer and meteorological mast are very small compared to that of the wind turbine. Data from times when either the wind turbine or the met mast was downstream of the house was also not removed. As shown in both Figure A-15 and Figure A-16, not only is it 50m away, but it is also 10m downhill from the turbine and was therefore also deemed to have a negligible effect on turbine performance. This assumption was confirmed by the agreement of the data obtained from this sector with that from other wind directions.

As described in IEC61400-12-1, power values were normalised using the air temperature recorded by the Zener diode. Unfortunately as the Zener diode was located inside the waterproof housing on the South side of the Glasshouse, it would have been particularly vulnerable to falsely high readings. 0.5m/s bins were used to produce the final power curve, as described in IEC61400-12-1.

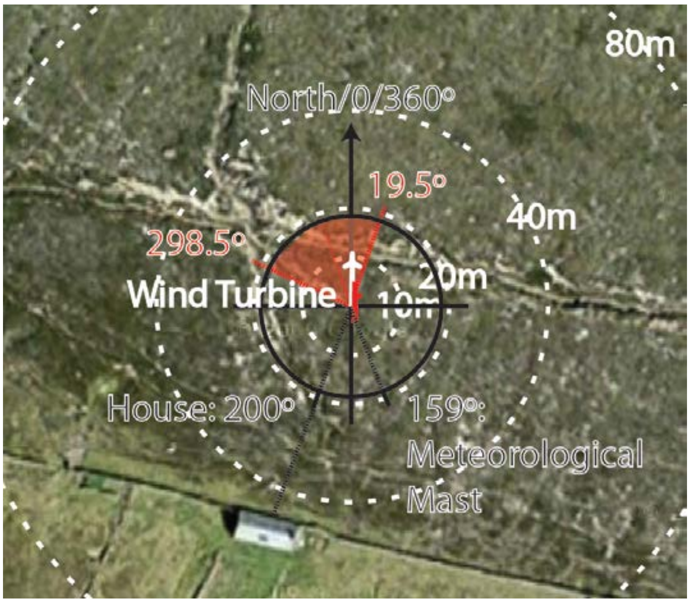


Figure A-15: Satellite photograph of the site showing radial contours of distance from wind turbine (white) and the excluded sector when the meteorological mast is downstream of the wind turbine (red). Image courtesy of Google Maps.

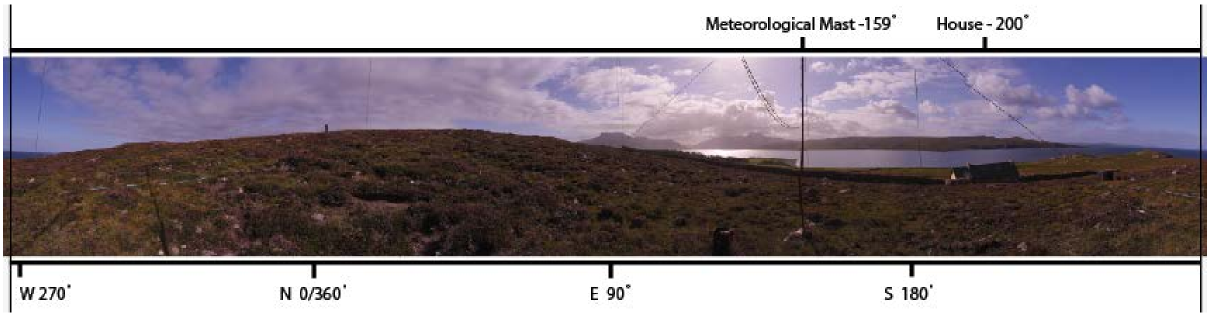


Figure A-16: 360° panoramic photograph of test site relating locations of potentially significant obstacles to flow onto the wind turbine.

The power curve shown in Figure A-17 was produced from the measured dataset, showing a peak power of 267W at 13.5m/s. This is significantly lower than the design value of 350W (Piggott, 2009).

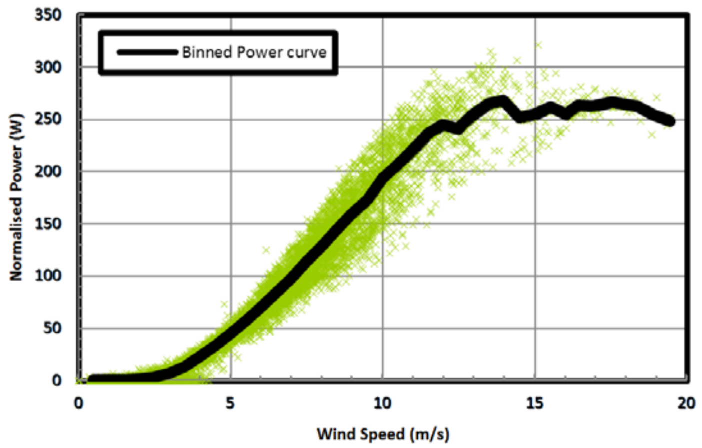


Figure A-17: Scatter plot of all data (after removing samples taken when anemometer in wake of turbine) with binned power curve.

Figure A-18 shows the predicted Annual Energy Production (AEP) of this wind turbine on sites with various annual mean wind speeds. Again, measured values are significantly lower than those quoted by Piggott (2009).

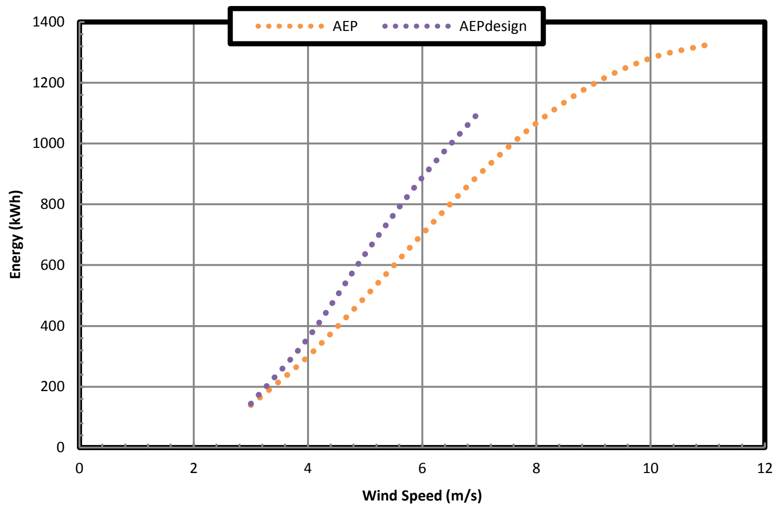


Figure A-18: Comparison of the measured Annual Energy Production (AEP) with the deign values, as stated by Piggott (2009).

Figure A-19 partly explains why the latter part of the curve appears rougher than the former: fewer instances of high winds mean that the data in this region is less reliable, even though it exceeds the minimum number of data points to be included in the curve, just 3 (IEC, 2005). In addition to this, the wind turbine uses a furling mechanism for overspeed protection in high winds. Wind turbines rarely reach steady state when furling as the balance between aerodynamic and gravitational forces is constantly shifting.

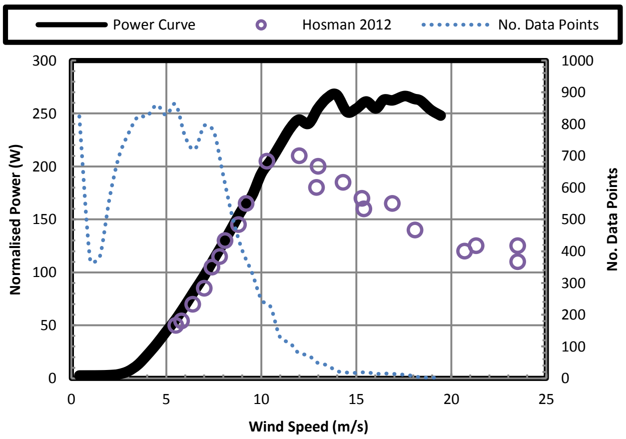


Figure A-19: Relationship between the number of data points and the reliability of the measured data.

Figure A-19 also shows the results obtained by Hosman (2012) in the TU Delft Open Jet Facility Wind Tunnel on an identical 1.8m locally manufactured wind turbine. It is clear to see that up to 10 m/s the two sets of data are virtually identical. However, as the furling tail begins to regulate the power output, then the results begin to differ. The machine tested in the wind tunnel has a much more severe furling action, quickly cutting off power in higher winds. Although this will protect the machine, it will sacrifice energy yield.

Figure A-20 illustrates the power coefficient, Cp, achieved by the wind turbine at various wind speeds, with a peak Cp of 0.25 at 4m/s. Again, the agreement with Hosman's (2012) wind tunnel data is remarkable until the furling action begins around 10 m/s.

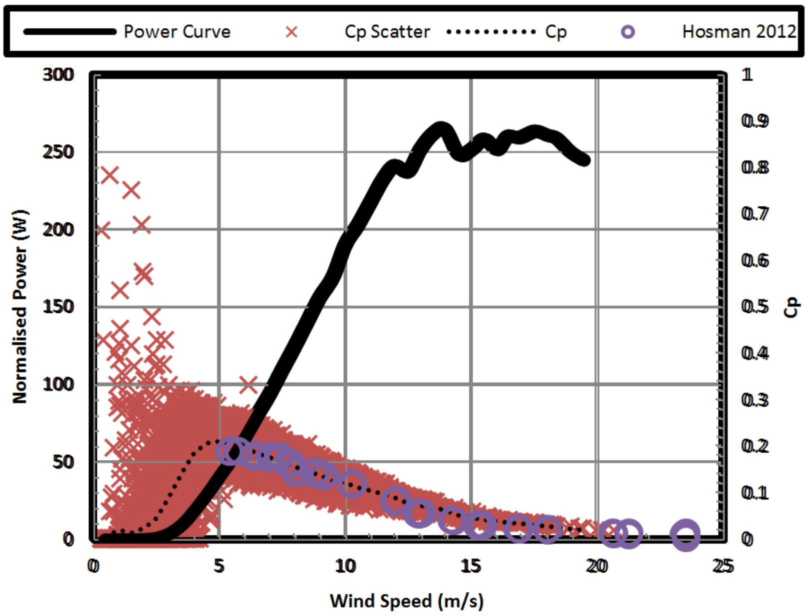


Figure A-20: Scatter plot of power coefficient, Cp, using all data (after removing samples taken when anemometer in wake of turbine) with binned power curve.

Conclusion

The performance of the 1.8m wind turbine located at the Glasshouse on Scoraig was monitored over a 4 month period and a power curve produced. Peak power was found to be 267W at 13.5m/s and the annual energy production on a site with an annual mean wind speed of 5m/s is predicted to be 495kWh. Although there were some minor deviations from the international standards used as a guide during the testing procedure, the experimental results showed little scatter after filtering out data from when the anemometer was in the wake of the turbine and were therefore assumed to be valid. The results of this study are backed up by findings from a similar wind tunnel study, although the behavior of the furling system does vary significantly between the two machines.

Appendix P. Interview questions for Scotland Case Study

Questions for SWT end- users:

- When & why did you move to Scoraig?
- Please describe the energy system you currently have in operation.

No. & type of equipment	*Power rating (W)*	*Installation date*	*Supplier*	*Cost (£)*
….	…	….	….	….

No. & type of appliance	*Power rating (W)*	*Average daily usage (h)*	*Importance*
….	….	….	….

  - Why did you choose this energy system?
  - Are you satisfied with the system?
  - Where did you live before you moved to Scoraig and how did you get your electricity there?
    - How does it compare?
  - Would you choose wind power again if you moved away from Scoraig?
- Do you think wind power has been successful on Scoraig? If so, why?
- What maintenance do you perform on your wind turbine? Who performs the rest of it?
  - Are you happy with the level of service offered by Hugh?
  - Are you happy with the amount that he charges his services?
- What problems have occurred with the wind/solar/petrol generator?

Date	Downtime	Component	How?	Why?	Spare supplier?	Spare cost?	Paid by?	Comments
….	….	….	….	….	….	….	….	….

Appendix Q. Wind resource estimations for household case studies

Ideally, wind resource data would be collected at each site for many years and averaged to give a mean wind speed for each month. Unfortunately due to constraints on time and resources, this was not possible. Instead, the wind data recorded by Piggott at his home from December 2009 onwards was analysed and compared to the wind speed data recorded during the power curve measurements at each site[158]. Figure A-21 shows the monthly average wind speeds at the Piggott household during this period (red bars). The average of these monthly averages (red line) is compared to the prediction made by NASA's (2013) global wind speed database, which is produced from long-term satellite measurements (black line). Whilst the NASA data agrees with the general trend of calmer summers and windier winters, it overestimates the wind resource, as it does not take into account local topographical effects and therefore is only accurate for "*terrain like airports*" (NASA, 2013: 1).

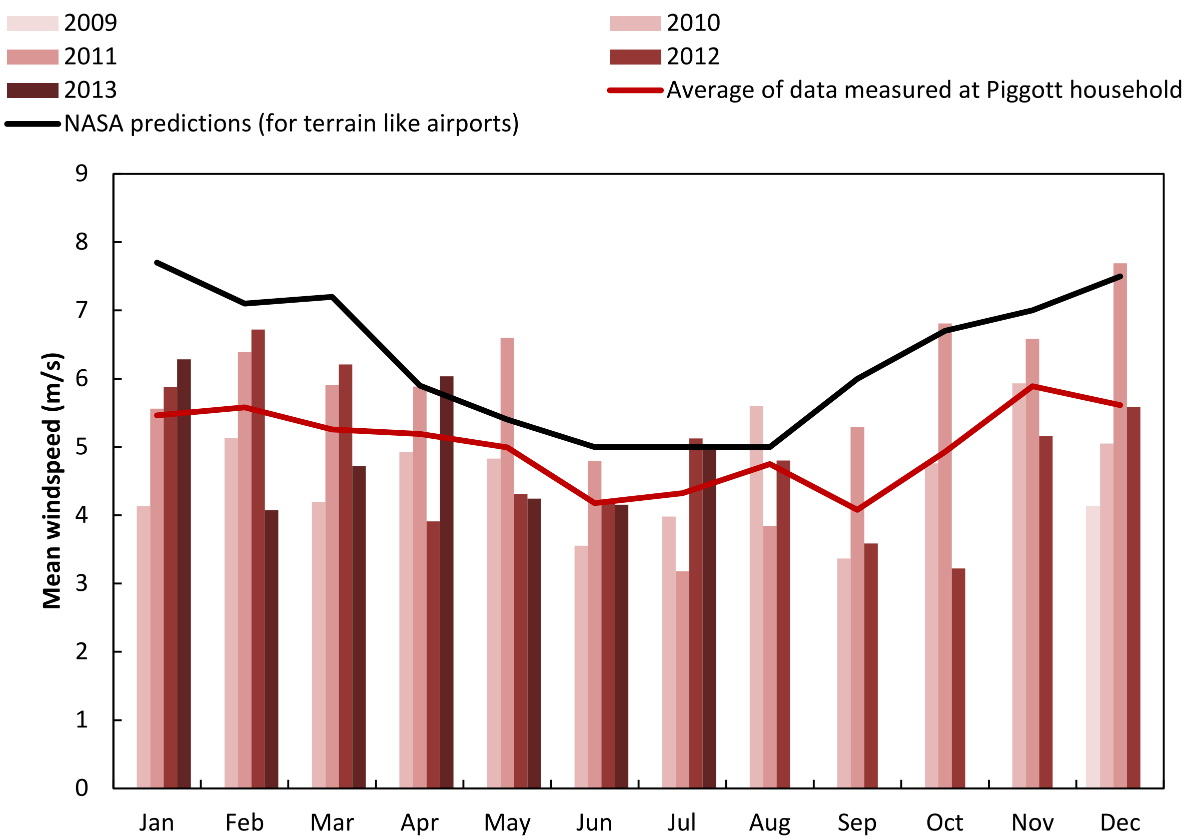


Figure A-21: Wind data recorded by Piggott at his home from 2009-present, compared to the optimistic predictions of the NASA (2013) database.

Figure A-22 shows the comparison of the data recorded at each of the three sites with the data recorded at the Piggott household during the corresponding months. It can be seen that the wind speeds recorded at the Whisken/McSweeny household were an average of 6% below those recorded

[158] Days when the system was down for maintenance were excluded from the dataset and only months with at least 20 days of data were included in the analysis

at the Piggott household, whilst at the Davy household, they were 10% above and at the Brown household they were 17% below. However, this data must be treated with caution, as although it is all measured at a height of approximately 10m, there are localised shelter effects that cause inaccuracies in the data: from the turbine tower at the Piggott household, where the anemometer is mounted on a boom, and from the turbines themselves at the three sites, where the anemometer is mounted on a separate mast at hub height. Whilst knowledge of each site suggests that the correction factor for John & Debbie's and Lee Brown's is realistic, the scaling factor for Andy & Susan's was adjusted from -6% to +6%, as the turbine is located just a few hundred metres from the Piggott household on a more exposed site.

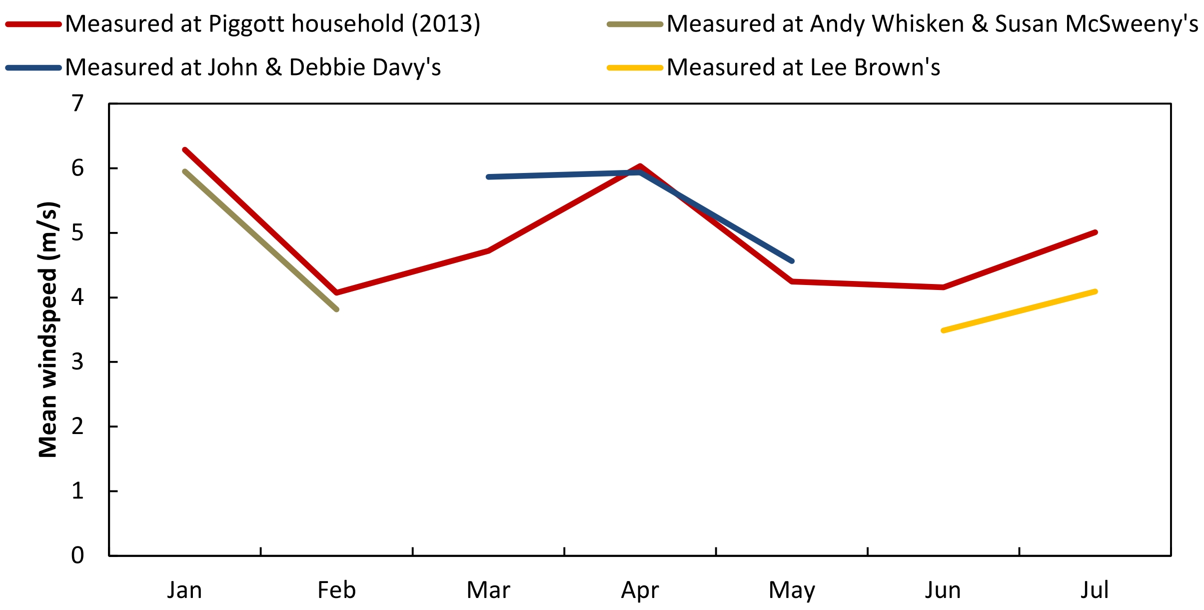


Figure A-22: Comparison of wind data measured at Piggott household with data measured at each of the three household case study sites during power curve measurements

Figure 6-9 shows the estimated monthly mean wind speeds for each site to be used as input data for the HOMER models. This data was produced by taking the averages of the monthly data recorded at the Piggott household and scaling it using the scaling factor determined above for each site. The averages of all monthly data measured at the Piggott household was used as the base profile to reduce the influence of inter-annual variation, as the latest year (Aug 2012-July 2013) was significantly calmer than previous years, with an annual mean of 4.74m/s, compared to 5.55m/s (Aug 2011-July 2012) and 5.25m/s (Aug 2010-July 2011).

Appendix R. Reliability and resilience of the power generation equipment from the household case studies

Whilst the statistics shown in Figure A-23 must be treated with caution due to the small sample size, the general trend seen in the previous chapters of solar PV's greatly superior reliability over LMSWTs is clearly illustrated by the fact that to date, none of the PV arrays have experienced a failure. The fact that generators appear to perform even better is misleading, as only equipment currently in operation is included in the analysis, so the fact that three generators were completely written off before these ones were installed is not represented. However, the statistics for the single hydro turbine seem to be more realistic, i.e. it experiences many small failures (Figure A-23a)) that are easily fixed (Figure A-23b), primarily from stones jamming in the pipe), so its overall availability remains high at 99% (Figure A-23c)).

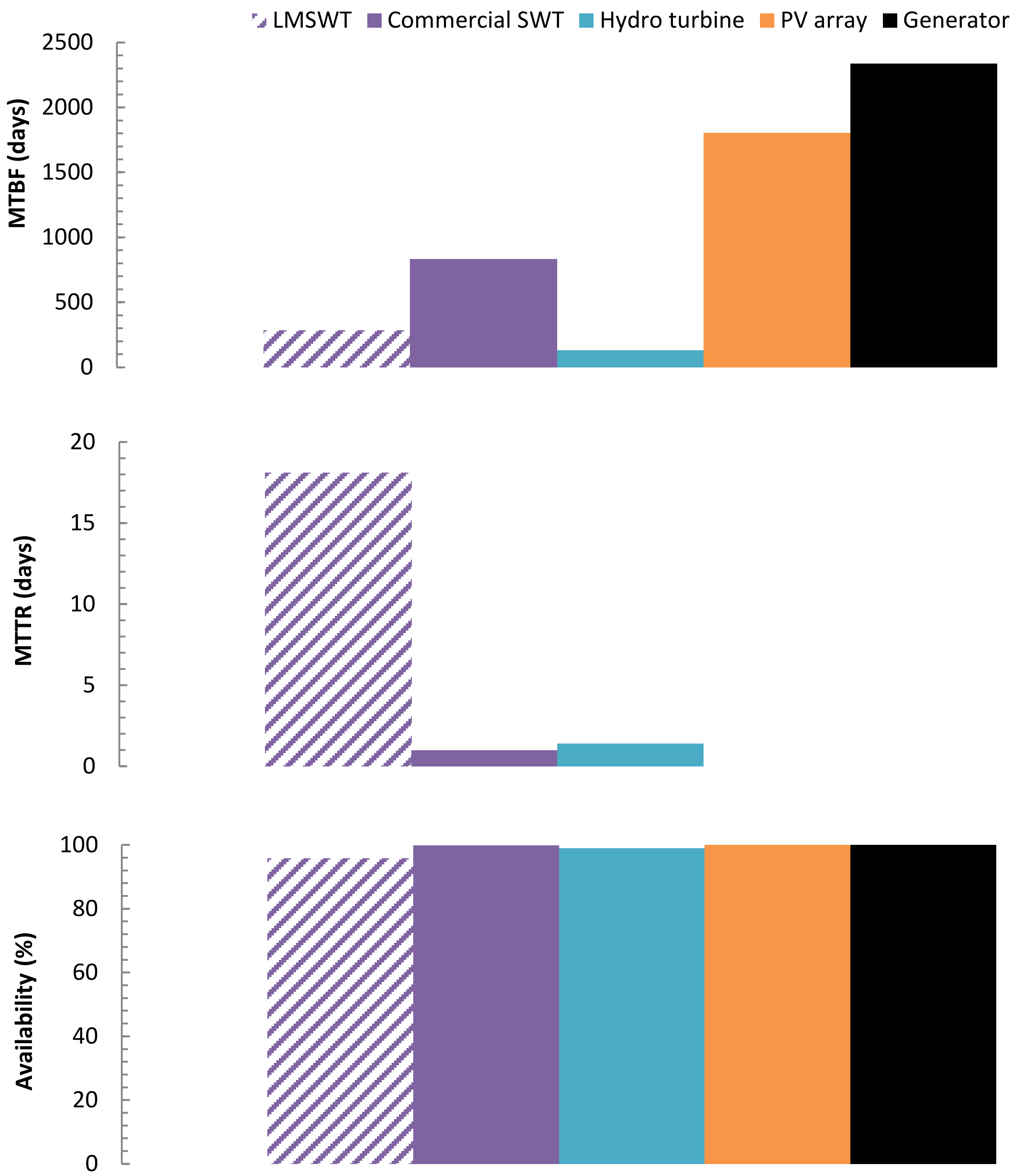


Figure A-23: Average a) Mean Time Between Failures (MTBF), b) Mean Time to Return (MTTR) and c) availability for each power generation technology installed in the three case study sites.

As expected, the commercial SWT (the Ampair Hawk installed at the Whisken/McSweeny household) has been more reliable than the three LMSWTs, with an MTBF of almost triple (Figure A-23a)), however as it has only experienced a single failure that was luckily easy to fix (the broken shackle that could have caused the whole tower to collapse if it hadn't been caught in time) means that the resilience of the system (indicated by the low MTTR in Figure A-23b)) cannot be compared fairly with the equivalent LMSWT data. In fact, it was predicted that the opposite would have been the case, i.e. the lack of available spare parts to repair the commercial machines was expected to mean that it would take longer to repair them.