Following the 'golden thread'

Exploring the energy dependency of economies and human well-being

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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The research was conceived, designed and undertaken by Lina I. Brand Correa, with conceptual and analytical feedback throughout the duration of the research from Julia K. Steinberger. Lina I. Brand Correa wrote the paper with comments and contributions from Julia K. Steinberger.

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Abstract

Climate change –one of the greatest threats to modern civilisation- has been largely driven by an exponential growth in world energy use in the last couple of centuries. However, societies and economies are dependent on energy use to maintain themselves and change. Thus, in this thesis I compare energy to a 'golden thread', which weaves through climate change, economic growth and human well-being. In this context, the challenge I set out to explore in this thesis was to find alternatives for decoupling societal and economic progress from environmentally harmful levels of energy use.

In order to open the possibility space for decoupling the energy dependency of the economy from climate change, I used the holistic theoretical framework of surplus energy and developed a novel methodology for calculating Energy Return On Investment (EROI) at the national level. Similarly, in order to open the possibility space for decoupling the energy dependency of society (human well-being) from climate change, I developed an original theoretical framework, integrating the concepts of energy services and human needs, and tested it using an innovative methodology.

I found that a national-level EROI can contribute to accelerate a transition away from fossil fuels, by providing evidence at a scale relevant for policymakers. Additionally, I found that the energy services and human needs framework, as well as the methodology to test it, provide a way to prioritise and explore alternatives of energy service delivery. I consider that both of these contributions point towards the possibility of having climate compatible energy dependent societies and economies, as long as there is a fundamental change in the framings, understanding, priorities and methodologies used to find and assess such possibility.

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Abbreviations

CO_2	Carbon Dioxide
EJ	Exajoules
EROI	Energy Return on Energy Invested
$EROI_{nat}$	National-level EROI
ES	Energy Services
GEMBA	Global Energy Modelling—a Biophysical Approach
GHG	Greenhouse Gas(es)
HDI	Human Development Index
HN	Human Needs
HSD	Human Scale Development
HUSES	HUman Scale Energy Services
IEA	International Energy Agency
IO	Input-Output
KW	Kilowatt
MROI	Multi-Regional Input-Output
NEA	Net Energy Analysis
NGO	Non-Governmental Organisation

Chapter 1

Introduction: Energy as the 'Golden Thread'

"Everything we can observe is energy in different forms" (Dincer, 2002, p. 141). Energy is the driver behind every process that occurs. "Energy is the cause and measure of all that there has been, is, and will be […], it is a fundamental property of existence" (Kostic, 2007, p. 1). When things (systems) interact with one another, energy is transformed and change occurs. Every single process - be it the photosynthesis in a cell, a falling feather or the locomotion of a train - involves energy transformations. Everything –including human beings and human societies- requires energy in order to be sustained and to change.

Throughout this thesis, I argue that an energy lens is beneficial for understanding fundamental changes and challenges to societies, economies and the environment. The UN's former secretary general Ban Ki Moon stated, at a "Sustainable Energy for All" event in Washington in 2012, that "energy is the golden thread that connects economic growth, social equity, and environmental sustainability"[1]. In this thesis, I have borrowed Ban Ki Moon's analogy of energy as a "golden thread" to portray the relationships I have analysed using an energy lens.

The golden thread analogy structures this introduction (see Figure 1-1). In section 1.1, I follow energy as it weaves through society and the economy. My initial account explores the interlacing of energy in historical accounts and earlier contributions to this subject from two perspectives (socio-historical and ecological economics), which provide a theoretical basis for this thesis. In section 1.2, I follow energy as it weaves through the environment, in particular in relation to climate change. In section 1.3, I provide a more recent account of the interlacing of energy around society and the economy, identifying research gaps. In section 1.4, I explain my overall research framing, as well as presenting my research aim and objectives. This section also contains the overall research design. Finally, section 1.5 provides a description of the structure of the thesis.

1.1 Energy dependency of society and the economy

The types and levels of energy that societies and economies have harnessed and used through time have changed dramatically. Societies have moved from having an uncontrolled solar-based energy system (hunter-gatherer societies), to a controlled solar

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[1] For Ban Ki Moon's full remarks see https://www.un.org/press/en/2012/sgsm14242.doc.htm

energy system (agrarian societies) to a fossil-based energy system (industrial societies) (Sieferle, 2001, Chapter I). In addition to a change in the type of energy, the amount of energy used by societies through time has also changed, following an overall global increasing trend that has become exponential in the last two hundred years (Haberl, 2002). Immense quantities of fossil energy constitute the lifeblood of modern societies. When a stable flow of energy to society is interrupted, for example through power cuts or interruptions in supply routes, societies become crippled: people get stuck in elevators, production processes stop, transport systems collapse, education and health support are harmed, and even political tensions rise (Verbong & Loorbach, 2012).

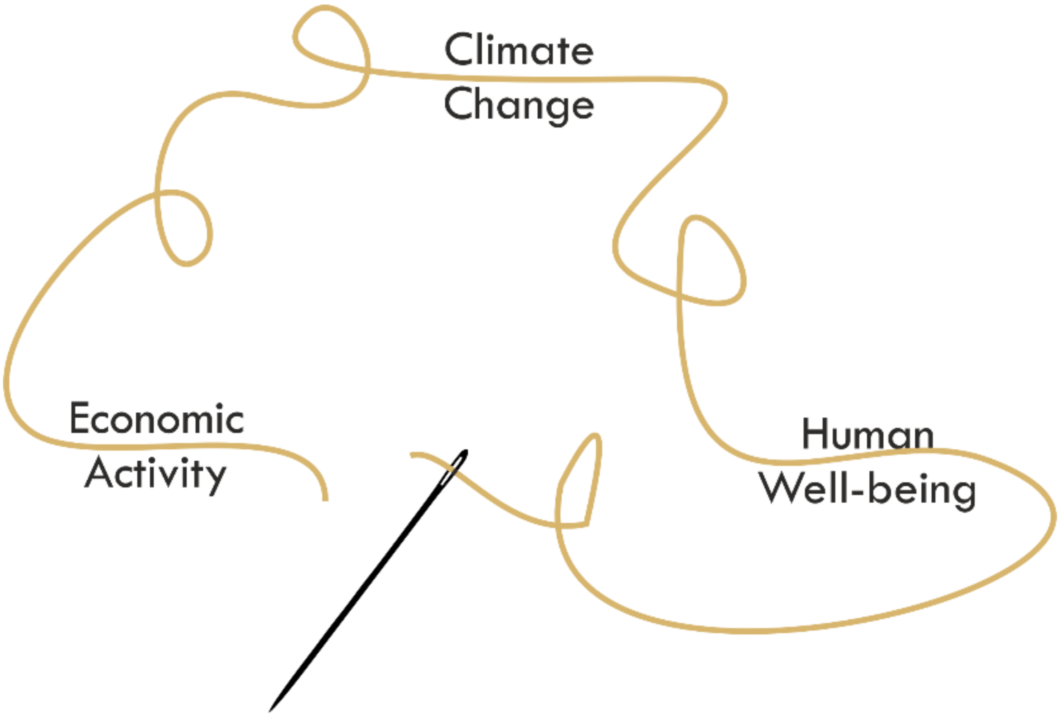

Figure 1-1. Energy as the "Golden Thread"
Source: Own elaboration.

The energy dependency of societies and economies has been mainly analysed from two different, but interrelated, perspectives: a socio-historical perspective and an ecological economics perspective. The former explores the interconnections between social change and diverse types and levels energy use, while the latter exposes the physical dependency of any production process, and thus of the economic system, on energy flows and transformations. In section 1.1.1 I start with a brief historical overview of the changes in types and levels of energy use before exploring the contributions that attempt to link such changes with societal transformations. And in section 1.1.2 I provide an outline of the theoretical foundations of ecological economics and how they are fundamental for understanding the energy dependency of the economy.

1.1.1 Socio-historical perspective

Humans have always extracted or captured energy resources and transformed them for their benefit. Early bipeds (around 7.5 million years ago) relied solely on their muscles to obtain food (Smil, 1994, Chapter 2). With time, humans developed tools that made it easier to hunt and eat (i.e. that improved the efficiency of muscle energy). After the end of the last ice age, at the start of the Holocene (between 9000 and 5500 BC), early humans developed agriculture, initially in fertile floodplains (Cipolla, 1978; Smil, 1994, Chapter 2). Where agriculture was not possible (e.g. steppes and savannahs) groups of humans remained nomadic and raised livestock as a source of energy (Sieferle, 2001, Chapter 1). By the AD times, agriculture had extended to the whole world, leading to increasing sedentarism (Cipolla, 1978). As human societies became more sedentary and complex, agricultural intensification increased, tools improved and humans started to harness the muscle energy of draft animals (and even other humans, through slavery), further increasing net energy returns when compared to hunting and foraging.

Pre-industrial societies also captured other external sources of energy, principally chemical energy from biomass in the form of wood, charcoal, crop residues and dung, and kinetic energy in the form of wind and water. It was only during the second half of the nineteenth century that human/animal muscle, biomass, wind and water lost their dominance in the energy mix of the Western world. Coal emerged as a major source of energy in in parallel to the invention of the steam engine, which in turn facilitated coal mining by pumping out ground water from coal mines (Daemen, 2004; Mitchell, 2011, Chapter 1).

However, the story was not the same for every nation in the world. Human/animal muscle, biomass, wind and water remained prevalent as the main sources of energy for many in the developing world (Smil, 1994). In fact, these sources of energy are still dominant for some segments of the world population today. In 2014, 1.06 billion people worldwide lacked access to electricity and 3.04 billion people lived without access to clean energy sources for cooking (SEforALL, 2017). Figure 1-2 shows how coal appeared in the energy mix, but also how the more traditional forms of energy have not disappeared from it.

As the twentieth century progressed, extraction of oil and gas started to dominate the global energy mix. In the later part of the century nuclear energy, hydropower and modern renewable energy also entered the combination. Modern societies have been marked not only by the variety of their energy sources, but also -and more importantly- by the magnitude of their energy use, prominently consisting of fossil fuels. It was only in the last 200 years, during and after the Industrial Revolution, that modern societies started to control quantities of energy like never before (see Figure 1-3). As a result we are now the most energy dependent generation of humans in world history (Kostic, 2007; Smil, 2008).

Even though energy has always been part of human existence, it was only around the time of the Industrial Revolution that a relatively clear concept of energy in scientific terms emerged (Garber, 2004; Kümmel, 2011; Smil, 2006). During the 19th century, many advancements in the understanding of thermodynamics were established, most notably the formalization of the second law by Clausius (Smil, 2006). Increasing use –and understanding- of energy both sparked and was enabled by the deep changes in the way of life that were happening during the Industrial Revolution.

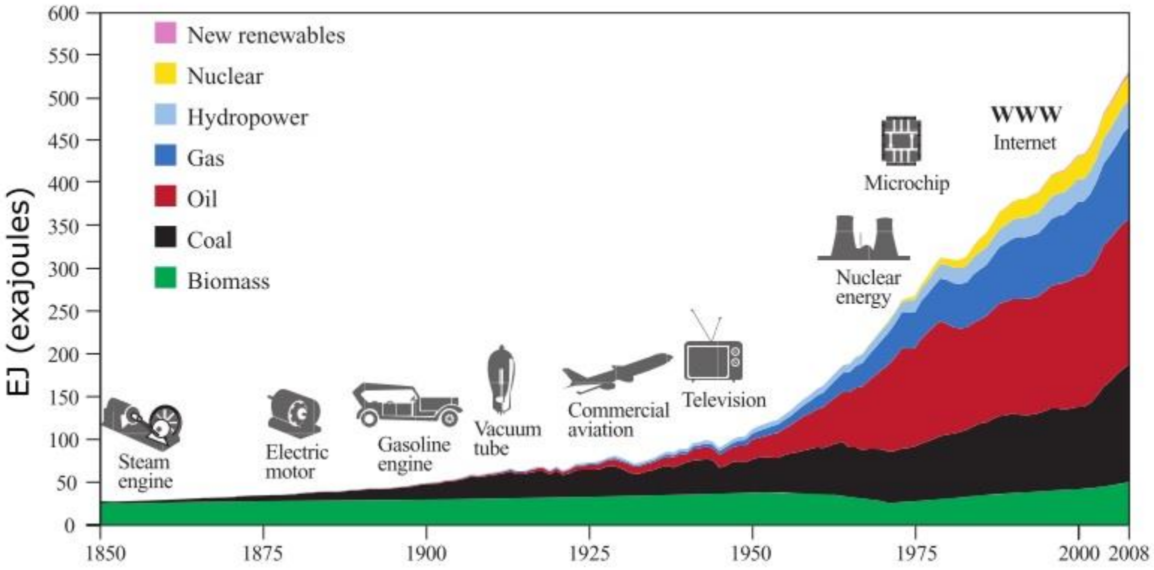

Figure 1-2. Historical global energy mix
Source: Grubler et al. (2012).

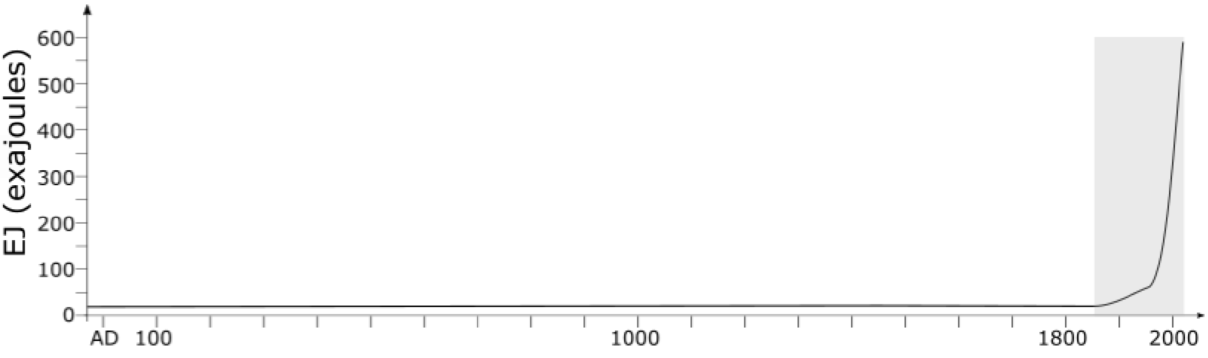

Figure 1-3. Global energy use in perspective
Note: the grey area is shown in detail in Figure 1-2.
Source: Own elaboration.

Moreover, the exponential increase in energy use spurred scientific interest to explore the interlinked nature of changes in available energy and changes in society, first from physical scientists, and later from social scientists (Nader & Beckerman, 1978). They found, through different avenues, how dependent societies are on energy flows. Energy theories of social and cultural evolution were often characterised by understanding societies as analogous to living forms (with different levels of complexity), requiring increasing energy flows in order to grow (Adams, 2004).

Chemists Wilhem Ostwald and Frederick Soddy in the early twentieth century viewed the social and economic progress of their time directly related to the mastery of enormous fossil fuel stocks (Cleveland, 1987; Daly, 1980). Soddy, explained the great advancements of society since the industrial revolution by the ability of humanity to use energy capital (non-renewable stocks) rather than energy revenue (solar flow) (Daly, 1980).

Mathematical biologist Alfred Lotka talked about the principle of energy maximisation as the driver of natural selection, of any type of system (an individual, a species, a society); i.e. the systems that will prevail are those who can maximise their net energy throughput (Adams, 2004; Cleveland, 1987). These physical scientists, aware of the laws of thermodynamics, were also aware that fossil fuels are non-renewable stocks that could limit the availability of energy flows in the future (Adams, 2004).

An early and influential example of a social scientist analysing this issue is the anthropologist Leslie White. Figure 1-4 summarises his argument. He defined the purpose of culture as the satisfaction of “the needs of man” (1943, p. 335). Thus, according to White, cultural progress is measured by the degree in which, and the efficiency with which, human-need-serving products (P) are provisioned. Two properties of cultural evolution derive from that. Everything else being equal, the degree of cultural development varies directly and in the same proportion as: i) the amount of energy controlled and expended by man (E); and ii) the efficiency (F) with which technology (T) uses energy (E). Therefore, P = E x F. White applied his reasoning to different types of societies across human history (in his words, savage, tribal, barbaric and modern civilizations).

Following a similar line of thought, the sociologist Fred Cottrell published in 1955 a comprehensive assessment on the role of energy in human societies. Cottrell focused on the “energy surplus” of processes and the role of energy as a subsidy of labour and enhancer of labour productivity, in order to explain social change (Cleveland, 1987). Cottrell defined surplus energy as “the energy available to man in excess of that expended to make energy available” and described it as “a social estimate of a physical fact” (Cottrell, 1955, pp. 11–12). He also related the development of complex institutions with the existence of an energy surplus, and vice versa.

I find White's and Cottrell's contributions particularly interesting for this thesis. On the one hand, although White does not specify what constitutes a human need, he mentions several examples: food as the most basic "bodily" need, shelter and defence, and companionship and distinction. Furthermore, White distinguishes needs from "ways of satisfying them" (1943, p. 335), through the use of human-need-serving products (P) and other human organism and habitat derived activities. On the other hand, Cottrell highlights the importance of considering the energy costs of making energy available for human use. Both of these insights are direct precursors to research conducted within this doctoral dissertation.

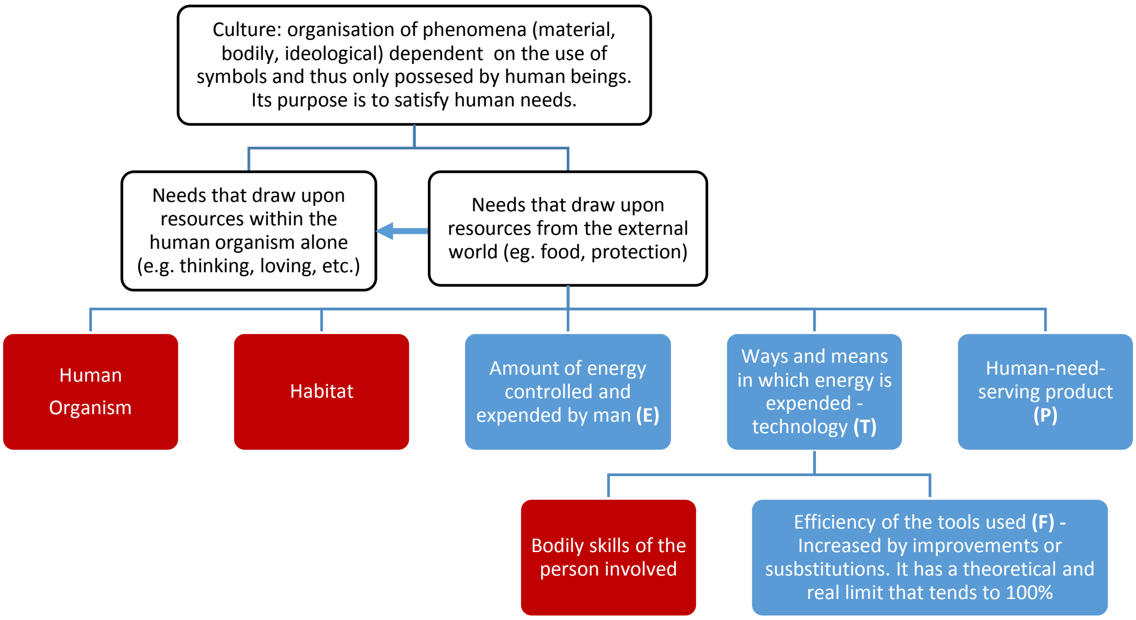

Figure 1-4. Graphical representation of White's (1943) "Energy and the Evolution of Culture"
Notes: Red squares are stable or average parameters, blue squares are variable parameters.
Source: Own representation.

These early theorists understood increases in a society's size and complexity alongside increased energy flows as evolution, which can be understood as "progress". However, they were aware that increased energy flows do not necessarily result in societal improvements, and certainly not for every segment of society (Nader & Beckerman, 1978). Cultures or societies have evolved or progressed (i.e. have grown and socially reproduced) while disregarding the needs of many (e.g. slaves and women) and the limits of the environment.

Anthropologist, Joseph Tainter (1988), studied precisely the limits to continuous increases in societal size and complexity. Tainter analysed in detail the Western Roman Empire, the Southern Lowland Maya and the Chacoans; noting that complex civilisations such as those were incapable of sustaining increasing levels of complexity because they could not find ever-growing amounts of energy, leading to their collapse. The reason for collapse is explained by complexity entailing diminishing returns on “problem solving”, where increasing energy availability is the only way to overcome societal challenges (Tainter, 1995).

In addition to increased surplus energy, increased complexity and increased cultural evolution, population growth was another major component of the social change of the time. Cipolla (1978) considered two major revolutions in human history, from the perspective of how these reflected changes in energy use and population growth: the Agrarian and the Industrial Revolutions. Figure 1-5 shows how increases in global population in a long term historical perspective behave very similar to increases in global energy use (shown in Figure 1-3).

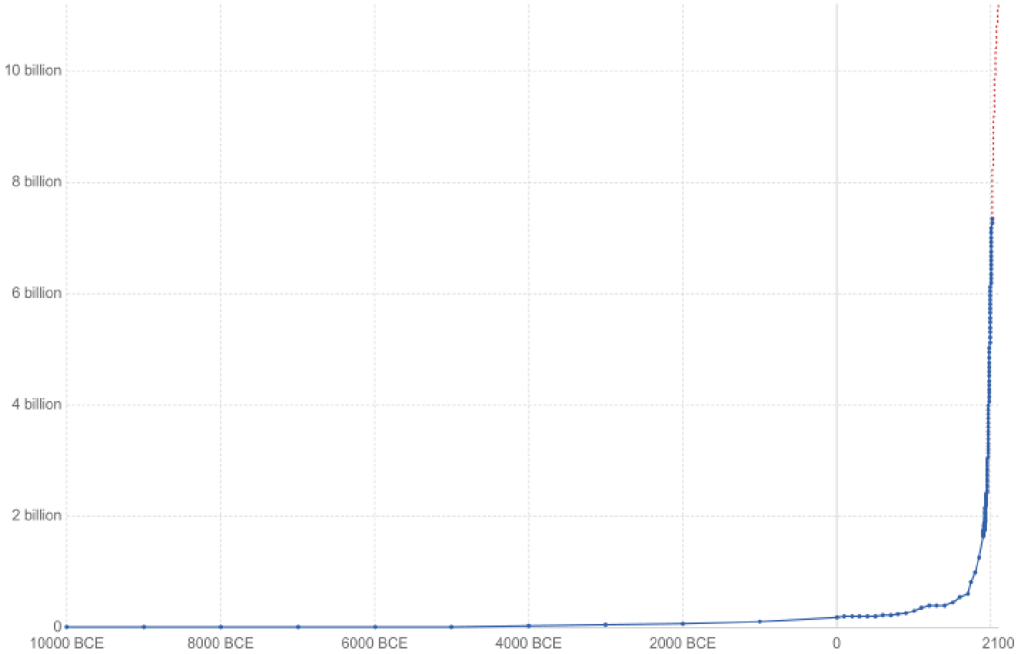

Figure 1-5. Global population in perspective
Source: https://ourworldindata.org/world-population-growth/

Thus, the deep social changes in human history, but particularly the ones brought by the Industrial Revolution, were highly intertwined with increases in energy availability, access, surplus and use. The authors highlighted above explored the tight coupling between energy and different aspects of social change, from population growth to cultural evolution, increased social complexity and collapse. This coupling, this intertwined nature of energy and society, is what I have called in this thesis the energy dependency of society[2].

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[2] In other words, what I have called here the energy dependency of society is the historical-empirical coupling (correlation) of energy use with many different aspects of social change. It does not imply a deterministic route for future societal changes.

1.1.2 Ecological economics perspective

The development of ecological economics occurred later than the development of the socio-historical perspective on energy. As such, the discipline of ecological economics was formally instituted in the 1980s[3]. However, the socio-historical and ecological economics perspectives are highly interlinked, with many authors in ecological economics arguing that the contributions of Soddy, Ostwald and Lotka, for instance, constitute the first building blocks for what is now known as ecological economics (Cleveland, 1987; Martínez-Alier, 1987; Røpke, 2004).

Røpke (2004) argues that three broad social changes and related discourses in the 1960s and early 70s, were fundamental in the birth of "modern" ecological economics as a discipline. First, the general awareness of environmental problems (particularly around chemical pollution and nuclear waste) in the 1960s, including Rachel Carson's famous book "The Silent Spring". Second, increased population growth and the fears around lack of sufficient resources to maintain it, exemplified by Paul Ehrlich's "The Population Bomb" and Meadows et al.'s "Limits to Growth". Third, the oil price shock of 1973 and the following years of energy crisis. I would add a fourth factor in the emergence of modern ecological economics as a discipline: the inability of mainstream economics to address environmental problems.

Ecological economics studies the economy and society as fundamentally dependent on the natural environment, and strongly differentiates itself from mainstream economics. More specifically, ecological economics seeks to explain the interactions of the economic system with the ecological system and society, both of which it is dependent upon (Edward-Jones, Davies, & Hussain, 2000). Two key features, stemming from the influence of thermodynamics and ecology, define ecological economics: the understanding of the economic process in biophysical terms (i.e. as flows of energy and matter); and a systems perspective, where economic process should be studied in conjunction with broader social and natural processes (Røpke, 2004).

Both of these key features (understanding the economy in biophysical terms and a systems perspective) imply analysing the economy as a subsystem of the environment, as opposed to the mainstream view of economics, where natural resources and the environment are either invisible or treated as externalities. This theoretical distinction is most clearly depicted in the different representations of the economy, shown in Figure 1-6. The circular flow of the economy (panel a), found in most economics text books, does not

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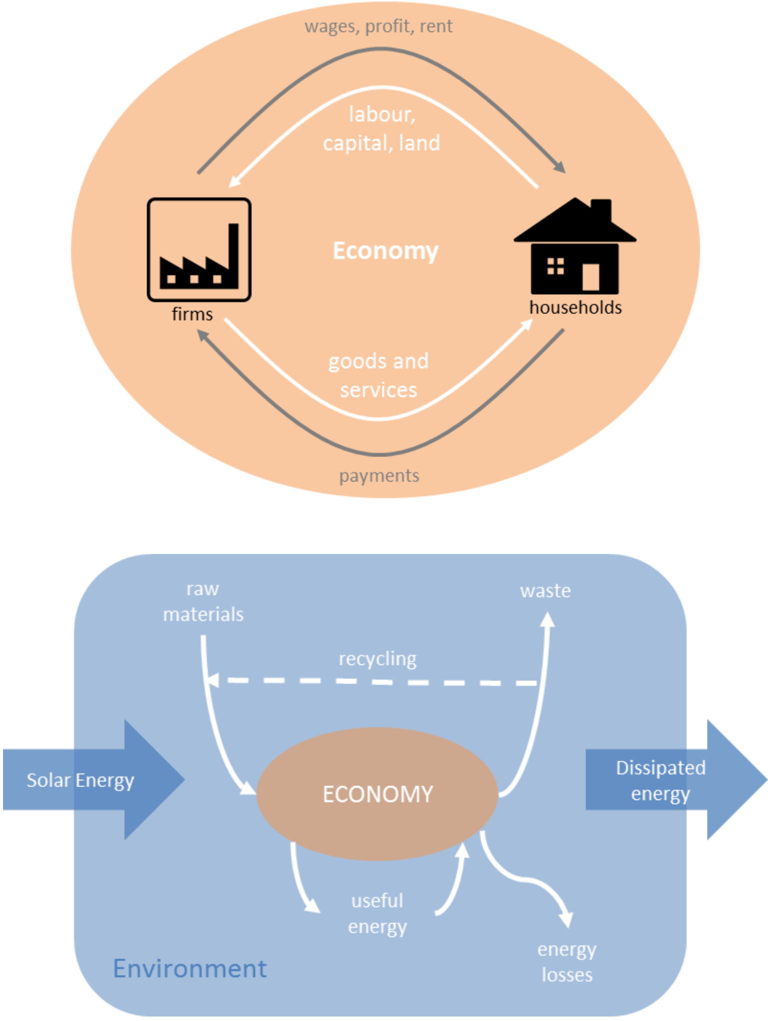
[3] Ecological economics gained institutional presence in 1987, with a meeting that took place in Barcelona that enabled the creation of the International Society for Ecological Economics (ISEE) and the journal Ecological Economics (Carpintero, 2013).

include any form of natural resources or waste, while the flows of energy and matter (panel b) has them as a central feature.

The earlier contributions that most influenced the development of ecological economics were those of Kenneth Boulding (1966a), Howard Odum (1971) and Nicholas Georgescu-Roegen (1971). They worked independently, but were making broadly a similar point in relation to understanding the economy in biophysical terms and using a systems perspective. However, it was Georgescu-Roegen who incorporated biophysical principles and thermodynamic laws into the language of mainstream economics, gaining recognition and generating controversy (Cleveland & Ruth, 1997).



a) Circular flow of the economy (mainstream economics)

b) Flows of energy and matter through the economy (ecological economics)

Figure 1-6. Mainstream (a) and ecological (b) representations of the economy
Source: Own elaboration.

An economist by training, Boulding was a transdisciplinary academic. His essay "The Economics of the Coming Spaceship Earth" (Boulding, 1966b) is easily remembered for his striking analogy of Earth being like a spaceship, i.e. a closed system where there are limited reservoirs for both resource extraction and waste disposal, but there is a constant flow of energy from the sun that can be captured. In the spaceship, humans must find a way of living in balance with the ecological system. However, Boulding points out that we are living as cowboys, who wonder around illimitable plains with a reckless and exploitative attitude. We are living as if Earth was an open system. Boulding's work introduced, in a comprehensive and memorable manner, systems thinking and biophysical limits into the understanding of how the economy works.

Biologist Howard Odum was also a systems thinker, who further developed the concept of maximum power principle (stemming from the work of Lotka) and applied it to ecological and other systems, including human societies (Cleveland, 1987). The principle states that any system, including the economic system, maximizes its use of available energy considering the constraints of the system (Cleveland, 1987). In the case of the economic system, the constraints are given by the technologies available. Thus energy (from biotic and abiotic sources) is a good tool for measuring flows from ecological to economic processes in the form of natural resources, and vice versa in terms of waste.

Georgescu-Roegen (1975), a mathematician, statistician and economist, fully engaged with thermodynamics through the concept of entropy. He described the economy and society as a subsystem of the environment, where high quality (low entropy) materials and energy are taken from the environment, degraded as they go through the economic system, and end up back in the environment as low quality waste (high entropy). By taking a systems perspective on the economy, ecological economics is concerned not only with the energy dependency of the economy, but also with the environmental consequences of energy use.

Thus, the serious environmental issues of the second half of the 20th century, coupled with the deficiency of mainstream economics to explain or deal with such issues, sparked the development of ecological economics. Ecological economics explicitly relates energy and material flows to the production of goods and services (the energy dependency of the economy), but also acknowledges the environmental consequences of waste disposal and pollution once goods and services are used (consumed).

In summary, energy availability is a limiting factor on the possibilities of what a society and an economy can achieve. In other words, societies and economies are dependent on energy, for it is energy that will enable or hinder certain directions of change. This should not be interpreted as energy determinism, however. Energy is a necessary, but not sufficient, condition for change. Furthermore, energy dependency does not mean that societies and economies can or should pursue ever-increasing flows of energy. "Indefinite growth of energy consumption, as in human population, is simply not possible" (Cook, 1971, p. 144). "There always will be limits to growth. They can be self-imposed. If they aren't, they will be system imposed" (Meadows, 2008, p. 103).

As we have seen in this section, human societies and economies have not historically self-imposed a limit on energy use. Quite on the contrary, they have used increasing quantities of energy. As a result, we are now facing already visible systemic limits. Some of these have been articulated together under the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). One of these environmental limits is climate change, driven by greenhouse gas (GHG) emissions from burning fossil fuels which currently dominate our energy systems. I will explore this system imposed limit of climate change in the next section.

1.2 Climate change and the need for “absolute” decoupling

Social and physical realities drive research in divergent directions. The fundamental changes and consequent societal challenges posed by the Industrial Revolution led to different explorations of the energy dependency of society. Similarly, the environmental movements and resource constraints of the 1960’s and early 70’s enabled the birth and further advancement of ecological economics, which includes many explorations of the energy dependency of the economy. Today, we are facing what can easily be called the most important threat to modern civilization: climate change.

Climate change is threatening the Earth’s basic life supporting systems, thus all life on Earth, including human life, is in danger. The challenges are even greater for developing societies, which are still to satisfy basic human needs for a growing population and which are likely to suffer the most adverse environmental consequences as a result of the multidimensional inequalities they face (IPCC, 2014). The scale of the challenge cannot be underestimated: “the Earth will take tens or hundreds of thousands of years to reach a new equilibrium following the pulse of carbon emissions sent into the atmosphere by humans mostly over the century from 1950 to 2050” (Hamilton, 2013, p. 193).

Climate science has shown the significant impact that global energy systems have had and continue to have on the Earth’s climate (IPCC, 2013). Energy has been consistently responsible for two thirds of GHG emissions globally (IEA, 2015a). The historical evolution of greenhouse gas emissions (in particular CO_2) to the atmosphere is tightly coupled with the historical evolution of energy use (see Figure 1-7). As David MacKay bluntly put it: “The climate problem is an energy problem” (MacKay, 2009, p. 5), and this has of course stimulated energy research in many directions.

From an engineering point of view, there is a vast amount of research around technological options to mitigate climate change. In particular, research has focused on renewable and low carbon energy technologies, as well as technologies to capture the CO_2 emitted during electricity generation. Additionally, energy efficiency has been portrayed as a low hanging fruit, which can deliver big energy savings at relatively low cost (European Commission, 2017; DECC, 2012; WEC, 2010). Related to the amount of academic and political attention, low carbon energy technologies, carbon capture and storage, and energy efficiency are the main components of most future scenarios of reduced CO_2 emissions (Rogelj et al., 2015); they are presented as the way forward in order to address the challenge of climate change.

However, climate change, as any other societal issue, is not purely a technological problem: "If society's implicit goals are to exploit nature, enrich the elites, and ignore the long term, then society will develop technologies and markets that destroy the environment, widen the gap between rich and poor, and optimize for short-term gain", because "technology and markets are merely tools to serve goals of society as a whole" (Meadows, Randers, & Meadows, 2004).

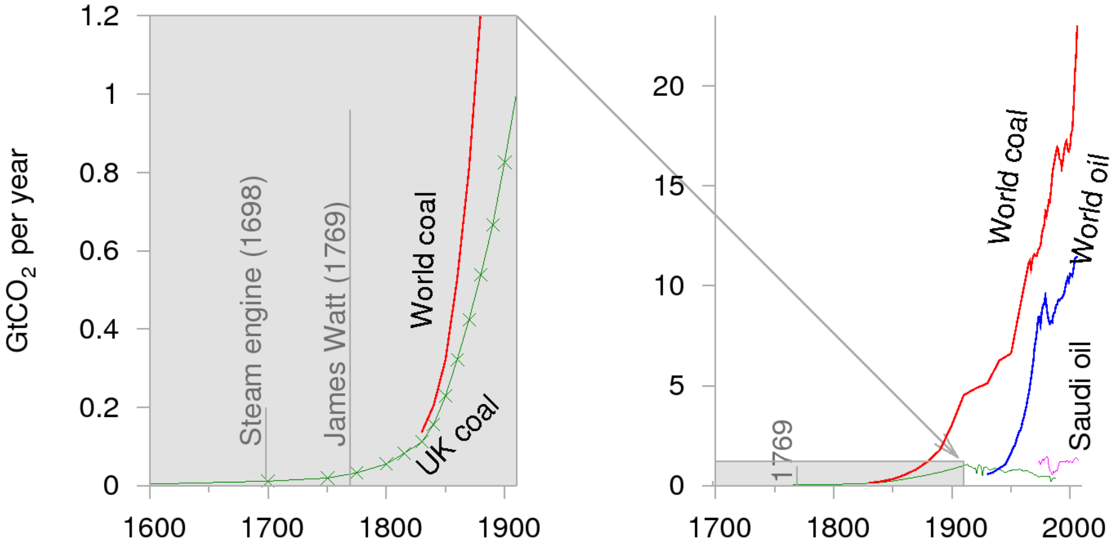


Figure 1-7. Historical energy production and CO_2 emissions
Notes: production rates are shown in billions of tons of CO_2.
Source: MacKay (MacKay, 2009, p. 6).

Despite optimistic scenarios and reports -in which effective climate change mitigation is invariably presented as within reach- and a certain amount of progress in deployment, low carbon energy technologies are still a long way away from replacing fossil fuels as our main source of energy (IEA, 2017a). Moreover, evidence that low carbon technologies in fact replace fossil fuels, as opposed to adding to their use (especially globally), is scant (York, 2012). Carbon capture and storage has not yet been deployed at a large scale, let alone at the rate needed to stay below a 2 degree Celsius of temperature rise compared to global pre-industrial temperatures (IEA, 2017b). Many social, technological, institutional and economic factors become structural constraints for change in general, and for innovation and diffusion of low carbon energy technologies in particular, to happen (Foxon, 2011).

Moreover, increasing energy efficiency (the ratio of energy outputs over energy inputs in a specific system) is often equated to energy savings due to reduced energy demand (Sorrell, 2015). However, three major challenges arise in measuring energy efficiency and its subsequent energy savings (see Sorrell, 2015). One, it is difficult to aggregate energy inputs that originate from different energy sources (e.g. petrol vs. electricity). Two, energy outputs can be measured at different stages of the "energy chain" (see Figure 1-8), and the most appropriate stage – energy services- is difficult to measure and its categories and boundaries are contested. Three, the reference state (against which energy savings are being specified) is either unavailable or inaccurate historical data on energy consumption, or unobservable counterfactual future scenarios of energy demand.

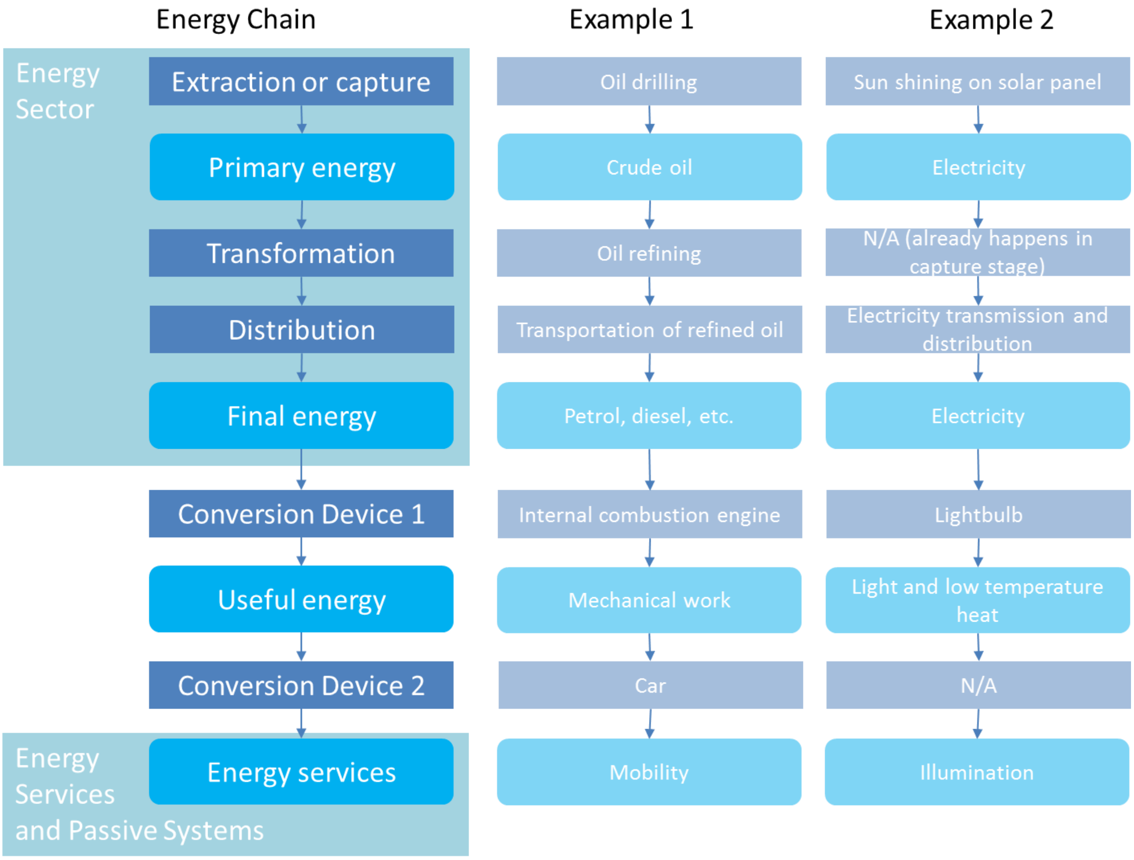


Figure 1-8. Diagram and examples of the "energy chain"
Source: Own elaboration.

In addition to the abovementioned challenges, improving energy efficiency might lead to what has been termed "rebound effect", where the energy (and associated cost) savings from increased energy efficiency end up being spent in other energy activities (perhaps even more energy intensive activities), eliminating to some degree or another the potential energy savings (Sorrell, 2010). Considering the prominence of energy efficiency in future scenarios for reduced CO_2 emissions from the energy sector, the rebound effect is surprisingly lacking from policy analysis (Brockway et al., 2017). Brockway et al. (2017) argue that the reason for that is that most research has measured the rebound effect at the micro level (direct and indirect rebound effects), rather than at the macro level (economy-wide rebound effect) where it could be very high.

The discussion around technological options to mitigate climate change can be framed more broadly in terms of decoupling. Decoupling is usually understood as reducing the dependency of societies and economies on resources (Jackson, 2009, Chapter 5), including energy (and CO_2 emissions). Thus, increases in energy efficiency (or reductions in the carbon intensity of energy) are a form of decoupling. Although they can represent a reduction in the *rate* of growth in energy use (or CO_2 emissions), they can be consistent with *overall* increases in energy use (or CO_2 emissions) (Peters, 2017). Therefore, a more nuanced view of decoupling is warranted.

Given the energy dependency of societies and economies (explored in section 1.1), , societies and economies will always be coupled with some level of energy use. However, the current level of energy use has major implications for disrupting planetary process, thus sizable decoupling is needed. Historical data shows that up to now, “relative” decoupling (i.e. reduced resource use per unit of economic output) has been the norm, but “absolute” decoupling (absolute reduction in the level of resource use, even when economic/social activity is increasing) has been scarcely evidenced (Jackson, 2009, Chapter 5; Peters, 2017).

Despite the limitations of tackling climate change as a purely technological issue, most of the evidence presented to policy makers tends to ignore such limitations and present with optimism the ways in which renewable energy, carbon capture and storage, and energy efficiency will “save us”. But perhaps more worryingly, this type of evidence shies away from questions of levels of economic activity and energy demand, and helps perpetuate current unsustainable practices of energy use (Anderson, 2015; Anderson, Le Quéré, & McLachlan, 2014; Shove, 2017).

1.3 Following the golden thread: recent research and some gaps

I have so far established that societies and economies are dependent on energy, and that climate change is largely an energy issue. Therefore, actions to mitigate climate change will require significant “absolute” decoupling of energy and CO_2 emissions from economic and social activities, particularly if high levels of economic growth continue (Foxon, 2017). In this thesis I try to move beyond traditional disciplinary boundaries and entrenched forms of enquiry in order to find alternative decoupling possibilities. In order to do so, I present below more recent research of the golden thread of energy as it weaves through the economy and society, and I identify two key research gaps, one in each of these areas, which are addressed in the substantive chapters of the thesis.

In relation to energy and the economy, I found the concept of “surplus energy”, originally coined by Cottrell (1955), inspiring. Recent research on “surplus energy” from the ecological economics community has taken the name of net energy analysis in general and EROI (Energy Return on Energy Invested) in particular, and it has focused on single source fuels (e.g. coal, oil, gas, wind, solar). However, national-level energy surplus has been less studied, and can strengthen the case for national energy policy-making to move away from CO_2 intensive fossil fuels, hence decoupling economic activity from climate change.

In relation to energy and society, I was motivated by questions about what “cultural evolution” (à la White, 1943) means, as well as what energy means. Specifically, I found that recent research on energy and society did not tend to engage in discussions about what services and benefits energy provides. Therefore, I undertook conceptual explorations around different conceptions of well-being, as well as how energy contributes to it. In addition, I found that in order to explore alternative possibilities of decoupling, these conceptual explorations needed to be developed into an innovative methodology and tested.

1.3.1 Energy and the economy

Given the tight correlation between energy use and economic growth, the links between the two have been studied extensively. Researchers that have both a mainstream and an ecological viewpoint of the economic system have addressed this link. From a mainstream point of view, the most abundant literature has been around causality tests, which try to establish whether economic growth causes energy use, energy use causes economic growth, both cause each other or there is no causation between them.

Causality type of studies have increased exponentially since the late 1970s, when the first journal paper exploring this issue was published by Kraft and Kraft (1978). Since then, new countries and new timeframes have been explored; panel studies, new statistical tools and tests have been implemented (see Bruns, Gross, & Stern, 2014; Chen, Chen, & Chen, 2012; Ozturk, 2010; Payne, 2010 for reviews). However, nothing like a consensus has been reached. Given the lack of consensus as well as ample methodological issues, causality tests have not yielded the greatest insights on energy-economy links.

From an ecological economics point of view, energy and economic growth have a more fundamental relationship than can be explained by causality tests. These empirical contributions stem from the theoretical foundations laid by ecological economics (see section 1.1.2), where the economy is considered a sub-system of the environment, and energy both enables (through high quality inputs) and indirectly constrains (through low quality waste) economic activity. Therefore, a focus for ecological economists has always been to adjust energy for quality.

Empirical attempts to examine the relationship between energy and the economy focused on testing for correlation between energy (adjusted by a quality factor) and GDP (Cleveland et al., 1984; Murphy & Hall, 2011a) and including energy in production functions (Kümmel, 1982, 2011; Kümmel et al., 1985; Pokrovsky, 2003; Stern, 1993, 2011; Stern & Kander, 2012). Robert Ayres and his different collaborators throughout the years pioneered the inclusion of useful work[4] as an adjustment for energy quality in trying to understand the importance of energy for economic growth (Ayres, 1997; Ayres, Ayres, & Pokrovsky, 2005; Ayres, Ayres, & Warr, 2003; Ayres, Turton, & Casten, 2007; Ayres & Voudouris, 2014; Ayres & Warr, 2005, 2009; Warr & Ayres, 2012).

Ayres et al.'s key conclusion was that unexplained technological progress in mainstream theory of economic growth could be explained in terms of increases in energy conversion efficiencies, providing high levels of useful work in the economy. Ayres' and colleagues empirical work showed that increases in energy conversion efficiencies were the engine behind economic growth for various industrialised countries during the 20th century. Ayres' work has been built upon by recent work from Brockway et al. (2014; 2015), Domingos (2013), and colleagues (Hammond & Stapleton, 2001; Heun et al., 2017; Serrenho et al., 2012; Warr et al., 2010; Williams, Warr, & Ayres, 2008). Finally, many ecological macroeconomic models have been developed which include energy as a variable (see Hardt & O'Neill, 2017 for a comprehensive review).

Another heterodox strand of work around energy and the economy is related to the energy cost of energy. As world population increases and economies grow, energy use tends to increase. However, in addition to being finite and CO_2 intensive, our main sources of energy, i.e. fossil fuels, seem to be becoming less available (more difficult to access and process for human use). This increased difficulty means that more energy is needed to obtain energy itself, which in turn reduces the ability to use as much of the energy flow for activities different from the energy sector (i.e. the net energy left for economic activities reduces). By using net energy analysis, the energy cost of any process is measured in relation to the energy returns.

One metric of net energy analysis is EROI. EROI stands for energy returned on investment, although sometimes it is also called energy returned on energy invested

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[4] The amount of actual physical work that can be done after energy is transformed up to its point of use.

(EROEI or ERoEI) (Murphy & Hall, 2010). The concept was first introduced by Charles Hall in his PhD thesis and the term (EROI) was first used by Cleveland et al. (1984). It is a dimensionless ratio and it is usually defined as “the ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question” (Murphy & Hall, 2010, p. 102).

In other words, EROI measures how much energy is left for the economy to use after taking into account the energy needed to “produce” such energy in the first place. The concept of EROI relates closely to the concept of “surplus energy” presented by Cottrell (see section 1.1.1). Thus, a higher EROI implies higher surplus energy, and is therefore necessary for maintaining and increasing economic activity and social complexity.

EROI has also been associated with the quality of the different energy sources, in the sense that a higher EROI value means that a bigger proportion of the energy delivered to society can go into economic activities other than to the energy sector (Murphy et al., 2011). The opposite is also true; a lower EROI value means that a smaller proportion of the energy delivered to society can go into economic activities rather than the energy sector. However, this could be considered to be a measure of economic potential, but not a measure of energy quality itself. Thus, the EROI of a certain resource can help to understand the real (net) energy gains from it[5], but it cannot provide information regarding its energy quality.

Perhaps more importantly, EROI has a say in relation to resource depletion and technological change, both of which are crucial to the economic system, particularly from an ecological economics perspective. A declining EROI in time means that resource depletion is outweighing technological change (Murphy et al., 2011), i.e. the amount of a certain energy resource (or its accessibility) is declining faster than the advancements in technology to harvest it more efficiently (Dale, Krumdieck, & Bodger, 2012a). The above is particularly clear in the dynamic EROI function included in the GEMBA (Global Energy Modelling – A Biophysical Approach) model, where EROI is a function of resource depletion and technological learning (Dale, Krumdieck, & Bodger, 2011a, 2012b).

However, most EROI studies have the “mine-mouth” as a boundary when evaluating the energy returned to society in relation to the energy required to get it, without including energy from processing stages (Murphy & Hall, 2010). This means that they establish the extraction stage as the boundary for energy outputs (numerator) and the direct and indirect energy and material inputs as the boundary for energy inputs

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[5] For example, the oil sands in Canada constitute a very big resource deposit. However, with an EROI of around 3:1, Canada’s oil sands net energy gains will only represent a third of the resource base (Murphy et al., 2011).

(denominator) (Murphy et al., 2011). Considering they are the most abundant in the literature, these types of studies are called “standard” EROI ($EROI_{stnd}$)[6].

They are particularly useful when comparing different fuels or energy carriers, or when analysing changes in EROI of a specific fuel over time (Lambert et al., 2014). For example, Murphy and Hall (2011b) analyse how a continuously declining EROI for oil over the last 40 years can have seriously adverse consequences on the economic production model that we currently use, i.e. an oil-dependent economic system.

1.3.1.1 National-level energy surplus (Gap 1)

A national-level measure of surplus energy, or national-level EROI, would enable answers to questions such as: how much energy are we using to extract/capture the energy our economies currently use? How has the energy cost of energy evolved over time? Are fossil fuels, the most emissions-intensive energy sources, requiring more energy for their extraction, and thus delivering less net energy to the economy? Can this information be used by policy-makers to inform a transition to other fuels?

As stated before, most EROI studies have the “mine-mouth” as a boundary when evaluating the energy returned to the economy in relation to the energy required to get it (Murphy & Hall, 2010). Single fuel studies show that the EROI of fossil fuels has been historically declining. However, EROI has not been calculated at a national level, which is more relevant for policy-makers. A broader boundary than the “mine-mouth” is needed in order to analyse the national-level energy surplus.

The most explicit attempt to calculate a societal EROI ($EROI_{soc}$) was undertaken by Lambert et al. (2013; 2014). But their calculations are entirely based on prices through energy intensities, which could be a disadvantage taking into account that prices are influenced by a number of non-physical factors and do not necessarily reflect resource availability or accessibility[7].

Therefore, it is important to attempt to develop alternative methodologies for calculating a national-level EROI ($EROI_{nat}$) that overcome the issue of prices, even if only partially to start with. A $EROI_{nat}$ would depict how much energy a country is spending to produce energy within its national territory, which is in itself a relevant metric. Additionally, analysing EROI dynamics at a national level could reveal which countries are producing energy at lower energy costs, and what that implies for a nation’s energy security and energy trade in the context of international energy markets. Furthermore, a

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[6] This nomenclature follows the one established by Murphy et al. (2011), in order to work towards a much needed consistency in EROI studies.

[7] If there is an assumption of competitive markets, prices can also be assumed to reflect quality, accessibility and scarcity. However, assuming competitive markets can be easily contested, especially in the energy sector.

national-level EROI is important for guiding an energy transition, since it has the potential to demonstrate how fossil fuels compare to renewables for specific countries, in terms of how much energy is required to extract/capture them through time.

This research gap is based on an already existing theoretical framework (that of EROI, net energy, surplus energy). Thus, the contribution of this thesis is mainly methodological and empirical. A broad description of how this gap has been addressed in this thesis is given in section 1.4.2, whilst Chapter 2 provides a much more detailed description, as well as results for the UK for the period 1997-2012.

1.3.2 Energy and society

Towards the end of the 20th century, social scientists considered the issue of the role of energy in society with more data to hand. More specifically, there was an interest in the role of energy for human well-being. The interest can be broadly classified into four categories: macro-level studies, household-level studies, energy poverty and development, and the political economy of energy.

The paper by Mazur and Rosa (1974) stands out as a primer in the macro-level studies category. The authors found positive correlations between energy consumption and various life-style indicators. Further studies have shown that the data at an international scale consistently behaves as a saturation curve, i.e. after a certain point, increased energy use does not translate into improvements on well-being (Alam et al., 1991; Alam et al., 1998; Dias, Mattos, & Balestieri, 2006; Martínez & Ebenhack, 2008; Rosa, Machlis, & Keating, 1988; Steckel et al., 2013; Steinberger & Roberts, 2010).

Additionally, within the climate change literature there has been work on the relationship between human development and carbon emissions (which could be thought as a proxy for energy use, particularly in a fossil fuel intensive world) at an international scale. Similar to the work on energy and human well-being, this work has shown that there is a saturation curve, particularly when using consumption-based accounting of embodied CO_2 in trade (Lamb et al., 2014; Rao, Riahi, & Grubler, 2014; Steinberger et al., 2012).

The exact point where further increases in either energy use (primary or final) or CO_2 emissions do not translate into further increases in human well-being is not universally defined nor static. José Goldemberg and colleagues (Goldemberg et al., 1985) attempted to calculate this exact point. They proposed that 1KW per person[8] was all that was needed for satisfying basic needs worldwide. The authors hypothesise that, in order to achieve universal need satisfaction, there need to be significant technological fixes,

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[8] KW is a unit of power (the ratio of energy use per time). In order to know how much *energy* a KW represents, we can convert it into KWh. Thus 1 KW per person is equivalent to 24 KWh per person per day or 8760 KWh per person per year (or 31.5 GJ per person per year).

primarily energy efficiency. These technological advancements seem to have happened, albeit at higher levels of energy consumption than Goldemberg would have wished. Steinberger and Roberts (2010) show a general global trend of decoupling between energy use and ensuing CO_2 emissions, and improvements in human well-being from 1975 to 2005. Yet, section 1.2 showed the problems surrounding technological fixes to social issues.

When analysing the different country trajectories, the outlook differs greatly due to country-specific circumstances. Longitudinal studies (Steinberger & Roberts, 2010; Steinberger et al., 2012) confirm Goldermberg's hypothesis, in the sense that basic levels of human well-being can be attained with low levels of CO_2 emissions or energy use: there are countries that have achieved relatively high levels of human well-being (life expectancy over 70 years) with relatively low levels of environmental impact (one tonne of carbon emissions, or 3.67 tons of CO_2e emissions, per capita), and these countries vary significantly in relation to their economic, demographic and geographic characteristics (Lamb et al., 2014). The countries that have succeeded in decoupling human well-being from climate change related impact have been referred to as being in "Goldemberg's corner" (see Figure 1-9). The existence of "Goldemberg's corner" and the fact that different types of countries are found there is reason for optimism – it is possible to be well without overshooting the Earth's capacity.

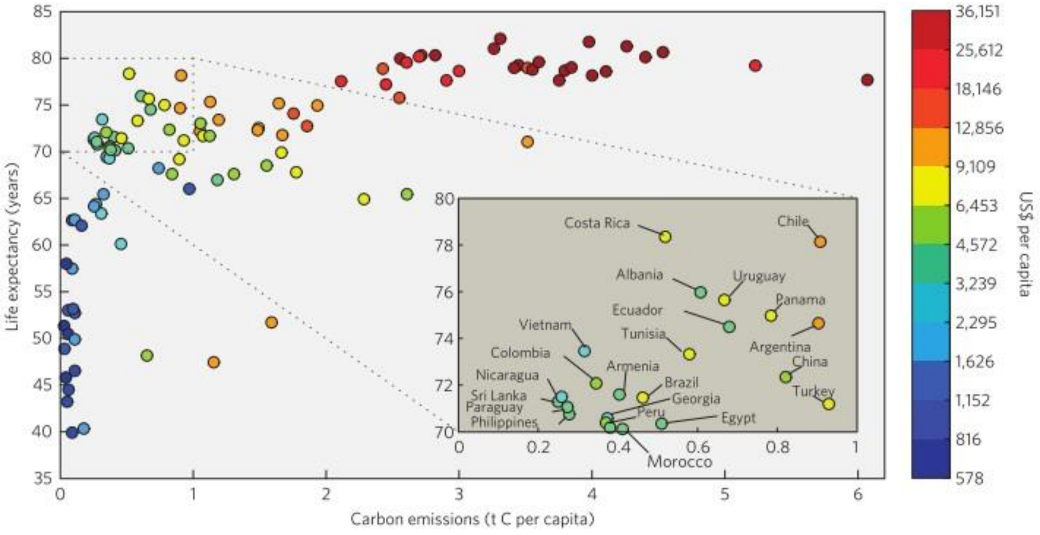

Figure 1-9. Goldemberg's corner
Source: (Steinberger et al., 2012).

However, one consistent fact across these macro-level studies is that increases in energy use or CO_2 emissions are closely coupled with increases in income (generally measured by GDP or GDP per capita). In fact, no wealthy consuming nations have been found in Goldemberg's corner (Lamb et al., 2014). Thus, if we consider progress or development to be equivalent to economic growth and higher levels of income, there is no possibility for achieving climate compatible societal advancements. In this same line of thought, some authors (T. Dietz & Jorgenson, 2014; Jakob & Steckel, 2014; Jorgenson, 2014) have pointed out the adverse climate consequences of following a market based and rising affluence path of development. Moreover, aggregated data, although important for giving an overall picture, tends to mask inequalities and deprivations within national averages.

At lower levels of aggregation, there is a vast literature on measuring household energy use and related environmental impacts, including CO_2 emissions. Most of these focus on the developed world (Baiocchi, Minx, & Hubacek, 2010; Collins et al., 2006; Dey et al., 2007; Druckman & Jackson, 2010; Gough et al., 2011; Herendeen & Tanaka, 1976; Lenzen et al., 2006; Minx et al., 2013; Peet, Carter, & Baines, 1985; Weber & Perrels, 2000; Wiedmann et al., 2006; Wier et al., 2001) with some work done around large emerging and developing nations such as India, China and Brazil (Cohen, Lenzen, & Schaeffer, 2005; Pachauri, 2007; Pachauri & Jiang, 2008). These studies analyse the influence of expenditure patterns and levels, as well as other socio-economic, demographic and geographic variables, on direct and indirect energy demand (or associated environmental impacts).

In general, these household-level studies combine national or multi-regional Input-Output tables with household expenditure data to calculate the direct and indirect energy requirements of household consumption. Overall, the results point towards increased energy demand from more affluent households, which is consistent with the macro-level findings in terms of increased income being tightly coupled with increased energy use. This is not surprising, since these studies tend to focus on consumption, and take the levels and patterns as given (i.e. they do not perform analysis in relation to well-being). One notable exception is the work of Rao and colleagues (Rao & Baer, 2012; Rao & Min, 2017), which sets up normative decent living standards from which they derive implications for energy demand.

From a lack of analysis of well-being in household-level studies, we move to the third category of studies around energy and society: energy poverty and development. This category closely studies specific issues that relate to well-being. The literature around energy (or fuel) poverty analyses how lack of access to energy can exacerbate conditions of poverty and deprivation (Bouzarovski & Petrova, 2015; Bouzarovski, Petrova, & Tirado Herrero, 2014; Day, Walker, & Simcock, 2016; Middlemiss & Gillard, 2015; Nussbaumer, Bazilian, & Modi, 2012; Pachauri et al., 2004). Similarly, but with a focus on the developing world, there exists a body of work that examines the implications of lack of energy access on different aspects of well-being, in particular, health (Bruce, Perez-Padilla, & Albalak, 2000; Horton, 2007; Markandya & Wilkinson, 2007; Wilkinson et al., 2007) and gender (Pachauri & Rao, 2013; UNDP & WEC, 2000).

Finally, the fourth category refers to the political economy of energy. This category operates at a much broader and theoretical level, but contains insights that may be relevant to empirical studies. Timothy Mitchell (2009) analyses the political economy consequences of coal-based societies compared to oil-based societies, in particular around democratic institutions. Naomi Klein has repeatedly pointed out how free market vested interests surround the ideological opposition to climate science (for example in Klein, 2011), and Espen Moe (2010) has unveiled the power of the dominant industries in particular historical times in shaping energy systems. Finally, Salminen and Vadén (2015) have deemed the extraordinary amounts of energy currently available to societies as the most defining characteristic of modern capitalism.

1.3.2.1 Energy services and human needs (Gap 2)

Energy constrains what societies can do. Our current energy systems are seriously compromising the stability of the Earth. Therefore, a deeper analysis of what we understand by energy and what we understand by societal progress is warranted. Therefore, I undertook an analysis of what energy is, what we use energy for, and of what human well-being consists of. Previous work on the link between energy and human wellbeing (section 1.3.2) is lacking in three important aspects.

First, previous research in general has interrogated the issue from a primary or final energy perspective. For example, macro and household-level studies use measures of energy that remain at the primary or final stages of energy transformations, or indeed use proxies such as CO_2 emissions. The same is true of energy poverty studies, which also consider energy costs. Energy and development work has started moving towards some energy services, particularly the service of heat for cooking. Indeed people actually demand, and relate to, energy services. In fact, the entire energy system exists solely for the provision of energy services (Cullen & Allwood, 2010a), therefore it is important to understand what the demand for energy services consists of.

Second, previous research has not addressed directly what well-being means. Most macro-level studies use aggregated measures or indices such as life expectancy or the HDI (Human Development Index), without discussing the sustainability implications of different conceptions of well-being (as recently highlighted by Lamb and Steinberger (2017)). Furthermore, by not questioning consumption and thus using it as a basis for their analysis, household-level studies tend to implicitly assume that well-being is equivalent to income (a conflation rooted in neoclassical economic notions of utility maximisation through budget expenditure). Related to this, the measures of well-being used in both macro-level and household-level studies do not consider the cultural specificities of different societies. Moreover, although the literature around energy poverty and energy and development enables considerations of cultural specificities, it examines very specific aspects of well-being, thus failing to engage in a holistic discussion about well-being.

Third, previous research has focused on either the macro, the household or the individual level. To the best of my knowledge, the relationship between energy and human well-being has not been studied at the community level, where deprivations around both energy services and well-being are experienced, but can also be acted upon in a self-reliant way through communal organisation (Ostrom et al., 1999). Additionally, not much research has been carried out in the developing world, with the exception of large emerging countries such as China, India and Brazil.

Therefore, I advanced a theoretical framework, where the concepts of energy services and human well-being are explored in detail, as well as being integrated in order to find alternative ways of using energy services as satisfiers of human needs. This contribution, while being similar in essence to that of Day et al. (2016), was developed in parallel to it. Opening up the option space (beyond efficiency improvements and increased consumption) is key for limiting the extent of climate change while increasing human well-being.

Additionally, I considered it important to apply and test this conceptual contribution. Thus, I developed an original qualitative methodology and undertook two case studies of the relations between energy service use and increasing human wellbeing in Medellín (Colombia), in an urban and a rural community. A brief description of the conceptual framework and the specific data collection methodology is in section 1.4.2, whilst a detailed account of these can be found in Chapters 3 and 4 respectively.

1.4 Research framing, question, aims and objectives

My research framing is built around the golden thread analogy, and informed by the elements I have described so far: the two perspectives on the energy dependency of society and the economy (section 1.1), the current context of climate change (section 1.2), and the research that has already been done in this area (section 1.3). Throughout this process, I identified two gaps in the energy dependency of the economy and society (also in section 1.3). Now I bring all of these elements together into a unifying research framing (graphically represented in Figure 1-10), with a guiding research question, an overall research aim and three distinct research objectives.

Following the golden thread, the energy dependency of society and the economy become clear. However, given the threat of climate change to life on Earth as we know it, significant decoupling of the benefits that human societies and economies derive from energy from its environmental impacts is essential. In order to contribute to opening the possibility space for this sort of decoupling to happen, it is important to move beyond the limitations of purely technological alternatives (Anderson, 2015; Anderson, Le Quéré, & McLachlan, 2014).

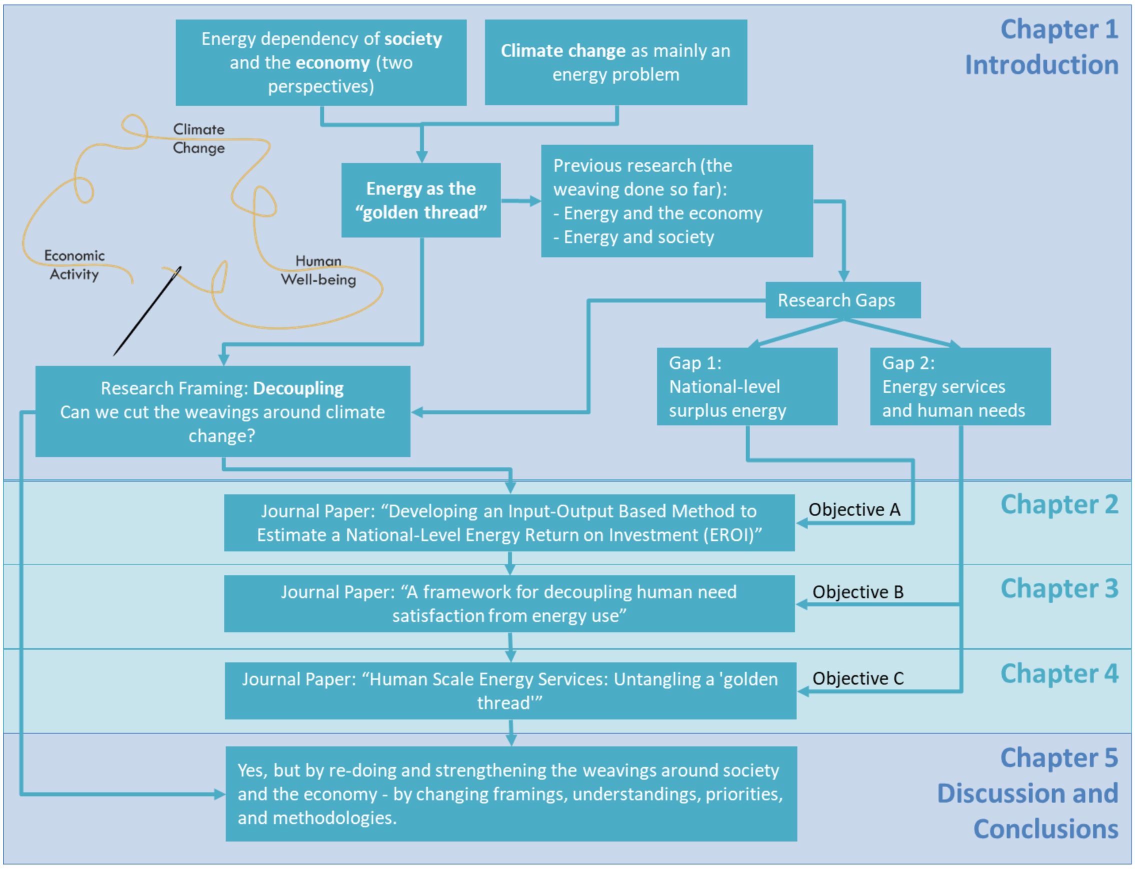

Figure 1-10. Research framing and structure of the thesis
Source: Own elaboration.

Therefore, this thesis tries to answer the question:

How are we to continue to support human societies and economies, which depend on energy for their functioning, while the very use of that energy is what is compromising the continuation of a stable Earth system? In other words, how are we to significantly decouple progress in human societies and economies from the negative environmental impacts of energy use?

The overall aim of the PhD project is to: further the understanding of the energy dependency of the economy and society, using a *socio-historical* and *ecological economics* lens, in order to provide alternative routes to decoupling in the face of the urgent need to mitigate climate change.

In order to fulfil that aim, there are a series of objectives:

A. To develop a novel methodology for calculating a national-level EROI in order to obtain important information for an energy transition at a policy-relevant level.

B. To advance a conceptual contribution for relating energy services and human needs, and providing sustainable alternatives to such a relationship.
C. To produce a participatory methodology capable of interrogating the conceptual framework, as well as to apply and test it in diverse communities.

In order to have a more nuanced understanding of decoupling, it is important to distinguish between the "goods" (for example economic activity, well-being), the "means" of obtaining those "goods" (for example energy), and the "bads" (for example climate change, environmental damage, resource exhaustion). Figure 1-11 (which is a more schematic version of Figure 1-1) depicts the relationship between these three elements.

Given the key intermediary role of energy (as the golden thread) in the relationship between economy and society, and climate change, the question of decoupling can be applied analytically to each connection. Thus, there are three possible points for decoupling the negative environmental impacts of energy from the benefits energy provides to human well-being and economic growth. This is shown in Figure 1-11 by three scissors. All three points can be consistent with relative and absolute decoupling.

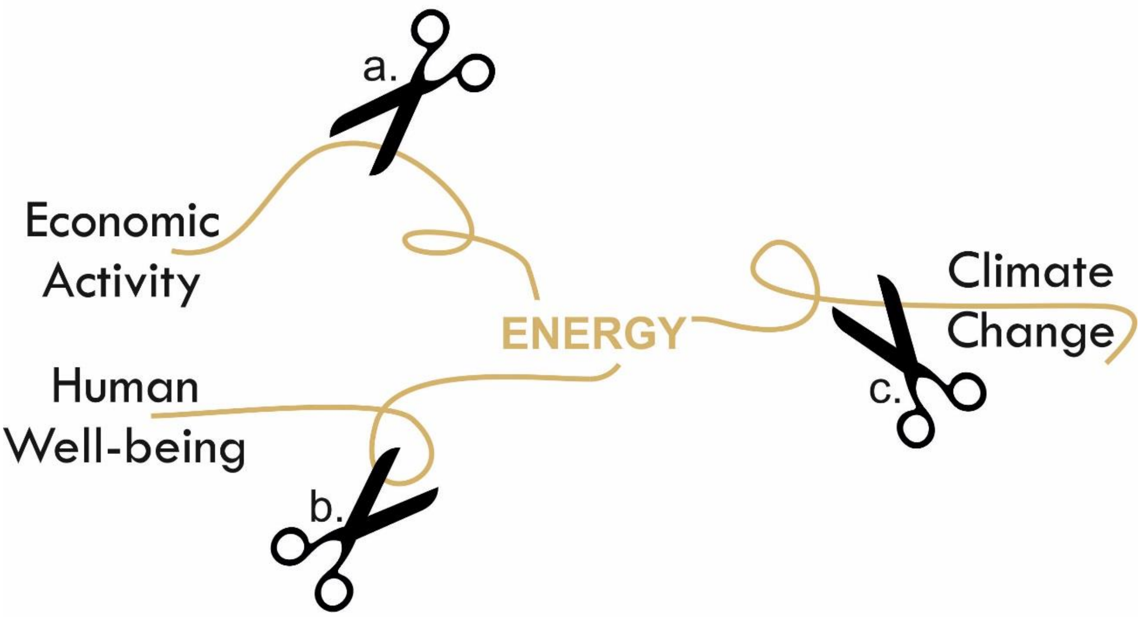

Figure 1-11. Points to decouple ("cut") the 'golden thread'

In Figure 1-11, point a. refers to decoupling economic activity from energy use, point b. refers to decoupling of human well-being from energy use, while point c. refers to decoupling of energy from climate change related impacts (mainly CO_2 emissions). As will be discussed in more detail in Chapter 5, this thesis delves into point b. (the decoupling of human well-being from energy use, and thus the negative environmental impacts derived from energy use) in Chapters 3 and 4; and it delves into point c. (the decoupling of economic activity from energy-related GHG emissions) in Chapter 2.

1.4.1 Putting it all together: a pragmatic research paradigm

Following Creswell (2009), any research design involves the intersection of philosophical worldviews (or research paradigms), strategies of inquiry (methodologies) and specific methods. Whether discussed or not, philosophical worldviews underpin every research process. They provide a general orientation about the world (what is real, what can be known, how it can be known) and the role of research and the researcher within that world. Thus, they shape the way in which research is done.

The overall aim of this thesis is a broad one. The gaps and related objectives are diverse in their nature. However, the whole project is driven by a concern for the role of energy in climate change. Therefore, I decided to adopt a pragmatic (problem centred) research paradigm, where the selection of methodology, methods and data depends on what is most suitable to address the objectives and try to answer the research question (Cherryholmes, 1992a; Morgan, 2014). This explains the use of both quantitative and qualitative methods.

Pragmatism takes human experience as its starting point: “based on the work of John Dewey, pragmatism points to the importance of joining beliefs and actions in a process of inquiry that underlies any search for knowledge, including the specialized activity that we refer to as research” (Morgan, 2014, p. 7). Pragmatism conceives research as a human experience of inquiry, where researchers engage in self-conscious decision-making in a careful and reflective manner (Morgan, 2014).

Any human experience, including research, is inherently contextual (historically and culturally located), emotional and social (our experiences and thoughts are shaped by others) (Morgan, 2014). Both my own experience of doing research and the objects of study (national-level surplus energy and energy services and human needs) were contextual, in the sense that they were influenced by my previous personal experiences, the research done so far in this area, the availability of data, contacts, etc.

Because of this, pragmatics recognise “that when we read the world we can never be quite sure if we are reading the “world” [empiricism or post-positivism] or reading ourselves [interpretivism or constructivism]” (Cherryholmes, 1992a, p. 14). Thus, in a pragmatic worldview, the metaphysical questions of ontology (what is real) and epistemology (how can we know what is real, what is true, what constitutes knowledge) are somewhat secondary.

The key element in the pragmatic conception of experience is action and the anticipated consequences of our actions as researchers (Cherryholmes, 1992b).

Subsequently, the decision-making process in the experience of research involves deciding which goals (problems, research questions) are most meaningful to pursue and which methods are most appropriate to achieve those goals (Cherryholmes, 1992b; Creswell, 2009; Morgan, 2014). Climate change is at the centre of my research as a hugely pressing problem, and the choices (actions) I made in researching this issue had the intended consequence of finding alternatives to avoid the most dramatic effects of climate change.

The choice of methods was an integral part of the experience of research inquiry undertook during this PhD. Within my “comfort zone” (given my academic background in economics), and with the intended consequence of finding evidence that could influence national-level policy making, I chose a quantitative method that could provide numerical evidence of the declining EROI for fossil fuels, to address Gap 1 (see section 1.3.1.1). As my PhD progressed, I realised the value and importance of other forms of knowledge and evidence. Thus for the empirical application of the conceptual framework (both related to Gap 2, see section 1.3.2.1), I chose a qualitative method that would allow me to analyse the actual experiences of communities and go beyond national-level numerical averages.

Furthermore, decisions of what to research and how (action) are influenced by our beliefs, and thus involve “values, aesthetics, politics, and social and normative preferences [which] are integral to pragmatic research, its interpretation and utilization” (Cherryholmes, 1992b). Value and normative elements usually are explored under axiology in other types of philosophical worldviews, however they are a central part of a pragmatic worldview. That is the reason why pragmatism can be well situated to tackle issues of social justice (Creswell, 2009; Morgan, 2014), for researchers that are concerned about it. These issues were particularly present in the work around human needs and energy services. The data collection method for addressing the energy services and human needs gap had the intended consequence of providing the communities involved with an opportunity to reflect upon their needs in a different way.

Below I provide a brief description of the methodology, methods and data used to address each of the identified gaps.

1.4.2 Methodology, methods and data

A common element between the ways I addressed the two research gaps is the use of non-traditional concepts and innovative methodologies, which allowed me to find decoupling alternatives beyond limited disciplinary spheres and established ways of enquiry.

The specific methodology, method (tool) and data that I used in this PhD was different for each of the two aspects of energy dependency that I was analysing and in direct answer to the research gaps I found. They are described in greater detail in Chapters 2, 3 and 4. However, I present here a brief overview.

1.4.2.1 National-level energy surplus

In relation to the energy dependency of the economy and the *national-level energy surplus* gap, I decided to develop a quantitative methodology within the already established theoretical framework of EROI. This theoretical framework formulates that in order to calculate the EROI of any process or region (including a national-level EROI), there are two basic components needed: energy inputs and energy outputs.

$$EROI = \frac{energy\ outputs}{energy\ inputs}$$

For a national-level EROI, energy outputs represent the total energy "produced" (i.e. extracted or captured) by a country. Data for produced energy is easily obtainable for most countries in the world. The data available from the IEA (International Energy Agency) is quite comprehensive and covers significant time spans (IEA, 2015b). However, for this research, energy outputs should not include losses or other energy used by the energy sector itself. Therefore, our methodology subtracts from energy outputs, the energy used by the energy sector itself.

Energy inputs for a national-level EROI represent the sum of direct and indirect energy used by a country's energy sector. Data on the energy industry's direct (own) energy use can also be obtained from the IEA. However, this is only one component of energy inputs. No statistical agency collects data on indirect energy use by the energy sectors. Thus, the main contribution of this quantitative methodology is to calculate the indirect energy (embodied energy used by the energy sector). I do that by developing and implementing a novel use of Input-Output matrix algebra to calculate indirect energy. Chapter 2 and Appendix A contain the full mathematical explanation of this method.

Furthermore, the UK was selected as the best country to apply this novel method, given its availability of a Multi-Regional Input-Output (MRIO) model, containing data for the UK and 5 world regions, for the period 1997-2012. The MRIO model was developed by colleagues at the Sustainability Research Institute using Input-Output data from the UK's Office of National Statistics (ONS, 2014).This method and the data used contain the interactions across a whole economy but also includes the interactions involved in international trade. It also represents an improvement from previous studies because it provides a calculation of indirect energy that does not rely solely on prices.

1.4.2.2 Energy services and human needs

For the energy dependency of society and the *energy services and human needs* gap, I chose to use a qualitative methodology, supported by a novel conceptual framework. For this gap I found no previous theoretical framework in which I could base my research. Therefore, I developed one based on the concepts of energy services and human needs. It is important to acknowledge that the work of Day et al. (2016) establishes a similar theoretical framework to the one I developed as part of my PhD, but our work was done in parallel and it differs mainly in relation to its specific understanding of well-being and methodological proposals. In this section, I will first briefly describe the concepts of energy services and human needs, followed by an account of how they fit together under the conceptual framework. Subsequently I give an overview of the qualitative methodology and the specific data collection method.

Energy services are what we actually demand from energy, they are the reason why energy systems are established all over the world. It is not kilowatts of electricity or cubic meters of gas that people want, it is illumination or heating or transportation or machine processing for specific activities. Furthermore, the delivery of a given energy service is not completely determined by specific technologies or energy conversion devices, and thus may be less bound to lock-in phenomena (Unruh, 2000).

In addition, systemic understanding of efficiency improvements can go beyond purely technical device-level issues towards the consideration of passive systems, the level of service and nature of service demand (Haas et al., 2008; Marshall et al., 2016; Nakićenović & Grubler, 1993). A service perspective could also impact the underlying driver of infrastructure configuration operation (including the delivery of energy services), from provisioning unconstrained demand to the supply of specific services taking into account the needs of end-users and focusing on efficiency (Roelich et al., 2015).

Continuing with a description of the concepts used here, human needs, as I understand them in this thesis, are a set of universal, finite and satiable preconditions to human well-being. They are compatible with eudaimonic views of well-being, where living a full and flourishing life is what defines “being well”. This is in contrast to hedonism, where being well is achieved by having a positive balance between pleasure and pain. Broadly speaking, the work of Amartya Sen (1999), Martha Nussbaum (2003; 2001), Len Doyal and Ian Gough (1991), and Manfred Max-Neef (1991) fit within a eudaimonic understanding of human well-being.

As argued in Chapter 3 and largely following O’Neill (2006; 2008a; 2008b), eudaimonic well-being (including human needs) are better suited for answering questions of environmental sustainability than hedonic well-being. Human needs in particular are satiable (thus, as well as lower thresholds, there are upper limits to resource use or consumption), non-substitutable (hence related to notions of strong sustainability), and universal across time and space (therefore allowing the consideration of the needs of futures generations).

Furthermore, by understanding human needs as universal preconditions to human well-being, the approach described in Chapter 3 incorporates important elements for policy action. In particular, human needs can be seen as constitutional rights, which have great normative power behind them. If human needs are preconditions for well-being, then society must aim at fulfilling these as much as possible (or at least removing the barriers for people to fulfil their needs). However, "universal" and "precondition" can lead to policy actions that are paternalistic and ineffective, because of the lack of consideration to the undeniably subjective reality of the lived experience. Hence Doyal and Gough (1991) and Max-Neef (1991) highlight the importance of participatory methods for policy development and community action.

Additionally, in order to include the important culturally specific element in the analysis of human needs, Doyal and Gough (1991) and Max-Neef (1991) introduced, almost in parallel, the notion of human need "satisfiers". Satisfiers are the means through which individuals, communities or societies satisfy human needs. Thus, the global variation of energy use for a given level of human well-being shown in macro-level studies, can be attributed to variations in the societal choices of satisfiers. However, the choice of satisfiers (which in turn influences energy demand) should not be taken as given.

For example, the expectations of what goods and services are considered "necessities" (or fundamental satisfiers of specific needs) have changed over time, towards more energy intensive goods and services. Walker et al. (2016) provided evidence of this for the UK and pointed out the fundamental contradiction that these escalating expectations pose on the need to reduce carbon emissions in a climate constrained world. How much energy we demand, what goods and services we consume, should be questioned and critically analysed, as everyday practices that involve energy use are not set in stone and can be changed (Røpke, 2009; Shove et al., 2008).

Having established the reasons for choosing the concepts of energy services and human needs, the conceptual framework develops two main elements. On the one hand, it establishes a fundamental relationship between energy services and human needs, by characterising energy services as satisfiers of human needs. In other words, the framework recognises that energy services, regardless of the way they are provisioned, are used to satisfy human needs. On the other hand, by the flexible nature of energy services and human needs, the framework opens the possibility of finding decoupling opportunities in the specific socio-technical provisioning systems of energy services and the societal characteristics of need satisfaction.

In order to apply and test empirically the two elements proposed in the conceptual framework, I developed a novel workshop structure as a data collection method. For the first element, I combined an example-based presentation and participatory discussion of energy services and human needs, with a need-by-need analysis of energy services as satisfiers. For the second element, I used Max-Neef's (1991) existential categories in an adapted way, in order to enable participants to propose alternative ways of provisioning an energy service.

Max-Neef (1991) proposes a matrix, in which satisfiers must be allocated at the interface between nine human needs (subsistence, protection, affection, understanding, participation, idleness, creation, identity, freedom) and four existential categories (being, having, doing, interacting). The former are used on the need-by-need analysis of energy services as satisfiers of human needs, whilst the latter are used as an evaluative tool for the communities involved to assess their possibilities of self-reliant community action for improved energy service delivery.

I chose Max-Neef's approach because it is well suited for conducting empirical research that is not extractive, allowing the communities involved to talk about their needs in a different way, and analyse self-reliant options for improved energy service delivery. In this sense, the process of empirically testing the framework not only provided interesting academic insights, but was also valuable in itself as a participatory exercise for community awareness and learning. This choice is reflective of my own values and normative preferences as a researcher, as discussed in section 1.4.1. Moreover, Max-Neef's approach has been demonstrated in the field, both in developed and developing contexts (Guillén-Royo, 2016; Guillen-Royo, Guardiola, & Garcia-Quero, 2017; Jolibert, Paavola, & Rauschmayer, 2014; Max-Neef, 1991), particularly in Latin America where a sense of community is very strong. It is also well-suited for the community level, which was my chosen unit of analysis for the empirical testing, supported by the gap found in the literature.

Finally, Colombia was chosen as a case study for several reasons: the country is in Goldemberg's corner but it has high levels of inequality, thus, it is important to explore it beyond national averages. Colombia has big potential for renewable energy developments, but beyond its technological possibilities, it is a country in transition from more than five decades of war, so there is space for questioning certain social practices and goals. Last but not least, my personal connection with the country provided important practical advantages for choosing it. Within Colombia, an urban and a rural community were chosen for comparability and variety, as well as personal connections with local NGOs.

1.5 Structure of the thesis

This thesis consists of 5 chapters. The first chapter is this introduction, where the rationale for the research is set out, as well as the specific focus and the approaches used to undertake the research. Chapters 2 to 4 correspond to published peer reviewed journal papers that I have led and developed during my PhD. Chapter 2 focuses on the national-level surplus energy, applied to the UK economy for the period 1997-2012 (addressing objective A and gap 1). Chapters 3 and 4 focus on the energy requirements of human well-being (addressing objective B and C, and gap 2). Finally, Chapter 5 presents the discussion and conclusions. The relations between the chapters are shown in Figure 1-10.

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Chapter 2

Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI)

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Abstract

Concerns have been raised that declining energy return on energy investment (EROI) from fossil fuels, and low levels of EROI for alternative energy sources, could constrain the ability of national economies to continue to deliver economic growth and improvements in social wellbeing while undertaking a low-carbon transition. However, in order to test these concerns on a national scale, there is a conceptual and methodological gap in relation to calculating a national-level EROI and analysing its policy implications. We address this by developing a novel application of an Input-Output methodology to calculate a national-level indirect energy investment, one of the components needed for calculating a national-level EROI. This is a mixed physical and monetary approach using Multi-Regional Input-Output data and an energy extension. We discuss some conceptual and methodological issues relating to defining EROI for a national economy, and describe in detail the methodology and data requirements for the approach. We obtain initial results for the UK for the period 1997–2012, which show that the country's EROI has been declining since the beginning of the 21st Century. We discuss the policy relevance of measuring national-level EROI and propose avenues for future research.

Key words

Energy Return on Investment (EROI); Multi-Regional Input-Output; net energy analysis; resource depletion; biophysical economics; energy transition.

2.1 Introduction

The concept of energy return on energy investment (EROI) is part of the field of study of net energy analysis (NEA), and is one way of measuring and comparing the net energy availability to the economy from different energy sources and processes. In broad terms, it can be understood as "the ratio of energy returned from an energy-gathering activity compared to the energy invested in that process" (Hall & Kiltgaard, 2012, p. 310). Building on a long history of ideas in biophysical economics (see, for example, Cleveland (1987)), this concept has been used by e.g., Hall and Kiltgaard (2012) as a basis for further developing an energy-focused approach to the economy.

This approach is driven by concerns around a decline in the EROI of fossil fuels and low levels of EROI for alternative energy sources. In the case of fossil fuels, it is argued that the depletion of easily recoverable fossil fuel reserves is outpacing technological advancements for the improvement of fossil fuel extraction, leading to decreasing values of EROI for these fossil energy sources (see e.g. Dale, Kumdieck, & Bodger, 2011; Gagnon & Hall, 2009; Lambert, Hall & Balogh, 2013). Moreover, some authors (Dale & Benson, 2013; Hall, Lambert, & Balogh, 2014) have argued that the EROIs of many renewable energy technologies necessary to decarbonise global energy supply are currently lower than the fossil fuels that they need to replace. However, it should be recognized that the EROI of renewable energy sources varies hugely depending on the technology and location. For instance, Raugei et al. (2012) and Kubiszewski et al. (2010) calculate that, for electricity generation, the latest solar and wind technologies respectively have EROI values comparable to gas- or coal-fired power plants . The future trends in the EROI of renewable energy systems are also very uncertain—being dependent both on the pace of technological innovation (which may increase EROI) and the need for increased back-up generation and storage (which may decrease EROI from a full energy system perspective).

The higher the EROI of an energy supply technology, the more "valuable" it is in terms of producing (economically) useful energy output. In other words, a higher EROI allows for more net energy to be available to the economy, which is valuable in the sense that all economic activity relies on energy use to a greater or lesser extent. Analyses of the EROI of different energy sources and extraction/capture processes using particular technologies are relatively common, e.g. (Hall, Lambert & Balogh, 2014; Cleveland, 2005). These are important in terms of presenting a picture of the potential contribution of individual energy sources to the energetic needs of the economy. However, less attention has so far been paid to determining EROI values for national economies, which requires a different methodological approach to traditional EROI analyses due to the mix of particular resource locations, exploitation times and technologies applied to "produce" energy, i.e., to extract fossil fuels and capture flows of renewable energy in a given national territory.

This paper aims to help with the need to develop a method for measuring EROI for national economies, in particular for calculating indirect energy investment, and thus contribute to the growing field of NEA. It does so by proposing a novel application of an Input-Output methodology using Multi-Regional Input-Output data for the UK for the period 1997–2012. This approach is described in detail in section 2.3, followed by the presentation and discussion of results in section 2.4, and some conclusions and policy recommendations in section 2.5. But firstly we explain the importance of a national-level EROI in section 2.2, as well as describe how it differs from other types of EROI, and discuss some of the methodological issues associated with EROI calculations in general.

2.2 A national-level EROI: the concept

Our aim in this paper is to develop an Input-Output based methodology to calculate a national-level EROI ($\mathrm{EROI}_{\mathrm{nat}}$). We start with a succinct background of the EROI concept and its different types. We then follow by putting forward some arguments on the conceptual relevance of a $\mathrm{EROI}_{\mathrm{nat}}$ as we have defined here. Finally, this section discusses persistent conceptual issues in the EROI literature and describes the conceptual choices we made.

2.2.1 Background

EROI (or EROEI) is a key metric in NEA. The concept of net energy (i.e., amount of usable energy after extraction and processing) dates back to the second half of the 20th Century (Hall, 1972; Hall, Lavine, & Sloane, 1979; Smith, 1960). The term (EROI) however, was first used in 1984 by Cleveland et al. (1984). It is a dimensionless number (also often expressed as a ratio) that expresses the result of energy returns over energy invested.

Most EROI studies consider an energy supply technology for a particular resource type and in a particular location. Such studies typically have the “mine-mouth” (or “well-head” or “farm-gate”) as the boundary drawn for evaluating the energy return in relation to the energy required to get it, without further transformation processing (Murphy & Hall, 2010). These EROI calculations are often referred to as “standard” EROI ($\mathrm{EROI}_{\mathrm{stnd}}$) (Murphy et al., 2011):

$$\mathrm{EROI}_{\mathrm{stnd}} = \frac{\text{energy output from extraction}}{\text{direct and indirect energy inputs}} \tag{1}$$

A simple graphical description can be found in Figure 2-1, showing how $\mathrm{EROI}_{\mathrm{stnd}}$ for a particular energy resource (oil) compares to EROI calculations with extended system boundaries. Other, less common, types of EROI calculations for a single energy source vary depending on the chosen system boundary (e.g., $\mathrm{EROI_{pou}}$ and $\mathrm{EROI_{ext}}$) and thus include more or fewer stages along the energy transformation chain. $\mathrm{EROI_{stnd}}$ is more commonly used to compare different fuels or energy carriers, or when analysing changes in EROI of a specific fuel over time and the consequences for the wider economy (see for example (Hall et al., 2014; Murphy & Hall, 2011b; Poisson & Hall, 2013)).

When a number of energy resources are examined within certain geographical limits, such as a country, then another type of EROI is needed: a societal or national-level EROI. Earlier attempts to calculate the net energy for a country include Leach (1975) and Peet et al. (1987), however they did not include trade in their calculations, a key element in a globalised world. A recent attempt to calculate a societal EROI ($\mathrm{EROI_{soc}}$) was undertaken by Lambert et al. (2013, 2014). They estimate the average EROI for all energy supply technologies deployed by a nation. $\mathrm{EROI_{soc}}$ is calculated by dividing the average energy obtained per dollar of spending (summed over different fuel inputs to the economy) by the primary energy needed to obtain one dollar's worth of economic production. Their results suggest that countries with higher societal EROIs have higher standards of living, as measured by the Human Development Index (HDI). Their calculations are based on price and energy intensity information, which may have some drawbacks. Prices might be influenced by factors other than physical resource scarcity, particularly in non-competitive markets. Thus, high prices do not necessarily correspond to scarce resources and vice versa, so a price-based approach may introduce distortions to the calculated EROI.

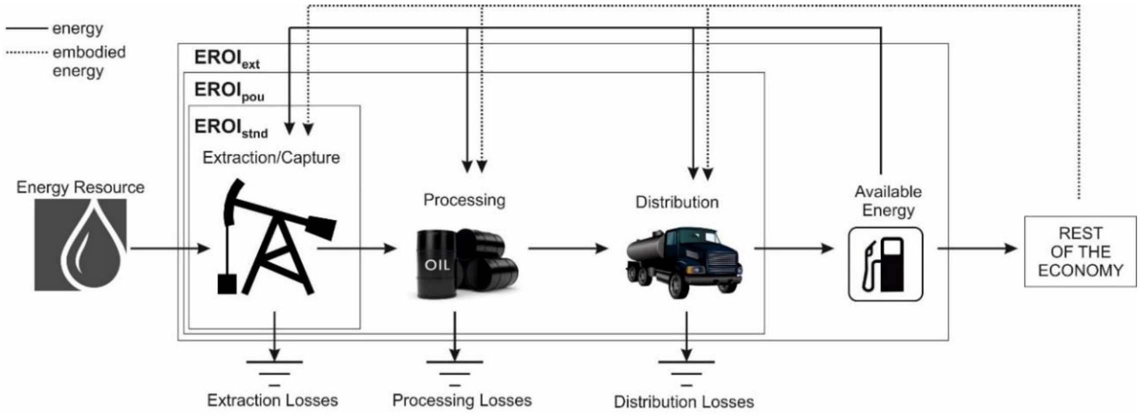

Figure 2-1. Types of EROI
Notes: $\mathrm{EROI_{stnd}}$: standard EROI. $\mathrm{EROI_{pou}}$: EROI at the point of use. $\mathrm{EROI_{ext}}$: extended EROI.

More recent studies that attempted national-level net energy estimations include the studies by King et al. (2015; 2015b), King (2015a), Fizaine and Court (2016), Herendeen (2015) and Raugei and Leccisi (2016). However, these studies diverge from our own in that they have either not accounted for energy trade (both direct and embodied) in calculating indirect energy (Fizaine & Court, 2016; King, 2015; King et al., 2015a, 2015b), they have focused on a single year (R. A. Herendeen, 2015) or they have focused on single energy sources rather than the aggregate production of energy by a nation (Raugei & Leccisi, 2016). Our approach represents a contribution to these efforts in that it combines three aspects of net energy analysis at a country level that have been pursued separately up to now: accounting for international energy trade in the calculation of indirect energy (in our case using an Input-Output framework), using data for a more than one year, and taking a national perspective. We will compare and discuss their results in more detail when presenting our results from this first application.

2.2.2 The benefits of a national-level EROI

There are three key reasons why a national-level EROI is important. Firstly, traditional energy analyses (i.e. mainstream energy-economic analyses that are widely used for decision-making purposes) do not usually address directly the issue of resource depletion or reduced accessibility (i.e., resources that are more difficult to extract/capture). In traditional energy analyses this might be addressed indirectly through prices and price projections, or perhaps through data and projections on reserves. However, we believe that EROI gives a better picture of resource depletion and accessibility, one that is based on energy accounting of extraction/capture processes. This is important because if a country is understood to require a given level of net energy input to support its economic activity, a declining EROI trend would imply that the total gross energy requirements of the economy could rise, even without economic growth. In this case, a national-level EROI becomes relevant for energy-economy analysis and national energy planning.

Secondly, when measured over time to take account of dynamic effects, EROI can provide valuable information about the relative resource depletion and technological change in resource extraction/capture. A declining EROI over time indicates that resource depletion is outpacing technological change (Murphy et al., 2011) (i.e., the quantity of output of a certain energy resource, or its accessibility (Dale et al., 2012a), is declining faster than the advancements in technology to harvest it more efficiently). Here the system boundary for EROI is established at the resource extraction/capture level, rather than including downstream transformation processes (we use the terms extraction and capture in order to include both the extraction of energy resource stocks, e.g. coal, oil and gas, and the capture of energy flows through its conversion to electricity, e.g. wind and solar). Therefore, a national-level EROI time series can be analysed together with other national-level energy-economic studies. This would provide additional information to improve our understanding as to how the dynamics of resource depletion (or accessibility) and technological change relate to energy quality and the dynamics of conversion efficiencies.

In particular, the development of a national-level EROI provides net energy analysis and insights at the same (national) scale as that required by policy-makers. For example, policy-relevant findings may include a better understanding of a country's overall resource depletion or reduced resource accessibility, and the energy investment requirements versus technological advancements of resource extraction/capture.

Thirdly, EROI has economic relevance since large energy returns in excess of the corresponding energy investments facilitate increasingly diverse economic activities. This is the case as the physical energy cost of energy supply is likely to have a larger economic impact than might be expected from its cost share. Assuming that firms are profit maximizing, markets are perfectly competitive and the economy is in equilibrium (as in neoclassical economic growth models), it is a mathematical result from the Cobb-Douglas production function that the partial output elasticity of the factors of production equal their respective cost shares of aggregate output (Heun et al., 2017). However, the cost share principle does not apply when using other production functions (e.g., CES function) (Brockway et al., 2017), and perhaps more importantly, it is theoretically contested by insights from ecological economics that highlight the vital importance of energy for economic growth compared to its historically low cost (Ayres et al., 2013; Kümmel, 2013). This is because if the physical cost of energy production rises then this might severely impact the productive resources available to the rest of the economy (in terms of labour, physical infrastructure and investment capital, for instance). A national-level EROI can help understand the potential for growth or change of a national economy in relation to the physical energy cost of extracting/capturing the energy it requires.

2.2.3 Conceptual issues and choices

The main persistent conceptual issues in the EROI literature are: how to define the boundary of analysis (as shown in Figure 2-1), how to account for embodied energy inputs (i.e. all the energy that went into a process; this is different from embedded energy, which relates to the energy content of specific materials or infrastructures), how to deal with temporality and how to account for energy quality. These issues are still being identified in recent EROI publications (Brandt & Dale, 2011; Murphy et al., 2011), but are largely the same as those that Leach (1975) identified and were discussed in a NEA workshop held in August 1975 at Stanford, California. We will discuss each of them in turn, providing our own conceptual choices for this specific definition of $EROI_{nat}$ and an explanation of the reasoning behind our choices (which were sometimes conceptual and sometimes practical). However, our choices are not necessarily intended to point towards final solutions to these methodological issues, but rather should be seen as contributing to the discussion of defining EROI at a national level.

2.2.3.1 Boundary of analysis

There is a consensus around the accounting starting point for EROI in general, regardless of the type. EROI “assumes that the energy in the ground (or coming from the sun) is not to be counted as an input” (R. A. Herendeen, 2004, p. 284). Therefore, EROI accounts for energy inputs once they have been either extracted or harnessed for human purposes, but not the energy content of the resource that is being extracted/harnessed (note that this start point of accounting for energy contrasts with the approach of another assessment tool: Life Cycle Analysis—LCA. In LCA the energy that is present in the environment or the energy source is the start point for accounting in measures of, for instance, cumulative energy demand).

However, there are three main considerations when assessing boundaries for EROI. Firstly, how many energy processing and transformation stages to take into account: primary energy, final consumption (of energy carriers) or useful energy. Primary energy generally refers to the energy extracted or captured from the natural environment (e.g., crude oil, coal, hydropower, etc.) (IEA, 2005). Final energy (also called secondary energy) generally refers to energy as it is delivered to the final economic consumer, after undergoing transportation and transformation processes (e.g., gasoline, diesel, electricity, etc.) (IEA, 2005). At the point of use, final energy undergoes one last transformation process as it passes through an end-use conversion device, for example furnaces, electric appliances or light bulbs. End-use devices transform energy into a form that is useful for human purposes, hence the term “useful energy” as the outcome of this last conversion process. Secondly, a decision is required as to the inclusion of energy inputs at each of the energy stages under analysis, i.e., should these inputs include embodied energy in capital equipment, operation and maintenance energy, energy consumed by the labour force, etc.? Thirdly, a consideration is required as to the range of energy sources that will be analysed, the geographical limits to be applied and the time frame to be considered.

In relation to the first consideration, how far to go along the energy chain in order to include more processing and transformation stages depends on the type of EROI (see Figure 2-1). Our definition of $\mathrm{EROI_{nat}}$ establishes this boundary at the first stage of extraction/capture of energy sources. We have chosen this stage for practical reasons, as it provides a well-defined starting point for a novel methodology that can be further built upon. In terms of most energy reporting (e.g., International Energy Agency—IEA—Energy Balances), this means energy “production”. Energy “production” does not include energy imports but it does include energy exports. In other words, we are assessing the energy extracted/captured in a country (energy returned), regardless of whether or not it is then exported and without accounting for energy imports (see Figure 2-2). This means that a country that imports all of its primary energy will not have an EROI value when using this methodology.

In relation to the second consideration, on the extent of energy inputs included at each energy processing and transformation stage, it depends on the specific EROI study. Most EROI studies include the direct energy and material (as embodied energy) inputs as well as the indirect energy and material inputs, i.e., the inputs required to make the initial inputs. We have decided to adopt this commonly used boundary in the calculation of $EROI_{nat}$ in order to make our results comparable to other results found in the literature.

Brandt et al. (2013) have developed a framework for tracking direct energy inputs as well as different number of indirect energy inputs. Further expansion of the boundary that determines the energy inputs can be made. For example, indirect labour consumption can be included, as well as the consumption of auxiliary services and the environmental impacts of the production of direct and indirect energy and materials. Hall et al. (2009) calculate $EROI_{ext}$ for US oil using an expanded boundary for the inputs. However, we consider these expansions to be an area suitable for further research, as an Input-Output framework is ideally suited to overcoming a key hurdle in national-level EROI analysis: allocating indirect energy use from different stages of the supply chain to the energy producing sectors.

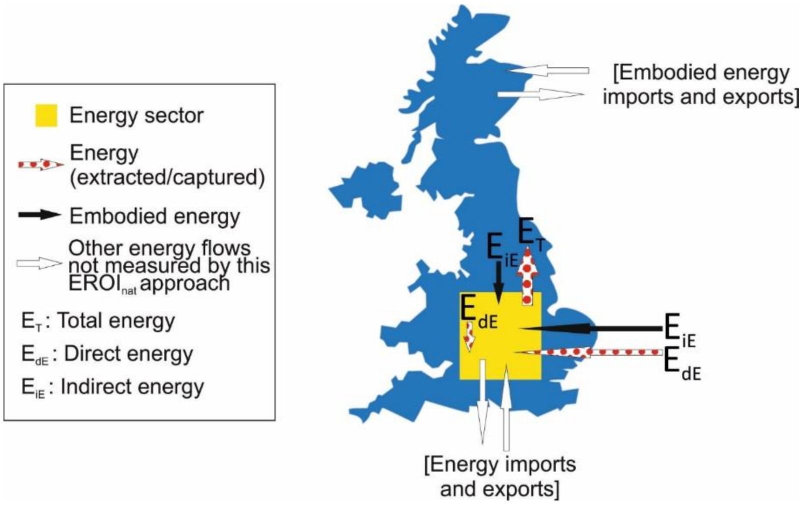

Figure 2-2. National level EROI—UK case
Notes: Black and dotted arrows represent what we measure, while white arrows represent flows that occur but that are not included in this approach to $EROI_{nat}$ given its boundary of analysis.

Third, there is the consideration of how many energy sources are being analysed, within which geographical limits and in which time frame. Many EROI studies focus on a single energy source in a single location at a particular point in time. Hall et al. (2014) and Murphy et al. (2011) have undertaken detailed reviews of published EROI values for single energy sources and regions. There are very few time-series EROI studies. Two exceptions are Brandt (2011), who conducted an EROI investigation of oil in California over the period 1955 to 2005 and Brandt et al. (2013) investigating EROI for oil sands in Alberta over the period 1970 to 2010. For it to be consistent with a national-level calculation, in our $EROI_{nat}$

the geographical limits correspond to a national territory, the number of energy sources analysed correspond to all the energy sources extracted/captured within that territory and the time frame is only constrained by data availability. Our proposed approach attempts to calculate $\mathrm{EROI}_{\mathrm{nat}}$ from a territorial production perspective (as opposed to a consumption perspective).

2.2.3.2 Accounting for embodied energy inputs

Depending on the chosen boundaries for the calculation of EROI, and data availability, a particular methodology can be applied for the accounting of embodied energy inputs. The two main methodologies used are process analysis and Input-Output (IO) (Murphy et al., 2011). The former is commonly used; it is a bottom-up approach most appropriate when assessing a single energy source through clearly defined processing stages (Murphy et al., 2011). As data collection can be problematic and time consuming when undertaking process analysis “from scratch”, established LCA data sets are sometimes used (see for example Harmsen et al. (2013)). Although, as Arvesen and Hertwich (2015) note, care is needed to ensure that LCA boundary conditions are consistent with the EROI calculation.

Given the boundary definition of our $\mathrm{EROI}_{\mathrm{nat}}$, we have chosen to use IO; a top-down approach that is more appropriate when the boundary is expanded to multiple processes (Murphy et al., 2011), e.g., when considering activities at a national level. This is due to it being able to quantify interrelationships across economic sectors (Murphy et al., 2011), and even enable the attribution of embodied energy inputs to traded goods and services. Physical flows are estimated from monetary economic data in this approach, which is based on an economic transactions matrix (a table where all inter-industry transactions within a year are recorded in monetary terms) combined with an energy extension vector (which contains the amount of energy used by each industry in energy units). Matrix algebra calculations are used to determine the energy “footprint” or energy requirements of each industry’s products, in our case energy production. This methodology is explained in detail in section 3.

2.2.3.3 Temporality

The timing of energy inputs and energy outputs over the functional life of the supply technology is important, since there are typically high energy inputs at the beginning (construction) and at the end (decommissioning) of the life of the energy extraction or capture location (see Figure 2-3). The issue of temporality does not, however, involve any sort of discounting of time (as it does in other types of metrics such as cost-benefit analysis). This is discussed in detail for the case of photovoltaic panels by Dale and Benson (2013), King et al. (2015a) and Dale (2012).

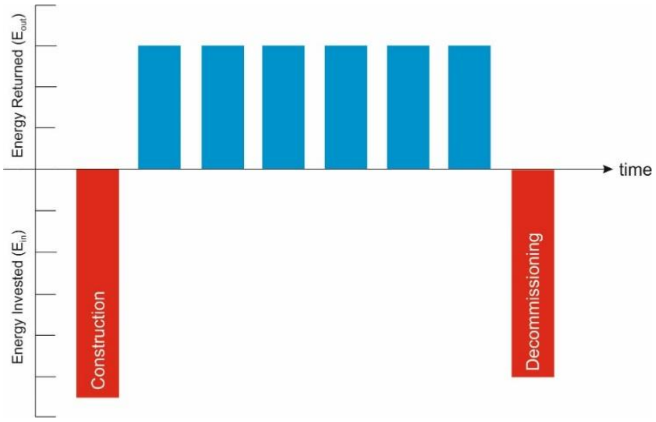

Figure 2-3. EROI inputs over time
Source**:** Own elaboration.

However, when the boundary is expanded over larger geographical spaces and several energy sources, obtaining such data for all energy sources is impractical, therefore a pragmatic approach is required. For our EROI_{nat} we assume that the temporal patterns of energy inputs will balance out, since not all energy extraction or capture projects will be at the same stage of development. Therefore accounting for EROI_{nat} in any given year broadly reflects the whole country's EROI across all energy sources irrespective of the stage of development of specific energy extraction and capture projects. However, as Murphy et al. (2011, p. 1893) point out "this assumption would be accurate only if the system is in 'steady state', i.e., not growing or shrinking". An example of a recent study that assumed the energy system to be in a steady state is that of Herendeen (R. A. Herendeen, 2015).

Note that this pragmatic assumption may fail to capture shortfalls in energy available to the economy for an interim period. For example, in the context of rapid mitigation to address climate change, there is a need to invest heavily in capture or extraction technology for particular energy sources in a short period of time. In these sorts of periods, EROI_{nat} values would be lower, and would be followed by periods of higher EROI_{nat} once the technologies are in place (Dale & Benson, 2013). However, as longer time-series EROI_{nat} values become available, the effect on temporality of low/high energy investment will become clearer, which in itself will be a valuable finding. Therefore, EROI_{nat} results should always be analysed in conjunction with energy investments and energy production data for the country being analysed. That way the assumption of the energy system being in a steady state can be determined to be true or not for the period under study, and the results can be interpreted accordingly.

2.2.3.4 Accounting for Energy Quality

How to account for the differences in energy quality of the different energy sources has been a persistent methodological issue in energy analysis, and hence also for conducting NEA. It is important to account for energy quality because thermal energy and electricity, for example, are very different in terms of their capacity to do work, but also in their density, cleanliness, ease of storage, safety, flexibility of use, etc. These differences should be accounted for since they are relevant for societies and economies. However, and despite its importance, most EROI studies do not undertake any form of energy quality adjustment. At a national-level, where different energy sources are being studied together, it becomes very significant to make energy quality adjustments in order to be able to compare "apples to apples".

There are, in general, two approaches for accounting for differences in energy quality: price-based and physical units (Murphy et al., 2011, pp. 1896–1899). The price-based approach is used more often when accounting for energy inputs using a top-down approach given the extent of economic data (Lambert et al., 2014). However, this approach rests on contentious assumptions of competitive markets and lack of accounting for externalities (Cleveland, Kaufmann, & Stern, 2000). The physical units approach on the other hand, is used more often in process analysis, where detailed physical data are available. Moreover, there is recent work that has been using physical units, in particular exergy, to account for thermodynamic energy quality at a national-level (Brockway et al., 2014; Brockway et al., 2015; Warr et al., 2010; Williams, Warr, & Ayres, 2008). Exergy can be defined as "the maximum possible work that may be obtained from a system by bringing it to the equilibrium in a process with reference surroundings" (Kostic, 2012, p. 816). As Gaggioli and Wepfer (1980, p. 823) state, exergy "is synonymous with what the layman calls 'energy'. It is exergy, not energy, that is the resource of value, and it this commodity, that 'fuels' processes, which the layman is willing to pay for" (for further details on exergy see Wall (1977, 1986, 2003), Kanoglu et al. (2012), Dincer (2002), Rosen (2002, 2006), Sciubba and Wall (2007)). Nonetheless, it is important to acknowledge that exergy does not account for certain aspects of energy quality that are important for economic purposes (e.g., capacity for storage, cleanliness, transportability, density, and so on) (Cleveland et al., 2000; Murphy et al., 2011).

We have not made a specific quality adjustment for the calculation of $\mathrm{EROI}_{\mathrm{nat}}$, and we consider this to be a key avenue for future research, ideally using useful exergy, particularly taking into account the social and economic importance of being able to compare fairly different energy sources based on their usefulness. For consistency purposes we have relied on the physical content method used by most international energy agencies, by which the primary energy equivalent of any renewable energy source is its physical energy content (IEA, 2016). Given that our boundary of analysis is taken at the production stage, this correction is less important than if we chose final consumption or useful energy as the boundary of analysis.

2.3 A national-level EROI: the data and the methodology

2.3.1 Input-Output and energy

Like many other energy analysis techniques, energy IO analysis was developed in the 1970s driven by the oil price shock of the time (Casler & Wilbur, 1984). It has been mainly used to quantify energy flows through the different economic sectors (see for example (Bullard & Herendeen, 1975; Bullard, Penner, & Pilati, 1978; Wright, 1974)). However, to the best of our knowledge, it has not been used to directly calculate an empirically-based national-level EROI value using an MRIO modelling approach. Following a similar line of enquiry, Brandt (Brandt, 2017) recently developed a mathematical Input-Output framework for assessing the mechanisms by which EROI affects a country's prosperity. We will now describe the data that we use to calculate $\mathrm{EROI}_{\mathrm{nat}}$ for the UK ($\mathrm{EROI}_{\mathrm{nat(UK)}}$) for 1997–2012, followed by a detailed description of the IO methodology.

2.3.2 $\mathrm{EROI}_{\mathrm{nat(UK)}}$: data

We use IEA data (IEA, 2015b) and a Multi-Regional Input-Output (MRIO) model to construct a Multi-Regional Input-Output model for the UK (UKMRIO), using IO data produced by the UK's Office of National Statistics (ONS, 2014). This data is supplemented with additional data on UK trade with other nations and how these other nations trade between themselves from the University of Sydney's Eora MRIO database. The Eora MRIO database (Lenzen et al., 2012; Lenzen et al., 2013) is used to disaggregate the UK's import and export data to further sectors from other world regions. Since Eora contains data from almost 200 countries, we are able to select the most appropriate regional grouping for the trade data. For this study, we construct six regions: the UK, the Rest of Europe, the Middle East, China, the Rest of the OECD, and the Rest of the World. We consider these regions to be the most appropriate ones for our analysis, since they group major economies as well as separating by key energy producers. The UKMRIO is based on 106 sectors, two of which are energy industries/sectors relevant to our boundary definition (i.e., extraction/capture industries). A basic structure of an Input-Output model is shown in Figure 2-4

Following a standard procedure in IO modelling, an environmental extension for energy production relating to each transaction is added in physical units (MJ), though the main IO table is based on monetary units (Roberts, 1978). This could be considered a drawback of this dataset, which uses a direct impact coefficient approach (or energy intensity approach). However, its use is justified by data availability and unit consistency. There are no MRIO energy extended databases that we know of that use a hybrid-unit approach, although a single region IO hybrid-unit matrix with an energy extension was constructed by Guevara (2014) for Portugal using IEA (International Energy Agency) data.

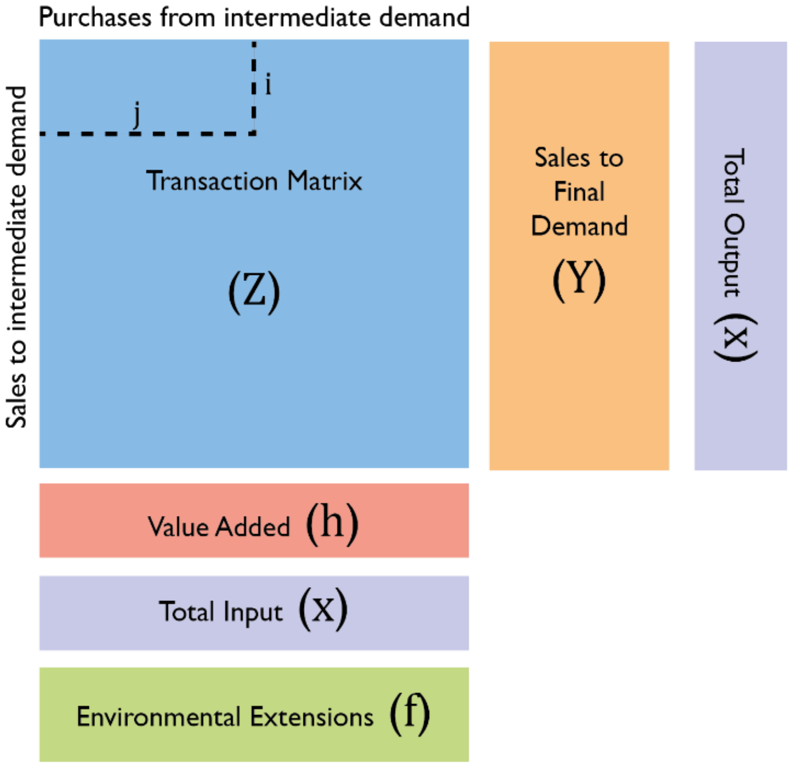

Figure 2-4. Basic structure of an Input-Output framework with and environmental extension.
Source: Elaborated by Anne Owen.

2.3.3 $EROI_{nat(UK)}$: methodology

Our approach aims to track all indirect energy investment requirements of the energy sector. It does so by using a whole economy's transaction matrix to allocate energy sales and purchases to every industry, and then track down the paths that lead to the energy industry itself. In this case, $EROI_{nat(UK)}$ attempts to trace the indirect energy flows used by the UK's own energy sector in order to extract/capture energy (represented by black arrows in Figure 2-2). By using a MRIO model, we can take into account indirect energy investments that originate overseas (see Figure 2-2). We consider it to be a novel application of a well-established methodology in the field of emissions accounting.

As described in section 2.3.1, the system boundary is drawn at the extraction/capture stage; therefore Equation (2) is consistent with Equation (1):

$$\mathrm{EROI}_{\mathrm{nat(UK)}} = \frac{\mathrm{E}_{\mathrm{out}}}{\mathrm{E}_{\mathrm{in}}} \tag{2}$$

where: $\mathrm{E_{out}}$ = net energy outputs from extraction/capture from the UK's energy sectors (or energy output from extraction in Equation (1)); $\mathrm{E_{in}}$ = direct and indirect energy inputs (from the UK and abroad) to the UK's energy sectors (as in Equation (1)).

The energy return at a national level, $\mathrm{E_{out}}$ is calculated using Equation (3):

$$\mathrm{E_{out}} = \mathrm{E_T} - \mathrm{E_{dE}} \tag{3}$$

where: $\mathrm{E_T}$ = total primary energy produced in the UK. This is taken from "production" in IEA energy balances; $\mathrm{E_{dE}}$ = total UK energy sector's direct energy use used to extract/capture UK's energy. This is taken from "energy industry own use" in IEA energy balances.

Similarly, the energy invested in producing this, $\mathrm{E_{in}}$ is calculated from Equation (4):

$$\mathrm{E_{in}} = \mathrm{E_{dE}} + \mathrm{E_{iE}} \tag{4}$$

where: $\mathrm{E_{iE}}$ = total indirect energy use (both from the UK and the other 5 regions) used to extract/capture UK's energy. In other words, this is the embodied energy used by the UK's energy extracting/capture sectors in order to produce energy.

Having constructed the UKMRIO model, $\mathrm{E_{iE}}$ can be calculated, following the detailed matrix algebra IO procedure described in Appendix A, together with a simple numerical example (see Appendix B).

Finally, the EROI at a national level for the UK is calculated by substituting these expressions into Equation (2), leading to Equation (5):

$$\mathrm{EROI_{nat(UK)}} = \frac{\mathrm{E_T} - \mathrm{E_{dE}}}{\mathrm{E_{dE}} + \mathrm{E_{iE}}} \tag{5}$$

2.4 Results and discussion

Applying the UK IO data, IEA data and MRIO model to Equation (5), we calculated the $EROI_{nat}$ for the UK for the period 1997–2012. We found that the $EROI_{nat(UK)}$ for the period increased from 12.7 in 1997 to a maximum value of 13.8 in 2000, before gradually falling back to a value of 5.6 in 2012 (Figure 2-5). This means that for every unit of energy the UK energy extracting/capture sectors have invested, they have obtained an average of 10.2 units of energy during the period 1997–2012. In other words, on average, 9.8% of the UK's extracted/captured energy does not go into the economy or into society for productive or well-being purposes, but rather needs to be reinvested by the energy sectors to produce more energy.

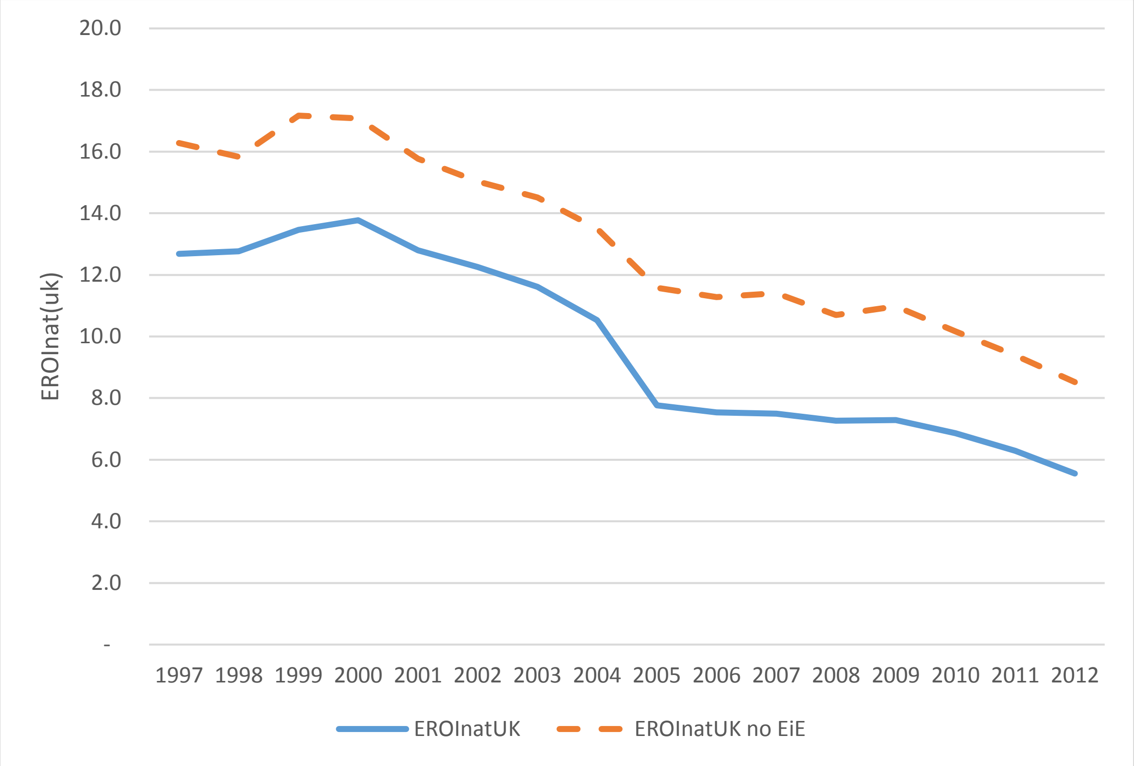

Figure 2-5. $EROI_{nat(UK)}$ (1997–2012): Comparison of results with and without indirect energy (E_{iE})
Source: Own elaboration.

This of course has implications for the energy sector, for resource management and technology development, and for the economy, as described in section 2.2. If Fizaine and Court (2016) are right in their assessment, where a minimum societal EROI of 11 is required for continuous economic growth (assuming the current energy intensity of the US economy), the UK is below that benchmark. It is important to note that although Fizaine and Court [26] use a completely different methodology to ours (econometric techniques), their boundary of analysis is set at the same national-level. However, since we are not accounting for energy imports, the EROI associated to the 84% of total primary energy supply that came from imports in 2012 into the UK (IEA, 2015b) might move the UK's consumption-based EROI above Fizaine and Court's benchmark. Nonetheless we consider their results useful in terms of showing certain consistency in the range of values for national-level EROIs and as a good contribution to the discussion.

Figure 2-5 also shows the relevance of including indirect energy (E_{iE}) in the calculation of $EROI_{nat(UK)}$. An $EROI_{nat}$ calculation, using only energy industry's own use as the energy inputs gives higher values because there is an element missing in the denominator. By including indirect energy use (E_{iE}), using the IO methodology described in section 3.3, we obtain a more complete view of the energy invested into the energy producing sectors. This is the key contribution of the methodology we outline here and a step forwards in the EROI literature. Our calculations for the UK without including indirect energy (E_{iE}) are the same order of magnitude to King et al.'s (2015b) calculations of EROI (or net power ratio—NPR as they call it). The evolution of the energy returned (numerator E_{out}) and the energy invested (denominator E_{in}) are shown in Figure 2-6.

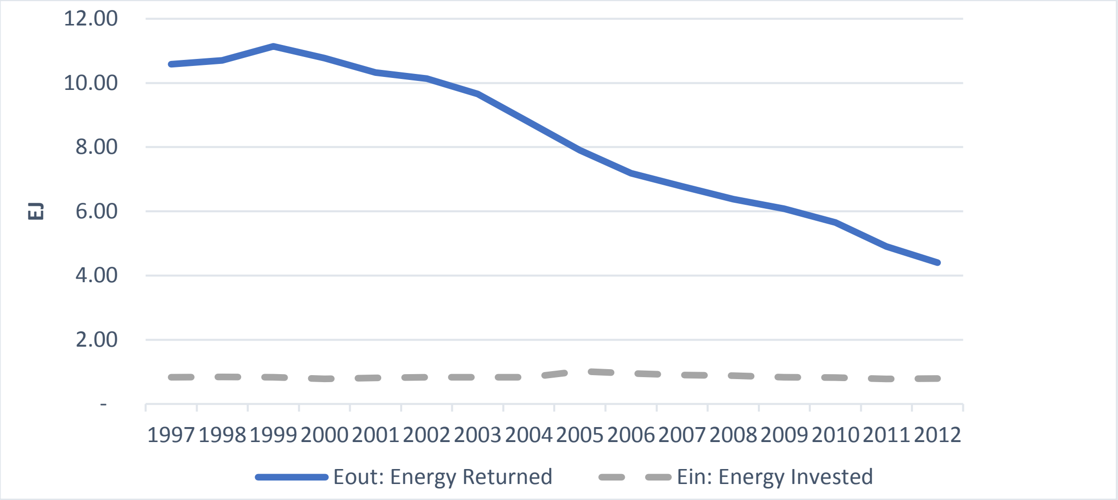

Figure 2-6. Energy Returned (E_{out}) and Energy Invested (E_{in}) in the UK (1997–2012). Source: Own elaboration.

Since 1999 the UK's production of energy has been declining steadily (compensated by increased imports that are not included in $EROI_{nat(UK)}$). For a national-level EROI from a production perspective, this means that we are extracting/capturing less energy by using a relatively stable stream of energy inputs. Thus the steady decline of $EROI_{nat(UK)}$ from 2003 onwards.

Furthermore, considering that oil and gas dominate the UK's energy production mix (see Figure 2-7), changes in the EROI values of these particular fuels are likely to dominate the changes in the UK's $EROI_{nat}$. From literature reviews on the EROI of different energy sources, there seems to be a consensus that on average coal has the highest EROI, followed by oil and then gas (Dale et al., 2012a; Murphy & Hall, 2010). Therefore, the steeper decline of $EROI_{nat(UK)}$ from 2010 onwards is partially explained by a reduction in the proportion of those three fossil fuels in the UK's total production (see Table 2-1).

One drawback of our current approach to calculating a national-level EROI is that it cannot provide energy source specific information about in which years energy investments are made and energy returns are obtained (we would see this as part of an extended future methodology). Therefore, the validity of our current results rests in the assumption the UK's energy system was in a steady state in terms of energy production between 1997 and 2012. We are aware that this is a very stringent assumption to make. As we suggested in section 2.3.3, these results should be analysed in conjunction with energy investment and production data, to assess how steady the system has been. We present in Figure 2-8 the financial investment data in the UK's energy production by source, where we can see that the system has been very stable in terms of fossil fuel and nuclear production. There have been significant investments in renewable sources, but since they only represent a small fraction of total UK production (see Figure 2-7), their effect should not be too big on our EROI data. However, in terms of energy production data, we can see from Figure 2-6 that the UK's energy production has been declining for most of the period under analysis.

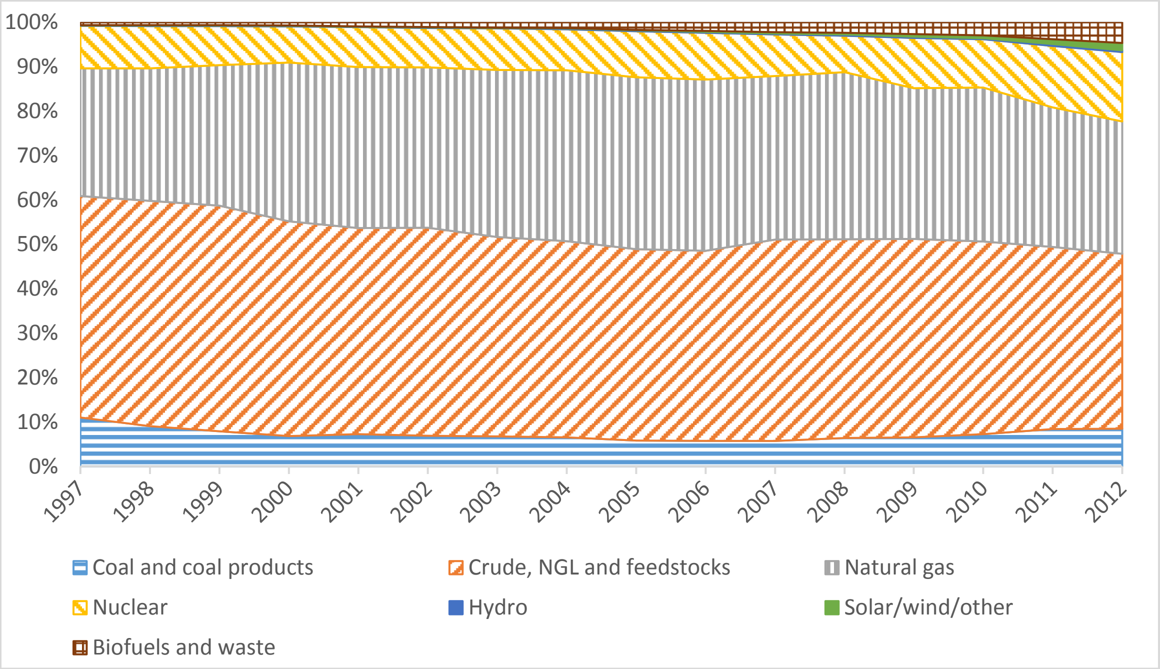

Figure 2-7. UK energy production: share of energy sources 1997–2012
Source: Data taken from IEA(IEA, 2015b).

Table 2-1. UK's rate of production of different energy sources (1997–2010 and 2010–2012).

Energy Source	Change in Production (%)	
	1997–2010	2010–2012
Coal and coal products	−0.6	0.0
Crude, NGL and feedstocks	−0.5	−0.1
Natural gas	−0.3	−0.2
Nuclear	−0.4	0.1
Hydro	−0.1	0.4
Solar/wind/other	13.5	14.2
Biofuels and waste	1.6	0.7

Data taken from IEA (IEA, 2015b).

We believe that there is value in this type of calculation in that by providing a time-series, our proposed approach offers an important long-term dynamic view of the evolution of EROI at a national scale, where periods of high energy investments in one energy source can be compensated with periods of high energy returned in other energy sources. The greater availability of IO data would allow for time-series to be constructed for other countries, and we suggest this to be undertaken as future research. In this sense, we present our results to the research community in the hopes of opening a constructive discussion.

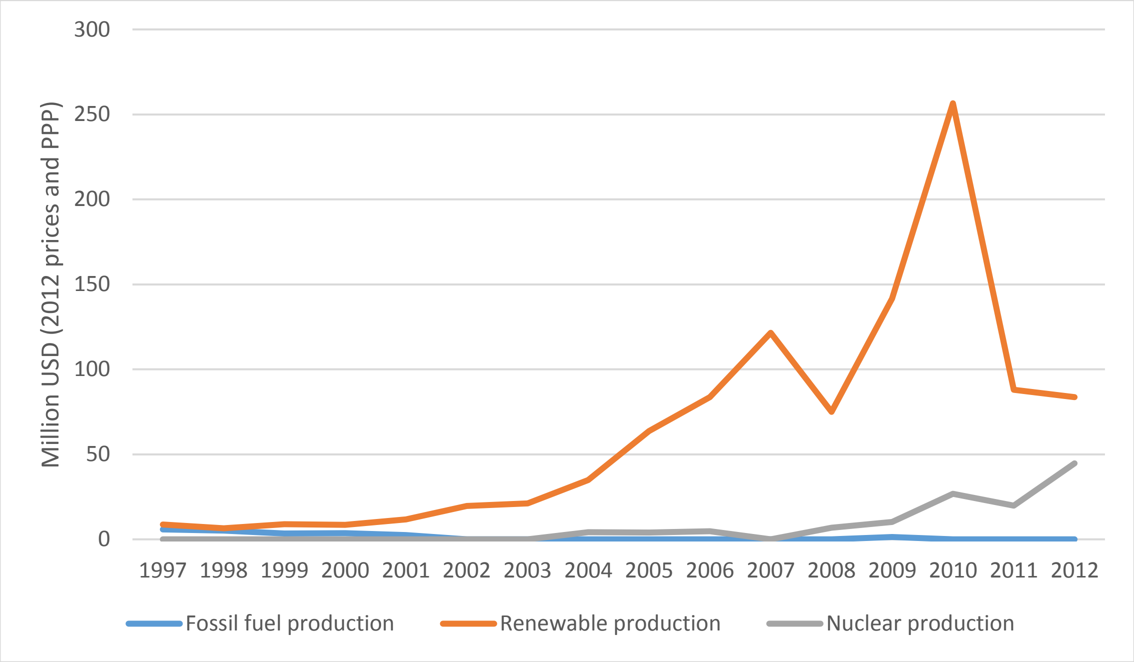

Figure 2-8. Financial investments in the production of UK's energy by source (1974–2012)
Source: Data taken from IEA (IEA, 2014).

2.5 Conclusions and policy implications

This paper developed and applied a new approach to quantify EROI for national economies, particularly when it comes to calculating indirect energy inputs. It contributes to the growing literature on net energy analysis. The approach is based on Input-Output analysis and is, to the best of our knowledge, a novel application of MRIO datasets which has been enabled by the advances in IO data gathering and computing power. Its key contribution is to provide an estimation of indirect energy investments at a national level. Hence, we consider it a step forwards towards the called made by Murphy and Hall (2010, p. 115) for improved "quantity and quality on the data on 'energy costs of energy generating industries'".

The relevance of a national-level EROI lies in its potential to inform national-level energy policy making: in general, countries should aim to have high levels of $EROI_{nat}$, since this means more net energy is available for use in the productive economy. The trends in $EROI_{nat(UK)}$ over time provide information on the relative resource depletion and technological change in the UK's energy sector. We found that the UK as a whole has had a declining EROI in the first decade of the 21st century, going from 9.6 in 2000 to 6.2 in 2012. This information is important, particularly for a country that is aiming to transition to a low-carbon economy. Low levels of $EROI_{nat}$ for a country investing heavily in renewables are to be expected initially. Our results show that towards the end of our period of analysis more energy was having to be used in the extraction of energy compared to the beginning of the century. This may be explained by a declining production of primary energy within the UK as well as more investments in renewable energy sources. This trend should be closely monitored by energy policy-makers, in order to ensure that, as renewable energy capture technologies improve, the $EROI_{nat(UK)}$ trend also improves.

Other authors (R. A. Herendeen, 2015; King et al., 2015a) have attempted to connect EROI values to the price of energy and other services in order to give them more policy relevance. We argue that the methodology described here has the potential to inform national and international energy policy. Once developed further, for more countries and more years, the results can answer important questions such as: Which countries are extracting and capturing energy with a better return to their energy invested? Which countries are doing better in terms of technological development and/or resource conservation? How do $EROI_{nat}$ values for different countries relate to their energy imports and exports? Therefore, we suggest two avenues for future research: first, apply this methodology for more countries and more years; and second, extend the methodology to develop a national-level EROI from a consumption perspective, i.e., expanding the boundary of analysis (an effort that would complement the work of Herendeen (2015)).

As a final thought, in 1974 the US passed a law such that “all prospective energy supply technologies considered for commercial application must be assessed and evaluated in terms of their ‘potential for production of net energy’” (Berndt, 1982). This was triggered by the 1973–74 oil crisis, where high energy prices led to a greater focus on energy efficiency and net energy returns. Once oil supply issues had returned to normal the law was abandoned as the additional calculations were regarded as unnecessary. Given the emerging interest in alternative tools for energy analysis and the pressing need of a transition to a low carbon economy, perhaps it is time to reinstate the importance of undertaking such analysis. Even if the EROI values of renewables may increase in future from current relatively low values—there is contrasting evidence on current values (Kubiszewski et al., 2010; Raugei et al., 2012)—we need to better understand what that would imply for our economies and societies. For the guidance of national energy policy, EROI at a national level could help inform policy decisions that aim to manage an energy transition (Carbajales-Dale, Barnhart, Brandt, & Benson, 2014).

Supplementary materials

The MatLab code we used for the calculations in this paper has been stored with the University of Leeds Data Repository at https://doi.org/10.5518/185 .

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Author contributions

The research was conceived by Lina I. Brand-Correa, Timothy J. Foxon, Paul E. Brockway, Peter G. Taylor and Claire L. Copeland; Lina I. Brand Correa identified Input-Output as an appropriate method to apply in the research. The design of the research was undertaken by Lina I. Brand-Correa and Anne Owen, with significant contributions from Paul E. Brockway; Anne Owen and Paul Brockway provided the data; Lina I. Brand-Correa, Paul Brockway and Anne Owen analyzed the data; Lina I. Brand-Correa wrote the paper with contributions from all the authors; Timothy J. Foxon, Peter G. Taylor and Claire L. Copeland provided conceptual and analytical feedback throughout the duration of the research.

Conflicts of interest

The authors declare no conflict of interest.

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Chapter 3

A Framework for Decoupling Human Need Satisfaction from Energy Use

L. I. Brand-Correa and J. K. Steinberger

Abstract

Climate change poses great challenges to modern societies, central amongst which is to decouple human need satisfaction from energy use. Energy systems are the main source of greenhouse gas emissions, and the services provided by energy (such as heating, power, transport and lighting) are vital to support human development. To address this challenge, we advocate for a eudaimonic need-centred understanding of human well-being, as opposed to hedonic subjective views of well-being. We also argue for a shift in the way we analyse energy demand, from energy throughput to energy services. By adopting these perspectives on either end of the wellbeing-energy spectrum, a "double decoupling" potential can be uncovered. We present a novel analytic framework and showcase several methodological approaches for analysing the relationship between, and decoupling of, energy services and human needs. We conclude by proposing future directions of research in this area based on the analytic framework.

Key words

energy services; human needs; well-being; development; climate change; mixed methods.

3.1 Introduction

Human societies require materials and energy for their activities, and these biophysical requirements (known as "social metabolism") have been increasing with population, economic growth and technological demands (Krausmann et al., 2009). The extent of global social metabolism is such that, during the last century, the physical scale of energy and material inputs and outputs from human societies has come to dominate important planetary biogeochemical cycles. This has led to the definition of a new geological era: the Anthropocene (Hamilton, 2013; Steffen et al., 2015).

Energy systems are recognized to be a core component of societies (Ayres and Warr, 2009; Cook, 1971; Cottrell, 1955; Smil, 2008; White, 1943) and necessary for development. Energy access was recently included in the UN's Sustainable Development Goals (UN, 2016) and the Sustainable Energy for All initiative (UN SE4ALL, 2014). Despite the importance of energy use, vast segments of the world's population live under conditions of severe energy deprivation, preventing them from living healthy lives or fully participating in their society (Karekezi et al., 2012; Pachauri et al., 2012), while an increasingly international consumer class drives the majority of emissions associated with energy systems (Chakravarty et al., 2009; Chancel and Piketty, 2015).

Energy systems are a key intermediary between environmental impacts and the functioning of societies, and thus the well-being of their members. The pivotal role of energy becomes even clearer in the context of a climate-constrained world, where fossil-fuelled energy systems are the largest contributors to GHG emissions (IEA, 2012a) and hence main drivers of climate change (IPCC, 2013). The challenge of achieving human well-being in the Anthropocene era has been summarised by Raworth (2012): can we live above social foundations but below an environmental ceiling, or within the "doughnut" of sustainability?

The centrality of energy in fuelling both human development and climate change can lead to pessimism regarding the achievability of universal social development and keeping climate change below harmful levels (Jakob and Steckel, 2014). In contrast, we believe that more optimism may be warranted. If instead societies' efforts –and energy systems- would be focused towards the satisfaction of human needs, it might well be possible to achieve universal well-being within planetary boundaries. In order to shape societies' efforts as outlined above, however, we need to understand more clearly the relationship between energy and human well-being. Day et al. (2016) have made significant advances in this direction from an energy poverty perspective, by applying the capabilities approach to conceptualize why energy is used and needed, as well as proposing a definition of energy poverty that is multi-dimensional and relevant to global North and South contexts.

The main objective of this paper is to present an analytical framework for exploring the complex problem outlined above, as well as for conducting research that can lead to relevant policy recommendations. To this end, we advocate for a need-centred understanding of human well-being (section 3.2). We also need to change the way we analyse energy demand, from energy throughput to energy services (section 3.3). By adopting these perspectives on either end of the wellbeing-energy spectrum, a "double decoupling" potential can be uncovered (section 3.4). Several methodological approaches are showcased in section 3.5 for analysing the relationship between, and decoupling of, energy services and human needs. The final section of the paper concludes and proposes directions for future research in this area.

3.2 Human well-being through a human needs lens

Defining and measuring human well-being (HW) are highly debated research areas. No single approach is likely to bring consensus: our goal in this section is simply to summarise two major schools of thought, and explain why we have selected the eudaimonic tradition as the most suitable for this research. We articulate our argument around three main points: the advantages of a eudaimonic[9] perspective in the definition of HW in relation to sustainability (section 3.2.1), the suitability of non-subjective assessments to measure HW (section 3.2.2), and the relation of human needs to HW (section 3.2.3). In this way, following O'Neill (2011, 2008a, 2006), we make the case for the superiority of the eudaimonic approach in sustainability research in general, and in relation to our specific question of energy requirements for human well-being in particular.

3.2.1 Eudaimonic and hedonic definitions of well-being

Not many would argue against policies that aim at improving human well-being. The wide range of meanings of well-being leads to confusion in research outcomes and policy implementations. Well-being is often equated to economic welfare (GDP per capita for example), it can be used to mean happiness (an individual state of mind), or it can have a more holistic meaning (like flourishing). The meaning societies give to well-being will directly influence the pathways they choose to follow in order to improve it, and these pathways will necessarily have some sort of environmental consequences. In the last centuries, improved well-being in capitalist economies has been seen through the lens of individual purchasing power rather than overall social outcomes. This is a direct consequence of a particular understanding of well-being (hedonic) and has translated into very serious environmental impacts.

Conceptualisations of well-being can be broadly categorised as either "hedonic" (pleasure-seeking) or "eudaimonic" (flourishing), reflecting their lineage back to the Greek philosophers Epicurus and Aristotle respectively (Ryan and Deci, 2001). The Hedonic school of thought sees well-being primarily as maximising pleasure (and minimising pain)

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[9] Eudaimonia is a Greek word that can be translated as "human flourishing". As Ryan et al. (2008, p. 143) explain, "eudaimonia is thus not conceived of as a mental state, a positive feeling, or a cognitive appraisal of satisfaction, but rather as a way of living."

(Dolan et al., 2006; Thompson and Marks, 2008): its principal modern representatives can be found in neoclassical economics utility theory, and in the area of subjective happiness research (Layard, 2010), whose flagship output is the World Happiness Report (Helliwell et al., 2016). It is fair to say that the hedonic school is dominant in research as well as ongoing popular and policy discourses. In contrast, the Eudaimonic school of thought sees well-being as the enabling of humans to reach their highest potential within the context of their society: it's most well-known modern representatives are Amartya Sen and Martha Nussbaum, whose capabilities approach (Nussbaum, 2015; Sen, 1999) has been implemented in the UN's Human Development Index – HDI (UNDP, 2016).

The hedonic understanding of well-being became dominant in social philosophy and economics with the development of the concept of utility by Jeremy Bentham in the 18th century – "utility is the property of any object that tends to produce the happiness or reduce the unhappiness of the party whose interest is considered" (Beckerman, 2011, p. 83). As economics developed, utility theory became grounded in a system of commensurable, continuous and transitive preferences, based on potentially infinite and insatiable individual wants (Kamenetsky, 1992). Thus utility maximisation became tightly interlinked with preference satisfaction through market consumption[10], which has two major implications: it creates an ethical void in which any consumption behaviour is justified in terms of individual well-being (Richards, 2013), and it paves the way for increased economic activity to become "the primary national policy goal in almost every country" (Costanza, 2014, p. 283).

Hedonism and its modern proponents have clear consequences for sustainability: effectively, any limits to consumption (e.g. limits on resource use, on environmental impacts or economic growth) can be immediately perceived as limits to HW from a mainstream economic perspective[11]. Many attempts to reconcile a hedonic understanding of HW with environmental sustainability result in policy instruments that are aimed at influencing individual behaviour (e.g. eco-labelling, education on energy efficiency, etc.). That is because, in a hedonic world, the path for improving an individual's well-being is psychological or cognitive: either improving a person's state of mind or changing their understanding of what contributes to well-being (i.e. their utility function) (O'Neill, 2008a; Trebeck, 2015). It is in this respect that hedonism has become especially attractive for some mainstream environmental circles: it should be possible to decouple well-being from increased consumption simply by shifting utility functions: by convincing people

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[10] The market is the institution that allows for the observation of people's choices, and therefore it is through market transactions that people's preferences are revealed.

[11] Not all economic theory understands consumption through utility maximisation. Contributions from heterodox economics that consider "systems of provision" address material and cultural elements of consumption by adopting a systemic and institutional view of the links between production and consumption (Fine, 2013).

what other elements (beyond consumption after a minimum level has been reached) are constituents of well-being (O'Neill, 2006). This viewpoint overlooks the many institutional and technological factors that lock people in certain lifestyles. In contrast, other approaches emphasise the importance of everyday social practices as key determinants of consumption patterns which are not easily changed (Røpke, 2009; Shove et al., 2008). By doing so, these approaches focus on the co-evolution of social norms and technologies, in which the role of individual choice is very limited.

Furthermore, the lack of stability in people's preferences makes hedonic well-being a poorly suited assessment of social policies. Adaptation and relativity are common criticisms of the logic of preferences (O'Neill, 2008a): The former refers to adaptation to different circumstances, whilst the latter refers to the positional relativity of an individual's self-assessment of the impact of income and material possessions on their well-being (Easterlin, 2001, 1974). This lack of stability does not allow for intercultural (or even interpersonal) comparisons, and thus makes the overall assessment of any social policy (e.g. redistributional policies) virtually impossible (Richards, 2013). Likewise, in a hedonic world, intergenerational factors cannot be considered when assessing well-being, since it is a static evaluation of an individual's particular experience(s). This is especially relevant for environmental and climate considerations, in which current actions inevitably have future impacts (O'Neill, 2008b).

In contrast, eudaimonic approaches are based on ancient Greek Hellenistic philosophers after Aristotle that aimed at describing "the good life" (*eudaimonia*) (Richards, 2013). For an individual to be well, she must be able to flourish and fully participate in her chosen form of life (Doyal and Gough, 1991). "Well-being is not just a matter of subjective experiences, it is a matter of what one can do or be in one's life" (O'Neill, 2006, p. 165). Eudaimonic well-being focuses on the individual in the broader context of her society (as opposed to atomic and isolated in time and space). Such a broadening of the unit of analysis allows for social institutions and political systems to be studied in light of their ability to enable individuals to flourish within them. Therefore, a eudaimonic understanding of well-being is better suited to address questions of sustainability and climate governance, where long term policy-making is likely to be pivotal. A similar argument can be made for the importance of intergenerational responsibilities in long term environmental sustainability. A eudaimonic view of HW allows for the inclusion in the analysis of a sense of social belonging to our community both in the past and future, hence it opens the space for intergenerational citizenship through the sharing of common projects and places (O'Neill, 2008b).

Many researchers in the field of international development have based their work on a eudaimonic understanding of well-being (see for example OPHI, 2015) (O'Neill, 2008b), focussing on multiple dimensions of poverty and its impact on social inclusion.

The emphasis on poverty alleviation leads to evidencing and reducing deprivations in specific areas considered vital for human development. Furthermore, as a result of focusing on human flourishing rather than individual preferences, eudaimonic approaches to HW have the potential to consider alternative patterns of resource use, which can be compatible with upper limits to consumption[12] (O'Neill, 2011, 2008b). Following O'Neill (2011), there are two main reasons eudaimonic well-being can address alternative levels of resource use. On the one hand, the different dimensions of HW in a eudaimonic sense (i.e. the dimensions necessary for people to flourish or to fully participate in society) can be fulfilled in many different ways, including less resource intensive ways. And on the other hand, the different dimensions of HW require different resources (including environmental quality) which are not substitutable between themselves, so that eudaimonic well-being may in itself require lower resource use. The ability to evidence profound deprivations as well as highlight alternative levels of resource use is a key strength of eudaimonic approaches, and may offer a coherent answer to recent appeals to study "sustainable consumption corridors" (Di Giulio and Fuchs, 2014).

"[… Hedonic] well-being matters, [but] it is not all that matters" (O'Neill, 2008b, p. 8). In other words, people's state of mind and feelings in a particular moment are important, however, they are not all that is important, and certainly not the most important thing to consider given the contemporary environmental crises. As Kahneman and Sudgen (2005, p. 176), advocates of hedonic well-being, recognise: "human well-being may be thought to depend […] also on other aspects of life, such as autonomy, freedom, achievement, and the development of deep interpersonal relationships, which cannot be decomposed into momentary affective experiences". In a hedonic world, these "other aspects of life" are a means to achieving positive emotions, but in a eudaimonic world they are valuable in themselves (O'Neill, 2008b), they are what societies (and physical production and consumption systems) should focus on delivering in an environmentally fragile world.

3.2.2 Classifying assessments of well-being

Unsurprisingly, given the fundamental division in philosophical viewpoints outlined above, eudaimonic and hedonic HW approaches utilise separate assessment tools and metrics, consistent with their divergent definitions of HW and consequently different research questions. In disciplinary terms, eudaimonic understandings of HW and their assessment tend to derive from international development, political economy and

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[12] Eudaimonic understandings of well-being are closer to a conception of individuals as heteronomous subjects rather than autonomous subjects (O'Neill, 2011): The former is related to concepts of dependence and vulnerability, which have been shown to be key in discussions around social justice (see for example Fineman, 2008), whilst the latter is in line with mainstream economic theory and classical liberalism.

sociology, while hedonic understandings (and assessment methods) tend to derive from mainstream economics and psychology[13]. On the one hand, international development and social science literature are trying to understand problems entrenched in societies, i.e. poverty, underdevelopment, social structures, social provisioning systems. On the other hand, economics and psychology are trying to understand the individual, because it is their main object of analysis. In this section, we clarify the consequences for assessing HW.

There are two general approaches for assessing (or measuring) HW: subjective and objective. These can be used to assess either hedonic or eudaimonic well-being. By objective methods we mean assessments made by an agent different from the subject itself and attempting to capture social arrangements. By subjective methods we mean the self-assessment of an individual's experiences. Examples of subjective and objective assessments of eudaimonic and hedonic well-being are summarised in Table 3-1 and critically discussed below in relation to their use in policy-making for sustainability.

Table 3-1. Examples of objective and subjective assessments of eudaimonic and hedonic well-being

Well-being assessment	Eudaimonic (flourishing)	Hedonic (maximising pleasure, minimising pain)
Objective	*Outcomes:* health, education, political participation, etc. *Means (satisfiers):* public expenditure budgets on health & education, available infrastructure and vital services (hospitals, schools, trained doctors and teachers, etc.). *Community participatory method:* Max-Neef's Human-Scale Development matrix of needs and satisfiers.	Income & expenditure studies (well-being as maximising utility through consumption, as making choices given budgetary constraints). Physiological measurement of emotions.
Subjective		Happiness
	Evaluative assessment (satisfaction with life)	

Source: Own elaboration.

Starting clockwise from the top-right, in hedonic well-being the most commonly used objective measurements are done through affluence or monetary wealth, based upon the link between utility and consumption discussed in the previous section. Individual income and expenditure, or GDP per capita at a more macro level are often used as proxies for HW. Stevenson and Wolfers (2008) amongst others for example, try to prove that

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[13] Of course this disciplinary categorisation is only a broad characterisation. There are some authors that come from a psychology disciplinary background that link themselves to the eudaimonic tradition of well-being, including Ryan, Deci and colleagues (Deci and Ryan, 2008; Ryan et al., 2008; Ryan and Deci, 2001), and Ryff (1989) amongst others. Additionally, Veenhoven (1991) is a sociologist as well as a key proponent of hedonic research.

income predicts hedonic well-being, measured in a subjective way. In addition to the criticisms of a hedonic understanding of HW outlined in the previous section, this assessment is particularly problematic in that it further justifies the continuous pursuit of economic growth as a main policy goal, and therefore underpins increasing global and intra-national inequalities (Piketty, 2014). Moreover, the focus on economic growth limits environmental policies to weak decoupling targets, rather than fundamental shifts in structure, scale and focus of the economy (Dietz and O'Neill, 2013). We have also included physiological measures of emotional states in this category, although we have not found much evidence of these being used in the broader well-being literature.

Stemming from psychology, subjective methods based on a hedonic understanding of HW have been used as the basis for measuring experienced utility (Kahneman et al., 1997; Kahneman and Sugden, 2005). These type of subjective self-assessments of HW (or happiness, as it is usually referred to) have been widespread and have become quite popular in policy-making (Helliwell et al., 2016; Trebeck, 2015). In contrast to income, which is theoretically unbounded, the metrics used here are generally on a bounded scale. Moreover, increases in average national income are often found not to lead to rises in subjective well-being (a phenomenon known as the Easterlin paradox (Easterlin, 1974)). Subjective well-being measures face many issues in relation to their internal logic of preferences, which was discussed above. Furthermore, the accuracy of a self-assessment of the impact of certain experience on an individual's well-being is conditioned by the narrative (or the order) of the events (O'Neill, 2006). Therefore, the suitability of these measures for long term policy-making is arguably limited.

Life satisfaction is a subjective evaluation method with both hedonic and eudaimonic aspects (e.g. using the Satisfaction With Life Scale (Dolan et al., 2006)). It is based on the notion that individuals can evaluate how their life is going in general (Dodds, 1997) rather than balance their feelings of isolated experiences (hedonic approach). These measures overcome some of the issues related to individual assessments of hedonic well-being. However, they remain ill-suited for the assessment of sustainability policies, mainly because there is no certainty as to which aspects of well-being individuals are assessing, under which criteria and in what time-scale.

Objective eudaimonic approaches have in common their insistence on multiple non-substitutable dimensions of human well-being, although they often differ on the exact dimensions or how to best measure them. The most widely known operationalization is the Human Development Index (HDI), which is based on the capabilities approach and it focuses on three dimensions of HW: education, life expectancy and income (note that in our classification, income belongs in the hedonic column). Sen was reluctant to define a set of dimensions, an exercise that was undertaken by Nussbaum[14]. Other authors have defined dimensions of HW in terms of human needs (HN) and therefore assess non-individual eudaimonic well-being in different ways (see Table 3-1 for examples). Despite the diversity of these assessments, there is great overlap and consistency in the categories (Alkire, 2002). Alkire (2002) and Kamenetsky (1992) argue that achieving well-being and satisfying human needs are the strongest source of motivation for human action, and the conceptual and empirical common ground between these approaches reinforces such argument.

The capabilities approach has been very successful in reaching world-wide policy-making through the HDI, and also in providing the basis for analytical frameworks used in development studies, which have been translated into policy strategies for poverty alleviation in several countries (OPHI, 2015), often through the lens of "multi-dimensional deprivations". The capabilities approach is measured at the individual level, which has sparked some criticisms for focusing too much on individual freedoms. For example, it has been seen as problematic in relation to current neoliberal policies: the capabilities approach can be consistent with the view of people achieving their needs individually, for instance through the market (Lamb, 2016; Navarro, 2000; Reader, 2006). However, these criticisms are open to debate, given the dependence of many capabilities on social relations and the need for collective action to build such capabilities.

In the next section we focus on non-individual assessments of eudaimonic well-being based on human needs. We argue that these approaches are particularly well suited for the assessment of how sustainably societies perform in terms of HW. Human needs introduce a normative goal of achieving minimally impaired participation in society. Therefore, the burden of (political) action shifts from the individual to all social groups (e.g. households, communities, governments, etc.) (Reader, 2006). Furthermore, they attempt to include cultural specificity and thus open decoupling possibilities, as well as avoiding paternalism.

3.2.3 The human needs approach

We have so far argued in favour of a eudaimonic understanding of HW in order to address the issue of improving people's well-being within environmental limits. Furthermore, we have discussed the different methods through which HW in these terms might be assessed, emphasizing the role of non-individual methods in encompassing crucial social factors. We now focus on the Human Needs (HN) approach (Doyal and Gough, 1991; Max-Neef, 1991), as eminently suitable to form the foundation for researching well-being within planetary boundaries. The key features of the human needs approach

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[14] Nussbaum's (2000) central human capabilities are: life; bodily health; bodily integrity; senses, thought, imagination; emotions; practical reason; affiliation; other species; play; and control over one's environment.

that single it out for this type of research are the enumeration of a finite, non-substitutable and well-defined number of human needs, and the distinction between the means employed to satisfy needs, or “satisfiers” and the needs themselves. We elaborate these points below.

The central idea of the theory of human need is that there are a finite number of self-evident (i.e. universal, recognizable by anyone), incommensurable (thus satiable, irreducible and non-substitutable) and non-hierarchical needs, which encompass the range of capabilities or dimensions of HW. It should be noted that the finite and well-defined nature of needs means they are eminently suited to empirical, quantitative research. These needs are prerequisites for living well within society: only when these are satisfied can well-being be achieved. In this sense, the conceptualisation of well-being is negative and minimalist: the goal is “minimally impaired participation in social life” (Gough, 2015). Needs themselves (the goals) are considered unchanging and universal, and that some objective harm will happen if they are not satisfied. However, human needs pose the risk of being considered paternalistic and externally imposed (although see also Nussbaum (2001) for a capabilities-related discussion of this point), which is why some authors (Guillén-Royo, 2016; Max-Neef, 1991) highlight the importance of participatory exercises in determining specific actions to achieve high levels of well-being.

For Doyal and Gough (1991) there are two basic HN categories which must be satisfied: physical health and autonomy, the latter being further divided into mental health, cognitive skills and opportunities. Furthermore, Doyal and Gough (1991) identify eleven intermediate needs (or “universal characteristics of need satisfiers” (Gough, 2015)) that typically derive in the satisfaction of their basic needs (see Figure 3-1). Similarly, Max-Neef (1991) has identified nine needs (subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom) that are expressed in four different ways: being (attributes), having (tools, norms), doing (agency) and interacting (social expressions in time and space) (see Figure 3-2).

Contrasting with the characteristics of needs (the goals), the means employed to satisfy HN are culturally, socially and temporally flexible. Max-Neef (1991) coined the term “satisfier” to describe the culturally-specific ways universal needs are fulfilled in practice. The inherent diversity of satisfiers enables the identification and comparison of radically alternative modes of social function and physical provisioning systems. The flexibility associated with satisfiers has allowed Gough and colleagues (Abu Sharkh and Gough, 2010; Gough, 1994) to assess the success of different political regimes in satisfying human needs. Alternatively, this flexibility in the satisfiers means they allow for in-depth qualitative research. Guillén-Royo (2016) has compiled contextual, conceptual and empirical aspects of the Human Scale Development (HSD) methodology developed by Max-Neef (1991), applied specifically to sustainable development. The HSD methodology is based on participatory workshops that enable communities to reflect on their own development pathways, and it will be discussed in more detail in section 3.5.

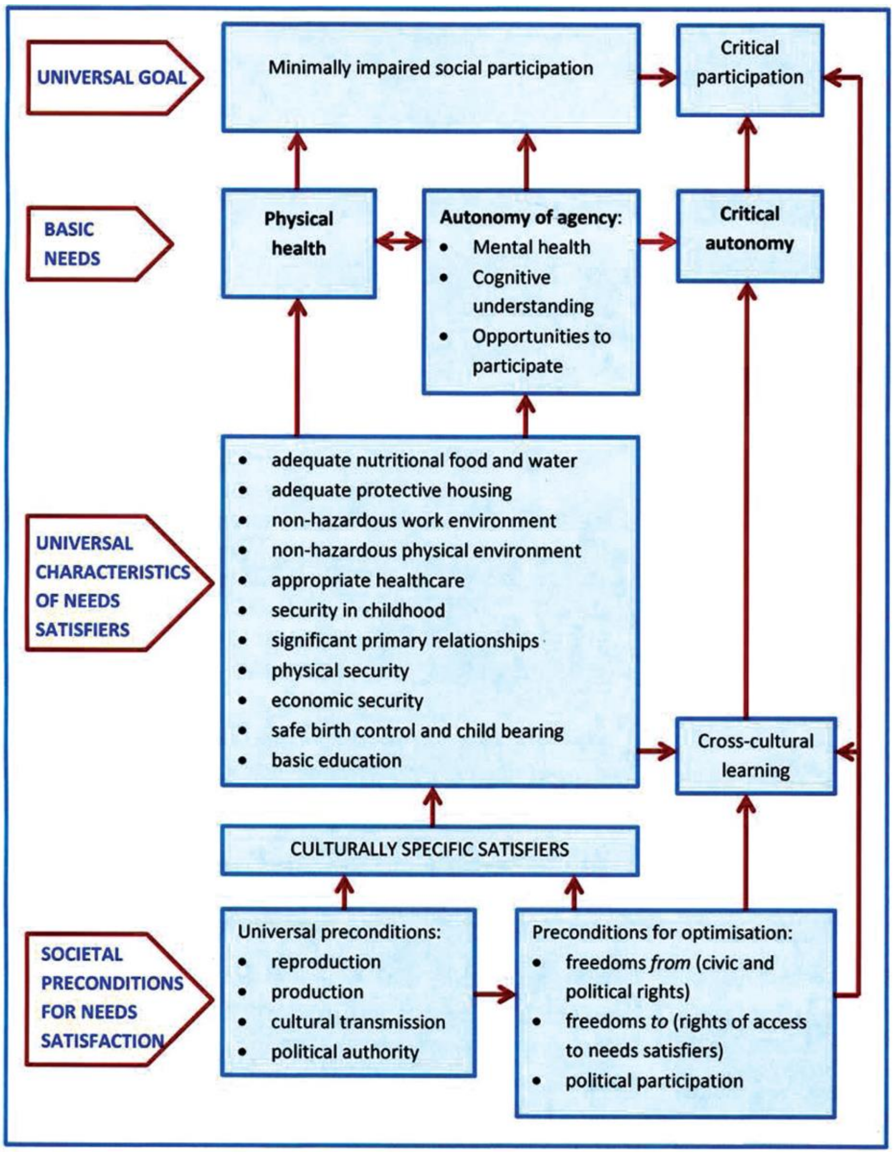

Figure 3-1. The theory of need in outline
Source: Taken from Gough (2015, p. 1196).

Finally, given that human needs are incommensurable and non-hierarchical, a loss in the level of satisfaction of one need (particularly when talking about minimum thresholds) cannot be substituted by more satisfaction of other needs (O'Neill, 2011). For instance, a loss in the level of satisfaction of the need of subsistence (e.g. in the case of malnutrition) cannot be satisfied by a gain in understanding (e.g. education), even though some satisfiers can be synergetic in the way the stimulate and contribute to the fulfilment of other needs (Max-Neef, 1991). However, the opposite is true: a gain in the level of satisfaction of one need can hinder the satisfaction of other needs. For example, the satisfaction of certain needs through environmentally harmful activities can prevent the satisfaction of other needs (Gough, 2015). In Max-Neef's (1991) work, these type of satisfiers can be classified as violators/destroyers, pseudo-satisfiers or inhibiting satisfiers. This conceptualisation enables the inclusion of environmental limits and limits to consumption and economic activity.

existential categories

axiological categories

	BEING	HAVING	DOING	INTERACTING
SUBSISTENCE				
PROTECTION				
AFFECTION				
UNDERSTANDING				
PARTICIPATION				
IDLENESS				
CREATION				
IDENTITY				
FREEDOM				

Figure 3-2. Max-Neef's matrix of human needs and satisfier categories
Source: Adapted from Max-Neef (1991).

3.3 Energy services

Within the human needs framework we have outlined above, we argue that energy services (ES) are vital "satisfiers" of human needs in many different ways: directly and indirectly, individually and synergetically, enabling and hindering. It is because of its role as "satisfier" that energy (through energy services) is a key intermediary between HW and planetary boundaries. We prefer the concept of ES for two main reasons. Firstly they are closer to satisfiers than primary, final or useful energy –ES, as opposed to Joules, are the ultimate reason why we demand energy. However, there are several challenges regarding their classification and measurement (section 3.3.1). Secondly because ES allow for the inclusion of additional efficiency improvement avenues that could result in decoupling of energy use from HW (section 3.3.2). We elaborate on these arguments below.

3.3.1 The energy "chain"

Within traditional energy analysis, there are three main links in the "energy chain" of energy flows: primary energy, final energy and useful energy (Grubler et al., 2012;

Jochem et al., 2000) (see Figure 3-3). Energy balances[15] report primary and final energy flows through the economy, but not useful energy flows. Primary energy generally refers to the energy extracted or captured from the natural environment (e.g. crude oil, coal, hydropower, etc.) (IEA, 2005). Final energy (also called secondary energy) generally refers to energy as it is delivered to the final economic consumer, after undergoing transportation and transformation processes (e.g. gasoline, diesel, electricity, etc.) (IEA, 2005). The majority of studies within traditional energy analysis[16] focus either on primary or final energy, both of which fall short in their relation to the exact purpose of energy use.

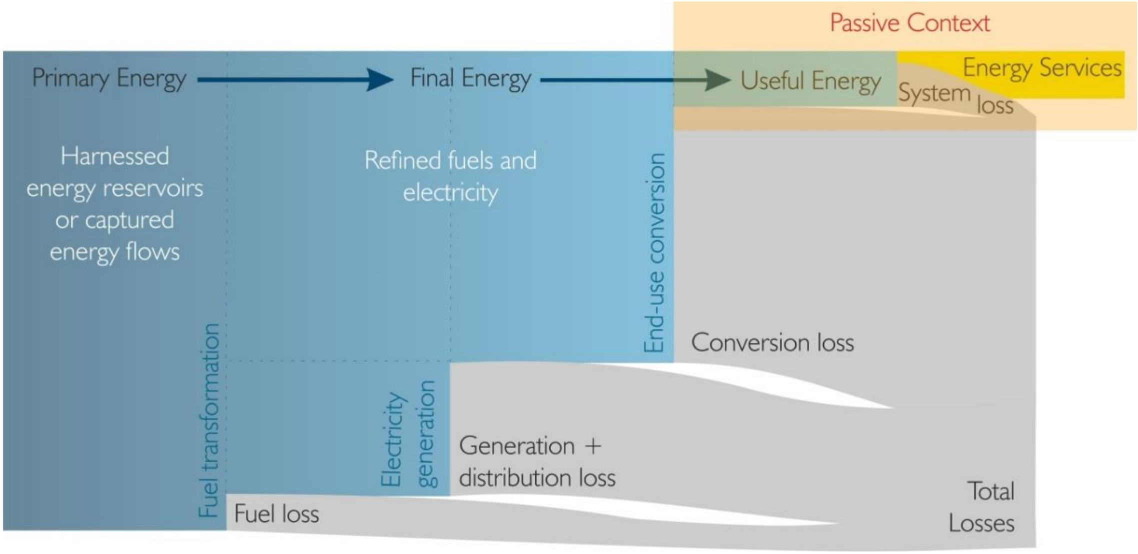

Figure 3-3. Energy chain from primary energy to energy services
Blue flows indicate energy units, whereas ES are measured in different units.
Source: Adapted from Cullen and Allwood (2010a).

At the point of use, final energy undergoes one last transformation process as it passes through an end-use conversion device, for example furnaces, electric appliances or light bulbs. End-use devices transform energy into a form that is useful for human purposes, hence the term “useful energy” as the outcome of this last conversion process. The types of useful energy are usually classified into heat (low, medium or high temperature), mechanical drive, light, electricity for appliances, and food (Brockway et al., 2014). Few analyses focus on this part of the energy chain, with an exception being a

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[15] Energy balances (derived from energy statistics) are provided by statistical agencies and research institutes, such as the IEA (2012b, 2008), the EIA (2014) and IIASA (2012). Commonly used energy balances are derived from internationally agreed standards that are congruent with economic statistics (UNSD, 2014). Additionally, they focus on specific types of energy: technical energy used in industrial supply chains and markets. As a result, they omit biomass used for food or fodder, as well as non-industrial processes, such as work done by draft animals or manual labour (Haberl, 2001). This may prevent a holistic view of the energy in society, particularly of food-fuel trade-offs (Haberl et al., 2011).

[16] Within other fields, particularly energy poverty, there is more of a focus towards energy services. See for example Nussbaumer et al. (2012) and Kaygusuz (2011).

growing amount of literature that comes from an exergy[17] perspective (Ayres et al., 2003; Brockway et al., 2015; Chen and Chen, 2009; Ertesvag, 2005; Nakićenović et al., 1996; Serrenho et al., 2012; Wall, 1990).

The final conversion step occurs within what Cullen et al. (2011) term a “passive system” (shown in Figure 3-3 as passive context). Within passive systems no more conversion processes occur, only energy dissipation given the irreversibility of the second law of thermodynamics. Thus “a passive [system] can be thought of as a reservoir or tank of stored energy” (Cullen et al., 2011, p. 1712). Cullen and Allwood (2010a) identified three basic passive contexts: vehicles (for example cars, trains and airplanes), factories (within them the passive systems are the different machines and furnaces) and buildings for commercial and residential use (they themselves can be passive systems for heating and lighting, and the different appliances within them are also passive systems). Within a passive system, useful energy delivers ES (Jochem et al., 2000).

ES constitute the last part of the energy chain and are therefore the ultimate “reason” why energy supply chains exist. In relation to the satisfaction of HN, individuals use ES as satisfiers, not Joules of primary, final or useful energy. This makes ES the crucial concept to analyse when examining the relationship between energy systems and HW (Day et al., 2016). Therefore, ES are in themselves recognised as important for human development (Kaygusuz, 2012; Modi et al., 2005) whilst the specific technical provisioning systems can be seen as culturally specific. Cullen and Allwood (2010a) identified eight final services that can be measured using physical data and that are a small number of distinct but comparable categories: passenger transport, freight transport, structure, sustenance, hygiene, thermal comfort, communication and illumination[18].

However, ES present significant challenges in terms of their measurement. They are each measured in units different from conventional energy units, which vary greatly between them but also depending on the author. Some examples are various physical quantities (i.e. passenger-km, Joules, m^3K, bytes, lumens/s) (Cullen and Allwood, 2010a, 2010b; Fouquet, 2014; Fouquet and Pearson, 2006; Knoeri et al., 2015); abstract energy service units (Haas et al., 2008); and units of heat or work (Sovacool, 2011). This variety of

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[17] Exergy can be defined as “the maximum possible work that may be obtained from a system by bringing it to the equilibrium in a process with reference surroundings” (Kostic, 2012, p. 816). As Gaggioli & Wepfer (1980, p. 823) state, exergy “is synonymous with what the layman calls ‘energy’. It is exergy, not energy, that is the resource of value, and it this commodity, that ‘fuels’ processes, which the layman is willing to pay for”. For further details on exergy see Wall (2003, 1986, 1977), Kanoglu et al. (2012), Dincer (2002), Rosen (2006, 2002), Sciubba and Wall (2007).

[18] Note that their list of ES does not include materials or goods and services with embodied energy, but rather the useful property of finished materials. Therefore, Cullen and Allwood’s classification of ES seems more appropriate in relation to human needs than the ones proposed by Haas et al (2008) and Sovacool (2011), which lack clear system boundaries.

units makes aggregation and comparability a difficult task (Roelich et al., 2015). Therefore, in terms of measurement, useful energy is the last part of the energy chain that can be measured in energy units, and therefore the closest concept to ES that can be aggregated and calculated (relatively) straightforward, using data from energy balances.

3.3.2 Efficiency in energy service delivery

ES are a set of limited ends which people demand from energy, but the way they are delivered varies greatly between societies and over time. This is similar to the universality of HN and the cultural specificity of satisfiers. A wider picture of potential efficiency improvement avenues appears by acknowledging this multiplicity of ES delivery possibilities. This in turn allows for possibilities of decoupling energy use from HW, i.e. less energy use in the primary or final stages of the energy chain for the same ES delivery.

There are four different approaches to energy efficiency measures in the delivery of ES, as outlined by Marshall et al. (2016): conversion device, passive system, service control and service demand level. Distinguishing between the four approaches allows for a better picture of potential efficiency improvements. Between each of the links of the described energy chain (primary, final and useful energy) conversion processes occur, and hence there are possibilities for technical efficiency improvements in the conversion devices (Summers, 1971). However, these are limited by the laws of thermodynamics. Improvements in passive systems are usually related to larger infrastructure investments and can provide clear long-term benefits (Knoeri et al., 2015; Roelich et al., 2015). However, changes in either of these may be hampered by lock-in phenomena (Unruh, 2000) and broader social and technical considerations. Service control is an alternative for optimizing energy service delivery when is needed only, e.g. programmable heating controls and motion-sensitive lighting (Marshall et al., 2016).

Finally, and potentially most interesting, service level efficiency measures imply a change in the nature or the level of the service required (Nakićenović and Grubler, 1993). Haas et al. (2008) refer to these as short term components of energy service demand, related to behavioural or cultural aspects. For private vehicle passenger transport for example, car sharing is a change in the nature of the energy service, or driving less is a change in the demand level of the energy service. However, these service level measures are limited by larger systemic aspects, such as transport infrastructure, population density, and quality of public transport, which Haas et al. (2008) refer to as long term components of energy service demand. Similarly, Day et al. (2016) have identified different points along the energy chain where interventions can be made to alleviate energy poverty using a capabilities framework.

For improving HW while reducing environmental impacts, understanding the relationship between ES and HN could allow the prioritisation of policy interventions on the most appropriate energy efficiency measures in the delivery of ES. For example in the case of transport (Mattioli, 2016) - if the delivery of transportation as an ES is found to be highly important for the satisfaction of health as a HN (by providing access to medical facilities), decision makers could decide whether to focus efforts on improving the efficiency of engines (conversion device), lightweighting the friction of cars and buses (passive system), traffic control measures (service control), or localised clinics or telemedicine[19] (service demand level through a change in the nature of the service provided).

3.4 Uncovering potential for double decoupling between well-being and energy use: the analytical framework

Our current context of environmental degradation and climate change, coupled with deep social deprivations, calls for "a profound shift […] in our intellectual approach to complex social problems" (Lamb, 2016, p. 185). Our analytical framework builds upon established, but disconnected, areas of research. On the one hand, it approaches well-being through the lens of eudaimonia in general and human needs in particular, as described in section 3.2. On the other hand, the framework focuses on energy requirements, analysed through the lens of energy services, as described in section 3.3. These approaches allow for robust (clear definitions)[20], empirical (quantifiable metrics)[21] and systemic (holistic) analysis, which enables the study of decoupling human needs from energy use: both through the open nature of need "satisfiers" (Guillén-Royo, 2016) and the large efficiency potential in energy service delivery (Cullen et al., 2011). In particular, the flexible nature of the "satisfiers" concept (secondary capabilities in Day et al.'s (2016) framework) lends itself to holistic analysis of the factors that influence the energy demand associated with the achievement of well-being, and thus the possibilities for their decoupling. Likewise, the flexibility associated with the energy services provisioning

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[19] Telemedicine is the "delivery of health care services […] using information and communication technologies". (World Health Organization Global Observatory for eHealth, 2010, p. 9)

[20] The approaches described in sections 2 and 3 are robust in terms of making a clear distinction between human needs (universal) and satisfiers (culturally and historically specific) on the one hand, and energy use and energy services on the other, This robustness allows to keep a clear conceptual understanding of where the decoupling opportunities might lie.

[21] Given the great variability of satisfiers and ways of delivering energy services means that the empirical task of finding quantifiable metrics is a complex one, with many assumptions to be made along the way, which should be clearly described in any empirical applications of this framework.

alternatives opens up additional avenues of efficiency improvements, and thus possibilities for decoupling energy services demand and primary energy supply.

The abovementioned flexibility of both "satisfiers" and provisioning of ES (social and physical "provisioning systems" respectively) is the key element of this analytical framework (see Figure 3-4). Day et al. (2016) refer to these decoupling opportunities as the different areas where to intervene for energy poverty alleviation. As shown in Figure 3-4, physical provisioning systems allow for example the analysis of physical characteristics (e.g. infrastructure) and the effect of different technologies (e.g. lock-in) on the specific energy service provisioning alternatives that a particular society has. In the same way, social provisioning systems allow for the analysis of social and cultural aspects (e.g. everyday practices and norms), economic institutions (e.g. market logics) and socio-political institutions (e.g. the role of the State) in relation to the specific human needs "satisfiers" that a society uses. This framework also enables the analysis of the spaces where these "systemic factors" overlap.

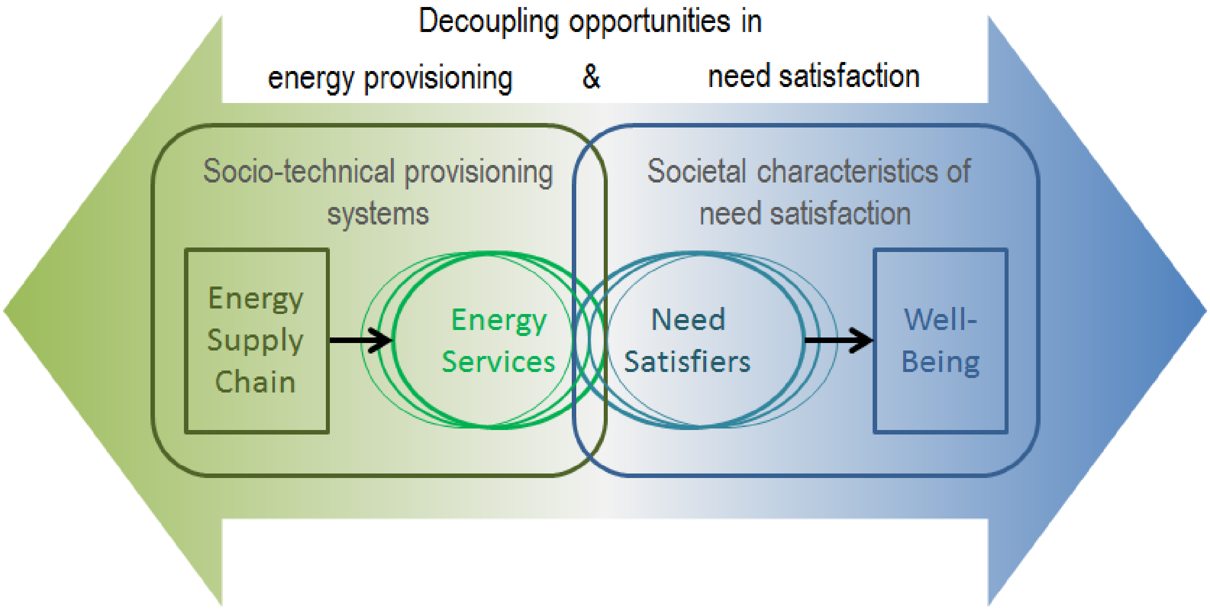

Figure 3-4. Analytical framework for studying the interdependency of energy and well-being
Source: Own elaboration.

A systemic analysis of this kind has the potential of bridging areas of research that have studied environmental and social problems in a disconnected way. For example, theory of practices (Shove et al., 2008; Shove and Walker, 2010) and systems of provision (Bayliss et al., 2013; Fine, 2013), together with technological lock-in analysis (Unruh, 2000), can be used to explain the choice of certain "satisfiers" and energy service provisioning alternatives. More importantly, however, are the decoupling alternatives that this analytic framework allows us to identify. The framework enables empirical research to go beyond the limitations of narrow approaches such as technical energy efficiency improvements (IEA, 2008) or economic incentives (OECD, 2011; UNEP, 2011).

Indeed some of the most important decoupling opportunities are likely to be found at the community level, for example economies of scale through provision of efficient networks of energy service delivery (Knoeri et al., 2015). The existence of collective supply systems (e.g. local supply networks or public transit) may enable economies of scale, in contrast with highly individualised systems, where each household has to use its own forms of energy to procure goods and services. In such cases, the description of alternatives through technologies or markets only is overly simplistic, since the appropriate unit of analysis is not the single actor using the technology, but instead the community or other larger unit making the decisions which enable individuals within it to use more or less energy to satisfy their needs.

3.5 Connecting energy services and human needs: the empirical framework

In this section, we propose a mixed-methods approach to implement empirically our analytical framework described above. The quantitative and qualitative methods described below have been used in the past, but in different contexts, and not in conjunction with each other. Past studies have aimed to relate energy and HW using, for example, total primary energy supply, final energy consumption or CO_2 emissions[22]; and life expectancy or the human development index. Hence, to the best of our knowledge, the links between energy services and human needs specifically have not been analysed. We consider this analysis to be very important given the potential advantages of using these particular concepts in the context of achieving well-being within planetary boundaries, as described in the previous sections.

3.5.1 Quantitative methods

A family of previous studies have focused on methods to relate energy and well-being that share a macro-level and often international scope. Their approach is top-down, observing larger systems, such as countries or regions within countries, in order to estimate their performance in terms of delivering well-being outcomes (human need satisfaction) at varying levels of environmental impact or energy use (see for example Alam et al., 1998; Dias et al., 2006; Dietz et al., 2012, 2009; Knight and Rosa, 2011; Lamb and Rao, 2015; Martínez and Ebenhack, 2008; Pretty, 2013; Rao et al., 2014; Smil, 2003; Steinberger

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[22] Given the current fossil fuel dependency of the global energy system, energy and CO_2 emissions are closely correlated, and therefore can be considered proxies.

et al., 2012; Steinberger and Roberts, 2010). This means they take macro (country) level variables and use statistical techniques to relate energy and HW, as well as finding a threshold level after which increases in the energy variable translate into only marginal (or none at all) increases in well-being. A caveat with these approaches is that they use national averages rather than distributions, and every country will have residents that use far more than they need from a sufficiency well-being perspective, as well as residents who have far too little. Nevertheless, these methods highlight what is currently possible, given the existence of large distributional disparities within countries.

Another family of previous studies has used methods that start bottom-up from a list of requirements for well-being (satisfiers) for an average household, and translates these into energy requirements (see for example Goldemberg et al., 1985; Zhu and Pan, 2007). A more recent study is the one undertaken by Rao and Baer (2012), which uses as a starting point the establishment of a bundle of minimum goods and services to achieve HW based on the "basic goods" work of Reinert (2011). The energy and carbon emissions embodied in that bundle are then estimated, thus finding an energy threshold or carbon entitlements. Rao and Baer (2012) propose to use Environmentally-Extended Input-Output data to implement this methodology, which is an established technique to calculate direct and indirect household energy use (Pachauri, 2007).

Both bottom-up and top-down approaches can be adapted to study the energy service requirements of well-being within the framework shown in Figure 3-4. However, the emphasis should remain upon gaining a deeper understanding of social and physical provisioning systems which underpin the relations between energy use and well-being. This can be done by including parameters which are characteristics of social and physical provisioning: such as infrastructure networks and access and human settlement characteristics for physical provisioning, and government and institutional quality, welfare regimes, equity, political and cultural participation for social provisioning.

Most of the energy-for-well-being research and methods we have described above have a lineage in energy-for-economic-activity: they are generally very aggregate and quantitatively focused, with little consideration given to individual, household or community specificities. As we have discussed, universal human needs may rely on a large diversity of "satisfiers" in practice, and this diversity should be reflected in the type and level of energy services relied upon. Therefore, we propose to use household surveys micro-data where possible, which contains information that can be used as proxies for ES and HN. This data is usually collected at the national level, but it has the potential for differentiated analysis at regional, income or other socio-demographic levels.

3.5.2 Qualitative methods

In order to capture the diversity of satisfiers used by a specific society, we propose complementing the quantitative method described above with a new qualitative approach, drawn from the Human Scale Development work of Manfred Max-Neef and his colleagues (Guillén-Royo, 2016; Max-Neef, 1991), as well as Oxfam's Humankind Index project in the United Kingdom (Dunlop et al., 2012). This approach uses participatory methods (consultations, workshops, focus groups) to explore the forms that need satisfiers or well-being dimensions take within a community.

This method must to be adapted and targeted in order to pinpoint not just the specific forms of need satisfiers, but the energy services underpinning them (especially challenging given the opaque nature of energy supply to consumers (Attari, 2010; Stern, 2014)). The energy service approach may be of great assistance here, since energy services are typically more meaningful to end-users than energy units themselves. The findings from the participatory research could then be translated into energy service levels and energy requirements depending on the national or regional infrastructure. We anticipate this approach to be extremely fruitful for the following reasons: first, it fully opens the "black box" connecting energy and human needs, since it relies on direct and in depth consultation with the people most concerned; and second, it has the potential to expose a great diversity of energy and energy service requirements of need satisfaction across different communities and social configurations. Both of these are extremely important in enabling the findings of this research to guide policies to low-energy delivery of HW.

3.6 Concluding remarks

Overcoming the pressing challenge of achieving universal human well-being within environmental limits is the motivation behind this paper. In order to do so, we propose an analytic framework that views human well-being through the lens of human needs and analyses energy demand through the lens of energy services. Human needs are universal social ends, which are satisfied or provisioned by culturally specific means. Their universality is important in terms of comparability between different societies, and their flexibility (cultural specificity) provides richness for a systemic analysis of sustainable alternatives. Societies demand energy at different levels as a means to satisfy their needs, and by analysing energy demand from an energy services perspective, we open up new pathways for the exploration of efficiency improvement alternatives, including in terms of social and physical provisioning systems.

Our conceptual approach is normative in that it seeks to identify what must be morally met (human needs), but it is not paternalistic in defining how they should be met (satisfiers) and by whom. Our empirical framework aims to identify alternative ways in which societies use energy to satisfy their needs and analyse them in terms of their environmental impact. This mixed-methods framework will provide insights on the cultural particularities of how different ways of delivering energy services are being used as human needs satisfiers, and on which systemic factors are influencing the choices of human needs satisfiers and energy services provisioning alternatives. Analysing the evidence in light of these systemic factors and cultural specificities would allow for the provision of much needed context-specific policy recommendations for the improvement of human well-being within environmental limits.

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Chapter 4

Human Scale Energy Services: Untangling a ‘Golden Thread’

L. I. Brand-Correa, J. Martin-Ortega and J.K. Steinberger

Abstract

Prioritising human well-being while avoiding further damage to the planet is a key challenge in the era of climate change. This paper examines the role of energy as an intermediary between climate change and socio-economic outcomes, with the ultimate goal of identifying ways of decoupling human well-being from energy use. Building on Max-Neef’s “Human Scale Development” framework and conceptualisation of human needs, we propose a novel community-level participatory approach to identify connections between energy services on the one hand and human need satisfaction on the other. This approach then enables communities to collectively consider and propose alternative ways to provide energy services. We compare the outcomes and reflect on the process of two exploratory workshops, undertaken in an urban and a rural area in Medellín (Colombia). Our results indicate that these communities view energy services as satisfiers of human needs, with significant differences between the communities. Furthermore, our approach enables the communities to broaden the solution space of energy service provisioning possibilities, thus constituting a promising alternative to the top-down technocratic perspectives currently prevalent in research and policy. We argue that this type of bottom-up approach is necessary to address the complex sustainability challenge of living well within environmental limits.

Key words

community; efficiency; energy use; participatory.

4.1 Introduction

Climate change poses great challenges to societies, chief amongst which is to preserve human well-being while avoiding durable harm to the planet's life support systems. These challenges are arguably greater for developing societies, which have yet to satisfy the basic needs of their growing populations. The poorest within these populations are likely to suffer the most adverse environmental consequences as a result of the multidimensional inequalities they face (IPCC, 2014). In this context, energy use is the key intermediary between environmental impacts and socio-economic outcomes. The UN's former Secretary-General Ban Ki-Moon described this crucial role of energy, when he stated that "Energy is the 'Golden Thread' that connects economic growth, social equity and environmental sustainability"[23]. The connection between energy and environmental sustainability is widely understood, and there is also a large body of literature concerned with the connection between energy and economic activity. However, the direct link between human well-being and energy use is much less studied.

We argue that the 'Golden Thread' that weaves through to human well-being is not energy (measured in physical units, e.g. kWh or joules), but rather *energy services* (for instance illumination, thermal comfort, mobility). Energy services, rather than energy itself, are what people demand (Haas et al., 2008), the benefits humans derive from energy carriers (Modi, McDade, Lallement, & Saghir, 2005), what contributes to people's well-being (Brand-Correa & Steinberger, 2017). This research aims to further investigate the connection between energy services and well-being, and to elicit bottom-up proposals of alternative energy service provision. These new proposals may inform the decoupling of energy use from human well-being, with the ultimate goal of achieving high levels of human well-being within planetary boundaries (Raworth, 2017; Rockström, et al., 2009; Steffen et al., 2015).

In this paper, we develop, test and demonstrate a community-level participatory approach, adapted from the Human Scale Development framework of Max-Neef (1991). This approach is based on human needs theories (Doyal & Gough, 1991; Max-Neef, 1991). In contrast with subjective and individualistic understandings of well-being, human needs consist of a finite, objective and universally comparable list of social pre-conditions for a "good life". In human needs theories, the focus is on the means employed to satisfy human needs: these means, called "satisfiers", are context-specific, and change according to time, place, culture, technology and so on (Doyal & Gough, 1991; Max-Neef, 1991). This specificity lends itself well to be studied at the community level (Max-Neef, 1991), where specific satisfier configurations are grounded.

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[23] http://www.un.org/press/en/2012/sgsm14242.doc.htm

Two communities, one rural and one urban, in the municipality of Medellín (Colombia) were selected as case study locations for our research. During the workshops, we first elicit the community’s views on the interrelations between energy services and human needs. We then build on these interrelations, opening up the discussion to generate alternative possibilities to satisfy human needs through energy services within each community. These community-based alternatives could eventually enable the decoupling of energy use and human well-being. In other words, the proposed approach is designed to lead to different ways of thinking of provisioning energy services in order to satisfy human needs. Furthermore, participation can be empowering for the communities involved through collective co-construction of knowledge (Guillén-Royo, 2016; Hammett, Twyman, & Graham, 2014; Max-Neef, 1991; Skovdal & Cornish, 2015). Hence the value of this research resides not only in its specific results, but also in its participatory process (which has been previously recognised as important in relation to energy research (Walker, Simcock, & Day, 2016)). This process can enable awareness building and self-reliant community action (Guillén-Royo, 2016; Max-Neef, 1991).

4.2 Literature and conceptual background

4.2.1 Previous research

The connection of Ban Ki Moon’s ‘Golden Thread’ of energy to environmental sustainability is widely understood (IEA, 2012; IPCC, 2013). The energy sector has historically been responsible for around two thirds of global greenhouse gas emissions (IEA, 2015), leading to policy promotion of renewable energy, energy efficiency and carbon capture and storage as the main part of national and international commitments to reduce greenhouse gas emissions (Rogelj et al., 2015). Additionally, a large body of research exists on the relationship between energy and the economy, including debates around the causality between energy (primary or final) and economic growth (Bruns, Gross, & Stern, 2014; Ozturk, 2010). An emerging consensus is that useful energy (a category that is much closer to energy services) has been shown to be vital for economic growth (Ayres & Voudouris, 2014; Cleveland et al., 1984; Cleveland, Kaufmann, & Stern, 2000; Stern, 2011; Stern & Kander, 2012; Warr et al., 2010).

The direct link between human well-being and energy use has been less studied, arguably because the focus of energy studies has traditionally been economic or technical, rather than social. Some exceptions can be found in quantitative research that has been carried out around the relationship between energy use (and ensuing fossil emissions) and human well-being at a national level (Goldemberg et al., 1985; Jorgenson, 2014; Lamb et al., 2014; Lamb & Rao, 2015; Martínez & Ebenhack, 2008; Mazur & Rosa, 1974; Rao, Riahi,

& Grubler, 2014; Steinberger & Roberts, 2010; Steinberger et al., 2012). These aggregate levels of analysis, however, fail to uncover the detailed linkages between specific types of energy use and social progress, as well as specific challenges faced by different communities, and thus are limited in their ability to inform directions for decoupling energy and human well-being. We thus agree with the perspective that participatory approaches are promising alternatives to mainstream top-down technocratic models to understanding energy use, and are especially well-suited to study its link to human well-being (Lamb & Steinberger, 2017; Rao & Baer, 2012).

There exists a significant body of research around energy poverty and energy vulnerability, particularly focused on the UK and Europe (Bouzarovski, Petrova, & Tirado Herrero, 2014; Day, Walker, & Simcock, 2016; Middlemiss & Gillard, 2015). In general, this research focuses on the lived experience of people in situations of fuel poverty (a more disaggregate level of analysis), and critically analyses the role of top-down policies in alleviating or aggravating such situations. In developing contexts, the focus has been mainly around the health impacts of energy provisioning (Bruce, Perez-Padilla, & Albalak, 2000; Wilkinson et al., 2007), and the poverty and equity effects of access to energy in general (Karekezi et al., 2012) and electricity in particular (Attigah & Mayer-Tasch, 2013; Pueyo & Hanna, 2015). At the household level there is also a body of literature assessing the energy requirements of households at different levels of income or through time (Druckman & Jackson, 2010; Lettenmeier et al., 2014; Pachauri, 2007). However, these fail to link energy to human well-being, that is, they do not explore the reasons why people use energy, or the benefits they might gain from it. Notable exceptions are the work of Rao and colleagues, which has an explicit “decent life” lens (Rao & Baer, 2012; Rao & Min, 2017), as well as the conceptual work of Day et al. (2016) and Brand-Correa & Steinberger (2017).

Thus, the relationship between energy and human well-being at the community level is still largely unexplored. We argue that this level of analysis is vital for answering questions around the cultural specificities of energy services as “satisfiers” of human needs, as well as for understanding the diversity of configurations in which energy services can satisfy human needs. Clear concepts are a necessary basis upon which to structure our analysis. Therefore, we now briefly outline our conceptual choices and the reasons why we believe they are conducive to our research goals.

4.2.2 Energy use through the lens of energy services (ES)

It is not raw energy sources (primary energy) or even fuels and electricity (final energy) which connect energy to human well-being, but rather the *services* that we obtain from energy. If energy is a “golden thread” linking social outcomes and sustainability, it is really energy services that weave through to human well-being. A precise definition of energy services (ES) has proved elusive. Fell (2017) condenses the meaning of the term in previous research under the following definition: “energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states”. Following Cullen and Allwood (2010), the ES (functions) that we used here are: illumination, heating, cooling, mechanical work, structure, food, information and communication, and mobility.

Cullen and Allwood’s (2010) categorisation stemmed from an attempt to map global energy flows from primary energy to energy services, in order to identify the aggregate potential of efficiency improvements, particularly at the “passive system” level (Cullen, Allwood, & Borgstein, 2011). We found this categorisation, which is largely consistent with others (Fouquet, 2014; Haas et al., 2008; Jochem et al., 2000; Modi et al., 2005; Nakićenović & Grubler, 1993; Sovacool, 2011), a comprehensive starting point at the level of global energy uses.

We then adapted their categorisation for our purposes, to make it consistent with the concept of “satisfiers” (see section 4.2.3) and to allow communities to explore energy services in the most abstract way possible. From Cullen and Allwood we kept the following categories: structure, (information and) communication, sustenance (renamed as “food”), “hygiene” (renamed “mechanical work”) and illumination. We removed the service of “freight transport” and included it, together with passenger transport, in the broader category of “mobility”. Finally, we separated “thermal comfort” into “heating” and “cooling”, in order to clearly elucidate differences in climatic conditions.

We argue in favour of the concept of ES, in relation to human well-being and in the context of environmental degradation, for two main reasons (with more detail in Brand-Correa and Steinberger (2017)). Firstly, energy is an invisible entity and a complex concept, whilst ES are tangible and relatable in terms of day-to-day activities. Therefore, ES can be connected to need satisfaction. Secondly, by analysing energy through an ES lens, additional efficiency improvement possibilities can be introduced, particularly in terms of passive systems and service level measures (Cullen et al., 2011; Marshall et al., 2016). These additional efficiency improvement possibilities can be translated into decoupling (i.e. less energy use (primary or final) for the same level of ES), which is key for sustainability.

4.2.3 Human well-being through the lens of human needs (HN)

The human needs (HN) understanding of well-being stems from the philosophical tradition of Eudaimonia, as opposed to Hedonism (for a more detailed conceptual description of these two traditions see Brand-Correa and Steinberger (2017)). Eudaimonia relates to the process of living well (O’Neill, 2006), of flourishing (M. Nussbaum, 2003; Sen, 1999), of being able to fully participate in society (Doyal & Gough, 1991). This is necessarily a social process that occurs over time (O'Neill, 2008), hence long-term sustainability is particularly relevant to achieving well-being.

HN are the preconditions necessary to achieve well-being in a eudaimonic sense. They are the basic requirements for people to be able to live well in society. Authors that address HN generally propose a finite list, highlighting a key difference from infinite wants (or preferences). Furthermore, needs are "self-evident (i.e. universal, recognizable by anyone), incommensurable (thus satiable, irreducible and non-substitutable) and non-hierarchical" (Brand-Correa & Steinberger, 2017).

There exist specific lists of needs developed by different authors, which have been determined in diverse ways[24]. Despite these divergences, Alkire (2002) and Lamb & Steinberger (2017) argue that the lists tend to converge around common dimensions. We have chosen to use here Max-Neef's (1991) Human Scale Development classification of HN (subsistence, protection, affection, understanding, participation, idleness, creation, identity and freedom), mainly because the participatory methodology associated with his theoretical construction. We expand on Max-Neef's methodological approach in the next section.

A HN understanding of well-being is most relevant for analysing sustainability (O'Neill, 2008). The universality of HN enables comparison between societies or communities, which is important when conducting empirical research. HN have a claim to strong sustainability; since they are non-substitutable and non-hierarchical, there is no possibility of improving or prioritising the fulfilment of one human need to the detriment of another (e.g. you cannot substitute ill health due to air pollution by improving your level of education). And, in contrast with the infinite wants and desires posited by neoclassical economics, HN are satiable.

Another important characteristic of HN is that there is a clear distinction between needs and "satisfiers" (Doyal & Gough, 1991; Max-Neef, 1991), between basic capabilities and specific functionings (Sen, 1999). Thus, the HN approach takes into account the different contexts and cultural specificities of the communities. The exploration of satisfiers furthers expands the analytic space to seek more sustainable ways of fulfilling HN.

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[24] For example, Doyal and Gough (1991) used the best scientific knowledge available (from both natural and social sciences) to determine their eleven intermediate needs. Nussbaum (2000) and Max-Neef (1991) determined their ten capabilities and nine needs respectively based on theories of justice and freedom, which also played a part in Doyal and Gough´s (1991) selection of two basic needs.

4.3 Methodology

4.3.1 Max-Neef’s Human-Scale Development (HSD) needs and satisfiers approach

Max-Neef’s approach to understand needs and satisfiers was initially intended to help grassroots movements in the 80s and 90s, particularly in Latin America, to take development issues into their own hands, and to break with the tradition of failed top-down development strategies in the continent (Guillén-Royo, 2016). This workshop-based approach was a tool to support participatory processes within communities, leading both to greater awareness of development challenges, and towards building self-reliance and improving human need satisfaction (Cruz, Stahel, & Max-Neef, 2009). Since then, Max-Neef’s Human Scale Development (HSD) approach has been widely used and adapted by researchers and practitioners of community-level sustainable development (Guillén-Royo, 2016).

Max-Neef’s (1991) HSD approach centres on a matrix of nine *axiological categories* (or HN) on the vertical axis (see section 4.2.3) and four *existential categories* on the horizontal axis. The latter are ‘being’ (personal or collective attributes), ‘having’ (institutions, norms, mechanisms, tools), ‘doing’ (personal or collective actions) and ‘interacting’ (spaces or atmospheres). During successive workshops the matrix would be filled with different types of satisfiers, which can be characterised in relation to whether they impede (destructive, inhibiting and pseudo satisfiers) or promote (singular and *synergetic*[25] satisfiers) human need fulfilment, or whether they are top-down (exogenous) or bottom-up (endogenous) in their conception and implementation (Max-Neef, 1991). This whole process empowers communities by enabling them to form a holistic view of their human need satisfaction and potential alternatives (Cruz et al., 2009; Guillén-Royo, 2016; Jolibert, Paavola, & Rauschmayer, 2014). Hence, we considered Max-Neef’s HSD approach to hold great promise for addressing the question of the link between ES and HN, and alternative ways of using ES as satisfiers.

A holistic view of human need satisfaction alternatives goes beyond market-based provision (having) and empowers communities to act where they can, thus improving their self-reliance (Guillén-Royo, 2016). For example, in the case of people facing unemployment and economic deprivation, the HSD approach allowed the community of Granada to think beyond the desire of “having” job creation as a main policy goal, and enabled them to see the interdependence of other social and environmental initiatives when it came to need satisfaction (e.g. empowering workers, citizen participation and

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[25] *Synergetic satisfiers* “are those which, by the way in which they satisfy a given need, stimulate and contribute to the simultaneous satisfaction of other needs” (Cruz et al., 2009, p. 2024).

urban gardening) (Guillen-Royo, Guardiola, & Garcia-Quero, 2017). Therefore, we argue that the potential that Max-Neef's approach presents, in terms of revealing broad interdependencies between different satisfiers and needs, can be adapted to search for a systemic view of the relationship between ES and HN. We describe our adapted approach below.

4.3.2 Human Scale Energy Services (HUSES): an adaptation of Max-Neef's HSD approach

We adapted Max-Neef's HSD framework of HN and satisfiers to explore the connections between well-being and energy use. We have called this adaptation HUSES (Human Scale Energy Services). We elicited connections between Max-Neef's nine axiological categories of HN (see section 4.2.3) and eight types of ES (see section 4.2.2). Moreover, we used Max-Neef's existential categories (see section 4.3.1) in order to enable the communities to think holistically about alternative strategies to provide an improved level of a selected energy service. The diagram in Figure 4-1 shows how the workshop parts described below relate to Max-Neef's original matrix.

Next we present a summary of the adapted workshop structure used in this research (a more detailed workshop structure can be found in the supplementary information). This workshop structure was established after a piloting phase taking place in the UK but in Spanish with a combination of Spanish and Latin American participants. The piloting led to improvements in the workshop design and terminology employed. The workshop is divided in three main parts as described below.

4.3.2.1 Part 1: Conceptual introduction of human needs and energy services

The goal of this stage of the workshop is to communicate the rather abstract concepts of human needs, satisfiers and energy services in a participatory workshop context, and establish whether these are relevant to daily activities and decision-making of the workshop participants.

Initially, participants are presented with eight categories of ES: illumination, heating, cooling, transport, information and communication, structure, food, and mechanical work. These ES are presented as things that require energy, but that can be provided in many different ways. We consider these categories to be broad enough to allow participants to think beyond specific or conventional energy sources and conversion devices. Participants are requested to provide examples of alternative ways of providing each energy service. These examples serve as a way to familiarise participants with concepts that might not be too obvious for them, as well as making sure there is agreement on the meaning of each energy service.

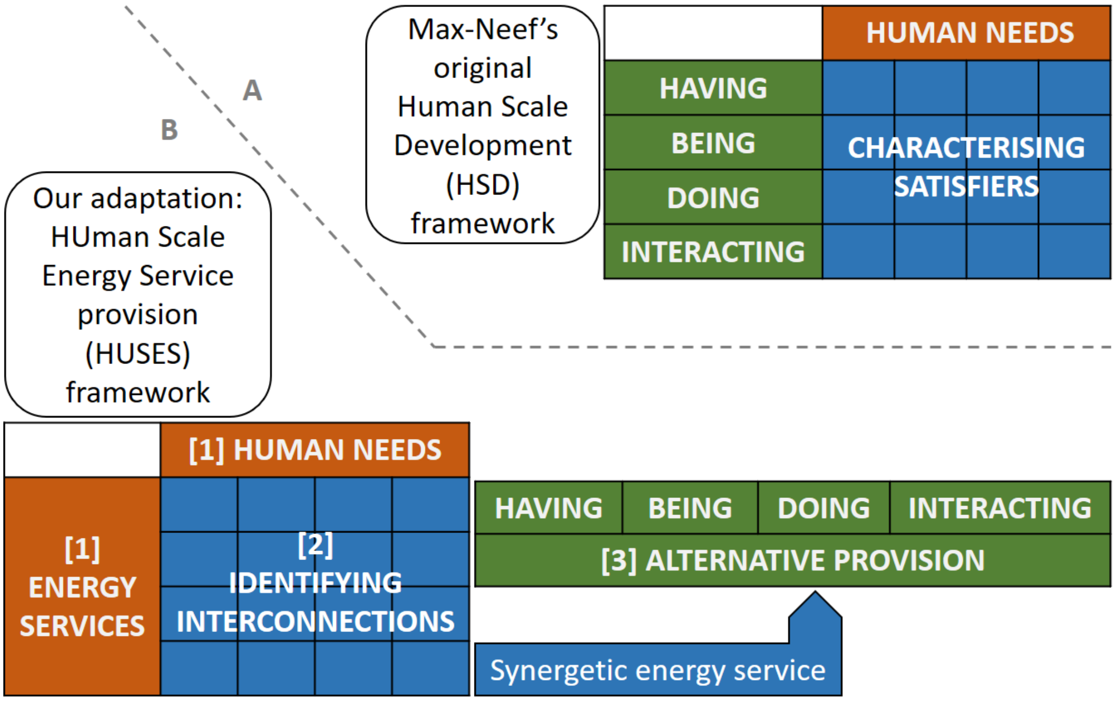

Figure 4-1. Diagrammatic representation of our HUSES framework in relation to Max-Neef’s HSD framework
Source: Own elaboration.

Subsequently, participants are presented with Max-Neef’s nine HN: subsistence, protection, affection, understanding, participation, idleness, creation, identity and freedom. Each of these is discussed briefly by the whole group, and participants are asked to think whether they could “be well” without each of them (e.g. would you be able to “be well” without freedom?). Furthermore, they are asked to relate these needs to their day to day community life: does the list make sense? Is there anything missing? Is there anything that is not so important? How are these needs felt by the community? None of the participants suggested any revisions (see section 4.5.1 for more details).

4.3.2.2 Part 2: Relating energy services and human needs and the quest for the most synergetic energy service

The goal of this second stage is twofold: to explore how ES serve as satisfiers of HN, and to identify the most synergetic energy service with the purpose of using it in the third part of the workshop.

To avoid making the workshop too long and maintain participant engagement, the participants are divided into four groups. Each group is given two energy service cards as well as two stickers of each human need. In their groups, participants analyse one energy service at a time, considering about which HN – if any - it contributes to satisfy, and sticking a sticker for each human need they identify as being satisfied by the energy service they are analysing.

Once all the groups have finished analysing their two ES, they present their choices to the rest of the participants as well as the reasons behind their choices. There is space for discussion of whether the choices make sense and whether there is agreement on the selected HN. At the outcome of this phase, the ES which connects to the largest number of HN is identified as the most "synergetic." The stickers provide a visual tool to easily identify the most synergetic ES.

4.3.2.3 Part 3: Improved energy service delivery

The goal of the final stage is to envision a community-led pathway to obtain an improved level of (or greater access to) the energy service selected in part two. For example, if a community selected the energy service of cooling, the goal now is to propose alternatives to have a better access to cooling in the community, for whatever purpose (human needs) they have found cooling important. At this stage, participants are divided into two groups and asked to use the existential categories of being, having, doing and interacting (Max-Neef, 1991). Each group must come up with a plan to improve their current level of energy service provision at their community. The existential categories are explained using a simple example. Considering the cultural importance of football for many societies, and in Colombia particularly, we derived a football-related example, which can be easily adapted to other sports that are more culturally relevant. We share the example below:

> *"Imagine you are someone who wants to* be *a great footballer. In other words, you want to achieve the highest level of technical and tactical ability. In order to do so, you need to have certain attributes, you need to* **be** *a certain way. You need to be passionate, committed, responsible, hard-working, and so on. But the people that surround you also need to be a certain way, like supportive and encouraging. So the category of* "being" *is all about personal and collective attributes. You would also need to* **have** *certain things, for example a football, some sports kit and appropriate shoes. But then again, you would also need to have some more collective things, like a team to play with and a league to compete against other teams; perhaps even a professional league where you wouldn't have to worry about working and could focus on training and playing. So the category of* "having" *is related to institutions, norms, mechanisms and tools. You would also need to* **do** *a number of things, for example train, eat well, watch football matches, study tactic and technique, go to the gym, etc. Some of these things you could do alone and some need to be done in group, so the category of* "doing" *corresponds to personal or collective actions. Finally, you would have to* **interact** *in certain spaces and at certain times. For instance, you would need a football*

> *pitch and predetermined training times. Thus the category* “interacting” *relates to spaces, times and atmospheres.”*

Finally, after discussing how to achieve an improved level of energy service delivery using the four existential categories, the two groups share the ideas with the rest of the participants and give feedback to each other, choosing an alternative that they all agree with. It is important to note here that the participants were not asked to address the environmental sustainability aspect of the proposed alternatives. Ways to integrate sustainability aspects in future research are explored in section 4.6.3.

4.4 Case studies

Two case studies were used to test the validity and feasibility of our proposed approach. It is important to keep in mind that these constitute a test of a novel approach, therefore the specific case-study outputs, even though interesting in our view, are specific to these two communities. The value of the contribution presented in this paper hence lies fundamentally on the reflections over the method itself and on the value that the process tested here can have for communities more widely.

4.4.1 Study site(s): the country, the city and the communities

Colombia was chosen as a case study country for two main reasons. Firstly, one of the authors has a personal and funding connection to the country, and secondly Colombia has relatively low energy use and relatively high human well-being at a national-level (Steinberger & Roberts, 2010). Therefore, it is a good example of national-level decoupling of energy use and human well-being, i.e. it has achieved (on average) relatively high levels of human well-being with relatively low levels of energy use. However, the country is very diverse in terms of physical geography (Kline et al., 2017), as well as cultural and socio-economic characteristics, with high levels of inequality. Thus, enquiring into the local realities that can reflect specific geographical, cultural and socio-economic characteristics becomes particularly important in Colombia, in order to go beyond what is hidden in national-level averages.

The particular administrative area of the city of Medellín was chosen for two main reasons. The first reason relates to the city’s socio-economic, historical and political particularities (Moncada, 2016). Medellín is Colombia’s second biggest city. It has undergone a significant outward looking transformation, which has earned the city two awards in the past four years[26] for tackling violence, undertaking “social urbanism” projects and improving social participation (Brand, 2013). However, the city still faces many inequalities and internal contradictions (Fukuyama Francis, 2011). Medellín’s particular approach to urban and regional planning (including a municipally owned utilities company and cable cars for public transport into marginalised communities), coupled with its many contradictions, make it an interesting case study. The second reason is practical, given the links we had with local NGOs that could support the fieldwork.

The specific communities that we worked with were El Faro and Palmitas. We acknowledge the complexities surrounding a definition of community (Howarth, 2001), however in these two cases we are considering the inhabitants of El Faro and Palmitas to each be part of a community, given the shared experience they have of the territory (including, crucially for this work, shared energy and transport networks and infrastructure), the shared settlement history and the sense of identity determined by the political-administrative boundaries they belong to. The latter also facilitates unity for projects and initiatives facing local authorities.

The communities were selected because they are a good example of the sort of specificities and inequalities that lie hidden in national averages: both communities are deprived from access to basic levels of ES as well as having below average satisfaction of HN (see Table 4-1), i.e. these communities represent a deviation of the national-level decoupling found for Colombia in previous studies. Therefore, these communities represent an interesting case to study what alternatives are available for real communities that are struggling both in relation to ES access and HN satisfaction, in a country where it is possible to achieve relatively high levels of HN satisfaction with relative low levels of energy use.

Furthermore, El Faro and Palmitas have a number of interesting similarities (see Table 4-1) and are both active communities that work closely with local NGOs (Techo and Penca de Sábila respectively), which facilitated access for the researchers. However, the communities also differ from each other in an important aspect. El Faro is located within the city, while Palmitas is lies on the outskirts of the city (see Figure 4-2). Therefore, the way of life and economic activities have mainly urban characteristics in the case of the former and mainly rural characteristics in the case of the latter, allowing to explore contrasting issues with regards to the use of ES as satisfiers of HN.

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[26] The “Most Innovative City” in 2013 (http://urbanland.uli.org/economy-markets-trends/which-cities-are-worlds-most-innovative-winner/) and the “World City Prize” in 2016 (https://www.leekuanyewworldcityprize.com.sg/laureate_medellin.htm).

Table 4-1. Socio-demographic and historic characteristics of El Faro and Palmitas

	El Faro (urban)	Palmitas (rural)
Area	6-7 hectares*	5779 hectares
Population	~1,500	~6,300
Households	~300 – overcrowding	~2,500
Community	Mostly displaced (~84%)	Mostly traditional farmers
History	Informal settlement	Formal settlement
Socio-economic status	Mostly poor households	Mostly poor households
Education	4% illiterate 20% no formal education 28% up to primary 45% up to secondary 3% college or university degree	7% illiterate 16% no formal education 44% up to primary 30% up to secondary 3% college or university degree

*Own estimation based on (Alcaldía de Medellín, 2015a). Note: Information for El Faro was taken from (Alcaldía de Medellín, 2015b; Mesa de Vivienda y Servicios Públicos Domiciliarios Comuna 8, 2013). Information for Palmitas was taken from (Alcaldía de Medellín, 2008, 2015).

4.4.2 Participant recruitment

Participants were recruited through local NGOs, which have regular presence in, and are trusted by, the communities. The NGO “Techo” is an international organisation concerned with poverty alleviation, mainly working in Latin America. In Medellín Techo is currently working with several communities, including El Faro. “Penca de Sábila” is a national not for profit organisation concerned with environmental and social aspects of sustainability. In its “social and environmental management of the territory” programme, it is currently working with the rural community of Palmitas, amongst others.

Participants were not offered any incentive to participate in the workshop, except for refreshments. They were recruited through a “snowball” effect (Skovdal & Cornish, 2015), where the community contact(s) with the respective NGO recommended and invited other members of the community who would have the time and the interest to participate, while trying to maintain a wide spread of views. The status of the NGOs in the communities as “insiders” assured us trusted access (even though we were complete “outsiders”), and the recruitment process ensured us that the participants in the workshops would be engaged and actively looking for alternatives to better their community.

As is common in this kind of research set up, more active community members were hence more likely to have attended our workshop, while the views of less engaged community members would not have been represented. It should be noted, though, that Colombia has a strong community-based approach to natural resources management and it is not uncommon for the population to engage in participatory process (see for example

Brown et al., 2016; Waylen et al., 2015). Therefore, we expected to have a good level of participation and variety of perspectives.

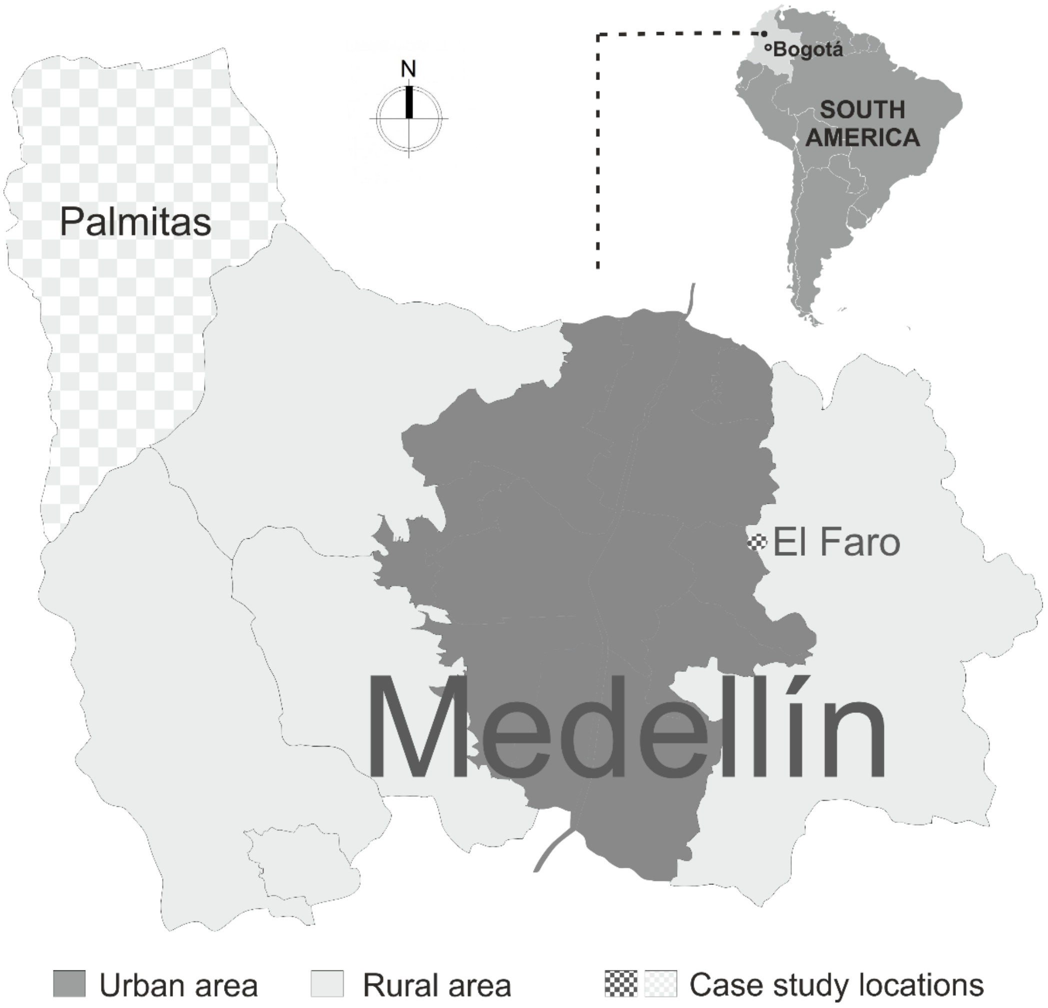


Figure 4-2. Map of El Faro and Palmitas (Medellín, Colombia, South America)
Source: Own elaboration.

Both workshops were undertaken in January 2017, on a Sunday for a duration of 3 hours, and in a location central to each community in order to reduce barriers to participation (and thus minimise exclusion). The workshop in El Faro had 10 participants (5 male and 5 female). Similarly, the workshop in Palmitas had 11 participants (4 male and 7 female). In both cases the participants were adults of ages ranging from approximately 30 to 70 years. Accurate population representativeness is not key (nor always possible in practical terms) to qualitative research of this kind, but rather having rich data to understand the context and meanings of the communities involved (Babbie, 2014). Nonetheless, having this variety of participants reassured us that we had a good spread of different views from the communities, particularly male and female views.

4.5 Results

4.5.1 Understanding human needs and energy services

During the first part of the workshops (see section 4.3.2.1), participants found the concept of ES very intuitive and they quickly came up with additional examples of different ways of provisioning each of them. For instance, participants from El Faro identified lightbulbs, the sun, the moon, candles and torches as different ways of providing lighting. Participants were even able to identify cases where two services were delivered by a single energy source, demonstrating a very good understanding of the concept. For example in the case of Palmitas, one of the participants asked: “what about the case of a bonfire? That provides me lighting but also heating”.

Furthermore, participants from both communities related easily to the HN categories. When asked whether they felt there was something missing or something not so necessary for human well-being, neither of the communities contested the nine categories. Thus, human needs were self-evident for these two communities. Nonetheless, they did ask for clarification in certain aspects, for example in which categories health and work would fall into (subsistence/protection and creation respectively). When asked how they felt those needs in their particular communities, it was difficult for them to select a particular need that they were lacking most, reflecting how these communities perceived needs as being deeply interlinked, irreducible and non-substitutable (i.e. incommensurable), and non-hierarchical. For instance, the community of Palmitas discussed how a lack of protection (from, e.g. landslides) would be linked to a lack in subsistence, creation and freedom. Similarly, the community of El Faro reflected on how communities had the capacity to “have” these HN, but that they were constantly being thwarted by top-down interventions that either deprived them or prevented them from satisfying their needs. These type of discussions reflected how both communities understood the underlying characteristics of HN: self-evident, incommensurable and non-hierarchical (Alkire, 2002; Brand-Correa & Steinberger, 2017).

4.5.2 Identifying links between energy services and human need satisfaction

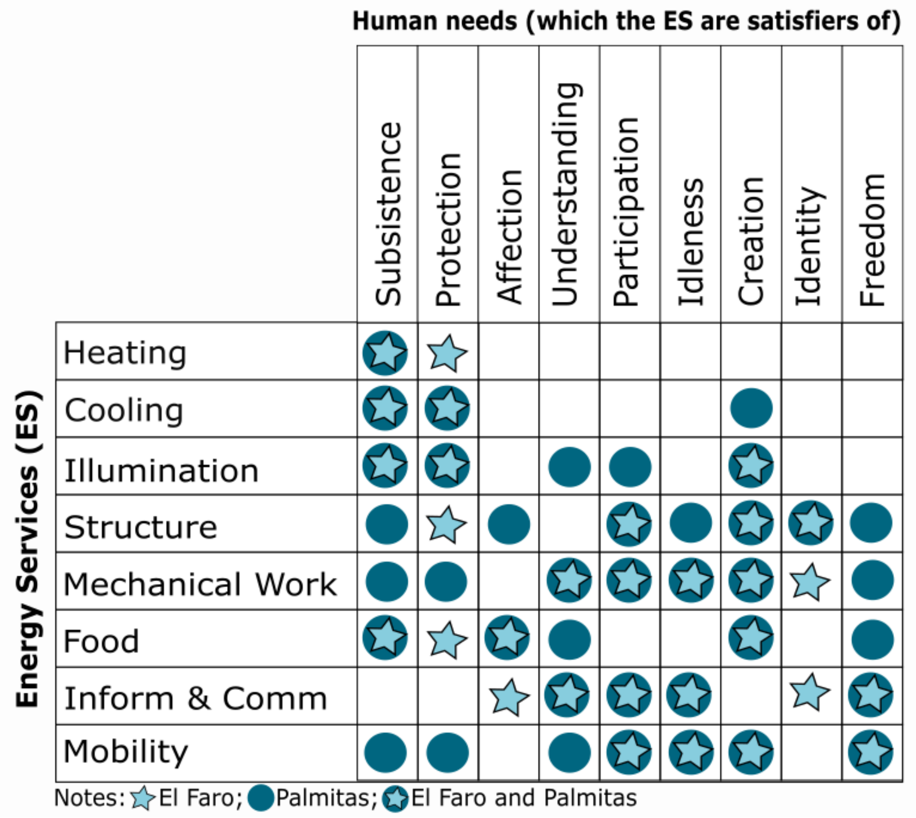
The second part of the workshops focused on relating ES and HN (see section 4.3.2.2), with the findings summarised in Table 4-2. It is interesting to note that, from the perspective of these two communities, all HN require at least one energy service (reading down the columns in Table 4-2). Conversely, some ES were considered more important than others for human well-being by these communities (reading across the rows in Table 4-2). For instance, heating and cooling were, for both communities, the least synergetic satisfiers. This might be explained by the fact that Medellín has a temperate climate all year round, so space heating and/or cooling is not a main concern. Nonetheless, they were considered important satisfiers for subsistence, given their importance for food storage and cooking. Of course how synergetic a particular energy service is, is specific to each community. We suspect that if we carried out this sort of workshop in a temperate zone, heating would be considered a much more central satisfier, and cooling more important in a tropical climate.

The commonalities and divergences between the two communities in Table 4-2are worthy of particular notice. The divergences are consistent with the expectation that satisfiers are specific to the particular circumstances of each community. But there might be some interesting elements to explore where commonalities are found, in terms of overlap of both selected and non-selected ES as satisfiers of particular HN (i.e. circle and star, and blank cells in Table 4-2, respectively). There is clearly an element of universality (between these two communities, but also beyond) in that the energy service of food is needed for subsistence. However, it is not clear whether we can say the same for the ES of cooling, heating and illumination in relation to subsistence, for example.

The nature of the workshops means the specific outputs would vary and very much subject to the individuals in the groups and their experiences and understanding of the workshop, thus explaining much of the selection of energy service as satisfiers of HN. However, it is worth highlighting some cases where the reasoning for selecting an energy service was strikingly similar. Continuing with the example of subsistence, heating and cooling were considered important in relation to cooking and food preservation, and illumination (from the sun) was recognised as vital for human beings. Illumination was also considered important for protection mainly in relation to street lighting (i.e. protection against violence). Another common line of argument in both communities was around the importance of structure as providing spaces to participate, create (and work), but also as providing a sense of identity (that is, where we meet, where we work, where we live, gives us a certain identity). Similarly, mobility was thought of an important satisfier for participation, idleness and creation, insofar it enables people to meet, go on holiday and go to work; it was also thought of as an important satisfier for freedom (i.e. being able to move to different places, close and far, is a sign of freedom in itself). Lastly, we found some common arguments around information and communication, where talking to others and having access to the media provides satisfaction of the need for understanding and idleness, as well as freedom.

In terms of the ES that the communities considered most important for human well-being (most synergetic), both communities considered structure, mechanical work, mobility, and information and communication particularly synergetic. How important each of the communities considered the ES to be varied, however. This might be explained, at least in part, by the urban and rural nature of their settings. In general Palmitas considered ES to satisfy more needs than El Faro. For example in the case of mobility, this could be explained by the fact that Palmitas is located in a relatively remote area when compared to El Faro, which, even though it does not have the best transport links, is located in the city.

Table 4-2. Relating energy services and human needs in El Faro and Palmitas



Energy Services (ES)	Human needs (which the ES are satisfiers of)								
	Subsistence	Protection	Affection	Understanding	Participation	Idleness	Creation	Identity	Freedom
Heating	✪	☆							
Cooling	✪	✪					●		
Illumination	✪	✪		●	●		✪		
Structure	●	☆	●		✪	●	✪	✪	●
Mechanical Work	●	●		✪	✪	✪	✪	☆	●
Food	✪	☆	✪	●			✪		●
Inform & Comm			☆	✪	✪	✪		☆	✪
Mobility	●	●		●	✪	✪	✪		✪

Notes: ☆El Faro; ●Palmitas; ✪El Faro and Palmitas

Source: Own elaboration.

4.5.3 Alternative energy service provisioning

The third part of the workshops focused on enabling the communities to think of alternative ways of provisioning the energy service which they selected as most synergetic (see section 4.3.2.3): El Faro chose information and communication (satisfying six HN) and Palmitas chose mobility (satisfying seven HN). It is important to summarise here the specific circumstances that both communities were facing at the time of the workshops, since these would have been likely to influence their choice of the most synergetic energy service as well as their alternative way of provisioning it.

The community of El Faro was undergoing a process of gathering the community together for various projects during the time of the workshop, including the construction of a community centre with the support of the local NGO, mobilising the community for the establishment of a community-based water tank and finalising the process by which the community would be recognised as a formal neighbourhood. Hence communicating important information to all members of the community was a very strong need they had at the time. The community of Palmitas was not undergoing any particular consultation or participation process at the time of the workshop, but moving their agricultural production to a point where it can be commercialised was a concern, given that they were doing it on foot, which takes a lot of time, effort and it can lead to damages in the products (e.g. bruising of bananas).

However, despite the particular circumstances of each community, the process of the workshop is reproducible and important. From Table 4-3 we can see that by using the existential categories as a tool for communities to think about alternative ways to reach an improved level of energy service provision, they were able to go beyond traditional top-down demands to local government or other institutions. For instance, the community of El Faro did not focus on the local government giving them spaces and mechanisms to inform and communicate with each other, but rather they thought of a way of effectively talking to each other. Similarly, the community of Palmitas did not think of demanding for a better road network or improved public transport to move their agricultural produce, but rather they came up with a cable car system that could be operated and maintained by the community itself. Both alternatives were mostly self-reliant in their nature, something that is part of the strengths of Max-Neef's HSD approach, where community self-reliance is considered the first step for tackling bigger systemic structures (Max-Neef, 1991).

4.6 Discussion

4.6.1 Energy services as satisfiers of human needs

The application of our methodology in the case of two communities allowed us to shed some light on the details of how energy services contribute to human well-being. We argue that our results not only point towards a confirmation that communities do actually see ES as satisfiers of HN, but that they were seen as very important for the well-being of the communities. In fact, all the analysed HN were considered to require at least one energy service as satisfier (see Table 4-2). This is in itself an interesting result, since it was a possibility in the design of the workshop that a particular energy service did not contribute to any human need. However, some HN required less physical pre-conditions or requirements than others. This was reflected in the number of ES related to each human need (see Table 4-2).

Table 4-3. Alternative energy service provision in El Faro and Palmitas

		Needs according to existential characteristics			
		BEING (personal or collective attributes) – nouns	**HAVING** (institutions, norms, mechanisms, tools) – words	**DOING** (personal or collective actions) – verbs	**INTERACTING** (spaces or atmospheres) – times and locations
Most synergetic energy service	**Information and Communication** (El Faro – to improve participation in community initiatives)	Committed. Persuasive (to convince people that it is worthwhile to participate). United.	Everyone's phone/mobile number. Information "diffusors" (people willing to talk to their neighbours). Results or success stories. Volunteers.	Create a message that motivates people. Produce information to reach outside the community. Census with a clear message and an invitation to participate. Ask how do people find out more easily about events.	All around the community.
	Mobility (Palmitas –to move the agricultural produce)	Associated. Collaborative.	Equipment for a cable car. Agricultural produce.	Apply for finance or do some fundraising activities. Install equipment. Coordinate schedules and routes for collection.	Foothills. Close to neighbouring producers.

Exploring the specificities and commonalities found in the two communities also revealed certain recurring lines of argument which might point towards an aggregate reality that can be generalizable, or at least serve as a basis for making hypotheses worth exploring further. Although the particular situations and understanding of the individuals involved in the workshops undoubtedly influenced the choices represented in Table 4-2, we believe that some common and differing elements are worth highlighting. The similar reasoning deployed by both communities in justifying some ES (i.e. mobility, structure, and information and communication) as satisfiers of different needs, points towards a shared (perhaps even generalizable) agreement of the importance of these ES for human well-being in modern societies. However, there is a clear difference in terms of how important these ES are for each of the communities, which can be partially explained by their rural and urban settings. We consider this a very relevant area for future research.

4.6.2 Decoupling energy service provision from human need satisfaction

One could have expected, that if we are looking for decoupling opportunities, to find some HN which did not require any ES as satisfiers. However, we expect most opportunities for decoupling come from different ways of providing ES (i.e. changes in the socio-technical provisioning systems of ES) and different ways of satisfying HN (i.e. changes in the societal characteristics of need satisfaction) (see Fig. 4 in Brand-Correa and Steinberger, 2017), not from denying or ignoring the physical dependence of human well-being.

An example of a change in the socio-technical provisioning system of a particular energy service would be related to alterations anywhere along the “energy chain” (Cullen & Allwood, 2010) and/or to changes in the material and cultural realities along the whole supply chain (Fine, 2013) of the energy service in question. An example of a change in the societal characteristics of need satisfaction would be related to social changes in the way needs are satisfied, in the way everyday social practices (Røpke, 2009; Shove & Walker, 2010) are enacted.

The community of Palmita’s proposed alternative way of delivering the satisfier of mobility (by using a cable car to move agricultural produce from farm to road, see section 4.5), consists of an example of a change in the socio-technical provisioning system as well as in the societal characteristics of need satisfaction. It involves various alterations[27] along the energy chain (e.g. use of a small combustion engine to power the cable car rather than leg muscles, an improved level of the service, etc.) and changes to the material and cultural realities along the supply chain (e.g. less effort and time to move the agricultural produce, new infrastructure, etc.). A similar analysis can be done around the proposed alternative way of delivering information and communication by the community of El Faro (by talking to each other, see section 4.5).

Thus, both proposed alternatives of delivering a particular energy service demonstrate the diversity of outcomes that can be obtained by using the HUSES approach, particularly by the use of the existential categories. This diversity appears both in the socio-technical provisioning systems and in the societal characteristics of needs satisfaction. We argue that this increase in the solution space is a positive step forward when trying to address the very complex problem of living well within environmental limits, and an improvement from the mainstream solution space of economic cost or technology-led solutions. A key element here is that the solutions come from the bottom-up, where locally generated knowledge can be used to overcome scientific, ethical and political challenges associated with establishing minimum requirements for human well-being (Baer, 2013; Lamb & Steinberger, 2017; Rao & Baer, 2012; Raworth, 2012).

The search for alternatives to provide ES using Max-Neef’s existential categories was, from the communities’ and NGO’s perspective, the most important aspect of the methodology, where the value of the process is revealed in terms of enabling self-reliant ways of thinking about human need fulfilment. We received positive feedback from both the participants and the NGOs about the workshops in general, but in particular about the final part. In other words, by using the existential categories of “being”, “doing” and

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[27] We cannot assess the abovementioned changes in the socio-technical provisioning system in relation to efficiency nor environmental performance, since we have not precisely evaluated how much energy the different alternatives would require nor how much emissions they would produce.

“interacting”, both communities were able to go beyond traditional aspirations of “having” and were able to critically reflect on their own role in provisioning satisfiers (in this case a particular energy service) to fulfil their needs. This goes in line with arguments that favour of the process of carrying out participatory approaches as a mechanism to empower communities (Hammett et al., 2014; Skovdal & Cornish, 2015).

4.6.3 Steps forward

It is important to note that during the workshops, the sustainability aspect of the proposed alternatives was not addressed directly, i.e. participants were not asked to think about the environmental impacts of the proposed alternatives. This is reflected in the case of Plamitas, where the community suggested an alternative that is actually more energy intensive than they previously had (from walking to cable car). This could be problematic, because we are ultimately interested in alternative ways of satisfying human needs within planetary boundaries. However, in very poor communities, where the initial levels of both energy services access and human need satisfaction are very low, the satisfaction of human needs may well involve higher levels of energy services use. Thus the focus must be on providing that energy in a sustainable way. An interesting avenue for future research will be to explore if that is also the case for affluent communities.

In order to include the sustainability element in future research, we propose two possibilities. The first one is to follow up the process with expert and stakeholder interviews or workshops (as outlined by (Doyal & Gough, 1991)), where the alternatives can be assessed in relation to their sustainability potential, in the context of international commitments, national goals and so on. The stakeholders should include people with technical knowledge of energy service provisioning, as well as local authorities with the institutional capacity to support these initiatives.

The second one is to do an analysis of ES as satisfiers using Max-Neef’s full matrix. That would enable the inclusion all HN and reflection on the type of satisfier that a particular energy service is. In our proposed approach, the relationship between ES and HN (Part 2, section 4.3.2.2) is analysed separately from the discussion of a specific ES as satisfier (Part 3, section 4.3.2.3). By carrying out the analysis simultaneously (as originally proposed by Max-Neef), communities could understand the interdependencies and contradictions between different satisfiers[28]. For example, mobility by the use of a private car can satisfy certain needs, but it can also go against the need for subsistence given the health impacts of pollution. Furthermore, communities can explore the different types of

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[28] Mattioli (Mattioli, 2016) describes these interdependencies and contradictions in the context of transport; how social and environmental goals are traded off more strongly when there is not a clear framework of human needs and satisfiers, and thus the focus is on what he calls “lower-order need satisfiers”.

satisfier that certain ways of delivering ES constitute, and focus on synergetic and endogenous ways of delivering ES. Following the previous example, communities could realise that a private car is an exogenous pseudo-satisfier, and that initiatives such as the cable-car are potentially more synergetic and endogenous.

4.7 Conclusions

We are faced with a double challenge: climate change and other planetary boundaries are being breached (Steffen et al., 2015) whilst many social foundations are not even close to being built. Raworth (Raworth, 2017) has described this as an issue of remaining within a “doughnut”, i.e. below planetary boundaries but above social foundations. The role of energy in staying within the doughnut is key. Our research aimed at contributing to the search for alternative ways of building social foundations without further breaching planetary boundaries, by using the concepts of energy services and human needs.

The design of the methodology was particularly tailored to help us address two concerns: (How) do energy services contribute to human well-being? And can a participatory approach enable communities to collectively construct energy service provisioning alternatives? By testing the methodology in the case of two communities in Colombia we were able to confirm that energy services are in fact perceived as satisfiers of human needs, but in different ways for different communities. This confirms the diverse nature of satisfiers, even when it comes to energy services.

Furthermore, the process of participatory workshops, using an adapted version of Max-Neef’s (1991) HSD approach we have called HUSES (Human Scale Energy Services), enabled the communities of El Faro and Palmitas to propose alternatives ways of provisioning the energy services of “information and communication” and “mobility” respectively. Such alternatives were self-reliant in their nature, and both communities realised their role in satisfying their needs. This is an encouraging result because, if it is coupled with further stakeholder and expert interviews or workshops focused on the environmental sustainability of the proposals, it might lead to decoupling of energy use and human well-being, in the specific case of energy services.

Additionally, our results point towards interesting avenues for future research, particularly around the analysis of the socio-technical aspects of alternatives for provisioning energy services and satisfying human needs. For example, this would include linking the specific ways in which energy services are used as satisfiers to the theory of social practices (Røpke, 2009; Shove et al., 2008), i.e. how the particular ways in which communities link energy services to human needs can be traced back to the co-evolution of social norms and technologies. Moreover, the general heterodox field of social provisioning and the specific method of systems of provision (Bayliss, Fine, & Robertson, 2013; Fine, 2013) could be used to understand the structures, processes, agencies and relations that led to the current (deficient) provisioning of particular energy services to the communities under study. We present this approach with the hope that it can be further refined through future research, and with the intention to provide a roadmap and a basis for continuing the explorations around decoupling human well-being from energy consumption.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

Discussion and Conclusions

Our economies and societies are dependent on energy. Economic growth and human well-being are coupled with energy (Ayres & Warr, 2009; Steinberger & Roberts, 2010). This would not be an issue if the ways in which we are currently supplying and using energy were not having catastrophic consequences on the environment (especially in relation to climate change). Therefore, there is an urgent need to find paths to decoupling the environmental damage caused by our energy systems and practices, from its benefits to economies and well-being. This PhD set out to contribute to that, by exploring the energy dependency of societies and the economy in alternative ways.

In particular, this PhD set out to answer the question: *How are we to continue to support human societies and economies, which depend on energy for their functioning, while the very use of that energy is what is compromising the continuation of a stable Earth system?* In other words, how are we to significantly decouple progress in human societies and economies from environmentally harmful levels of energy consumption? Thus, the overall aim of the PhD project was to: further the understanding of the energy dependency of the economy and society, using a *socio-historical* and *ecological economics* lens, in order to provide alternative routes to decoupling in the face of the urgent need to mitigate climate change.

Finding decoupling possibilities from a situation of dependency is not easy, and purely technological or economic solutions will not suffice (Anderson, Le Quéré, & McLachlan, 2014). I will argue that uncovering alternative decoupling possibilities requires, amongst other things, three elements: moving beyond single disciplinary boundaries, looking outside traditional concepts, and exploring different methods. It requires, for example, combining disciplines such as physics for the understanding of energy and energy systems, economics for the appreciation of economic processes, ecology for a systems perspective on the intertwined weavings of energy, and social sciences for an awareness of social structures and logics. It also requires looking beyond primary energy supply and final energy use, in order to see surplus energy and energy services; beyond individual happiness, in order to see flourishing. Finally, it requires exploring different methods to be able to find answers at the appropriate level.

In this section, I will expand on the abovementioned elements through the insights I gained in the process of addressing the two research gaps I identified: national level surplus energy, and energy services and human needs. I elaborate on these insights for decoupling in section 5.1, whilst at the same time providing a synthesis of the results from each gap (each weaving of the golden thread of energy). In section 5.2 I discuss the limitations of each of the components. Then, in section 5.3, I provide some overarching reflexions on decoupling and consider possible future research avenues to broaden our understanding of decoupling. Finally, in section 5.4 I provide some general concluding remarks.

5.1 Synthesis of the results and insights for decoupling: cutting the energy weaving around climate change

I established in the introduction that societies and economies are fundamentally dependent on energy. This implies that "total" decoupling is not possible, i.e. it is not possible to have societies and economies that do not use any energy at all. Nonetheless, given the urgency of climate change mitigation, significant decoupling is paramount.

"Relative" decoupling is fairly common (UNEP, 2011, p. 5, Jackson, 2009, Chapter 5) and consistent with the progress made so far in relation to emissions reductions via energy efficiency improvements and low carbon energy technologies. However important, this progress is insufficient (Anderson, 2015; Anderson, Le Quéré, & McLachlan, 2014) because it is also consistent with overall increases in resource use (Peters, 2017). Therefore, an absolute reduction in energy use (or an absolute reduction in the climate change impacts of energy use) is needed to avoid a climate catastrophe, i.e. "absolute" decoupling is needed. In order to achieve absolute decoupling, overall energy use (or overall CO_2 emissions) has to remain stable or even decline, while there is economic growth or increases in human well-being.

With a view to finding significant decoupling alternatives, my PhD focused on exploring in detail the energy dependency of societies and the economy. In order to fulfil that aim, there were a series of objectives:

A. To develop a novel methodology for calculating a national-level EROI (Energy Return on Energy Invested) in order to obtain important information for an energy transition at a policy-relevant level.
B. To advance a conceptual contribution for relating energy services and human needs, and providing sustainable alternatives to such a relationship.
C. To produce a participatory methodology capable of interrogating the conceptual framework, as well as to apply and test it in diverse communities.

Below I will describe how I have addressed each of these objectives, synthesise the results I obtained, and more importantly, reflect on the insights I gained for decoupling from the energy weavings around the economy and society.

5.1.1 Decoupling of economic activity from climate change

As established in section 1.1.2, energy underpins economic activity (Ayres & Warr, 2009; Cottrell, 1955; Georgescu-Roegen, 1971; Kümmel, 2011). However, in order to maintain economic activity without surpassing planetary boundaries – climate change in particular- (Rockström et al., 2009; Steffen et al., 2015), a transition to low-carbon energy systems is urgently needed.

In order to guide such a transition, traditional economic assessments of different energy technologies do not suffice (Carbajales-Dale, Barnhart, Brandt, & Benson, 2014). In other words, the traditional understanding of energy for economic growth (e.g. projections of energy supply based on future predictions of economic growth, or cost assessments of different energy supply technologies) is not enough. A holistic understanding of the energy system is needed.

Therefore, I framed my approach in the heterodox and interdisciplinary area of ecological economics. In particular, the concept of surplus energy provides an integrated understanding of the energy system, where the energy requirements of energy supply are incorporated at the centre of analysis, providing insights into both energy depletion (or lack of accessibility) and technological advancements in the extraction (or capture) of energy.

In addition to framing my research in a heterodox area and using a non-traditional concept, I developed a novel quantitative methodology in Chapter 2. The methodology allowed me to address objective A, and demonstrate the applicability of net energy at a national-level to inform a low-carbon energy transition. By proposing and testing a novel methodology to calculate national-level surplus energy, we provided information at a level that is useful for national energy policy-making. This is in contrast with most EROI studies that focus on a lower level of aggregation (Brandt, 2011; Cleveland, 2005; Dale, Krumdieck, & Bodger, 2011; Hall, Lambert, & Balogh, 2014; Poisson & Hall, 2013).

The results from a first application to the UK, for the period 1997-2012, for the three main fossil fuels (coal, oil and gas), show that the EROI for fossil fuels being extracted in the UK has been declining since the new millennium, to more than half of its value in 2000. This result is mainly driven by a sharp reduction in the fossil fuel extraction ("production") in the UK, whilst maintaining a more or less constant level of energy invested. Thus, for the same amount of energy investment, the UK is getting less energy out of the ground.

The consequences of a declining EROI are serious, considering the energy dependency of the economy described in the introduction. The reason is that more energy is needed to produce energy, and therefore less energy is available to use in the economy.

In the case of the UK, by the year 2012, for each unit of energy invested to produce (i.e. extract or capture) energy in the country, 5.6 units of energy were obtained. That means that almost 20% of our energy is used “parasitically” in producing energy, rather than being used for economic purposes. Furthermore, there are consequences in relation to energy security. The only way the UK has been able to compensate for a declining EROI has been through increasing imports, which mean the country is more dependent on energy supplies from the rest of the world.

Relating this to the urgent need to mitigate climate change, the declining EROI helps justify a transition away from fossil fuels: a declining trend in EROI is not sustainable for economic activity. A declining trend in EROI might approach what has been called the “net energy cliff” (Murphy & Hall, 2010), where after a certain point, the increases in the energy cost of energy lead to an abysmal fall in the net energy available for the economy. If the UK wants to avoid such a situation, it needs to shift its energy supply away from EROI declining energy sources.

Therefore, a national-level EROI proved useful to provide insights for decoupling fossil energy from economic activity. It implies moving beyond a focus on extraction at all cost, towards a more systemic view of the energy system. Not only to recognise the climate impacts of fossil fuels, but also to recognise the depletion of fossil energy available at a reasonable energy cost. The evidence provided by a national-level EROI for the UK support the case for decarbonisation of the country’s energy system, and hence are consistent with the decoupling of economic activity from the climate change impacts of energy use (point c. in Figure 1-11). Whether this decoupling is relative or absolute would depend on the rate at which the decarbonisation occurs in relation to economic growth.

Our national-level EROI does not question the energy dependency of the economy (it does not attempt to “cut” the energy weavings around economic activity, as in Figure 1-11, point a.), and thus it does not provide evidence to support the absolute decoupling of energy use from economic growth. However, economic growth needs not to be taken for granted. The goal of economic activity must be questioned. Certainly, how it has been measured so far, using GDP, has been repeatedly challenged (Cobb, Halstead, & Rowe, 1995; Costanza, 2014; Van Den Bergh, 2009), as well as the inequality implications of market-based capitalism (Chancel & Piketty, 2015; Piketty, 2014). Therefore, I explored the possibilities of decoupling the weavings around climate change from a societal perspective, prioritising human well-being rather than economic activity.

5.1.2 Decoupling of human well-being from climate change

There is a highly unequal pattern of energy use worldwide, now as well as historically (as discussed in section 1.1.1). Such a pattern has resulted in some segments of the world population being energy deprived, whilst other segments are driving unsustainable levels of energy use. International level studies have shown that energy is key for development and human well-being, but there is a saturation point where further increases in energy use do not translate into increases in well-being (Martínez & Ebenhack, 2008; Steinberger & Roberts, 2010). Therefore, and considering the climate impacts of current energy systems, there is a compelling need to find ways of increasing human well-being whilst maintaining or reducing overall energy use.

In order to think about decoupling opportunities in that sense, traditional technological and economic approaches are not enough. Thus, I situated my research in the intersection between ecological economics, energy studies, and well-being and development theories. This allowed me to explore in Chapter 3 the relationship between energy and well-being at a fundamental level, reassessing the meanings around energy use/demand (towards energy services), and the meanings of progress (towards human needs). I found that human needs provide an important normative basis on what should be provided by societies, but still allowing for cultural specificities. Furthermore, focusing on human needs also implies a move towards notions of justice, sufficiency and upper limits (Di Giulio & Fuchs, 2014), as well as questioning consumption, the satisfiers we are choosing and the provisioning systems we rely on (the market).

I also developed a way of integrating these meanings and concepts, addressing objective B. I developed a novel framework for analysing the relationship between energy services and human needs, contributing to an emerging field on the social aspects of energy use, with a particular focus on well-being (Bouzarovski & Petrova, 2015; Day, Walker, & Simcock, 2016). Through this framework, energy services are understood as "satisfiers" of human needs. This conceptualisation is powerful, in the sense that it allows to establish an energy services–human needs spectrum. I found that decoupling opportunities appear at both sides of the spectrum.

On one side, decoupling opportunities can be uncovered in terms of efficiency improvements along the energy chain up until the delivery of energy services (including improvements in passive systems). In other words, energy services provide the flexibility for different ways of providing the same service, including alternatives that are less energy or emissions intensive. On the other side, decoupling opportunities can be uncovered by analysing the societal characteristics of need satisfaction, including the choice of satisfiers and the practices associated with the satisfaction of human needs.

In addition to a novel conceptual framework, in Chapter 4 I developed a novel qualitative methodology as a way of testing the framework, and exploring the scarcely studied community level. It was an adaptation of Max-Neef's (1991) human scale development methodology and workshop structure, which has been recognised as a useful tool for assessing and working towards sustainable development in practice (Guillén-

Royo, 2016). In particular, using the needs categories as well as the existential categories was innovative, respectively for relating to energy services and human needs and exploring alternative ways of provisioning a particular energy service. The developing of this methodology, as well as its empirical application, addressed objective C.

I applied the methodology in an urban and a rural community in Medellín (Colombia), and it was successful in relating energy services to human needs for the two communities. I found interesting commonalities and differences. The commonalties point towards the vital importance that some energy services play in the satisfaction of human needs, and thus towards areas of prioritisation for policies around energy service access and delivery. The differences, however, remind us of the importance of considering the specific circumstances of societies and communities when it comes to the way energy services are delivered and perceived.

The methodology also gave the communities the opportunity to think about alternative ways to provide a specific energy service. In this respect, the research showed how a participatory process is in itself important. The methodology was designed to avoid being an extractive research process. Thus, process learning for future replication was central, in particular in relation to finding alternative provisioning of energy services. Max-Neef's methodology promotes shared learning and empowerment, since the communities can analyse their situation and think about what they can do about it.

Relating this to the urgent need to mitigate climate change, I found that the conceptual framework and the qualitative methodology provide the basis for decoupling human need satisfaction from energy use (i.e. they attempt to "cut" the energy weavings around human well-being, as in point b. in Figure 1-11).The possibility space for decoupling is initially opened through the integration of sound concepts in the conceptual framework. Furthermore, relating energy services and human needs in practice enabled the identification (and thus prioritising the delivery and access to) energy services that are key for human well-being. Additionally, the participatory process of finding alternatives for energy service provision opens up the decoupling possibility space even further, because it allowed communities to find alternatives to the satisfaction of human needs through energy services that they could provide. Whether this decoupling is relative or absolute will depend on each community's specific circumstances (e.g. current levels of energy use and need satisfaction). The possibility space for decoupling is initially opened through the integration of sound concepts in the conceptual framework. Furthermore, relating energy services and human needs in practice enabled the identification (and thus prioritising the delivery and access to) energy services that are key for human well-being. Additionally, the participatory process of finding alternatives for energy service provision opens up the decoupling possibility space even further, because it allowed communities to find alternatives to the satisfaction of human needs through energy services that they could provide.

5.2 Specific limitations

This section describes, for each of the research gaps (national-level surplus energy, and energy services and human needs), the specific limitations of the research I conducted in this PhD and possible ways of addressing them in future research.

5.2.1 National-level surplus energy

One of the main limitations of the national-level surplus analysis is related to data availability. We chose the UK because it was the country with best Input-Output data available, yet the data was not as detailed as we would have wished. Input-Output tables are divided into economic sectors. The energy industry sectors are few and aggregated. Thus, we were not able to calculate $EROI_{nat}$ for individual fossil fuels nor for renewables. These data constraints mean that our results, even though comparable with other analyses (Fizaine & Court, 2016; King, Maxwell, & Donovan, 2015), should be taken as informative of a general trend, rather than exact ratios of energy return on energy invested.

A national-level EROI for individual fuels, including renewables, has the potential to influence policy-making further for a transition to low carbon energy systems. Our results (for a combination of coal, oil and gas) imply the need to move away from fossil fuels, but do not specify which particular fuel performs worst in terms of EROI, nor do they provide an alternative. Previous studies on single fuels point towards renewables (particularly wind and solar PV) having an increasing EROI (Baskut & Ozgener, 2012; Carbajales-Dale, Barnhart, & Benson, 2014; Hepbasli, 2008; Kubiszewski, Cleveland, & Endres, 2010). Therefore, there is a need for compiling more disaggregated data for Input-Output tables, which is consistent with what other Input-Output applications have called for (Owen et al., 2017).

Additional limitations of this analysis are related to the different boundaries of analysis that we used for the initial application of $EROI_{nat}$ in the UK. First, in this PhD $EROI_{nat}$ was calculated at the production level, not the use (or consumption) level. This means that the EROI compared the direct and indirect energy inputs necessary to "produce" (in this case extract) energy, with the total amount of energy produced in the national territory of the UK. Thus, further research should try to expand the boundary of analysis of the national-level EROI in order to get to the use level. That is, compare the direct and indirect energy inputs necessary to produce, transform and transport energy to the point of use, with the final amount of energy used in a country.

However, the way that energy statistics are organised makes this a complicated task. The statistics for the final amount of energy used in a country are allocated to using industries. This makes it difficult to trace back which industries produced, transformed and transported which portions of that final amount of energy, and thus how much energy was used in producing, transforming and transporting energy. I have continued to explore this issue with my colleagues, and we are assessing the reliability of undertaking this tracing back using the energy source data from the IEA.

Second, our methodology calculated $EROI_{nat}$ within the national territory of the UK. However, given that we used multi-regional Input-Output data, there is the data available for calculating $EROI_{nat}$ for other countries or world regions. Expanding the applications in future research to other territories would provide inputs for answering questions such as: How does $EROI_{nat}$ relate to energy security? Do energy exporting countries have a higher EROI than energy importing countries?

Third, the different timings of energy investments (usually large at the beginning and end of an energy project – construction and decommissioning) and energy returns (usually relatively constant throughout the lifetime of an energy project) were not considered in our $EROI_{nat}$ application for the UK. Energy investment data is not readily available at a national-level, and it is difficult to translate financial investments into energy investments. By having a time series of $EROI_{nat}$ for the UK for 16 years (1997-2012), we argue that the differing timings of energy investments and returns smooth out. However, future research should consider in particular the energy investments of the energy sector for construction and decommissioning of energy projects. One way of doing this is by calculating the energy footprint of capital investment data available in Input-Output tables. This, of course, comes with its own set of challenges.

5.2.2 Energy services and human needs: conceptual framework and its application

The conceptual framework brought together two different fields of enquiry. Energy from an energy services lens and human well-being from a human needs lens. Moreover, it related them through the concept of need satisfiers. On reflexion, the framework has the potential to expand the fields of inquiry it draws upon. For example, the systems of provision approach (Bayliss, Fine, & Robertson, 2013; Fine, 2013) can be implemented to explore the economic, material and technological interdependencies that result in a specific configuration for the delivery of energy services. Another example lies in the theory of social practices (Røpke, 2009; Shove et al., 2008), where the logics of everyday life, cultural norms and technological lock-in can shed light into the selection of specific need satisfiers.

There was a shift in the definition of energy service categories from Chapter 3 to Chapter 4, explained to some degree in the latter, but further reflected upon here. Chapter 3 focused on Cullen and Allwood's (2010) categories of energy services because of their clear boundaries, measurability and comparability (see section 3.3.1). Their categorisation derives from the analysis of global energy systems, and therefore includes only energy services that are derived from the use of external energy and conversion devices. This is the most common understanding of energy services and presents a clear distinction between energy services and need satisfiers (which is consistent with Figure 3-4, where energy services and need satisfiers sometimes, but not always, overlap).

In Chapter 4, however, Cullen and Allwood's categories were modified for the purposes of empirically applying the framework (see section 4.2.2). In particular, our concern was to have energy service categories defined as broadly and abstractly as possible, in order to not constraint or lead participants into thinking of specific conversion devices when thinking of a particular energy service. This change meant that many need satisfiers could be characterised as energy services. For example, walking and talking, traditionally more easily related to need satisfiers, would now fit in the energy service categories of mobility and information and communication respectively.

In practical terms, broadening the energy service categories probably did not make a significant difference in the workshops, and it allowed participants to think about energy services as need satisfiers in an unrestricted way. However, analytically it can mean that the distinction between energy services and need satisfiers became more blurred. One way of clearing the distinction is considering that energy services only become need satisfiers when they are used in a certain way, when they serve the purpose of satisfying human needs (and not wants). In other words, acknowledging that energy service *become* need satisfiers if they are used to satisfy human needs. Another way of reflecting on when energy service act as need satisfiers is by analysing need satisfiers holistically, through Max-Neef's full matrix, and reflecting on where specific energy services come in.

Moreover, in relation to the qualitative methodology, specific procedural improvements in the design of the cards and on the information recorded can be made (see section 4.6.3 for more details). More fundamental reflexions on the qualitative methodology revolve around the third part of the method, where participants had to come up with alternative ways of provisioning a specific energy service. The strength of this part relied on the use of Max-Neef's existential categories (being, having, doing and interacting). However, the participants were not asked to focus on the sustainability aspect of the proposed alternatives. Questions around the environmental sustainability of the alternatives can be overcome by either complementing the workshops with expert interviews or by expanding the realm of the workshops themselves, so that participants can explore this aspect.

Similarly, the alternatives were very small scale, limited to what the communities could do, and the workshop did not enable the communities to think about broader structural issues. A possibility to overcome this issue would be to use Max-Neef's (1991) full matrix. By doing so, communities could analyse the interactions between different energy services as need satisfiers, as well as the different types of satisfiers. The latter include types of satisfiers that are in detriment of other needs (thus, environmental limits can be incorporated), and types of satisfiers that are outside of the control of influence of the community (thus, representing broader structural barriers).

Following from the lack of analysis of broader structural issues, the members of the communities were analysing their own needs and how energy services acted as satisfiers. This could be considered as an incompatibility of units of analysis: individual assessments versus community-level issues (which was the chosen unit of analysis). However, given the consensus-building nature of the approach, the assessments of individual participants should not be the focus of the analysis, but rather the aggregated results to which all participants agreed. Future research should keep this in mind when analysing data, and reinforce the need to reach consensus during data collection.

Finally, future research should expand the geographical realm of application of this methodology into different cultures, different income levels and different timeframes (enabling people or communities to think about the past and about the future through, for instance, archival research and backcasting). By analysing all these different realms, an understanding of which elements are stable (needs) and which elements can be changed (satisfiers) can start to emerge.

5.3 Integrated reflexions on decoupling and proposed future avenues of research

Despite the abovementioned limitations, the research I conducted throughout this PhD, taken as a whole, provided some important considerations for energy decoupling. In first place, before searching for decoupling possibilities, a deep understanding of energy dependency is warranted. This understanding must go beyond disciplinary boundaries, and in particular beyond traditional technological and economic analysis. This has been done in this thesis up to a certain point, however, future research should continue to expand into transdisciplinary work, including fields such as political economy, sociology, arts, and political sciences, amongst others, as well as other strands of non-academic knowledge.

In second place, in order to uncover a broad range of decoupling possibilities, research should provide evidence from different perspectives, levels of analysis and geographical settings. In terms of perspectives, this includes the supply side (like in the case of surplus energy) and the demand side of energy (like in the case of energy services and human needs). In terms of levels of analysis, it includes the national and the community level (which were interrogated here), but also further levels such as international, intra-national, regional, household and individual level. In terms of geographical settings, this thesis studied the UK and Colombia, two very different countries, but there is potential for interesting results of future research carried out in a greater variety of cultures, socio-demographic communities and political regimes.

In third place, decoupling research requires clear concepts, which at the same time provide enough flexibility to account for "real world" heterogeneity of energy systems, technologies, cultures, circumstances, geographies, and histories. I believe that the concepts used in this PhD, especially those of energy services and need satisfiers, provide a lot of flexibility for alternative (more sustainable) ways of providing energy services and satisfying human needs. However, key for finding such alternatives is being critical and self-reflective of the satisfiers we choose as a society, which is no easy task. My proposed qualitative methodology goes some way in that direction, but it could be strengthened by a broader analysis of satisfiers, "expert" interviews or a combination of both.

Linked to the abovementioned need for critically interrogating the set of satisfiers a particular community uses, there is an issue in relation agency and structure. The ability of a particular community to enact change is constrained by broader social structures. How to recognise and address power and vested interests? The systems of provision approach offers an option to interrogate consumption of certain commodities (which can be satisfiers) in a vertical way, so that production (including material conditions) and consumption (including cultural elements) are connected (Fine, 2013).

There is also an issue of how communities understand themselves and well-being. How can this type of research be implemented in more individualistic settings? How to convey a eudaimonic view of well-being in context where other understandings of well-being prevail (including hedonism)? One possibility is to draw from at academic contributions such as Soper's "alternative hedonism", where momentaneous pleasure and consumption are taken as a starting point for pushing for change in some of the more unsustainable satisfiers (Soper, 2008).

Finally, there is a question of how to make this type of research have a more evident impact on policy-making. The broad field of net energy has tried to influence the policy-making sphere for some time. One of the main aims of expanding the boundary of analysis of EROI to the national-level was precisely to make it more policy relevant. Thus, further calibration and applications of the methodology might make it appealing to energy policy makers. Furthermore, there seems to be a growing political appetite for promoting well-being alongside economic growth (for example David Cameron's policy on measuring well-being in the UK). However, well-being tends to be used loosely depending on the political goals pursued, thus the importance of involving non-political actors, such as communities.

5.4 Concluding remarks: climate compatible energy dependency

Overall, I found that both of the weavings done in this PhD provided some insight into the energy decoupling of economies and societies, while appreciating the energy dependency of both. On the one hand, we cannot keep using fossil fuels when they have a declining EROI - the consequences for economies would be very serious. On the other hand, we need to keep providing energy services that are vital for the satisfaction of human needs (our societies are dependent on it), but do so in culturally specific and sustainable ways.

As I mentioned before, however, these insights stemmed from novel understandings, framings, priorities and methodologies. To open the possibility space for decoupling the energy dependency of the economy from climate change, a holistic theoretical framework was needed. I found such a framework in the work around surplus energy (Cottrell, 1955), net energy and EROI. The EROI work contributes to the ecological economics perspective on energy, addressing a specific methodological gap. By doing so, it also highlights the challenges a declining EROI represents for a national economy, given the energy dependency of economies.

To open the possibility space for decoupling the energy dependency of society (human well-being) from climate change, a novel and holistic theoretical framework was needed. I developed such a framework by integrating the concepts of energy services and human needs through the notion of need satisfiers. Furthermore, in order to find decoupling possibilities in practice, I developed a novel qualitative and participatory methodology and applied it in two communities in Colombia. The energy services and human needs work contributes to the socio-historical perspectives on energy, by conceptually defining and empirically demonstrating the energy dependency of human well-being.

I consider that both of these contributions point towards the possibility of having climate compatible energy dependent societies and economies, as long as there is a fundamental change in the framings, understanding, priorities and methodologies used to find and assess such possibility.

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Appendix A

A.1. A Note on Notation

A bold lower case letter represents a vector. A bold capital letter represents a matrix. Non-bold lower case and capital letter represent scalars. A vector with a “hat” ($\widehat{\ }$) represents a diagonal matrix, whose diagonal elements are the elements of the vector. **I** is the identity matrix, and is a matrix of zeros whose diagonal is made of ones.

A.2. Multi-Regional Input-Output Matrix Structure, with an Energy Extension

Consider the transaction matrix Z (Figure A1). In the top left hand corner of Z is the UK data, followed by 5 world regions (the Rest of Europe, the Middle East, China, the Rest of the OECD, and the Rest of the World). Each region contains 106 industry sectors. Z displays sales by each industry in rows and the columns represent purchases by each industry. In other words, reading across a row reveals which other industries a single industry sells to and reading down a column reveals who a single industry buys from in order to make its product output. A single element, z_{ij}, within **Z** represents the contributions from the *i*th supplying sector to the *j*th producing sector in an economy. The **Z** matrix is in monetary units.

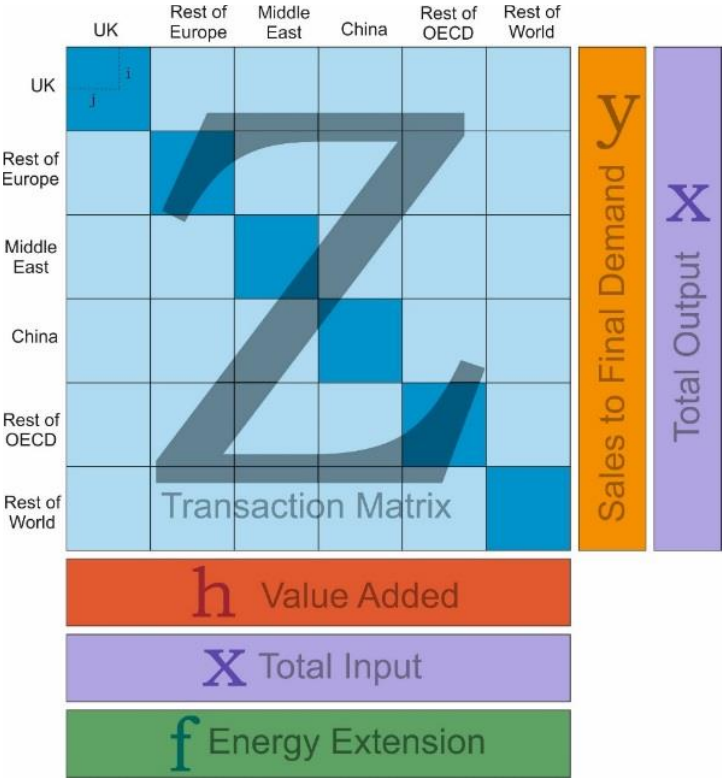


Figure A1. Basic Structure of the UK MRIO.

Reading across the table, the total output (x_i) of sector *i* can be expressed as in Equation (A1):

$$x_i = z_{i1} + z_{i2} + \cdots + z_{in} + y_i \tag{A1}$$

where y_i is the final demand for the product produced by the particular sector. Essentially, the IO framework shows that the total output of a sector can be shown to be the result of its intermediate and final demand. Similarly if a column of the IO table is considered, the total input of a sector is shown to be the result of its intermediate demand and the value added in profits and wages (**h**). The sum across total output (**x**) and total input (**x**) will be equal.

A.3. Basic Calculations: Obtaining the A, L and F Matrices

If each element, z_{ij}, along row *i* is divided by the output x_j, associated with the corresponding column *j* it is found in, then each element z_{ij} in **Z** can be replaced with:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{A2}$$

forming a new matrix **A**, known as the direct requirements matrix. Element a_{ij} is therefore the input as a proportion of all the inputs in the production recipe of that product.

Equation (A2) can be re-written as:

$$\mathrm{z_{ij} = a_{ij}x_j} \quad (A3)$$

Substituting for Equation (A3) in Equation (A1) forms:

$$\mathrm{x_i = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + y_i} \quad (A4)$$

Which, if written in matrix notation is $= \mathbf{Ax} + \mathbf{y}$. Solving for **x** gives:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad (A5)$$

Equation (A5) is known as the Leontief equation and describes output **x** as a function of final demand. $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse (denoted hereafter as **L**). Therefore Equation (A5) can be re-written as:

$$\mathbf{x} = \mathbf{Ly} \quad (A6)$$

Consider a row vector **f** of annual energy produced required by each industrial sector (an environmental extension in Figure 2-4). Then it is possible to calculate the energy intensity (**e**) by dividing the total energy input of each sector by total sector output (**x**), in terms of joules per pound for example, as follows:

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \quad (A7)$$

In other words, **e** is the coefficient vector representing energy per unit of output.

Multiplying both sides of Equation (A6) by **e** gives:

$$\mathbf{ex} = \mathbf{eLy} \quad (A8)$$

and from Equation (A7) we simplify Equation (A8) to:

$$\mathbf{f} = \mathbf{eLy} \quad (A9)$$

However, we need the result $(\mathbf{f})$ as a flow matrix $(\mathbf{F})$, rather than a scalar, and so we use the diagonalised $\hat{\mathbf{e}}$ and $\hat{\mathbf{y}}$ as shown in Equation (A10):

$$\mathbf{F} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}} \quad (A10)$$

F is produced energy in matrix form, allowing the UK's use of energy from the full supply chain of extraction/capture to be determined. **F** is calculated by pre-multiplying **L** by energy per unit of output and post-multiplying by final demand. Energy is reallocated from extraction/capture sectors to the sectors that use this produced energy.

A.4. EROInat Specific Calculations: Obtaining Indirect Energy

We will use Input-Output analysis techniques to calculate total indirect energy use (both from the UK and the RoW) used to extract/capture UK's energy. This is E_{iE} in

Equation (5) from the main text. To calculate E_{iE} we calculate a new flow matrix $\mathbf{F^0}$ which shows the UK's total use of energy from the full supply chain *if there was no flow to the energy sectors*. The indirect energy use is therefore the difference between $\mathbf{F}$ and $\mathbf{F^0}$.

To calculate $\mathbf{F^0}$, we generate a new version of the transactions matrix, $\mathbf{Z^0}$, which is exactly the same as $\mathbf{Z}$ apart from the fact that $\mathbf{Z^0}$ has zeros in the cells that represent the UK energy sector's expenditure on all other energy products.

Let $\mathbf{Z^0}$ contain n regions and m sectors. Sectors c to e are the energy sectors and region k is the UK. An element of $\mathbf{Z^0}$ is z_{ij}^{rs0} which represents the monetary flow from sector i in country r to sector j in country s. We know that $z_{ij}^{rs0} = 0$ if i and j belong to the set of energy sectors (c to e) and if region $s = k$ (the UK). In other words:

$$\mathbf{Z^0} = \mathrm{z_{ij}^{rs0}} = \left\{ \begin{matrix} 0 \text{ if } \mathrm{i, j} \in \{\mathrm{c}, \dots, \mathrm{e}\} \text{ and } \mathrm{s = k} \\ \mathrm{z_{ij}^{rs0}} \text{otherwise} \end{matrix} \right\} \tag{A11}$$

Then

$$\mathbf{F^0} = \mathbf{\hat{e}}(\mathbf{I} - \mathbf{Z^0}\widehat{\mathbf{x^{-1}}})^{-1}\,\mathbf{\hat{y}} \tag{A12}$$

and:

$$\mathrm{E_{iE}} = \sum_{\mathrm{r}}^{\mathrm{n}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \mathrm{F_{ij}^{rk}} - \mathrm{F_{ij}^{rk0}} \tag{A13}$$

Essentially, $\sum_{\mathrm{r}}^{\mathrm{n}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \mathrm{F_{ij}^{rk}}$ is the sum of all the direct and indirect energy that forms energy inputs to make UK energy products.

$\sum_{\mathrm{r}}^{\mathrm{n}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \sum_{\mathrm{j} \in \{\mathrm{c},\dots,\mathrm{e}\}} \mathrm{F_{ij}^{rk0}}$ is the sum of the direct energy that forms energy inputs to make UK energy products.

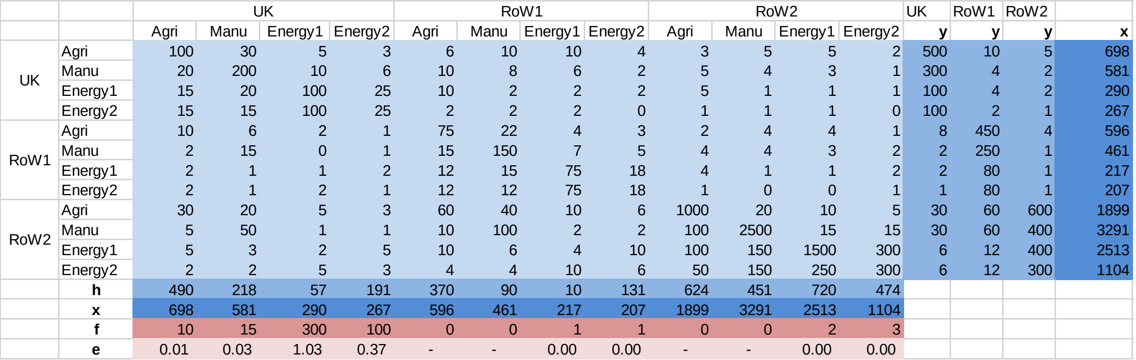
And the difference is the sum of the indirect energy that forms energy inputs to make UK energy products.

Finally, we do this for each of the 16 years (1997–2012) we have data for.

Appendix B

We present here a simple numerical example. Let's assume we have a 3 region model (UK, rest of the world 1—RoW1 and rest of the world 2—RoW2). Each region has 4 sectors, two of which are energy producing sectors.

Z, y, h, x, f and e are presented in Figure A2.



		UK				RoW1				RoW2				UK	RoW1	RoW2	
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	y	y	y	x
UK	Agri	100	30	5	3	6	10	10	4	3	5	5	2	500	10	5	698
	Manu	20	200	10	6	10	8	6	2	5	4	3	1	300	4	2	581
	Energy1	15	20	100	25	10	2	2	2	5	1	1	1	100	4	2	290
	Energy2	15	15	100	25	2	2	2	0	1	1	1	0	100	2	1	267
RoW1	Agri	10	6	2	1	75	22	4	3	2	4	4	1	8	450	4	596
	Manu	2	15	0	1	15	150	7	5	4	4	3	2	2	250	1	461
	Energy1	2	1	1	2	12	15	75	18	4	1	1	2	2	80	1	217
	Energy2	2	1	2	1	12	12	75	18	1	0	0	1	1	80	1	207
RoW2	Agri	30	20	5	3	60	40	10	6	1000	20	10	5	30	60	600	1899
	Manu	5	50	1	1	10	100	2	2	100	2500	15	15	30	60	400	3291
	Energy1	5	3	2	5	10	6	4	10	100	150	1500	300	6	12	400	2513
	Energy2	2	2	5	3	4	4	10	6	50	150	250	300	6	12	300	1104
	h	490	218	57	191	370	90	10	131	624	451	720	474				
	x	698	581	290	267	596	461	217	207	1899	3291	2513	1104				
	f	10	15	300	100	0	0	1	1	0	0	2	3				
	e	0.01	0.03	1.03	0.37	-	-	0.00	0.00	-	-	0.00	0.00				

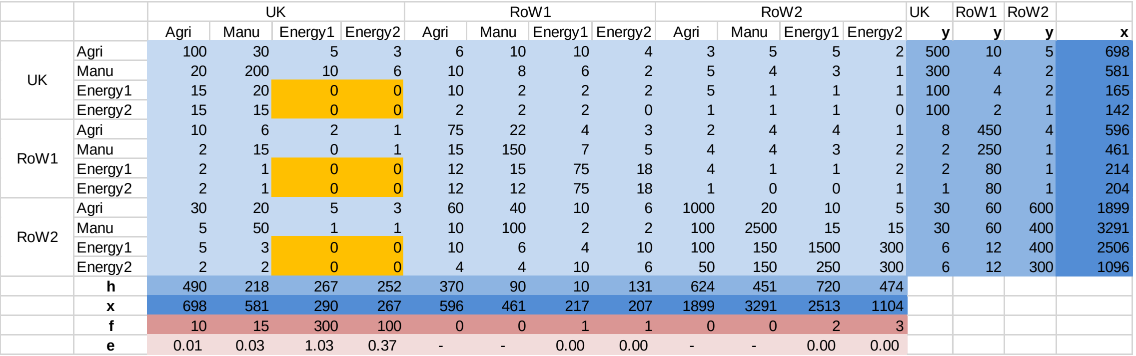
Figure A2. Numerical example: Z, y, h, x, f and e.

After applying Equations (A1) to (A10) we obtain **F**, shown in Figure A3.

		UK				RoW1				RoW2			
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2
UK	Agri	8.7	0.4	0.1	0.0	0.2	0.2	0.1	0.0	0.1	0.1	0.1	0.0
	Manu	0.8	12.2	0.3	0.1	0.5	0.4	0.2	0.1	0.2	0.1	0.1	0.0
	Energy1	26.7	31.4	178.2	18.3	18.3	6.6	4.3	2.2	8.3	2.7	1.6	1.4
	Energy2	9.4	9.7	24.7	45.2	3.7	2.1	1.3	0.4	1.7	0.8	0.5	0.3
RoW1	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.0	0.0	0.0	0.0	0.1	0.1	0.6	0.1	0.0	0.0	0.0	0.0
	Energy2	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.5	0.0	0.0	0.0	0.0
RoW2	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.3	0.9	0.3
	Energy2	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.5	0.4	1.3

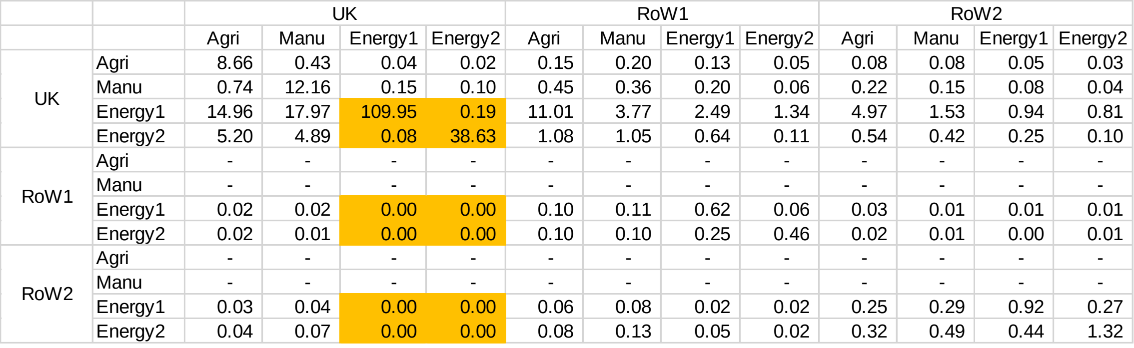
Figure A3. Numerical example: F.

In order to calculate E_{iE}, following Equations (A11) and (A12), we create $\mathbf{F^0}$ from $\mathbf{Z^0}$. The latter is shown in Figure A4 and the former is shown in Figure A5.



		UK				RoW1				RoW2				UK	RoW1	RoW2	
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	y	y	y	x
UK	Agri	100	30	5	3	6	10	10	4	3	5	5	2	500	10	5	698
	Manu	20	200	10	6	10	8	6	2	5	4	3	1	300	4	2	581
	Energy1	15	20	0	0	10	2	2	2	5	1	1	1	100	4	2	165
	Energy2	15	15	0	0	2	2	2	0	1	1	1	0	100	2	1	142
RoW1	Agri	10	6	2	1	75	22	4	3	2	4	4	1	8	450	4	596
	Manu	2	15	0	1	15	150	7	5	4	4	3	2	2	250	1	461
	Energy1	2	1	0	0	12	15	75	18	4	1	1	2	2	80	1	214
	Energy2	2	1	0	0	12	12	75	18	1	0	0	1	1	80	1	204
RoW2	Agri	30	20	5	3	60	40	10	6	1000	20	10	5	30	60	600	1899
	Manu	5	50	1	1	10	100	2	2	100	2500	15	15	30	60	400	3291
	Energy1	5	3	0	0	10	6	4	10	100	150	1500	300	6	12	400	2506
	Energy2	2	2	0	0	4	4	10	6	50	150	250	300	6	12	300	1096
	h	490	218	267	252	370	90	10	131	624	451	720	474				
	x	698	581	290	267	596	461	217	207	1899	3291	2513	1104				
	f	10	15	300	100	0	0	1	1	0	0	2	3				
	e	0.01	0.03	1.03	0.37	-	-	0.00	0.00	-	-	0.00	0.00				

Figure A4. Numerical example: Z°.



		UK				RoW1				RoW2			
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2
UK	Agri	8.66	0.43	0.04	0.02	0.15	0.20	0.13	0.05	0.08	0.08	0.05	0.03
	Manu	0.74	12.16	0.15	0.10	0.45	0.36	0.20	0.06	0.22	0.15	0.08	0.04
	Energy1	14.96	17.97	109.95	0.19	11.01	3.77	2.49	1.34	4.97	1.53	0.94	0.81
	Energy2	5.20	4.89	0.08	38.63	1.08	1.05	0.64	0.11	0.54	0.42	0.25	0.10
RoW1	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.02	0.02	0.00	0.00	0.10	0.11	0.62	0.06	0.03	0.01	0.01	0.01
	Energy2	0.02	0.01	0.00	0.00	0.10	0.10	0.25	0.46	0.02	0.01	0.00	0.01
RoW2	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.03	0.04	0.00	0.00	0.06	0.08	0.02	0.02	0.25	0.29	0.92	0.27
	Energy2	0.04	0.07	0.00	0.00	0.08	0.13	0.05	0.02	0.32	0.49	0.44	1.32

Figure A5. Numerical example: F°.

Finally, we apply Equation (A13) and obtain E_{iE} of 117.64.

Assuming we obtain from the IEA for our numerical example $E_T = 425$ and $E_{dE} = 130$, we can insert these components in Equation (5) and obtain $EROI_{nat(UK)} = 1.1$

$$EROI_{nat(UK)} = \frac{425 - 130}{130 + \ 117.64}$$