The impact of a grid-connected building's design characteristics on its ability to participate in energy arbitrage schemes by using battery storage under real-time electricity pricing conditions

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Abstract

The Building sector is responsible for a significant part of the worldwide energy consumption and the consequent carbon emissions. Their energy consumption depends on several factors, such as their heating, ventilation and air-conditioning (HVAC) configuration and design characteristics. Due to the energy transition and focus on sustainability, the building sector has evolved with several building types of different attributes mentioned in the literature. Most of these types are considered to work in synergy with the grid, relieving pressure on the infrastructure. Smart Grid Optimised Buildings (SGOBs) are fully-electric and constitute a novel concept according to which buildings must be in close relationship with the grid, responding to its notifications and using their integrated systems such as battery storage to perform specific services, such as arbitrage and exporting excess electricity back to the grid. While the majority of the research and the literature have focused on either large-scale energy storage towards the maximisation of the revenue streams or on small-scale building integrated storage in combination with renewables, there is a significant research gap on the utilisation of battery storage in buildings and the impact their design characteristics have on their arbitrage performance. This project suggests three operational dispatch strategies for battery-enabled building arbitrage under real-time electricity prices, implemented in MATLAB. Commercial buildings with different design characteristics are simulated (DesignBuilder/EnergyPlus) and used as input of the MATLAB model to investigate their suitability to participate in the arbitrage scheme. In terms of the percentage of the peak loads shifted, the fabric's energy efficiency was proved to have the highest impact on the building's arbitrage, followed by the ventilation strategy and the window-to-wall ratio (glazing). Cost-benefit analysis was performed for a 10-year period, including a financial reward mechanism to make the arbitrage scheme as cost-effective as the no storage scenario; the average reward was calculated to be 22.84p/kWh shifted when exports take place and 16.66p/kWh shifted without exports.

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I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.

MAIN BODY OF THE THESIS FOLLOWS

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Abbreviations

AC – Alternating Current

AMI – Advanced Metering Infrastructure

ASHP – Air Source Heat Pump

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

B2G – Building-to-grid

BES – Battery Energy Storage

BEV – Battery Electric Vehicle

BIM – Building Information Modelling

BM – Balancing Mechanism

BMS – Battery Management System

BSS – Battery Storage System

BSUoS – Balancing Services Use of System

CAES – Compressed-air Energy Storage

CBA – Cost-Benefit-Analysis

CCS – Carbon Capture & Storage

CCU – Carbon Capture & Utilisation

CES – Community Energy Storage

CF – Compactness Factor

CfD – Contract for Difference

CHP – Combined Heat and Power

CIBSE – Chartered Institution of Building Services Engineers

CoP – Coefficient of Performance

DBEIS – Department for Business, Energy and Industrial Strategy

DC – Direct Current

DER – Distributed Energy Resources

DG2G – Distributed-generation-to-grid

DLH – Dynamic Low High

DNO – Distribution Network Operator

DOD – Depth of Discharge

Domestic Hot Water – DHW

DR – Demand Response

DRHI – Domestic Renewable Heat Incentive

DSF – Demand Side Flexibility

DSM – Demand Side Management

DSO – Distribution System Operator

DSR – Demand Side Response

DST – Daylight Saving Time

DSY – Design Summer Year

DTU – Demand Turn Up

DUoS – Distribution Use of System

EER – Energy Efficiency Ratio

EES – Electrical Energy Storage

EFR – Enhanced Frequency Response

EFTA – European Free Trade Association

EMTM – Electricity Market Target Model

ERGEG – European Regulators' Group for Electricity and Gas

ERI – Electricity Regional Initiative

ES2G – Energy-storage-to-grid

ESO – Electricity System Operator

ESS – Energy Storage System

EU – European Union

EV – Electric Vehicle

FES – Flywheel Energy Storage

FFR – Firm Frequency Response

G2V – Grid-to-vehicle

GB – Great Britain

GDP – Gross Domestic Product

GHG – Greenhouse gases

GSHP – Ground Source Heat Pump

GSP – Grid Supply Point

GUI – Graphical User Interface

H2G – Home-to-grid

HVAC – Heating, ventilation and air-conditioning

ICT – Information and Communication Technologies

IDNO – Independent Distribution Network Operator

IEA – International Energy Agency

IPP – Independent Power Producer

ISO – Independent System Operator

ITO – Independent Transmission Operator

LCO – Lithium cobalt oxide

LCOE – Levelised Cost of Electricity

LFP – Lithium iron phosphate

LFS – Low Frequency Static

Li-on – Lithium-ion

LMO – Lithium manganese oxide

LTO – Lithium titanate

MES – Mechanical Energy Storage

MFR – Mandatory Frequency Response

NaS – Sodium-sulphur

NCA – Lithium nickel cobalt aluminium oxide

NDRHI – Non-domestic Renewable Heat Incentive

NEMO – Nominated Electricity Market Operator

Ni-Cd – Nickel Cadmium

NIEI – Northern Ireland Electricity Networks

NIST – US National Institute of Standards and Technology

NMC – Lithium nickel manganese cobalt oxide

NPC – Net Present Cost

NWD – Non-working day

nZEB – Nearly Zero Energy Building

O&M – Operation and maintenance

Ofgem – Office of Gas and Electricity Markets

P2H – Power to Hydrogen

P2P – Peer to peer

Pb-A – Lead-acid

PHES – Pumped-hydro Energy Storage

PHEV – Plug-in Hybrid Electric Vehicle

PMV – Fanger’s Predicted Mean Vote

PPD – Fanger’s Predicted Percentage of Dissatisfied

PV – Photovoltaics

PX – Power Exchange

R&D – Research & Development

RES – Renewable Energy Sources

RFB – Redox Flow Battery

ROCOF – Rate-of-change-of-frequency

RTP – Real-time-pricing

SCoP – Seasonal Coefficient of Performance

SDAC – Single Day-Ahead Coupling

SF – Shape Factor

SFP – Specific Fan Power

SG1.0 – First generation Smart Grid

SG2.0 – Second generation Smart Grid

SG3.0 – Third generation Smart Grid

SGOB – Smart Grid Optimised Building

SHGC – Solar Heat Gain Coefficient

SIDC – Single Intraday Coupling

SMES – Super Magnetic Energy Storage

SO – System Operator

SOC – State of Charge

SPF – Seasonal Performance Factor

STOR – Short-Term Operating Reserve

T&D – Transmission and Distribution

TES – Thermal Energy Storage

TNUoS – Transmission Network Use of System

ToU – Time-of-use

TRY – Test Reference Year

TSO – Transmission System Operator

UK – United Kingdom

UPS – Uninterruptible Power Supply

USA – United States of America

V2G – Vehicle-to-grid

VAC – Ventilation and air-conditioning

VAT – Value Added Tax

VRFB – Vanadium Redox Flow Battery

ZEB – Zero Energy Building

1. Introduction

1.1 Background and motivation

Buildings consume enormous amounts of energy worldwide and therefore are responsible for a significant proportion of carbon emissions and the consequent ramifications for the environment. The energy consumed in buildings is either produced locally or transferred through the electrical grid and heat network [1]. As there has been an important shift towards sustainability in the recent years, a number of emerging and innovative technologies have received different but increasing amounts of popularity and deployment, contributing towards the so-called energy transition and the relevant challenges. It is inevitable that the building sector has to evolve as well in order for the transition to be eventually complete [2].

Despite having a largely passive role in today's energy network, buildings are expected to gradually become prosumers by both producing and consuming energy, taking advantage of local energy generation and storage. Therefore, they will have a close bidirectional interactive relationship with the future smart grid [3]. This research focuses on a building type which constitutes a novel concept, the Smart Grid Optimised Building (SGOB). An SGOB can be thought of as meeting its service obligations to its occupants and minimising its operational cost and footprint to its owner while actively engaging with the electricity provider enabling best use of the available resources. Receiving information and prompts from the grid network, the SGOB can determine the appropriate level of participation based on the intelligence of the embedded systems and the service obligations it has to its stakeholders [4], [5].

Undoubtedly, electricity is one of the most important fuels for the building sector. In the United Kingdom (UK), the overall electrical demand has fluctuated through the years and its significance is expected to increase with the electrification of heat that will also increase the pressure on the existing infrastructure [6], [7], [8]. However, the options provided to most building types are limited when it comes to electricity tariffs as buildings do not have access to the wholesale market. In the UK, both the standing charge (£/day) and the retail electricity price (£/kWh) offered by electricity suppliers are constant with only one cheaper tariff offered during the night period [9]. In 2018, Octopus Energy became the first energy supplier to offer smart time-of-use (ToU) tariffs with Octopus Agile, a beta product that allows customers to check the half-hourly energy prices for the following day, tied to the wholesale prices, in order to identify the cheapest time slots, adjust their consumption and avoid the expensive peak hours of the day [10], [11].

One of the emerging technologies, mentioned above, is energy storage which is based in a relatively simple idea and can be deployed at the building scale. Energy Storage Systems (ESS) are charged when technoeconomic conditions allow it, for example when cheap energy is accessible, and its energy content can be later discharged to meet local building loads or balance the frequency of the electrical grid. Pumped hydro, compressed-air, batteries, supercapacitors and flywheels are some of the ESS used for applications of different scales [12].

As systems switch from large-scale conventional energy sources to smaller scale renewables of intermittent nature, the system consists of components with conflicting properties and it is increasing complicated to run it effectively. Energy storage can enable buildings to provide services to the electrical grid through the adjustment of the building loads that can be either increased or reduced for a certain number of hours per day. In this way, demand side management (DSM) can relieve pressure on the infrastructure and reduce the peak electrical loads which result in extra costs for the energy provider, avoiding the need for expansion and reinforcement of the electrical network that would require substantial network and infrastructure investments. The full technical potential of DSM is inherently uncertain as it relies on the building design characteristics and the temperature range within which lies the thermal comfort of the occupants [13], [14], [15].

There are several projects that have investigated the demand side response (DSR) capabilities of commercial buildings by either changing the HVAC configuration or by utilising energy storage and renewable energy sources (RES) [13], [16]. However, the building design characteristics have not been examined in combination with energy storage and real-time pricing (RTP) to understand which buildings are more suitable to provide such a service to the modern electrical gid and the future smart grid. Besides the HVAC system, design includes the construction materials that the building envelope consists of as well as the building geometry.

As the Smart Grid creates an opportunity in which both current and future buildings can be incentivised to operate within national grid-aligned drivers, building-integrated storage can be used to maximise the benefits from these incentives. This would allow buildings to enter the electricity market as energy storage vectors and contribute to the energy transition [4], [5].

This thesis focuses on the utilisation of battery storage systems (BSS) in buildings of different design characteristics, not only for the buildings to meet their local building loads through time-shifting but also to export electricity back to the grid. As different operations can be followed, three operational dispatch strategies have been adopted and consequently implemented. The long-term financial implications are also of critical importance and have been examined in detail.

1.2 Scope and Aim of the Thesis

The current thesis involves non-domestic buildings whose energy demand is met exclusively by electricity. Therefore, residential buildings and energy systems which run on fossil fuel (e.g. natural gas boilers) are outside the scope of the thesis. Electrical storage systems are considered for the needs of the project and more specifically, battery storage has been chosen due to its high energy content and their building-wise size suitability.

The aim of this research is to investigate, evaluate and compare the impact of a grid-connected building's design characteristics on its ability to participate in energy arbitrage schemes by using battery storage, under RTP conditions. The thesis has the following objectives:

1. Develop a techno-economic battery storage arbitrage model for non-domestic buildings that will enable them to respond dynamically to real-time electricity prices, shift their loads and export electricity back to the grid.

2. Investigate how the arbitrage operation of buildings is affected by their design parameters and define the most appropriate building design for BSS-enabled arbitrage.

3. Conduct a cost-benefit analysis (CBA) to assess economically the cost-effectiveness of the suggested scheme, considering both current and future capital costs, and suggest a financial mechanism to reward buildings for their participation into the scheme.

1.3 Thesis outline

The current chapter provides some background information and the motivation behind the project as well as its aim and objectives. The remainder of the thesis is structured as follows:

Chapter 2 - Literature Review

This chapter consists of four subchapters and provides a literature review and background information on the energy network, the electrical grid, energy storage and finally energy in the building sector.

Chapter 3 – Methodology

The methodology chapter presents detailed information, documentation, assumptions and formulae used for the creation of the building models, real-time electricity prices and the storage arbitrage algorithm. Additionally, it explains the criteria based on which selected buildings are chosen for further investigation and includes the sensitivity analysis parameters.

Chapter 4 – Building Simulation Results

In this chapter, the results from the building energy simulations are presented in terms of their electrical loads and thermal comfort after a brief demonstration of the simulations output.

Chapter 5 – Arbitrage Results

The arbitrage results are presented, using 2017 RTP electricity data, focusing on the impact of the individual building design characteristics on the arbitrage performance. After a summary of the chapter, the selection of the building cases to be used in Chapter 6 is discussed.

Chapter 6 – Sensitivity Analysis

A total of 9 parameters are investigated in the sensitivity analysis to evaluate their impact on the arbitrage results of the previous chapter. These include several battery and inverter capacity sizes, RTP data for 2018, different weather data etc.

Chapter 7 – Cost-Benefit Analysis

This chapter investigates the cost-effectiveness of the arbitrage schemes for a 10-year period while proposing a financial reward for the buildings, for a 10-year period. A case study is included comparing the economics between a 10-year and a 20-year period.

Chapter 8 – Summary and Conclusions

This chapter summarises the thesis, presents its conclusions and makes suggestions for further work.

2. Literature Review

2.1 Energy Network Challenges

2.1.1 Current status in Europe

Energy is of fundamental importance for the well-being of society, industry and economy and therefore must be safe, secure, sustainable and affordable. According to the European Commission, the existing energy systems in Europe will require decades in order to shift towards higher levels of sustainability and security [17]. Global warming and the consequences of energy crises on human life made the governments around the world reconsider their energy strategies and invest on RES [18]. Additionally, as the need for energy is growing and energy demand is expected to increase [19], it becomes increasingly difficult and expensive to identify and exploit conventional energy sources that exist in limited amounts and unreachable locations. In this direction, RES are considered to play a major role in the energy policy of the European Union (EU) as they have the capacity to cover an important part of the European energy demand, reduce the dependence on fossil fuels (such as coal, oil and natural gas) and develop a sustainable energy sector and the economy in general. A common policy and vision regarding the EU energy supply is of fundamental importance to achieve the transition to an energy system with a higher RES proportion, for all member states [18].

According to Eurostat [20] and regarding the final energy consumption by fuel in EU27, between 1990 and 2021, EU countries are gradually abandoning solid fossil fuels whose usage dropped from 86.93 to 19.04 Mtoe, between 1990 and 2021. For the same years, oil and petroleum products saw periods of both increasing and decreasing usage, but they were reduced from 374.56 to 327.46 Mtoe. On the other hand, electricity received a significant increase from 162.24 to 213.86 Mtoe, constituting the second most consumed fuel after oil and petroleum products. Natural gas remained an important fuel throughout the years, but its usage dropped between 2010 – 2014 and now occupies marginally the third place. Finally, as renewables and biofuels have become more popular, their share increased significantly from 38.62 to 110.44 Mtoe. It should be noted that the previously mentioned figures do not include nuclear energy which is considered to be part of the total energy supply, also known as primary energy.

Concerning the installed electrical capacity per fuel in the EU27, three main observations can be made using data from [20] :

- The total installed electrical capacity grew from 506.63 to 991.05 GW between 1990 and 2021, an increase of approximately 96%. This demonstrates the growing importance of the electricity infrastructure and therefore electricity as a fuel.

- In spite of a continuous increase for 22 years and having reached a peak value of 426.57 GW in 2012, the capacity of the conventional combustible fuels has been generally decreasing since then, reaching 379.38 GW in 2021.

- The RES capacity of the electrical network grew uninterruptedly from 121.88 GW in 1990 to 501.92 GW in 2021. Their recent popularity can be seen more clearly by comparing their respective capacities between 2006 and 2021. More specifically, for the period in question, the capacity of wind power increased significantly from 45.61 to 188.37 GW while solar photovoltaic power went up from 3.21 GW to 161.88 GW.

2.1.2 Current Status in the UK

The UK government presents the energy consumption of the country per sector, providing data for the domestic, services, industrial and the transport sector. While most of the areas covered are self-defining, it should be noted that services include three subsectors and more specifically commercial, public administration and agriculture. Figure 2.1 was compiled using data provided by the Department for Business, Energy and Industrial Strategy (DBEIS). The total final energy consumption decreased from 147.268 to 128.14 Mtoe between 1990 and 2021. In both the years 1990 and 2021, the most popular fuels were petroleum, natural gas and electricity in descending order, having had received fluctuations during that period [21].

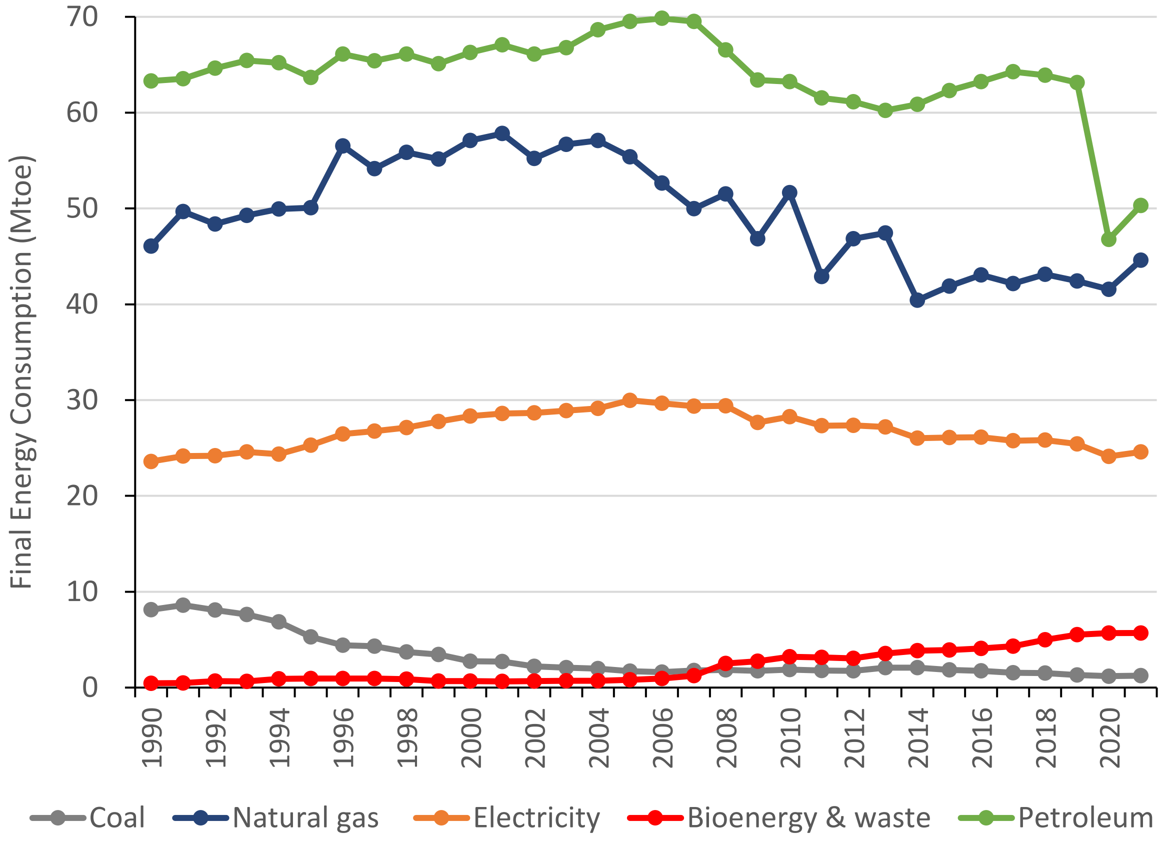


Figure 2.1 – UK Final Energy Consumption (1990 – 2021)

It is clear that between 1990 and 2021, the industrial sector has seen a significant decline from 38.66 to 22.76 Mtoe, consuming now just 2.04 Mtoe more than services. This clearly demonstrates a significant shift in the UK economy from the industry towards the services sector. Natural gas usage has remained relatively constant in the domestic and services sectors with only a minor increase while electricity also received a small rise, from 8.07 to 9.41 Mtoe in the domestic sector and from 6.43 to 7.37 Mtoe in services. It should be pointed out that in 2021, electricity was the second most used fuel in all sectors but transport. As its usage is insignificant in transport, when compared to petroleum, it occupies the position of the third most used fuel, overall [21].

Regarding the electrical capacity of the UK and the nature of its components between 2010 – 2019, while the total capacity has fluctuated throughout the years and reached a peak value of 90.44 GW in 2010, there have been some fluctuations since, reaching 77.92 GW in 2019. The conventional steam stations have seen their popularity significantly decreasing from 37,058 to 16,334 MW, clearly signalling the country's shift away from traditional fossil-fuel powered steam turbines. At the same time, wind, solar and other renewables have been increasing their contribution significantly, along with the combined cycle gas turbine stations. Hydroelectric, pumped hydro and nuclear power stations have maintained their position in the energy mix without any major changes. On the other hand, wind and solar energy managed to have a combined capacity of more than 1 GW, for the first time, in 2007. Twelve years later, their capacity significantly increased to 12.63 GW. The capacity of other renewable sources (bioenergy, wave and tidal) also went up significantly, from 1.52 GW in 2007 to 7.76 GW, in 2019 [22].

It is therefore clear that while the exact numbers vary, there are similarities in the European and UK energy system. Petroleum dominates the transport sector, electricity and natural gas constitute the most popular fuels for the rest of the sectors. At the same time, RES play an increasingly important role as part of the electrical grid with solid fossil fuels being gradually phased out. At the European level, electricity is now the second most used fuel overall, after catching up with natural gas.

2.1.3 Legislation

Ambitious policy decisions are vital to achieve a functioning and competitive energy market in Europe. The energy policy of the EU established the continuous physical availability of energy products and services, at an affordable price, as a common objective of its member states. The significance of energy related emissions is also highlighted [17].

At the same time, the basic energy policy goals include security of supply, competitiveness and sustainability as mentioned in the Lisbon Treaty that entered into force on 2009 [23]. The treaty also promotes the interconnection of energy networks, energy efficiency and savings as well as the utilisation of RES. This energy policy is reflected in European and British legislation which adopted energy and climate change objectives:

- With the Climate Change Act 2008, the UK became the first state in the world to set legally binding targets to combat climate change. More specifically, the UK Government has to ensure that the net emissions of greenhouse gases (GHG) for the year 2050 are at least 100% lower than the 1990 baselines [24], [25].

- The Renewable Energy Directive 2009/28/EC promoted the use of RES by setting a mandatory target of 20% of energy originating from RES in the total EU energy consumption and a 10% target in the transport sector, by 2020. According to the directive, support must be given to decentralised RES technologies and local energy security while the development of renewable energy and increased energy efficiency should constitute two interconnected parameters [26]. Under the revised directive 2018/2001/EU, a higher binding renewable energy target of 32% until 2030 came into effect [27].

- The European directive on the energy performance of buildings (2010/31/EU) recognised the importance of the expanding building sector as it consumed 40% of the total energy consumption in the Union. Priority was given towards reducing and managing building demand whilst local and climatic conditions were taken into consideration. The individual member states are responsible of setting the minimum requirements for the energy performance of both new and existing buildings [28].

- The Energy Efficiency Directive 2012/27/EU introduced a legally binding target of 20%, regarding the energy efficiency improvement of the EU member states by 2020. The measures to achieve the mandatory target included building renovation, energy efficiency obligation schemes, energy audits and energy management. Furthermore, special focus was given on heating and cooling efficiency, building renovation, energy transformation as well as transmission and distribution [29], [30].

2.1.4 Buildings

The buildings and construction sector were responsible for 36% of the final energy consumption and 39% of energy and process-related CO_2 emissions, in 2018. Furthermore, the worldwide emissions from the building sector reached a record value in the same year, 2% higher than 2017 [31]. Regarding the breakdown of buildings and the construction sector in terms of the final energy consumption, residential and non-residential buildings were responsible for 22% and 8% of the sector, respectively, transport accounted for 28% and the construction industry itself had a 6% contribution, in 2018. The energy use of buildings reached the 120 EJ milestone value in 2013 and has been continuously increasing since then. Furthermore, electricity has been the most popular fuel throughout the period in question, used for approximately 30% of the 2018 energy consumption and followed by natural gas and biomass. Minor fuel participations can also be seen for renewables, commercial heat and coal. Efforts to increase energy efficiency in buildings have been continuous; however, they have not been sufficient as the population has been increasing as well, leading in floor area expansion needs and therefore in a higher overall energy demand. States around the world have been introducing new policies in an effort to innovate, further improve the energy efficiency of the sector and bring the emissions down [31].

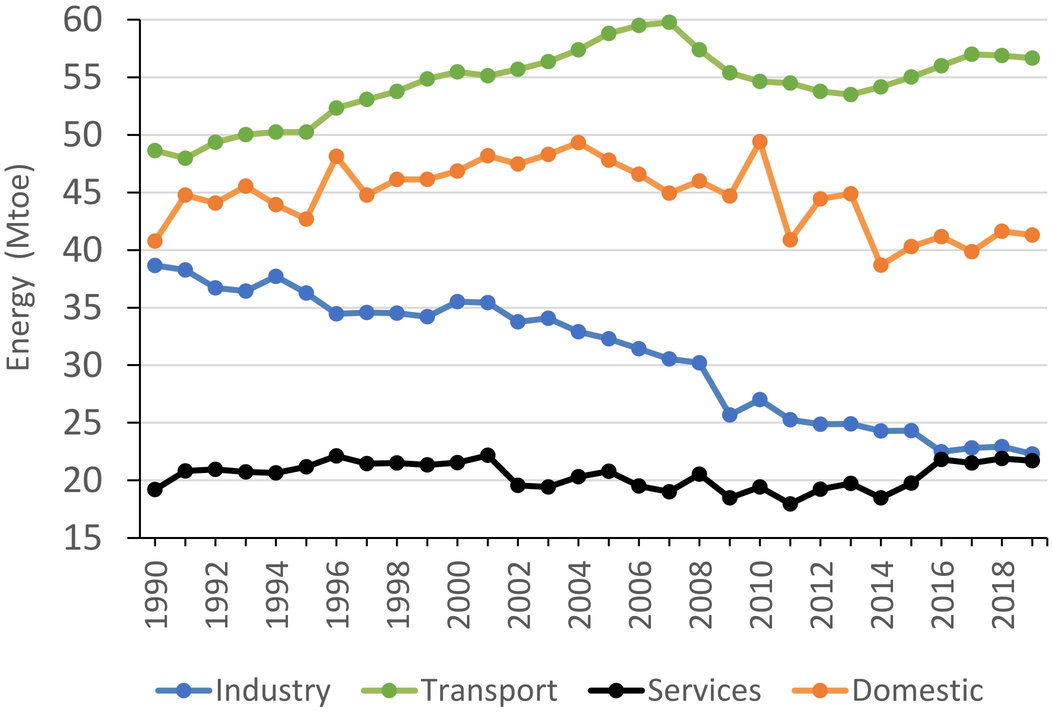


Figure 2.2 – UK Final Energy Consumption by sector between 1990-2019 (Adapted from [32])

Concerning the energy consumption of buildings in the UK, DBEIS do not classify buildings as a separate sector. More specifically, statistics are released every year for the Domestic, Transport, Industry and Services sectors. Therefore, residential buildings can be found in the domestic sector while services include commercial and public administration buildings as well as agriculture. The final energy consumption by sector in the UK is shown in Figure 2.2, between 1990-2019. It is clear that transport has been leading the charts with the domestic sector following second, having had received several variations throughout the years. Additionally, the energy consumption in the industrial sector has declined significantly, from 38.66 Mtoe in 1990 to 22.30 Mtoe in 2019, indicating that the UK economy has shifted away from the industry to a services-based economy, with both sectors consuming approximately 22 Mtoe, in 2019. Concerning commercial buildings, electricity has received a growing popularity, despite some minor reductions that have taken place since 2009, and remains the most popular fuel after surpassing natural gas in 1997. The reverse trends can be found for the public administration subsector with natural gas leading the figures since 1990 and electricity following second, since surpassing petroleum in 1997. Finally, regarding the domestic sector, natural gas is considered the undisputed leader with a consumption of 26,650 ktoe (65%) in 2019 while 8,927 ktoe (22%) were attributed to electricity, for the same year [32], [33].

Different numbers can be found in the literature for the energy-related activities of the building sector. According to [34], the sector is responsible for the 30 – 40% of the primary energy consumption in developed countries while the respective values for developing countries drop to 15 – 25%. In the United states of America (USA), buildings account for 40% of the primary energy consumption and consequently for 40% of the total carbon dioxide emissions, half of which take place in the domestic sector (21% and 20%, respectively).

As highlighted by [35] and mentioned above, regarding their classification by DBEIS, buildings are not usually recognised as a separate sector by energy agencies and organisations and therefore their energy consumption can be approximated by aggregating certain subsectors. While this methodological oddity has resulted in inaccurate estimations towards the quantification of the buildings' final energy consumption, it is clear that buildings and their several types are responsible for a major slice, in the energy consumption pie. In the EU, energy consumption of the building sector has increased overall by 1% per annum since 1990 and more specifically, 1.6% per annum for non-residential buildings and 0.6% for dwellings. Commercial buildings in the USA are responsible for 46% of the entire sector's energy consumption, with 55% of this consumption originating from electricity. It is also pointed out that end-uses of energy in commercial buildings vary significantly depending on the location, e.g. in China, there is a focus on lighting and office equipment loads while heating, ventilation and air-conditioning (HVAC) applications, especially space heating and cooling, are more important in the USA.

It is estimated that non-domestic buildings contribute towards 25% of the European building stock's energy consumption while the wide variety of the activities taking place result in a highly heterogeneous building sector, especially when compared with the domestic sector. Additionally, they consume 55% more electricity in kWh/m^2 than domestic buildings with the percentage varying geographically as different values can be found in EU countries [1].

Li et al. [36] highlighted the significance of the building sector as a key component of the energy system and the total energy use, globally. The sector's final energy consumption is estimated around 31% worldwide, with percentages varying regionally between 22 and 57%, creating challenges for sustainable development as a result of the increasing amount of emissions and air pollution. At the same time, the rapid rates of urbanisation and climate change have led to a constant growth of the sector's energy consumption, especially through the increasing temperatures, extreme weather events and the urban heat island effect. The authors highlighted the need for a better understanding of buildings' energy spatiotemporal patterns and environmental impacts, particularly for scientists and parties involved in the decision-making process. Moreover, a variety of factors affect the sector's energy consumption, including ambient temperature, building design, occupant behaviour and performance of the embedded systems, such as HVAC and lighting.

Harputlugil et al. [37] focused on the interaction between buildings and occupants supporting that as an increasing amount of people spend their time indoors, the need to reduce the energy demand of the building stock is getting stronger. It is quoted that "*contrary to general belief, buildings do not consume energy: people do*", pointing out that occupant behaviour is often either ignored or not well-understood as an element of the built environment. This is of critical importance, especially since occupants can have a significant impact on a building's energy footprint through the HVAC system and consequently affect its thermal performance.

Finally, according to [38], commercial and institutional buildings also carry a symbolic meaning by representing the socioeconomic status of any country. Besides being responsible for a significant portion of the energy consumption and the consequent carbon emissions, the building sector also consumes 25% of water and 40% of the world resources. Therefore, it is vital to improve the energy efficiency of existing operational buildings as a way to mitigate their environmental impact. In this way, the amount of primary energy required is reduced along with the CO_2 emissions. The idea behind improving buildings' energy efficiency is simple: utilise smaller amounts of energy for the same operations, such as lighting, heating and cooling, without compromising the thermal comfort of the occupants. Legislation and building standards have focused on the construction of energy efficient and sustainable buildings; however, as new buildings constitute only a small percentage of the entire sector, particularly in developed countries, improving existing buildings is of paramount importance.

2.1.5 Energy Trilemma

Back in 2006, the European Commission had identified in its Green Paper the importance of a common European energy strategy that should have the three main objectives of sustainability, competitiveness and security of supply. At the same time, the EU member states were urged to take all the necessary actions as a considerable amount of time is required to bring innovation in the energy sector through a long-term commitment [39].

Today, energy sustainability is based on three main parameters and more specifically on energy security, energy equity and environmental sustainability. According to the World Energy Council, these three parameters constitute the energy trilemma, as illustrated in Figure 2.3. Achieving all the energy trilemma components is a complicated process with interconnected links that involve a significant number of participants, including private and public entities, administrations, regulators, socio-economic factors and environmental concerns. It should be taken into consideration that decarbonisation, digitalisation and decentralisation are the main three drivers of the energy sector transformation, offering new opportunities to advance on the energy trilemma [40].

As [41] supported, the three energy trilemma competing forces represent different disciplines and more specifically politics, society and the environment, respectively. The authors recognised that there is no perfect solution for solving the energy trilemma equation while society should focus on balancing these three aspects of the energy policy instead of prioritising economics over the environmental impacts, a common practice in many countries. A revised version of the Energy Trilemma was presented by [42] and includes a triangle consisting of four smaller triangles that represent energy finance, energy law & policy, energy security and the environment.

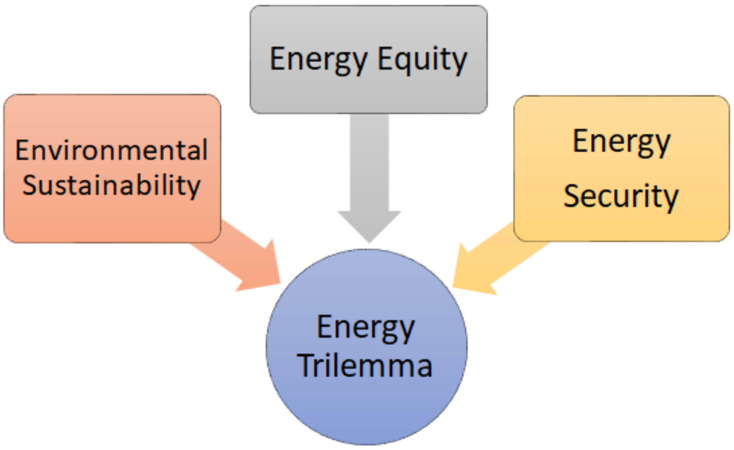


Figure 2.3 – The Energy Trilemma

Energy law and policy is placed in the centre of the larger triangle with the remaining components constituting the three vertices. In this way, the complexity of the issue and the interconnection of all the different variables is highlighted. According to [43], addressing the energy trilemma would affect directly the effectiveness of climate change mitigation initiatives but this will take place in a different way and under unique conditions, from country to country. Energy poverty is often examined as a separate field of study along with energy affordability.

Progress on a suitable energy policy is often impeded by complex regulations while any suggested changes generate difficult negotiations amongst several parties, such as energy generators, distributors and politicians. The circumstances and challenges differ from country to country, but the common problem lies indeed around balancing the energy trilemma [44]. For example, on the Energy Trilemma Index 2022, the top five countries with the highest overall index and balance score were Sweden, Switzerland, Denmark, Finland and the UK. However, a high overall index is not necessarily translated to high performance scores of the three specialised indices. It is noted that the UK's energy system highly depends on natural gas but its energy security is not affected due to the lack of reliance on Russian imports [45].

The three dimensions of the energy trilemma are of different and contradictory nature; however, in order to meet the diverse energy challenges in different countries, it is essential to execute through these dimensions. As [46] pointed out, *"the improvement rate in trilemma achievement generally increases along with energy transition improvements in all three dimensions*". The energy transition is bringing for the first time changes of a significant degree, on a worldwide scale, for the energy network.

2.1.6 Energy Transition

The decarbonisation of modern society and its economic growth depends on innovative energy technologies. This was recognised by the establishment of the European Strategic Technology Plan (SET-Plan) which aimed at promoting certain low carbon technologies, boosting relevant research and development (R&D) and demonstration projects and pushing in this way towards their rapid commercialisation. To achieve a sustainable European energy system by 2050, the importance of several energy technologies is recognised, such as photovoltaic solar electricity, wind energy, biomass power generation, carbon capture & storage (CCS), marine energy, fuel cells & hydrogen and electricity storage technologies. As the EU objectives include the reduction of the GHG emissions by 80-95% by 2050, a significant transformation of the energy system throughout Europe is necessary, especially the power sector with major structural reforms required [47].

As [48] supported, after the Paris agreement priority should be shifted from raising climate change related awareness towards forming a sustainability transition for a desirable future. The authors highlighted the need to transition from fossil fuel to renewable energy and a low carbon world while it is pointed out that sustainability transition is a notion referring to the energy transition mechanisms at play. In this direction, transition management is a common perspective in the sustainability transition debate. According to [49], the relationship between technological and regulatory advancements will be critical for the energy transition in Europe while any agreed principles have to be implemented in three different levels of governance, and more specifically the national level, the cross-national level that involves the cooperation mechanisms of a certain number of member states, and the EU level.

In 2018, [50] reported that several energy sectors around the globe were at a critical juncture, on a path towards a sustainable future. There is also the mention of the relevant trilemma amongst sustainable, affordable and secure energy, previously mentioned in section 2.1.5. In addition, technology is considered as the key driver of the transition to a low carbon energy system. Electric energy storage is highlighted as an emerging and promising technology capable of integrating renewable and conventional energy sources into the same system by removing any temporal constraints between energy production and consumption. On the other hand, there are high costs associated with the technology and therefore a proper assessment is needed to identify the economic benefits of its utilisation. Finally, for a successful energy transition, the energy markets and the respective regulatory framework and energy-related policies will have to react to the energy challenges by changing, evolving and adapting, accordingly [50].

According to [51], the energy transition has been leading to an energy system with lower carbon emissions while the pressure on the electric power systems, and the electric sector in general, in Europe, and in several other parts of the world, has been significantly increasing. Instead of the conventional large power plants based on fossil fuels that transmit energy through long lines and high voltage, the future grid is expected to focus on decentralised energy generation such as wind and solar power, as well as energy storage. The authors pointed out that here is going to be a growing interlink of the electricity sector with other critical parts of the infrastructure and the energy system, rendering electricity much more important for modern and future economies. This interlink can be achieved through the appropriate Information and Communication Technologies (ICT) to enable an efficient and at the same time intelligent utilisation of energy.

2.1.7 The Future Energy System

It is clear that the future energy system will be fundamentally different. Despite that there are still a lot of uncertainties around the necessary changes, decarbonisation is expected to be achieved through the inclusion of large amounts of intermittent renewable energy into the energy network. The Smart Energy System, a concept towards a 100% renewable energy scenario in the EU by 2050, proposes the integration of all energy-related sectors in order to introduce flexibility that is not reliant on fossil fuel. Figure 2.4 demonstrates the Smart Energy System approach, and all the interactions present among resources, energy conversion and the end-use energy demand. Wind, solar energy and bioenergy are of fundamental importance while electrical and thermal storage are required in order to mitigate the issues of fluctuating electricity and heat. Additionally, electric vehicles are present as part of the transport sector while heat pumps play a major role towards the electrification of heating and cooling [52].

A significant part of the transport sector is expected to be electrified. However, energy-dense fuels will still be required for bigger vehicles such as airplanes, ships and lorries. Biofuels could fill that particular gap but at the same time it is extremely important to ensure that sufficient amounts of biomass are available. In this direction, renewable synthetic fuels, electrofuels, are utilised [53].

Connolly et al. [52] expected nuclear power plants to be removed from the energy mix, in the long term, because of the associated political, environmental, financial and security concerns as well as the nuclear waste issue. It is pointed out than an energy system largely based on renewables cannot be easily combined with nuclear power due to its lack of flexibility. Finally, the authors also highlighted that the structure of the present energy system is relatively simpler with a lower number of interactions between the different sectors and segregated energy branches. The future smart energy system will introduce unique benefits from the integration of all the different sectors, as presented and discussed above. In both studies, the authors acknowledge the fact the future Smart Energy System can differ from Figure 2.4 due to economic uncertainties, technological barriers, implementation challenges and other important limitations, always present when modelling in the long-term and especially up to the year 2050.

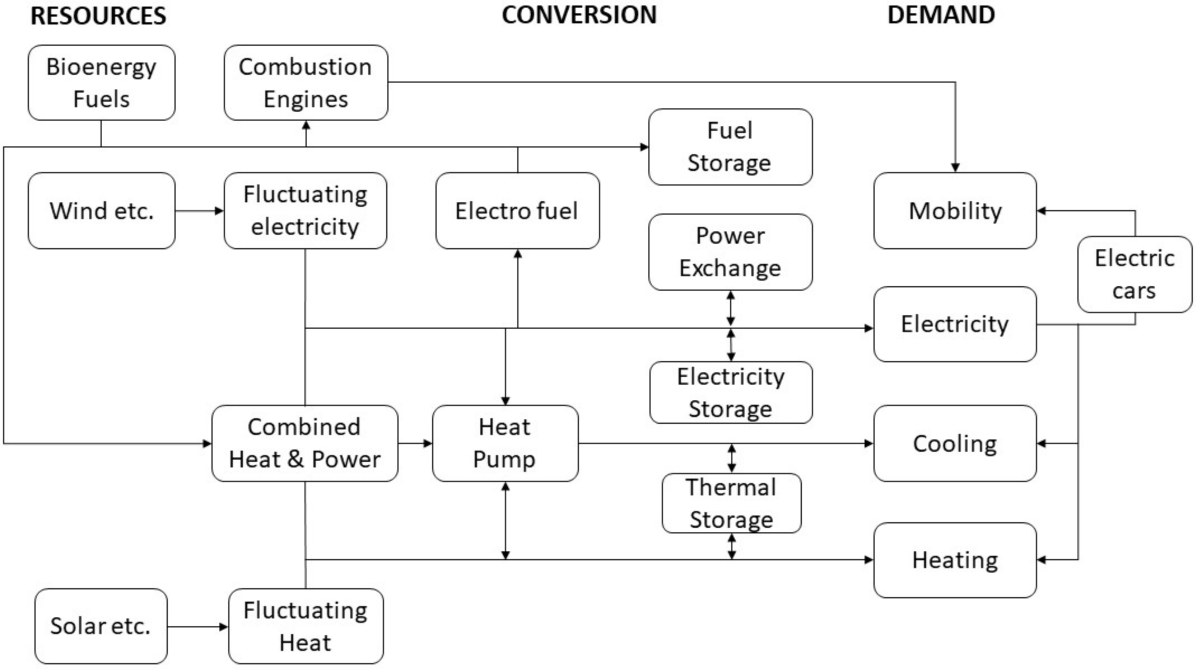


Figure 2.4 – Interactions between sectors and technologies in a future Smart Energy System (Adapted from [53])

Regarding the European transition of the future energy system, the electricity system must be prepared for the integration of an increasing number of renewables. The European electrical grid is close in accomplishing a structural change that includes higher levels of digitisation and decentralisation. Further work is needed to achieve this target at the distribution scale with a multi-level architecture for data exchange and power flows and successfully integrate different parts of the network, particularly transmission, distribution, smart buildings and microgrids [54].

Additionally, the EU should invest in low-carbon technologies towards growth and the decarbonisation of the economy, especially in renewable energy, energy storage, CCS or carbon capture & utilisation (CCU), energy efficiency in the building and the industry sectors. The energy system should be considered as a whole while focus must be given on the integration of its components through smart grid systems and smart solutions. The need for further innovation and research on batteries, bioenergy and renewable fuels is highlighted by [54]. The promotion of policies for the decarbonisation of the industry and buildings is necessary while recognising that there are significant challenges towards that direction. The industry is already considered to be among the most efficient energy sectors, facing mostly technical challenges and process non-energy emissions. Solutions could include enhanced recycling of materials and guaranteeing carbon prices for specific industries. Regarding the building sector, efficiency targets have proven to be difficult to achieve. Buildings need to be refurbished at a faster rate while refurbishments should specifically target deep energy demand reductions [54].

Regarding the UK, [55] supported that uncertainties around nuclear power, CCS, bioenergy, electricity generated from renewable sources and demand-side changes would have a significant impact on long-term decarbonisation pathways of the future energy system. It is claimed that natural gas has a very broad range of demand across all the different scenarios while there are cost-effective solutions to replace the UK nuclear power sector with other low-carbon electricity generation systems. The availability and utilisation of certain technologies will also have an effect on other technological options, a mechanism coined by the authors as "*complementarity and substitutability of technologies*".

Similarly, [56] investigated the technical interdependency in the UK's transition to a low-carbon energy system. For the building sector, electrification will be competitive with district heating and tied to building retrofit and thermal storage in order to deal with peak demand and the intermittent nature of the power supply.

Finally, the transition of the power networks from fossil fuels to low-carbon technologies, especially RES, will eventually lead to heat and transport electrification by 2040. Despite the fact that wind and solar photovoltaic power systems can already complete economically with conventional fuels and the associated costs, their power output is dependent on the weather conditions and therefore their contribution of electricity into the power network might vary over time and from region to region leading to intermittency of power supply [57]. It is argued that a future UK power network based exclusively on RES could experience important operational issues with imbalances between supply and demand and consequently stabilisation issues on the network frequency. Furthermore, an increasing electricity consumption would have uncertain ramifications for the stability of the network and would potentially require an expansion of the electrical network infrastructure. Significant research is currently conducted that follow multi-vector energy network and Integrated Energy System approaches to address the rising challenges [57]. Modelling the future energy system requires challenging interdisciplinary research that can be complicated and messy, urging for pragmatism to be included in innovative energy economy models [58].

2.2 The Electrical Grid: Present and Future

2.2.1 Introduction

The modern electrical grid is based on alternating current (AC) that is used to convey electricity over long distances by increasing the voltage levels through transformers. The electrical network was originally designed and built between the 1930s and the 1970s and it still relies on aged power equipment and infrastructure. However, it now constitutes the largest single network in the world, incorporating various levels of complexity and designed to be one-way systems that deliver AC power from large power stations to load centres. Infrastructure expansions have gradually stopped in the western world and developed economies since the 1970s; however, during the same time, significant grid investments took place in developing countries, such as China and India [59].

Also, in the recent years, an increasing amount of renewables, distributed power networks and microgrids have penetrated the aging AC power grid. More than a century after its domination in the power sector, AC now faces serious decarbonisation challenges and renewed competition from direct current (DC) over longer distances [59]. The electrical grid has become an increasingly complex system in which the electricity demand has been continuously growing, resulting in grid reliability, sustainability and environmental issues. All these reinforce the need for the transition to an intelligent grid, commonly known as the smart grid, which is capable of making complex decisions and functioning adaptively and interactively with all the grid elements. This is in contrast with the traditional monodirectional approach where centralised generation is followed by electricity transmission and distribution up to the end user [60]. A detailed comparison between the current conventional and the future smart grid will follow, later in this chapter. In the new Post Carbon Society, the four necessary pillars of energy systems are:

- Renewable Energy
- Buildings as power plants
- Energy storage
- Smart grids and plug-in vehicles

It is clear that the transformation of the current inflexible conventional electrical grid to the future smart grid will be both a requirement and a characteristic of the future energy system, as previously mentioned. Nevertheless, it is important to point out the very close relationship, co-dependence and interdependence of these four pillars which will require financial, political and public support as well as technological, societal and behavioural changes [61]. Therefore, the electrical grid needs to fully integrate renewable energy, buildings and plug-in electric vehicles. Energy storage also has to be integrated into the system; however, at the same time, it acts more than a simple network component by helping towards the integration of other parts of the network into the smart grid.

2.2.2 Renewable Energy Sources and Intermittency

Traditional base load-power from conventional fossil fuel, nuclear power stations and geothermal energy introduces inflexibility and does not allow the system to adapt to any load variations. As mentioned above, the electrical grid was not built to incorporate high amounts of intermittent and variable electricity sources like solar, wind and wave power [62]. The intermittency issue is very challenging due to the fact that renewable energy is currently considered one the most attractive options towards achieving sustainability, energy security and decarbonisation.

Because of their stochastic nature and consequent uncertainty around their temporal and spatial output characteristics, the grid operators are not able to control the output originating from RES and therefore scheduling and distributing their energy is not as flexible as with the traditional electric generators such as thermal power plants and hydropower. As this RES generation is random and cannot be controlled or scheduled, it has the potential to introduce frequency and voltage fluctuations which can consequently affect the balance and the stability of the network. This is the reason that renewable flexible capacity is of critical importance [63]. More specifically, voltage fluctuations are an important issue as they affect the overall power quality, especially in high penetration levels of renewable sources. For example, when a large wind turbine is connected to a weak distribution network, voltage variations might take place, especially during the starting and stopping process [64].

Zappa et al. [65] pointed out that a power system based on 100% renewables is not feasible even when RES supply is deployed at sufficient amounts because of their intermittency and variable output that can potentially lead to imbalances between electrical demand and supply, a problem not encountered in systems based on conventional fossil fuel. An electrical grid consisting only of 100% RES must use dispatchable renewable technologies, such as hydro, geothermal, bioelectricity as well as energy storage, in order to rectify this issue and satisfy any unmet demand. At the same time, there are limitations both in the short and the long term that have to be taken into account. Regarding the first category, these dispatchable RES come with technical constraints that affect their reaction time; therefore, they might not be able to provide supply within the required time frame to keep the system balanced. In the long term, it must be acknowledged that variable RES, especially wind and solar, cannot generate the same amount of electricity annually. Consequently, an assessment towards designing a 100% RES system must address both the short and the long-term reliability issues. It is worth mentioning the definition of the grid reliability as adopted by the authors: *''the ability of the power system to deliver electrical energy to all points of utilisation within acceptable standards and in the amounts desired''.*

On the other hand, [66] argued that the existing electricity generation and energy storage technologies can be successfully used for an uninterrupted operation of the power network. The stochastic nature of RES is expected to create challenges for the stability of the system due to the overall "lower physical inertia" and potential differences between supply and demand. Nevertheless, this can be resolved by integrating synthetic inertia through the implementation of the appropriate power algorithms which should take into account the RES power output and the availability of energy storage. The authors included a number of key technologies that could play a major role in achieving a 100% renewable electricity system by 2050. Solar photovoltaics, wind turbines, hydro, geothermal and biomass are included for power generation while solar thermal, electrical heating and heat pumps are mentioned for heating purposes. Concerning storage, there are four battery types considered based on their size: utility-scale, residential, commercial and industrial with all but the first being used to enable components of the network to become prosumers. Pumped hydro and hydrogen storage are also mentioned.

There are mixed opinions regarding hydrogen and its future as part of the electrical grid in the context of integrating RES and as an energy storage solution, in general. Storing large amounts of power with hydrogen could be problematic given the relatively mediocre efficiency when producing hydrogen from electricity (~65%). When taking into account the energy losses associated with the compression, pumping/tanking, storage and later utilisation of the hydrogen, only 25% of the initial energy can be used e.g. by a fuel-cell powered vehicle. In fact, this figure could be considered to be high and in practice the real value could reach efficiencies of around 10% [67].

On the other hand, [68] argued that several successful hydrogen-related case studies have taken place, highlighting that power-to-power hydrogen storage proved to be less expensive than batteries in a 100% renewable Californian electric power subsystem. It was demonstrated that residential buildings with high energy efficiency could become self-sufficient by utilising solar panels and hybrid hydrogen home storage systems, reducing the annualised costs by up to 80% when compared to lithium-ion (Li-ion) batteries leading to a cost-effective and decentralised energy autonomy.

Furthermore, power to hydrogen (P2H) is mentioned as another solution with significant potential, taking advantage of any excess electricity generated by renewables such as wind turbines and converting it to hydrogen though electrolysis. In this way, P2H could be used to control the demand profile and contribute towards the stability of the electrical network. However, there is uncertainty regarding several parameters of the involved energy systems making difficult to conduct a risk analysis; therefore, several methodologies have been proposed [69].

As increasing amounts of variable RES are deployed and become increasingly a significant part of the grid, balancing supply and demand will be dependent on demand response (DR) and energy storage. In this direction, any feasibility studies on future grids must include DR while utility storage and flexible generation will be critical towards achieving a balanced grid. Distributed generation such as rooftop photovoltaics combined with small-scale battery storage are expected to be popular in future power systems [70].

Similarly, [71] investigated the role of renewable energy in the global energy transformation and highlighted that future power systems consisting of 85% RES will include significant amounts of intermittent sources, especially photovoltaics and wind, making the utilisation of flexible dispatchable power, transmission interconnections, energy storage and demand-side management necessary for the stability of the network. The deployment of the smart grid and its innovative digital technologies will be crucial and additional measures will be needed, including market reform, new business models and operational practices. The authors concluded that the four innovation trends for the future power system are digitalisation, decentralisation, flexibility and electrification of end use. Electrification is expected to be an important area that will provide synergies between RES and energy efficiency while it has the potential of coupling the two sectors, enabling further the integration of renewable energy in the electrical grid.

According to [72], due to the intermittent properties of renewable generation and more specifically the variation of solar radiation and wind speed, their participation in the electricity network will increase uncertainty; therefore, specific measures need to be taken in system design and installation. The authors highlighted two solutions in order to balance the network: standby power generation plants based on traditional fossil fuel and electricity storage. However, both options have disadvantages as fossil fuel plants are inefficient when operating on various capacities that differ from their regular operating point while electrical storage is expensive, and losses take place because of the roundtrip efficiency. Academic and industrial research can be divided in two categories when it comes to their approach for the integration of RES into the grid. The first category focuses on the design and structure of the electrical grid, particularly on the locations of key parameters such as generators, energy storage and their interconnecting transmission network. The second one considers the design of the grid to be fixed while focusing on optimising the operational decisions of the network that involve electricity generation and transmission as well as energy storage utilisation for a given time period.

Finally, [73] supported that the conventional electrical grid needs to be improved in order to cope with the increasing amounts of photovoltaics and the intermittency of RES introduced into the system. Energy storage is considered a disruptive technology, technically speaking, that has the potential to act as an energy buffer, transform the energy supply mechanism for end-users and improve system stability. Therefore, intermittent RES with different generation properties can be coupled with battery storage in order to enable the transition from the current traditional grid to the future smart grid.

2.2.3 Electrification of Heat

In 2013, the UK Government published the report "The future of heating: Meeting the challenge", highlighting the fact that half of the final energy in the UK was used for heating purposes, either for buildings or the industrial sector. Therefore, the transformation of building-level and industrial heat is a requirement towards achieving high levels of decarbonisation, as set out in the UK Climate Change Act 2008 [74]. For the building sector, it is essential for the heat demand to be reduced while promoting energy efficiency and decarbonisation of heating and cooling supply. Options include improving the buildings' thermal efficiency through thermal insulation and replacing fossil-fuel powered boilers with alternative technologies, such as heat pumps, solar thermal and biomass boilers. Heat pumps will constitute an increasingly effective and convenient method towards decarbonising the heat supply, both for heating and cooling purposes. As heat pumps utilise heat originating from the environment, they are considered as renewable heat sources [75].

In the EU, the heating sector is responsible for 50% of the total energy demand, 75% of which is met by fossil fuels. Additionally, in 2017, only 10% of the global heat demand was covered by renewables. Nevertheless, as increasing amounts of RES are used for electricity generation, renewable electricity is a reliable option with great potential for decarbonising the heating sector. In this direction, heat pumps and other devices can be used towards the electrification of heating. Heat pumps utilise electricity to convert energy from a variety of sources, such as air, water and the ground, to heat that can be used for space heating as well as hot water supply, in both domestic and commercial buildings. They can successfully integrate intermittent RES into the electrical grid and are considered to be among the most energy efficient and environmentally friendly technologies. In 2019, heat pumps were responsible for just 3% of the total building heating demand, worldwide. However, their popularity has increased significantly in the recent years as it is recognised that their utilisation will reduce GHG emissions and consequently contribute to the energy transition to a sustainable future. Performance varies based on the heat pump technology such as air source (ASHP) and ground source heat pumps (GSHP) [76].

According to [77], the electrification of the heating sector will impact the future energy consumption profiles. The increasing amounts of distributed generation from renewables, especially photovoltaics, will also act as an additional driver towards heat electrification. The literature also makes special mention of heat pumps for their capacity to manage intermittent RES which can be further enhanced when combined with energy storage. Finally, heat pumps can potentially link electrical grids and district heating networks, leading in the establishment of an integrated smart energy system. Therefore, they are considered as key technologies that will enable the transformation and decarbonisation of thermal energy.

Regarding the use of heat pumps in the UK and the EU, most of the scenarios estimate that heat delivered by heat pumps will increase significantly by 2030 or 2050 and the popularity of district heating networks will grow in areas not massively served by heat pumps. It is important to mention that these projections concern not only residential, but also commercial buildings. It is supported that other technologies, including district heating, are reliable and competitive heating options; however, heat pumps are expected to play a major role and constitute part of the solution towards a low carbon future [78].

Two UK mechanisms have promoted the usage of renewable heat technologies towards the reduction of carbon emissions: Domestic Renewable Heat Incentive (DRHI) and the Non-Domestic Renewable Heat Incentive (NDRHI). Eligible technologies for the first category include biomass boilers and pellet stoves, flat plate and evacuated solar thermal panels as well as ASHPs and GSHPs. There are specific technical requirements for all the systems, such as a minimum seasonal performance factor (SPF) of 2.5 for both heat pump types. DRHI provides payments every three months for 7 years, for every kWh used towards space heating or domestic water heating while NDRHI provides payments for 20 years [79], [80]. DRHI and NDRHI are closed to new applicants as of 2022 and 2021, respectively [81], [82].

The future role of heat pumps was further reinforced by [83] who summarised key stakeholder publications regarding the future of heating. In particular, electrification of heating and decarbonisation of the electricity supply is mentioned in several studies while the role of heat pumps varies per scenario, depending on the mix of the technologies that will prevail. While the extent of their usage cannot be fully predicted, heat pumps are undoubtedly expected to be a part of the solution towards heating electrification.

2.2.4 Electric Vehicles

The decarbonisation of the transport sector is expected to take place with the help of low-carbon footprint technologies, especially plug-in hybrids (PHEVs), battery electric (BEVs) and fuel-cell powered vehicles, while advanced biofuels will constitute an additional option. Electricity is anticipated to have an increasingly significant role in the following decades when it comes to road transport [84]. In 2019, the popularity and market share of BEVs differed in Europe with some countries taking the lead, such as Norway (42.4%), Netherlands (13.9%) and Iceland (7.8%). The mean market share of BEVs was 2.3% in EU and EFTA countries [85].

BEVs are considered to be the most reliable option for the future. However, their high capital cost is associated with the battery cost and it is seen as a significant factor that impedes the market penetration of electric vehicles. The continuous reduction of battery costs are highly encouraging as between 2007 and 2014, they dropped 14% per year, from $1000/kWh to $410/kWh, approximately. In 2017, the costs were between $155 – 360/kWh while it is predicted that they will further decrease between $100 – 122/kWh, in 2030. The UK market sales of hybrid and battery electric vehicles were 1.7%, 2.1% and 2.7% for the years 2017-2019. Despite the fact that their percentages are low, they are increasing. Based on the literature, consumers are worried about the availability of charging infrastructure and the battery range [86]. The adoption of EVs is seen to accelerate from 2024 onwards with people having access to home charging more likely to buy one [87].

The International Energy Agency (IEA) forecasts that, in 2030, the global electricity demand from the electric vehicle feet is going to reach 551 TWh under its Stated Policies Scenario while the respective demand for the Sustainable Development Scenario is expected to be 979 TWh. There are different assumptions taken into consideration but it is worth comparing the two forecasts value with the 2019 historical global electrical EV demand, which was just 79 TWh [88].

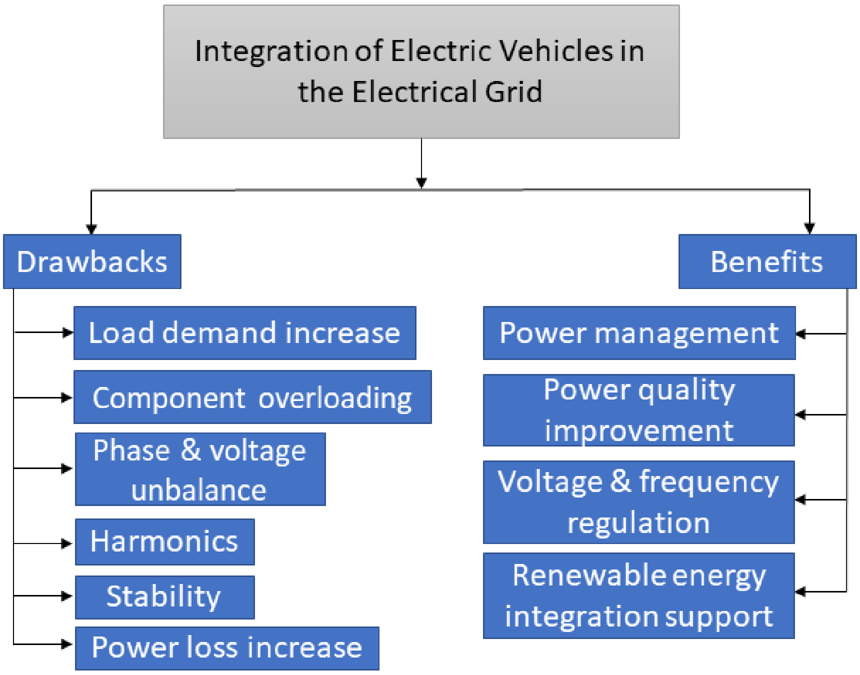


Figure 2.5 – Integration of Electric Vehicles in the Electrical Grid: Benefits and Drawbacks (Adapted from [89])

Regarding the integration of the electrical grid with electric vehicles, until recently, their linkage was insignificant. However, the situation is rapidly changing, and the growing electrification of the transport sector is no longer compatible with the traditional business models adopted by the power sector. In fact, it will put pressure on the grid infrastructure as the EVs have the potential to affect the network's load profile. Figure 2.5 lists both the advantages and disadvantages of the EV integration in the electrical grid. In more detail, when it comes to the advantages, EVs can assist towards the integration of RES, acting as energy storage devices and renewable energy buffer to reduce emissions and costs. Through scheduled charging and discharging, EVs can improve power management and the electrical peak demand can be met by scheduled discharging during the peak hours. Also, they can provide frequency regulation by keeping the frequency of the AC grid constant at 50 or 60 Hz as well as voltage regulation by exchanging reactive power. On the other hand, there are critical drawbacks and challenges as it has been previously mentioned that the wide adaptation of EV technology can lead to a significant load demand increase for the power sector. Furthermore, as the EV loads are nonlinear and require large amounts of electricity in a short time period, they have the potential to lead to power instability. Harmonics injection can also take place through the generated harmonics by the EV chargers' electronics [89].

There is an increasing amount of interest regarding EVs as promising alternative energy sources for stationary applications. In more detail, it is supported that they can constitute virtual power plants in order to either charge their batteries or sell any excess electricity when not in use. In this way, EVs can reliably provide power supply to consumers, such as buildings, and the electrical grid, contributing to its flexibility, efficiency and balance. Virtual power plants consists of several grid-connected distributed power generation and storage units, including RES. A potential integration of EVs with virtual power plants could introduce flexibility to the grid, supply additional electricity and therefore stabilise demand, for example by providing electrical energy at times of peak demand in buildings through the utilisation of bidirectional converters. Therefore, integrating EVs to the grid could be a pragmatic economical strategy for the energy sector and the grid [90].

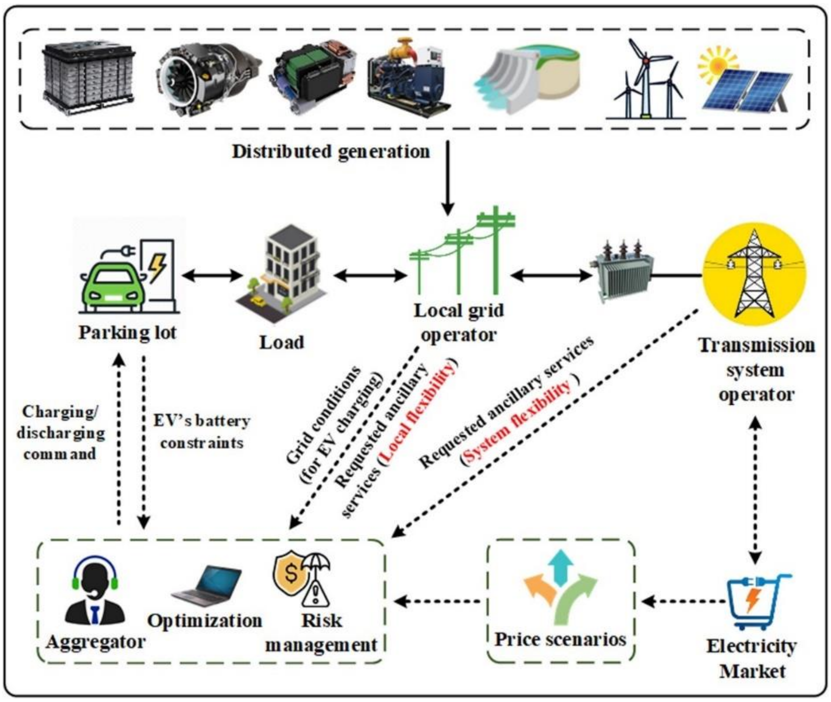


Figure 2.6 – Smart charging of electric vehicles in power systems. Reproduced with permission from [91]. Copyright 2022, Elsevier.

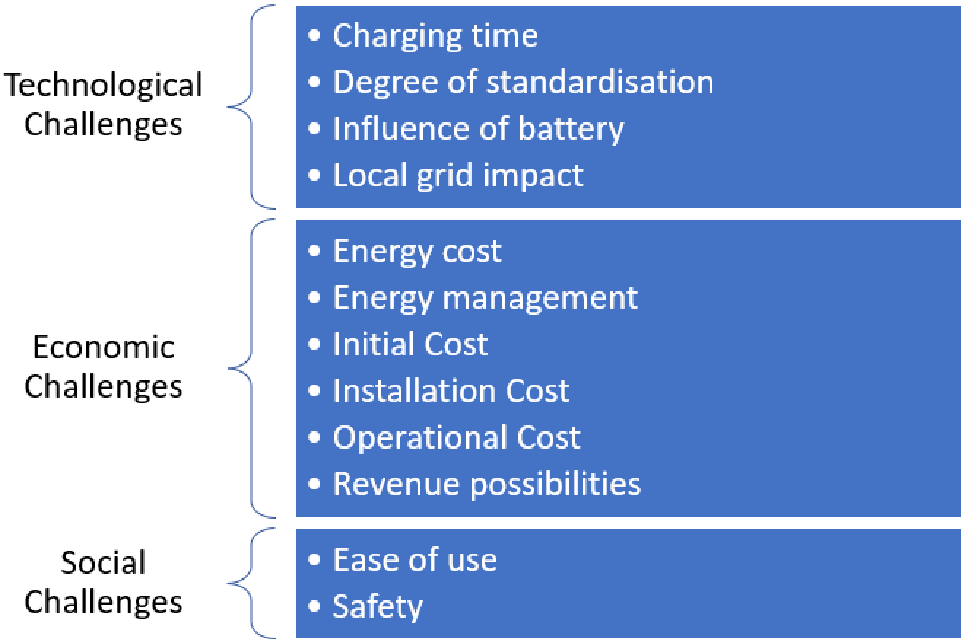


Figure 2.7 – Challenges related to smart charging of EVs (Adapted from [91])

EV batteries can be considered to be large-scale distributed energy storage and they can bring significant benefits to the electrical network through smart charging. More specifically, their potential role is demonstrated in Figure 2.6 where it can be seen that EVs can provide services to the grid. For bidirectional power exchanges to be possible, vehicle-to-grid (V2G) and grid-to-vehicle (G2V) detailed dispatch strategies are required. V2G refers to the EVs providing (ancillary) services to the electrical grid e.g. during hours of peak demand (peak-shaving) while G2V is about charging EV batteries and meeting their needs e.g. in times of low demand (load valley filling). These are only a couple of services that can take place with others being voltage support, reduction of power losses etc. It is worth highlighting that there are significant grid-related challenges of technical, economic and social nature that are summarised in Figure 2.7. Concerning the critical technical challenges, increasing demand arising from the need to charge a growing number of EVs could result into expensive power generation solutions such as gas turbines and congestion of lines and transformers while having a negative impact in the overall operation control of the network. Furthermore, as current power networks at the distribution level are not designed to be bidirectional, EVs could potentially be used to meet local loads. Finally, while EVs could enter the electricity market with the potential to diversify them, suitable financial motives will be needed to convince EV owners and users to participate in price-based schemes; there is a currently an absolute lack of policy or any pricing mechanism [91].

2.2.5 Electricity Market in Europe

Electricity constitutes one of the most regulated sectors of the economy, including ownership, entry conditions, tariffs and quality standards. However, there has been a huge liberalisation process for the last thirty years, transforming the entire industry and introducing competition and incentives for innovation. Deregulation led to privatisation of utilities, the creation of an independent regulatory authority, third-party access to transmission and distribution systems infrastructure and new competitors entering the market. Marino et al. [92] supported that a reduction on deregulation intensity following major reforms has a negative impact on innovation while the main market parameter affecting innovation is the degree of contestability, the difficulty level under which a firm can enter or leave the market. Countries able to accelerate their liberalisation process will benefit from an increasing production efficiency as well as price reductions. On the other hand, staying behind will hinder gains stemming from innovation and will lead to a less efficient electricity market.

In 2006, Electricity Regional Initiative (ERI) were launched by the European Regulator’s Group for Electricity and Gas (ERGEG). ERI, consisting of seven local directives, was conceived as a way to transition to a pan-European electricity market, often termed as Electricity Market Target Model (EMTM). EMTM is based on the idea of Market Coupling that includes two types of coupling. Volume coupling is possible by the *'coordinated utilisation of available interconnection capacity*' while price coupling is more sophisticated as both price and volume coordination between different countries are required. The majority of ERI made important progress in integrating electricity markets that were part of each initiative. The most characteristic example was the ERI for Northern Europe, Nord Pool Spot, the first market in the world where electricity was traded in 2002 among four Scandinavian countries. The major wholesale electricity markets in Europe are presented in Table 2.1. It is interesting to point out that Great Britain is the only country in the continent participating in three power exchange markets (PXs) while the rest of Europe has a maximum number of two PXs. Finally, the EPEX Spot day-ahead auctions also include Austria and Switzerland [93].

ERI developments led to market mergers and cooperation between different states. For example, in 2015, EPEX SPOT and APX Group integrated their business in order to create the Power Exchange for Central Western Europe and the UK. The company mentioned that the integration in question would further decrease obstacles in power trading by enforcing common rules for the entire region, common admission process and harmonised trading systems [94]. NordPool is currently the leading power market in Europe, as a Nominated Electricity Market Operator (NEMO) in 15 European countries, including the UK, with 360 companies from 20 countries currently trading on its day-ahead and intraday markets. It is worth mentioning that 120 TWh of electricity were traded in the UK day-ahead market, only in 2018 [95].

Table 2.1 – Major wholesale electricity markets in Europe [93]

Country	**Power Exchange**	**Markets**	**Physical Trading**			**Financial Trading**	
			Day ahead	Intraday continuous		Future	
			Auction	Spot	Prompt	Base	Peak
Great Britain	APX-ENDEX	APX Power UK	✓	✓	✓		
		ENDEX Power UK				✓	✓
	N2EX	N2EX	✓	✓	✓	✓	
	ICE	ICE				✓	✓
Nordic Countries	NordPool	NordPool Spot	✓	✓			
		NASDAQ OMX			✓	✓	
France & Germany	EPEX	EPEX Spot	✓	✓	✓		
	EEX	EEX Power Derivative				✓	
Netherlands & Belgium	APX-ENDEX	APX POWER NL	✓	✓			
		ENDEX POWER NL				✓	✓
		Belpex	✓	✓			
		ENDEX POWER BE				✓	✓
Spain & Portugal	MIBEL	OMIE Spain	✓	✓			
		OMIE Portugal				✓	
Italy	GME	MPE	✓	✓			
	IDEM	IDEX				✓	

Additionally, new EU legislation came into force, in 2019, and more specifically the Directives 2019/943 on the internal market for electricity and 2019/944 on common rules for the internal market. According to the European Commission, the directives will make the EU electricity market fit for the clean energy transition, increase connectivity between the nation-states, integrate energy originating from RES and enhance consumer protection. Emphasis is given to the introduction of new emission limits for power plants receiving subsidies as well as grid flexibility and resilience [96].

Mayer and Trück [97] pointed out that due to the creation of wholesale electricity markets, electricity became a type of commodity that could be traded. However, its attributes made electricity significantly different than other commodities and financial assets, making in this way the electricity spot market unique to a certain extent, especially because of the requirement for generation and consumption to take place at the same time. Therefore, the market would be susceptible to price spikes and high volatility, making their forecast and modelling a growing research field. The largest markets in Europe are considered to be NordPool for the Scandinavian region, EPEX Spot for Germany, France and Switzerland and APX for the Netherlands and the UK. Day-ahead auctions constitute the oldest transaction mechanism while intraday markets followed later.

The aim of the relevant legislation is to increase the competition and functionality of the EU electricity market as a whole rather than the fragmented markets it replaced. As the integration of the markets increases, the market efficiency improves, and electricity prices are reduced. It is important to highlight that the influence of national monopolies must be reduced in order to improve the stability of the electricity sector and increase the coordination between different states through interconnectors. Liberalisation and integration is not an one-off activity but a dynamic process that requires the continuous participation of all the key players and regulators [98].

The development of EU single market in electricity has been impressive when taking into account all the structural and institutional changes that have taken place since 1996. In this direction, the EU legislation with its directives was of fundamental importance, especially when considering the additional help of the European Commission's competition authority to promote further reforms. 'Regulatory convergence' was achieved in a relatively high pace while it is reasonable to assume that this would not have been the case if the single market were absent. However, improvements are needed with the European Commission itself admitting that the EU single electricity market is still a work in progress [99].

Regarding the different timescales of the electricity market, electricity can be traded years, months or weeks in advance, one day in advance (day-ahead), during the same day that energy is needed (intraday) as well as in real time (balancing). In more detail, future & forward markets refers to long term contracts which deal with a specific amount of energy traded on a specific price. A forward is a contract between two parties while a future contract includes standardised product(s), originating from an organised market. Furthermore, in the day-ahead market, bids and offers are submitted by the market participants before a designated gate closure that may vary from country to country. Afterwards, the spot price is established based on the submitted bids and offers through a price clearing [100]. The majority of Europe is part of the Single Day-Ahead Coupling (SDAC) mechanism under which wholesale electricity markets from several regions are coupled, taking into account any cross-border transmission limitations. The aim of the SDAC scheme is to create a '*pan-European cross-zonal day-ahead power market*' [101]. During the day, market participants can modify existing agreements or create new contracts through program declarations.

Similarly to SDAC, the Single Intraday Coupling (SIDC) has established an EU cross-zonal intraday electricity market to enable market players across the Union to trade electricity during the day that it is needed until one hour before delivery time. The importance of the intraday market has been increasing in the recent years due to the high amounts of variable RES involved in electricity generation. SIDC promotes competition, increases liquidity and allows market players to quicky adjust to unexpected changes in electricity consumption [102]. Finally, the balancing market allows real-time electricity trading in order for Transmission System Operators (TSOs) to keep the balance between supply and demand. Any differences between the contracted and the actual electricity traded is usually settled between the parties involved, the day after delivery takes place. The timelines of the electricity market are reflected below, in Figure 2.8 [100].

According to [103], two key characteristics of the European electricity markets are self-dispatch and balancing responsibility, both of which are related to the need for balancing the grid. The former basically allows the market actors to decide how to use their generators but at the same time they have the obligation to submit their generation and consumption schedules in advance. The latter refers to the financial responsibility of the market participants derived from any deviations from the submitted energy schedules and the consequent grid imbalances. As it is normal for deviations to take place, market actors can bilaterally trade electricity in the forward, day-ahead and intraday markets as soon as they have a more detailed knowledge of their supply and demand requirements. In fact, they can take advantage of several opportunities to make the necessary corrections and eliminate any financial risks, especially considering the fact that markets might have different gate closure times.

Nevertheless, imbalances can still take place under certain circumstances, making the need for an additional market, called balancing market, necessary towards the stability of the grid. In this way, the TSO has the capacity of implementing last minute corrections, under real-time conditions.

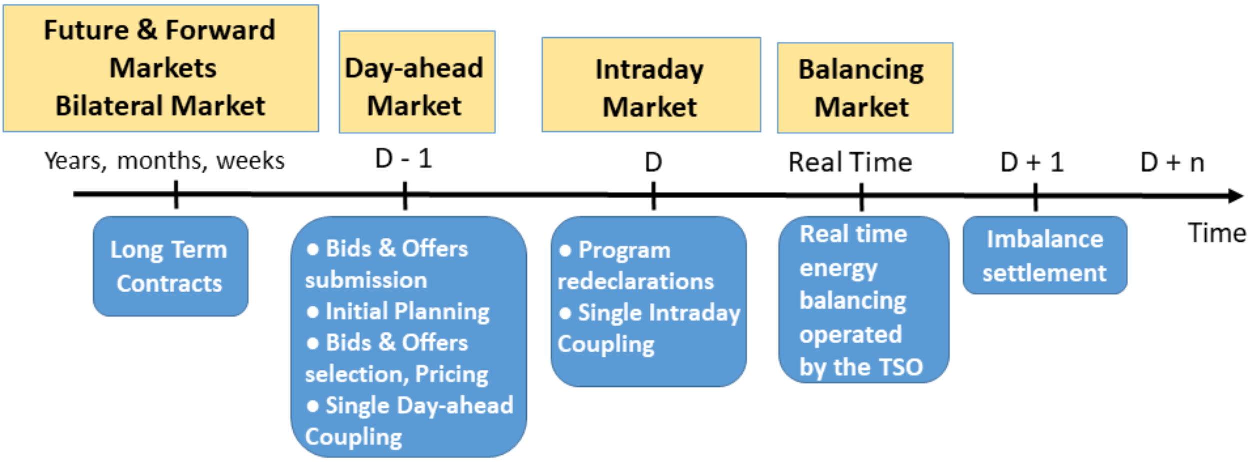


Figure 2.8 – Electricity markets and their timescales in Europe (Adapted from [100])

Hirth and Ziegenhagen [104] highlighted the fact that the need for balancing power has increased due to the utilisation of variable RES whose output depends on weather conditions. The authors explained the importance of balancing the integrated power systems on a short temporal scale, usually from seconds up to hours. As the ramifications from frequency variations can be devastating, such as the destruction of electrical machines including generators, it is vital to keep the frequency of the AC grid stable at 50 or 60 Hz. TSOs are the bodies who operate the transmission network and therefore manage the balancing power. Their main responsibilities in relation to balancing the network are as follows:

- Identify the capacity amount needed to be reserved for balancing power purposes ex ante.
- Purchase that capacity and specify its price accordingly ex ante.
- Utilise the balancing power and determine the imbalance price in real time.
- Reset the system financially and allocate costs through imbalance price or grid fees ex post.

Commenting on the differences between balancing capacity and balancing energy, [105] noted that the objective of the balancing capacity market is to reserve a sufficient amount of power for its future activation. The balancing energy is later activated in real time to balance supply and demand using all the available balancing resources, procured at the previous stage. According to the EU regulations that established a guideline on electricity balancing, the balancing energy market must be decoupled from the balancing capacity market; this allows any balancing electricity bids to be submitted in a separate auction, near to real time. The authors also pointed out that the balancing markets differ from spot markets, such as future and day-ahead, as the TSO constitutes the only buyer of the market.

As increasing decarbonisation of the power network takes place, [106] argued that effective proposals on market design are needed to tackle current issues. There is a consensus amongst the European Commission, the industry and regulators that a new market design is needed; however, the debate around this design is still ongoing with several disagreements regarding the new direction. The authors highlighted that the design of electricity markets, which are liberalised, decentralised and interconnected, has an impact on the market participants' incentives and behaviour, forming dependencies between the design of sub-markets. Also, the terminology around market design is often not well defined with researchers being vague and not specifying the part of the electricity market they refer to. The several levels of governance and the different needs of each nation-state have created a complicated market design in Europe. Consequently, any suggestion on improving the market design has to take into account the system aspect of the electricity markets as well as their complex nature and interaction with each other.

According to [107], assessing the degree of the European Market integration has been the focus of the existing literature. With increasing liberalisation and cross-border capacities constituting the two parallel policies of the EU since 2005, the unbundling of vertically integrated monopolies created the necessary foundations for competition in generation and supply markets. The authors noted that under certain conditions, ownership unbundling can potentially lead to a reduction of investments, at the transmission level. The degree of market integration grew between 2010 and 2012; however, due to the increasing market penetration of intermittent RES, the market integration was then reduced until 2015. Despite the current degree of market integration, the effects of national unilateral initiatives should not be underestimated as at the end of the day, member-state governments still have to follow their national energy policies which sometimes are not in accordance with the wider EU efforts for further integration. A characteristic example is Germany's effort to phase out nuclear power by promoting variable RES through feed-in tariffs (FITs), leading to the increase of spot electricity prices in neighbouring countries.

2.2.6 Electricity in Great Britain

The transportation network for electricity consists of two key mechanisms, transmission and distribution. The transmission system is a very high voltage network, capable of conveying electricity throughout the entire island of Great Britain. Entities which require high amounts of power, such as industrial consumers (refineries etc.), are connected to the transmission network. Electricity is generated in central plants that are powered by several types of fuel, including natural gas, coal and nuclear while smaller scale renewable energy systems (e.g. wind turbines) can also be connected to the transmission network. The main objective of the Transmission System is *"to deliver generation to the distribution networks"*. The connection established between Transmission and Distribution Systems is called a Grid Supply Point (GSP); therefore, every distribution system is considered to be a GSP Group. Smaller scale generation systems, such as photovoltaics and wind turbines, can be connected to the Distribution Network rather than the Transmission Network due to their lower output and location and are known as Embedded Generation. In Great Britain, the Distribution Network is divided in 14 separate geographical areas with electricity flowing freely between them and its volume being measured through metering at the limits of each area [108]. A simplified structure of the transportation network used for electricity in Great Britain is shown below, in Figure 2.9.

National Grid owns and operates the high-voltage Transmission Network in England & Wales while there are two TSOs in Scotland, Scottish Power Energy Networks for the southern part of the country and Scottish & Southern Electricity Networks for northern Scotland. Overall, the transmission network is operated as a whole by the National Grid Electricity System Operator, often referred to as National Grid ESO, which is responsible for the stable and secure operation of the entire network [109]. Regarding the lower-voltage distribution network, there is a total of 14 licensed Distribution Network Operators (DNOs) which belong to the following six separate groups: Northern Powergrid, Scottish & Southern Energy Networks, SP Energy

Networks, UK Power Networks and Western Power Distribution. There is also a number of smaller licensed networks which are owned and managed by Independent Distribution Network Operators (IDNOs). As both the TSOs and DNOs constitute natural monopolies, they are regulated by the Office of Gas and Electricity Markets (Ofgem) in order to protect the consumers from any potential power abuse [110].

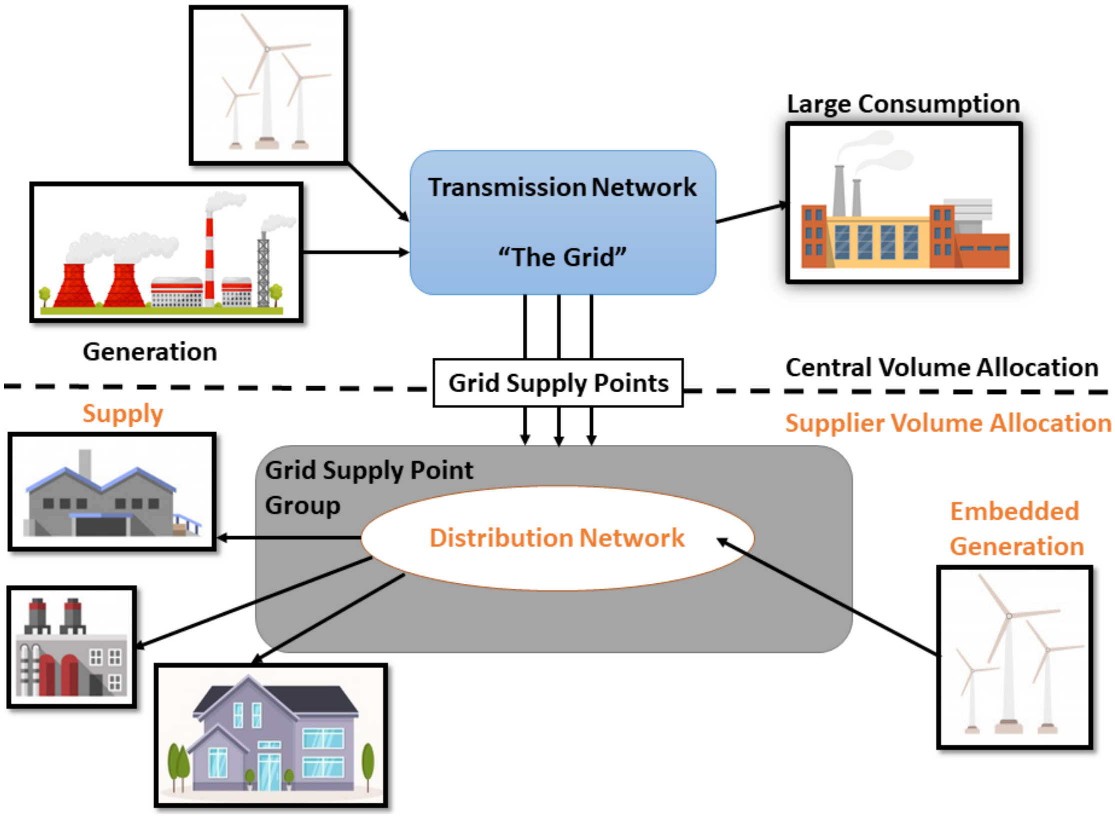


Figure 2.9 – Transportation of electricity through transmission and distribution. Black and orange text refer to Transmission and Distribution Network elements, respectively (Adapted from [108])

It is vital to point out that all the above refer to the electricity network of Great Britain which by definition does not include Northern Ireland. The two geographical regions have independent electricity systems which are governed and regulated separately. The Single Electricity Market of Ireland was established in 2007, to comply with the European Commission's requirements for EMTM, as a cross-border market that includes both Northern Ireland, a constituent country of the UK, and the Republic of Ireland [111]. In Northern Ireland, the transmission network is owned and operated by Northern Ireland Electricity Networks (NIEI) which also owns the distribution network of the country. NIEI is an autonomous organisation, regulated separately by the Utility Regulator [112]. This research focuses on the electricity network of Great Britain and therefore any references to the UK should be taken into account, only in the GB context and its grid.

According to [113] and their report on the resilience of the electrical grid in Great Britain, the high-voltage 400 kV transmission network supplies electricity to the distribution networks where electricity's voltage is significantly reduced, with 33 kV or 11 kV power being provided to towns, hospitals, businesses or industrial users while only 11 kV is used towards domestic electricity usage (240 V). Customers purchases electricity from the retail market through a number of suppliers. The so called "big six" companies supply approximately 95% of the market with the rest of the market being covered by smaller suppliers which do not own their own generation installations. The report also highlighted the importance of the energy trilemma when it comes to energy policy and the decarbonisation of the electrical network. The trilemma was defined by the UK Government as "*the challenge of keeping the lights on, at an affordable price, while decarbonising our power system*" while the National Grid adopted a simpler definition of "*supply, sustainability and affordability*".

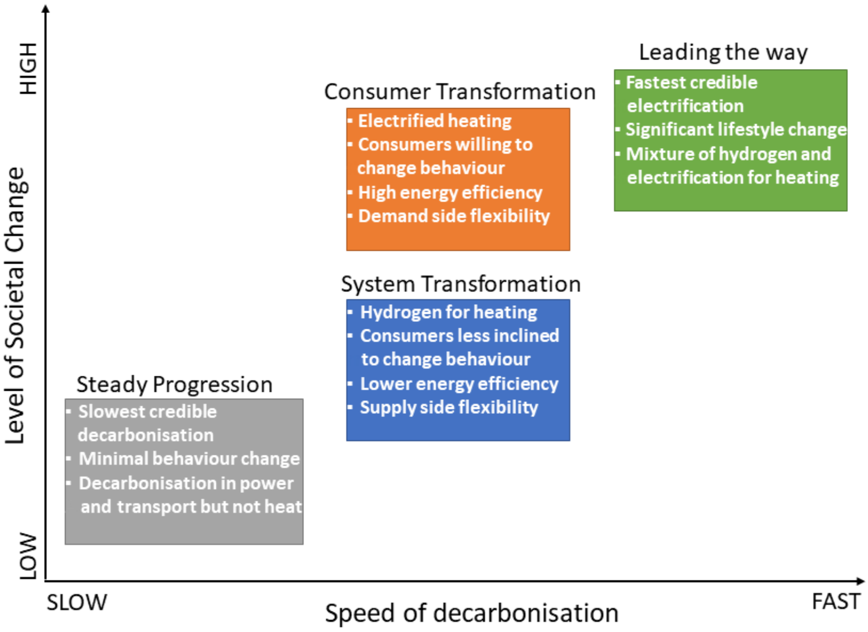


Figure 2.10 – Future Energy Scenarios for Great Britain (Adapted from [7])

Recognising the continuous changes and the necessity of the energy system evolution, National Grid ESO releases every year its future energy scenarios for Great Britain, pointing out urgent investments that need to take place regarding energy infrastructure, supporting energy policy decisions and investigating the impact of energy consumption changes until 2050 to reach the net zero emissions target. The 2020 Future Energy Scenarios are illustrated, in Figure 2.10, along with their key characteristics and the respective speed of decarbonisation and level of societal change required. In more detail, Steady Progression assumes the slowest credible speed of decarbonisation with minimal behavioural changes and all sectors but heat decarbonised. Leading the way constitutes the exact opposite scenario when it comes to the decarbonisation rate and the behavioural changes adopted by consumers while electrification and hydrogen are the options chosen for the decarbonisation of the heating sector. The remaining two scenarios both require a moderate decarbonisation speed, but discreet differences can be seen. The Consumer Transformation scenario requires a relatively higher level of societal change, electrified heating, demand side flexibility and high energy efficiency. On the other hand, under System Transformation, hydrogen is widely used for heating purposes while there is lower energy efficiency and flexibility is now present on the supply side [7].

When compared with the 2019 historical data, for the year 2030, it can be seen that the annual electricity demand and peak demand are expected to remain in the same levels, with a marginal increase under Consumer Transformation and Steady Progression. On the other hand, the total installed capacity of the electrical network, its low-carbon & renewable capacity as well as interconnector and energy storage capacities are predicted to grow with the increases being more significant for Consumer Transformation and Steady Progression. All scenarios show an important decrease regarding the annual mean carbon intensity of electricity, from 167 in 2019 to a range between -6 and 89 g CO_2 e/kWh [7].

Finally, for the year 2050, major changes are expected for the electrical network with the majority of the key grid parameters predicted to increase significantly. In more detail, the electricity demand is expected to be between 452 – 627 TWh/annum (308 TWh in 2019), the total installed capacity between 224 – 334 GW (112 GW in 2019) out of which 140 – 248 GW are low-carbon & renewables (54 GW in 2019). Furthermore, interconnectors are up between 16 – 27 GW (5 GW in 2019) and installed energy storage capacity is 25 – 60 GW (4GW in 2019). The rest of the key energy parameters, such as natural gas, hydrogen and bioenergy further demonstrate the interdependence and co-dependence of certain technologies, as highlighted at the end of Chapter 2.1. It is also worth mentioning that while some scenarios assume a wide adaptation of one specific option (e.g. electric heating, hydrogen) others take into account a hybrid approach that includes more than one technology (e.g. Leading the way).

National Grid ESO as the system operator for Great Britain is responsible for ensuring that supply and demand on the transmission network are balanced. Every day is divided in 48 settlement periods with a duration of 30 minutes each. Approximately, 90% of electricity trades take place through bilateral contracts in future and forward markets while an additional 5% is negotiated within power exchanges up to two days in advance. The net imbalance that needs to be resolved usually represents 2% of the total electricity demand. The actions that the National Grid can take to maintain the network's stability are to change the generation output of power plants through the balancing mechanism of bids and offers, to reduce demand through contracts with large industrial power stations and to moderately reduce the voltage for short periods of time. The National Grid recovers the total cost of balancing services through a Balancing Services Use of System (BSUoS) charge. Generators and suppliers are liable for these charges which are calculated at a daily basis as a uniform tariff for all users, depending on the amount of electricity added or removed from the grid. For example, the range of BSUoS tariffs was £1 – 3/MWh, for the year 2013 – 2014 [114].

There are several balancing services in Great Britain, with each service having its unique technical and temporal requirements. As presented by the [115], the most prominent balancing services along with their brief description are, as follow:

- **Frequency Response**: There are two types of this service, Mandatory Frequency Response (MFR) and Firm Frequency Response (FFR). The technical characteristics are similar, but while FFR is open to any providers, MFR is open to generators only. MFR is described as "*an automatic change in active power output in response to a frequency change*" to keep the frequency close to 50 Hz. It is divided into three subcategories with individual requirements: primary, secondary and high (tertiary) frequency response. The first two subcategories deal with low frequency conditions while high frequency response restores a higher than needed frequency within the operational limits [116].

- **Enhanced Frequency Response**. EFR is presented as an innovation project which includes in total two products, Low Frequency Static (LFS) and Dynamic Low High (DLH), procured weekly through the EPEX Spot Auction Platform. The LFS service has a 49.6 Hz frequency trigger with a full response required within one second and a duration of 30 minutes. DLH has similarities with the FFR dynamic service but requires equal amounts of primary, secondary and tertiary frequency response [117].

- **Black Start**. This service differs from the previous as it is provided towards recovery in the case of a partial or a total shutdown of the national transmission network. There is an extensive list of technical requirements, including back-up fuel supplies, a high power output of 35-50 MW, a frequency range between 47.5 and 52 Hz for a duration of three to seven days and the ability to provide at least three consecutive black starts [118].

- **Fast Reserve.** This is the provision of rapid delivery of active power (≥ 25 MW/minute), for at least fifteen minutes through either increasing generation output or reducing consumption from demand sources. Its objective is to control frequency variations from unpredictable changes in generation or demand. The service is divided into three subcategories: Firm Fast Reserve, Optional Fast Reserve and Optional Spin gen [119].

- **Short-Term Operating Reserve (STOR)**. STOR is similar to Fast Reserve, providing power in cases of unpredictable changes or generation unavailabilities; however, its technical requirements are less demanding with at least 3 MW provided for a minimum of two hours. Ideally, the response time of the STOR provider should be less than 20 minutes, but in any case, not higher than 240 minutes. Smaller service providers can also participate through an aggregator [120].

- **Demand Turn Up (DTU)**. DTU is designed to encourage users and generators to either increase demand or reduce generation during times of high variable RES output and low national demand, such as during the night and weekend afternoons in the summer period. Its response time and duration are not standardised, as in the previously mentioned balancing services. Nevertheless, its technical requirements seem to be the most flexible (minimum of 1 MW) and based on the 2018 historical data, the response time of approximately 6 hours required is relatively high [121].

- **Balancing Mechanism (BM) Start Up.** Two elements constitute this service: BM Start up and hot standby. The first refers to all the steps required in order to make the generator ready to be synchronised with the system, within BM timescales of 89 minutes, while the unit is expected to be in a state of readiness during hot standby. System constraints and the unit's technical characteristics will be considered prior to the BM Start Up instruction with economics and units efficiencies also playing a major role in the decision making process. BM Start Up provides additional on-the-day generation when deemed necessary. 336 instructions for the service were issued, in 2016 [122]**.**

- **System Operator to system operator.** SO to SO includes services that are offered mutually with other TSOs that are connected to Great Britain's transmission system through interconnectors which are capable of adjusting both the flow and the volumes of electricity based on the circumstances. This service is instructed dynamically and not used regularly, at most one time per month [123].

- **Demand Side Response (DSR).** Energy users can increase, decrease or shift their electricity demand in real-time through DSR. Large industrial and commercial users, small to medium size companies and aggregators are eligible to participate in this service which is "*all about intelligent energy use*". Participation in DSR can increase the security of supply, reduce costs and give more control to the customers [124].

Table 2.2 – Balancing Services and their characteristics in Great Britain [115], [4]

Service	Mandatory/Firm Frequency Response			Black Start	Short-Term Operating Reserve	Demand Turn Up	Fast Reserve
	Primary Response	Secondary Response	High Frequency Response				
Response Time	≤ 10 seconds	≤ 30 seconds	≤ 10 seconds	≤ 2 hours	≤ 20 minutes (maximum of 240 minutes)	Not standard; Mean value for 2018 was 6 hours and 6 minutes.	≤ 2 minutes
Duration	≤ 20 seconds	≤ 30 minutes	Indefinite	3 – 7 days	≥ 2 hours	Not standard; Mean duration for 2018 was 4 hours and 36 minutes.	≥ 15 minutes
Power required	Generally, 10-100 MW or more. Depends on the size of the power plant and the Transmission Operator.			35 – 50 MW Additional requirements needed.	≥ 3 MW	≥ 1 MW	≥ 25 MW/minute
Rewards	FFR: Availability fee (£/h) Nomination (£/h) Window Initiation (£/window) Tendered Window Revision (£/h) Response Energy Fee (£/MWh) MFR: Holding Payment (£/h) Response Energy Fee (£/MWh)			• Availability (£/settlement period) • Exercise Price (£/MWh) • Contribution sums	• Availability (£/MW/h) • Utilisation (£/MWh)	• Availability (£/MW/h) • Utilisation (£/MWh)	• Availability (£/hour) • Utilisation (£/MWh) • Nomination (£/hour)
Comments	FFR is open to any providers that can meet the technical requirements, including generators, energy storage and aggregated demand side response. MFR is open to generators only.			Procured from power stations that can start main blocks of generation onsite, without reliance on external supplies.	Open to anyone with the technology to increase generation or reduce demand	Increase demand or reduce generation at times of high RES output & low national demand	Increasing output from generation or reducing consumption from demand sources.

Table 2.2 lists key balancing services in Great Britain and was compiled by using all the necessary information provided by [125]. It can be noticed that there is a variety of payment mechanisms that are used to reward the providers of the balancing services. The utilisation fee (£/MWh) constitutes the most used payment while nomination and availability fees are also common, paid in accordance with the amounts of time during which a provider was available or a combination of the time and the capacity offered (£/settlement period, £/hour or £/MW/hour). Additionally, while some services are available to any users which can technically meet all the listed requirements, others are only available to generators or restricted to either BM or non-BM providers. Other balancing services do exist (e.g. Reactive power, intertrips), but they are not described in detail or mentioned as their role is comparatively trivial.

Their response times can be seen, for comparison purposes, in Figure 2.11. MFR and FFR are the most demanding services with a response time of only 10 (primary and tertiary) or 30 seconds (secondary). EFR is not listed as only one part of the service has a relevant requirement. For DTU, the average response time value for 2018 is included while services without a specific response time are absent from the figure.

It is critical to point out briefly the economics surrounding the balancing services, as presented by the National Grid, in Figure 2.12, per category. In Great Britain, the total cost of balancing services was £1.79 billion, for the 2020 calendar year. The exact amounts spent per balancing service can be seen, with Constraints (£1123.79 million) taking the lead and Response (£132.47 million) following second. According to [125], actions are needed within the Transmission Network to protect equipment and the integrity of several parts of the system, within the Security and Quality of Supply Standard. In this direction, generators are occasionally asked to constrain their electricity output. However, as the amount of electricity that would have been produced is still needed, an equal amount is purchased by the TSO from a different part of the network to compensate for that difference. Constraints consist of three main categories: transmission, voltage and rate-of-change-of-frequency (ROCOF) constraints. It should be highlighted that constraints are dealt with a variety of mechanisms such as bids & offers, contracts, trading as well as SO to SO services. Finally, it can be observed that the economics of balancing services are grouped presented slightly differently when compared with their original definitions and information, at the National Grid website.

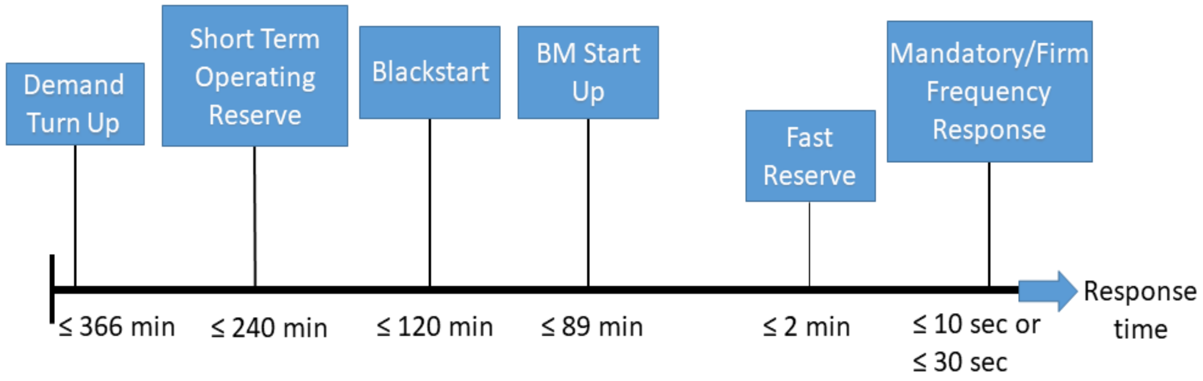


Figure 2.11 – Response time requirements for key Balancing Services in Great Britain

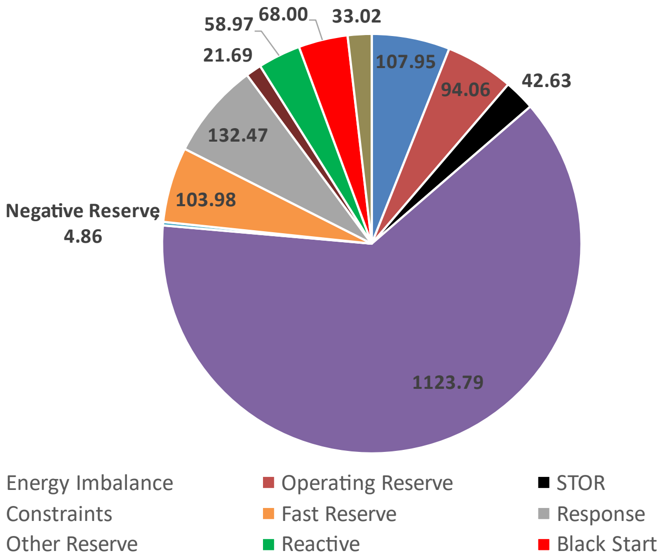


Figure 2.12 – Total balancing costs (£m) in Great Britain for the 2020 calendar year

On 1 January 2021, as the transitional period after Brexit ended, Great Britain left EU's internal energy market. Great Britain has a total of four interconnectors, connecting the entire island with France, the Netherlands, Belgium, France and Northern Ireland. Electricity trades are no longer managed through Single Market tools, including market coupling which only apply to EU Member States and any transactions take place on third-country terms. According to the Trade and Cooperation Agreement, signed by EU and UK, both signatories have accepted to create a new energy and climate change framework for their future cooperation which will guarantee the efficiency of the cross-border trading arrangements and future actions against climate change, respectively. The agreement also includes the possibility for future separate arrangements for trading through the existing interconnectors, a close relationship between the EU and UK TSOs and energy regulators as well as a new coupling model. However, it should be pointed out that the model in question, referred to as "*multi-region loose volume coupling*" model, is different and expected to be less efficient than the previous system in place. All the above do not apply to Northern Ireland which is still part of the Single Electricity Market. Finally, the UK is no longer a part of the EU Emissions Trading System and the European Atomic Energy Community (Euratom) which constitutes the Single Market for trading nuclear materials and technology [126].

Geske et al. [127] investigated the cost of bilaterally uncoupling British-EU electricity trade due to the UK's exit from the EU Internal Energy Market (Elecxit). The authors pointed out the unique complexity of negotiations that exists in the electricity sector and the fact that the exit from Euratom will lead to indirect consequences for the electricity sector as well. Besides the market uncoupling that inevitably follows the new status of the UK as a "third country", there is also the potential for interconnector utilisation fees. As the majority of economic forecasts predict that Brexit will reduce the UK gross domestic product (GDP), it will also have an impact on the level of electricity demand and the amount of generation capacity, leading to a reduction of the required investments. This can be considered as fortunate, especially if the post-Brexit UK becomes a less attractive destination for international investors. On the other hand, Brexit's advocates support that the country will be able to attract more businesses by relaxing its regulations. It was concluded that a less efficient market and the cancellation of previously planned interconnectors could potentially lead to an increase of €700 million per year, for generator costs. The additional costs depend on the future development of British and French electrical grids and are expected to further increase to €2.7 billion per year should France maintain its nuclear-based power system.

2.2.7 Smart Grid: Definition and Characteristics

The conventional grid consists of five main assets which constitute Makansi's electricity value chain: source, generation, transmission, distribution and delivery [128]. The model has been adjusted in order to include the additional assets of fuel storage, energy storage as well as the dump loads. It is vital to point out the monodirectional nature of the conventional grid, both electricity and information-wise, and the absence of feedback loops. Dump loads represent excess electricity which is highly undesirable due to the consequent revenue losses. The revised traditional electrical grid value chain can be seen, in Figure 2.13. As the complexity of the electrical grid has increased significantly, grid reliability and efficiency are required towards mitigating any energy and environmental sustainability issues, always taking into account the energy trilemma. In this direction, a smarter grid is needed, commonly referred to as smart grid, which makes use of a bidirectional flow of information to enhance the efficiency, stability and responsiveness of the system whilst reducing consumer costs [60].

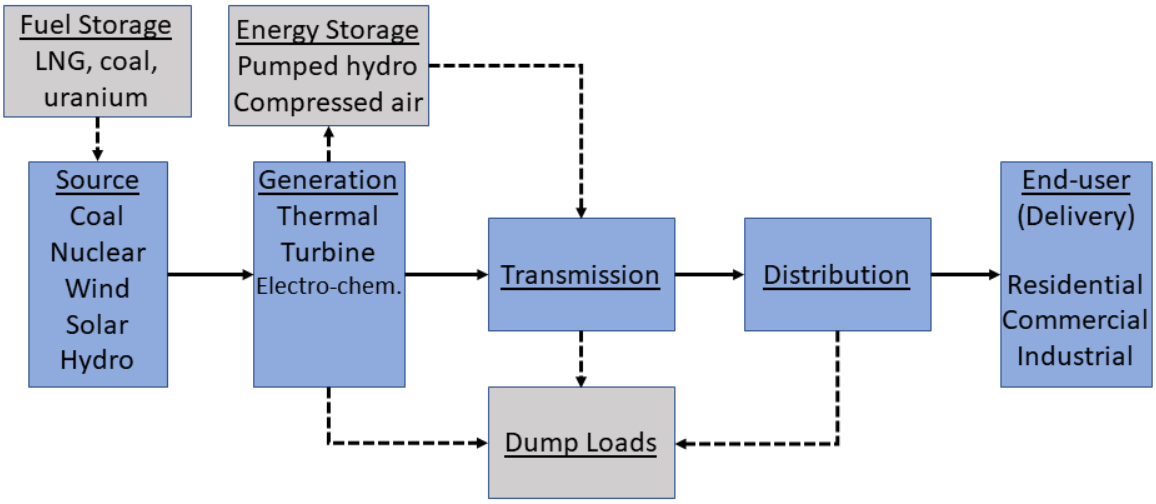


Figure 2.13 – Traditional Electrical Grid Value chain (Adapted from [60])

In the current "generation-centric" electrical grid, large AC generation plants are interconnected with the high-voltage transmission network. Afterwards, the voltage is reduced in substations to make it suitable for distribution and supply the loads, either directly or after voltage transformation. Therefore, intelligence is only present at central locations, and in substations up to a certain extent. On the other hand, a smart power grid can use its intelligence to integrate all the different elements of the network, delivering in this way affordable and sustainable electricity in a secure and efficient way. Important features of the smart grid are smart metering, DSM, smart energy storage, emissions trading and EVs [129].

According to the IEA, a smart grid is an electricity network that takes advantage of digital and advanced technologies in order to monitor and manage electricity, from the generation level to the end-users, meeting successfully variable demands. Additionally, utilising the smart grid capabilities, all the market participants, such as the generators, grid operators, end-users and market stakeholders are co-ordinated, every part of the network is operated in an efficient way, while the associated costs and the environmental impacts are minimised. At the same time, the stability, reliability and resilience of the system have the potential to reach their optimal level. Smart grid technologies are the answer to the current challenges faced by the grid operators around the world, including ageing infrastructure, growing demand for electricity, the need for integration of variable RES into the network and improve security of supply. The evolution of the electrical grid will result into the network's growing complexity, not only in terms of the electricity flow but especially when it comes to the required amounts of the information involved through communications. Finally, the addition of energy storage in different parts of the network and electric vehicles can also be seen when comparing the present and future versions of the electrical grid [130].

Tuballa and Abundo [131] argued that a Smart Grid cannot be created from zero; on the contrary, smart grids and their importance emerged as a part of the continuing effort to modernise the current grid and make it environmentally friendlier and greener. The autonomy of a smart grid can help towards the integration of the increasing contribution of distributed RES and improve the overall delivery of power to the final consumers. At the same time, the intelligence of the network has the potential to make the grid neat and capable of operating in automation. Regarding the smart grid as a concept, the authors believed there is no widely accepted definition with both simple and complicated descriptions trying to make their case. The Korean Smart Grid Roadmap 2030 supports that a smart grid is a next-generation network which integrates information technology into the current electrical grid in order to optimise energy efficiency. To achieve this objective, a bidirectional exchange of real-time information is necessary between electricity suppliers and consumers.

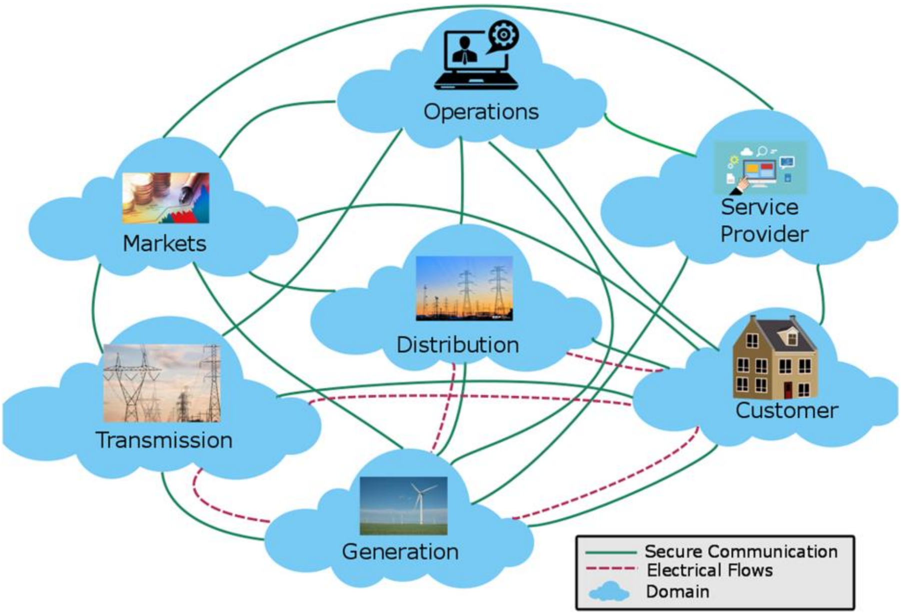


Figure 2.14 – Original NIST Smart Grid conceptual model. Reproduced with permission from [132]. Copyright 2021, Elsevier.

The US National Institute of Standards and Technology (NIST) suggested a conceptual model, according to which the smart grid is considered as an end-to-end electrical grid, from generation to (and from) customers, with unique interactivity taking place between the different domains. The NIST model was also used by the EU who made certain adjustments by adding distributed energy generation sources. The original and the revised smart grid model can be seen, in Figure 2.14, with all the associated electricity and communication exchanges. According to the EU definition, the smart grid is "*an electricity network that can intelligently* *integrate the behaviour and actions of all users connected to it- generators, consumers and those that do both- in to efficiently ensure sustainable, economic and secure electricity supply”* while the US Department of Energy supports that a Smart Grid *“uses digital technology to improve reliability, security, and efficiency of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources*”. Finally, it is noted that additional definitions can be considered based on the smart grid technologies, functionality and benefits [133].

Different schematics regarding the operation and the components of the smart grid can be found in the literature. Their differences depend on the approach followed and the level of simplicity or complexity of the system. According to [134], generation, transmission, distribution and the consumer constitute the vital components of the system while distributed generation are expected to play a major role, enabling end-users to generate electricity and become active participants rather than passive elements of the grid. The smart grid should be able to support bidirectional flows of electricity while the appropriate data communications infrastructure must enable the collection, processing and distribution of data. Concerning the structure of the future smart grid, the network includes a variety of power grids, distributed generation, distributed storage and also various customer loads such as electric vehicles.

The vital importance of communications and intelligence is also highlighted by [135] and more specifically the integration of controls, sensors and advanced communications into the current electrical grid will render the smart grid capable of several smart features. When it comes to the smart grid’s energy balance management feature, several components are part of the mechanism, including distributed energy sources, integration of RES, energy storage, optimisation of energy usage, generation & loads forecasts, buying and selling of energy and finally, frequency control. RES and their role within the smart grid as distributed generation can have a positive impact towards the reduction of carbon emissions. This is in contrast with the traditional grid where the inflexibility of the distribution network does not allow energy storage or local power generation to have an active role, at the distribution level.

A schematic representation of present and future electricity networks, as suggested by [136], is shown, in Figure 2.15. It can be observed that while present electricity networks have a relatively simple and linear structure, the future smart grid is expected to be more complicated and to introduce decentralisation via distributed generation and energy storage whose presence is visible in different parts of the network. The complexity and the interactions between all the different network components are significantly higher with the integration of electrical storage being beneficial for the entire electrical chain, including the generators, TSOs, DNOs and the final consumer.

Kolhe [137] supported that the smart grid is anticipated to be less centralised and at the same time more consumer-interactive. The transition to a smart electrical grid will eventually change the business model, in the entire electricity sector. The role of distributed RES and energy storage technologies is also highlighted with the latter enabling users to interact with the network by participating in energy generation and demand side management. However, major changes are required in terms of the current grid's planning, design and operation in order to properly utilise the new technologies, integrated within the smart grid. There are vital economic, technical and commercial challenges to achieve the Smart Grid network vision; therefore, R&D and demonstration projects are needed towards the modernisation of all the different aspects of the power network.

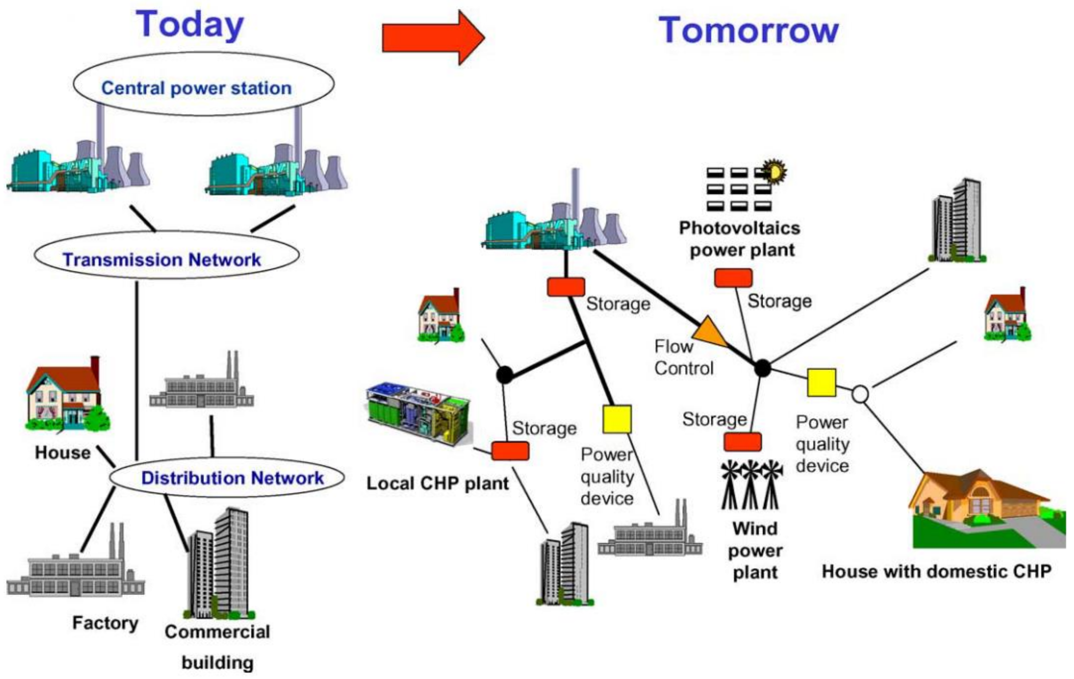


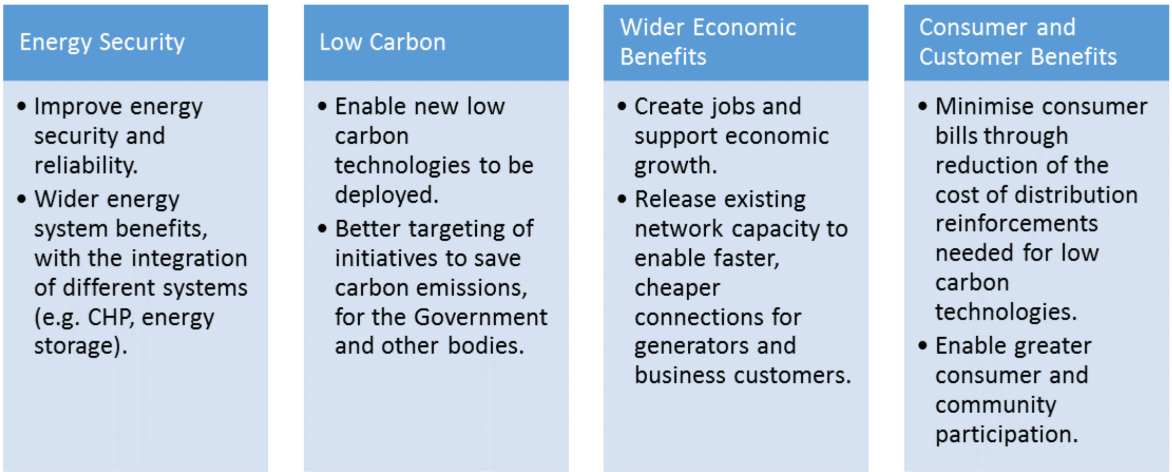
Figure 2.15 – Present and future electricity networks. Reproduced with permission from [136]. Copyright 2005, Elsevier.

The benefits of the digital smart grid are several, including continuous monitoring, automatic control and recovery, while decoupling of energy generation and consumption is possible through the utilisation of energy storage systems. In contrast, the traditional grid requires simultaneous energy generation and human attention to system disruptions. A smaller amount of data and sensors are involved but at the same time, the end user has fewer options, control is limited, and system recovery is manual [60], [131].

Figure 2.16 lists the benefits of the Smart Grid, classified by category, as reported by [138]. More specifically, the smart grid with its intelligence, automated control and responsiveness will improve energy security and reliability and help towards the integration of different subsystems into the grid. Furthermore, it can help towards the low carbon transition by accommodating key technologies such as electric vehicles and heat pumps which can be used along with distributed generation to balance supply and demand. Systems synergies can bring new opportunities, including arbitrage, while advanced sensors and temperature controls can optimise heating demand by taking into account the occupancy rates.

The wider economic benefits are also significant, not only in terms of jobs and economic growth, as more affordable and faster connections will be available for both generations and business customers, including several options for balancing supply locally with demand side response and energy storage; in this way, expensive network reinforcements will be either avoided or deferred. Finally, the smart grid has the potential to transform the behaviour and the interaction of consumers with the energy network. Taking advantage of the necessary equipment, such as smart meters, costumers will be able to access real-time information regarding their energy costs and also be rewarded for using energy at off-peak periods and generate energy during peak hours of the day [138].

Carvallo and Cooper [139] argued that the emergence of the advanced smart grid and its new energy architecture are inevitable, describing in detail the evolutionary state of the conventional grid and the future smart grid. Until recently, the electrical grid was considered to be extremely reliable; however, given the new circumstances, the grid needs to be redesigned. According to the authors, there are three evolutionary states for the smart grid: first generation (SG1.0), second generation with the Advanced Smart Grid (SG2.0) and the Smart Grid of the Future (SG3.0). The foundations of SG1.0 include advanced metering infrastructure (AMI), DR and distribution automation, where energy management systems (EMS)/SCADA also play an important role by collecting data from distributed elements of the transmission and distribution network, for monitoring and control purposes. SG2.0 adds EVs, distributed generation, such as photovoltaics, and energy storage, with the three elements constituting the new class of Distributed Energy Resources (DER). Energy roaming and peer-to-peer (P2P) energy trading are later added on SG3.0.



Energy Security	Low Carbon	Wider Economic Benefits	Consumer and Customer Benefits
• Improve energy security and reliability. • Wider energy system benefits, with the integration of different systems (e.g. CHP, energy storage).	• Enable new low carbon technologies to be deployed. • Better targeting of initiatives to save carbon emissions, for the Government and other bodies.	• Create jobs and support economic growth. • Release existing network capacity to enable faster, cheaper connections for generators and business customers.	• Minimise consumer bills through reduction of the cost of distribution reinforcements needed for low carbon technologies. • Enable greater consumer and community participation.

Figure 2.16 – Categorised Benefits of the Smart Grid according to Ofgem (Adapted from [138])

It is expected that inside SG2.0, the integration of the utility with the end users will take place, under a number of different services: building-to-grid (B2G), home-to-grid (H2G), V2G, energy-storage-to-grid (ES2G) and distributed-generation-to-grid (DG2G). Additionally, the presence and importance of energy storage for the future grid is highlighted as, according to the authors, it “*promises to be a game changer*” enabling new business opportunities based on its charge/discharge operations and location inside the network. Despite being called “the *Holy Grail for electric industry redesign*”, its large scale deployment remains a technical challenge for utilities. The term “*energy storage*” is mentioned 118 times, in the entire smart grid book by Carvallo and Cooper, indicating its importance as a component of the network [139].

In the same direction, [60] supported that a truly dynamic power grid requires both information and energy storage while they argued that the latter should be a separate asset class in a central role within the smart grid environment. This would have the potential to increase the value of energy storage investments while supporting the operation of the smart grid. Both benefits of energy storage in the smart grid and vice versa are reported as the deployment of smart grids are necessary towards the wide utilisation and implementation of energy storage while energy storage itself can also meet certain objectives of the smart grid. Currently, its grid capacity is not sufficient in order to be considered as a separate asset and specific policies will be needed in order for energy storage to support the operation of the future smart grid.

2.3. Energy Storage

2.3.1 Energy Storage Technologies

Energy storage is not new as a concept or a technology; in fact, hydroelectric power stations have been running and fully operational for almost 150 years, with the Cragside power station being a characteristic example since 1870, located in Northumberland, UK. In hydroelectric stations, the conversion of potential to electrical energy is regulated by the penstock valve, the storage capacity is a function of the water volume in the reservoir, while the power output depends on the rating of the generator in use. The importance of storage was recognised in the late '50s in an effort to maximise the benefits of using renewable energy sources. As RES are highly dependent on climatic and weather conditions, the introduction of storage could increase the energy yield. The timescale under which energy storage systems (ESS) can be used and serve their purpose can differ, depending on the application in question [140].

Some of these applications include integration of RES, energy arbitrage, balancing and ancillary services, as well as frequency regulation, peak shaving and voltage control. Details about energy storage applications are presented in a later chapter of the current report. In terms of electrical ESS, the system imports electricity from an electrical grid and then converted into a form that can be stored. Later, when it is desirable, the stored energy is converted back to electricity with the ESS being discharged. This is reflected in Figure 2.17 where all the components of an ESS are shown, including the control system and the interface, for the charging and discharging operations. The type of the input power can vary [141]. The interface component varies as well, for example it consists of an inverter and a rectifier to convert DC to AC and vice versa, in the case of a battery system.

The classification of energy storage to electrical and thermal systems is considered relatively vague and does not take into account the unique and special capabilities of each system, regarding the energy conversion and any physical or chemical processes that might take place in the between. Energy storage can be grouped in four main categories: mechanical (MES), electrical (EES), thermal (TES) and chemical energy storage. The exact ESS terms can differ in the literature, for example a combined electrochemical category could include both batteries and supercapacitors [142]. This preference is deemed as necessary in order to reflect the proper properties and the uniqueness of electrochemical systems. Therefore, for the needs of the current project, the classification suggested by [143] is taken into account and divides energy storage in two main categories: EES and TES. Each system has its unique benefits and downsides, depending on its characteristics and the application in question.

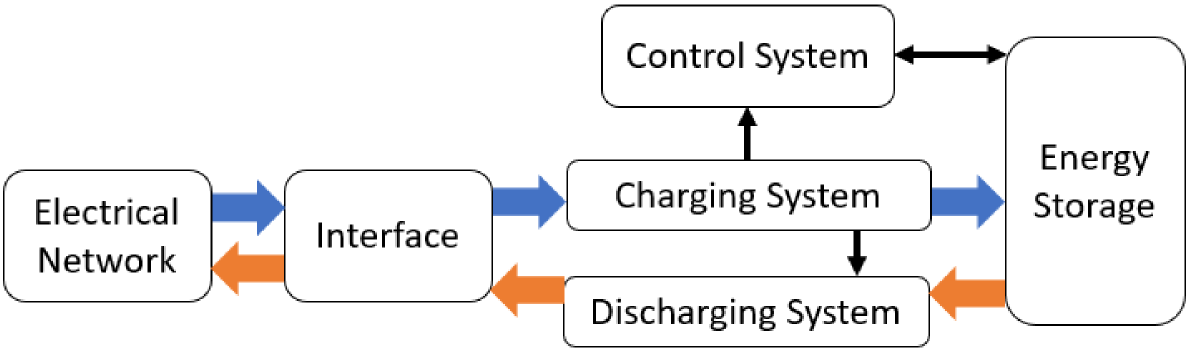


Figure 2.17 – Energy Storage System Components (Adapted from [141])

TES consists mostly of sensible and latent heat storage which is outside the scope of this research and omitted from the rest of this thesis. Therefore, energy storage from this point will refer specifically to EES which converts electrical energy from a power network into a form that can be stored for a certain amount of time and then converted back to electricity, when needed. Important EES systems some of which will be also described later include pumped hydro energy storage (PHES), compressed-air energy storage (CAES), flywheel energy storage (FES), several electrochemistries of battery energy storage (BES) such as Li-ion and sodium-sulphur (NaS), super magnetic energy storage (SMES) and finally supercapacitors.

It should be highlighted that ESS, besides their classification by form, can also be categorised based on their function. The first category includes systems capable of providing power quality and reliability which is generally characterised by a relatively small amount of respective energy. The second category involves around systems designed for energy management. As shown in Figure 2.18, batteries are ESS suitable for both categories depending on the scale of the system. However, it is important to mention that these categories are not absolute and subject to change due to the continuous technology developments. For example, flywheels with higher energy to power ratio have been developed by several manufacturers while advanced batteries have demonstrated suitable characteristics for pulse power [144].

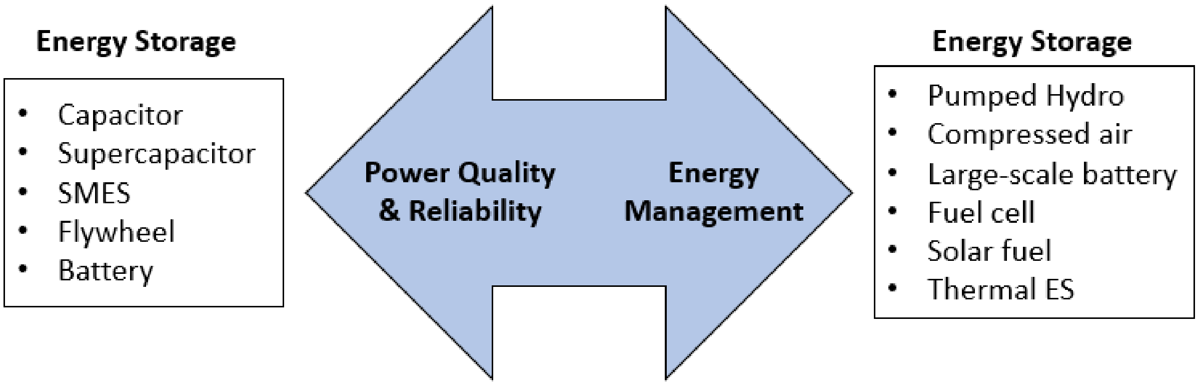


Figure 2.18 – Energy Storage Classification by function (Adapted from [144])

Several criteria are taken into account when choosing an EES technology for a given application and include life time, energy efficiency and power density, energy and power capabilities, response delay time, self-discharge rate, efficiency, duration, technical maturity, ability to change its power output often, capital cost, operation and maintenance (O&M) costs, size and safety [145], [146]. While these parameters refer to EES systems, their relevance can be extended to all energy storage technologies. Figure 2.19 gives some first vital information, regarding the power capabilities and discharge times of several systems, indicating the possible scales of each technology [147].

PHES and CAES are large-scale energy storage systems, mostly used for high-power long-time applications. For example, the Dinorwig pumped hydro station in the UK constitutes a characteristic example of the technology with an energy capacity of 10 GWh and 1,728 MW of power. Dinorwig has been operational since 1983, while the first pumped hydro scheme in the UK opened in 1963. Since then, PHES have been used to provide balancing and ancillary services to the National Grid [148].

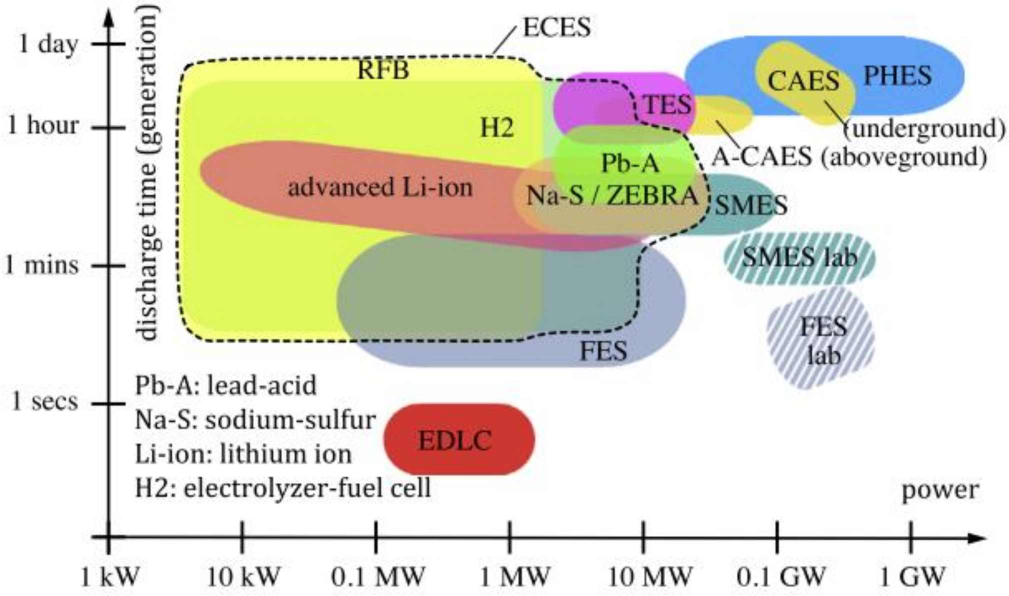


Figure 2.19 – Discharge time vs Power for different energy storage technologies. Reproduced with permission from [147]. Copyright 2014, Elsevier.

BES has very broad ranges of power and discharge times, between 5 kW – 50 MW and from a few seconds to almost a day, respectively, depending on the properties of the different electrochemistries. More specifically, advanced Li-ion and redox flow batteries (RFB) are observed to have the highest power ranges of this category while lead-acid (Pb-A) and NaS batteries also achieve high power values and discharge times. These broad ranges confirm the classifications of Figure 2.18 above, concerning the suitability of BES for both energy and power applications. As the current research is focused on the utilisation of energy storage in buildings, priority is given on BES while information on PHES is also provided due to the technology's popularity in Great Britain.

2.3.2 Energy Storage Characteristics

It is understandable from the previous section that there is a wide range of energy storage technologies, each one with its unique characteristics and applications. Their suitability for any given application depends on several parameters. More specifically, the energy storage capacity is the amount of energy that can be stored in the system, energy density (Wh/L) describes the nominal volumetric energy density and power density (W/L) is the available power per unit volume. Similarly, specific energy (Wh/kg) is the energy per unit mass and specific power (W/kg) describes power per unit mass, in this case kilogram. Despite using per mass units, specific energy and power are often mentioned in the literature as energy and power density , complimenting the per volume units [149].

Furthermore, the lifetime of a storage system is usually measured in years or cycles and indicates a number for which the ESS is expected to be operational, and the roundtrip efficiency is the ratio of energy released by the ESS to the energy required to charge it over each cycle, including all losses. Usually, lifetime is expressed in years while the cycling capacity indicates the systems' lifetime in cycles. Power output is the amount of power that can be discharged within the duration of a typical discharge and response time refers to the time required for the ESS to start providing its power output. All the ESS parameters are summarised in Table 2.3 [150]. It should also be mentioned that based on the scale of the ESS used, different metric prefixes can be used for most of the parameters listed (e.g. MW, GW, MWh). Finally, daily self-discharge refers to the stored energy lost per day even when the ESS is inactive. This is also mentioned in the literature as daily parasitic loss. The technical characteristics for selected technologies are listed in detail, in Table 2.4. It is clear that these technical properties can vary drastically, not only from system to system but for the same technology as well as values found in the literature can often differ. Based on their technical capabilities, some systems are more capable of meeting a specific objective than others.

Table 2.3 – Energy Storage Properties [150]

ES Parameter	Unit
Energy Capacity (rating)	kWh
Energy density	Wh/L
Power density	W/L
Specific energy	Wh/kg
Specific power	W/kg
Charge/Discharge duration	[any time unit]
Power output (rating)	MW
Response time	[any time unit]
Lifetime	years, cycles
Roundtrip efficiency	%
Daily self-discharge (parasitic loss)	%

Castillo and Gayme [150] highlighted the versatility of energy storage technologies towards providing a variety of services to electrical grid. More specifically, they can be treated as a generation asset, transmission asset or integration asset for renewable energy sources. Certain systems are even capable of providing all the mentioned services at the same time as the associated time-scales often overlap, allowing a single energy storage installation to serve several functions. At the same time, the authors believe that the large portfolio of storage technologies and their versatility in multiple applications have the potential to create a challenge when it comes to decision making and the overall evaluation of their technical benefits. Finally, according to [149], energy research is conducted in five main categories of applications: electricity supply, ancillary services, grid support and integration of renewables. In the future, energy storage technologies are expected to be fully matched with their corresponding applications.

Table 2.5 introduces additional characteristics of selected technologies, relevant to their temporal profile. As in the previous table presented, a broad range of values can be found in the literature, especially for their lifetime in cycles or years. Regarding their response time, BES are capable of responding within milliseconds. When it comes to the lifetime of ESS, either in cycles or years, a wide range of values can be found in the literature, especially for Li-ion batteries with a lifetime between 5 – 100 years. This is due to the fact the Li-on is essentially a subgroup of BES as it consists of several battery chemistries. Finally, it is also important to have a first look at the capital costs associated with ESS along with their maturity level, presented in Table 2.6. Mature technologies are usually preferred due to the already existing operational expertise while increasing a technology's maturity always leads to a cost reduction [143].

Table 2.4 – Characteristics of selected Energy Storage Technologies [143], [149], [150], [151], [12], [152]

Energy Storage Technology	**Energy density Wh/kg (Wh/L)**	**Power density W/kg (W/L)**	**Power rating MW**	**Energy rating MWh**	**Round trip efficiency**
Pumped Hydro	0.2 – 2 [143], [151], [12] (0.5 – 1.5) [143], [150], [12]	(0.2 – 2) (0.1 – 0.2) [151]	100 – 5,000 [143]	500 – 8,000 [152]	65 – 87 [143], [152] 75 – 85 [150]
Batteries					
NaS	150 – 240 [143] 100 – 240 [12] (150 – 250) [143], [150]	150 – 230 [143], [12] (120 – 160) [12]	0.05 – 8 [143], [151] 0.05 – 50 [12]	6 – 600 [12] 0.4 – 244.8 [152]	80 – 90 [143], [150] 70 – 90 [12] 70 – 85 [4]
Nickel-Cadmium (Ni-Cd)	30 - 80 [152] 75 [149] (15 – 80) [151]	150 – 300 [149] 100 – 160 [152] (75 – 700) [151]	0.01 – 40 [151], [12]	10^{-5} – 1.5 [12]	60 – 73 [12] 60 – 80 [151]
Vanadium RFB (VRFB)	10 – 30 [143] (20 – 70) [151]	(0.5 – 2) [151] (0) [150]	0.005 – 7 [12] 0.01 – 10 [150]	0.01 – 10 [12] 1.2 – 60 [152]	85 – 90 [143] 60 – 85 [12]
Pb-A	35 – 50 [149] (50 – 80) [151]	75 – 300 [149] (90 – 700) [151]	0.001 – 50 [12] 0 – 20 [151] 0.05 – 10 [151]	0.1 – 100 [12] 0.01 – 40 [152] 0 – 20 [151]	70 – 90 [12] 75 – 90 [151]
Li-ion	75 – 200 [143] 150 – 200 [149] (200 – 500) [143], [150] 200 – 400 [151]	500 – 2000 [143] 200 – 315 [149] (1,300 – 10,000) [151]	0 – 0.1 [143] 0.1 – 50 [12] 0.1 – 5 [150]	10^{-5} – 100 [12] 0.0015 – 50 [152]	85 – 90 [143] 85 – 95 [12], [150]

Table 2.5 – Additional Characteristics of selected Energy Storage Technologies [143], [149], [150], [151], [12], [152]

Technology	**Response time** [12]	**Self-discharge %/day (%/month)**	**Suitable storage duration** [143], [12]	**Lifetime in years**	**Cycle life**
Pumped Hydro	1 – 3 min	No [152] Very small [151] 0.005 – 0.02 [12]	h – months	20 – 60 [143] > 50 [151]	> 15,000 [151] > 50,000 [150]
Batteries					**Cycles (80% DOD)**
NaS	ms	0.05 – 20 [12] <20 [151]	s – h	10 – 15 [143], [151], [150]	4,000 – 40,000 [150] 2,500 [143] 4,000 – 4,500 [12]
Ni-Cd	ms	0.067 – 0.6 [12] (5 – 20) [149]	min – day	5 – 20 [151] 10 – 20 [12]	1,000 – 1,500 [12] 3,500 [152] 2,500 [149]
VRFB	ms	0.2 [12] Small [151]	h – month	5 – 15 [12] 5 – 10 [143]	> 10,000 [151] 12,000+ [143] 10,000- 13,000 [12]
Pb-A	ms	0.1 – 0.3 [151] 0.033 – 0.3 [12] (2 – 5) [149]	min – day	5 – 15 [12] 3 – 10 [150]	400 – 1,500 [12] 500 – 800 [150]
Li-ion	ms	0.1 – 0.3 [151],[12] (<1) [149]	min – days	10 – 16 [150], [152] 5 – 15 [12] 5 – 100 [151]	2,000 – 5,000 [12] 1,000 – 10,000 [149]

Table 2.6 – Costs of selected Energy Storage Technologies [143], [150], [151] [12], [152]

ES Technology	**Capital Cost**		**Maturity**
	$/kW	**$/kWh**	
Pumped Hydro	600 – 2,000 [143], [151] 1,000 – 4,000 [150]	5 – 100 [143], [151] 100 – 250 [150]	Mature [12]
Batteries			
Sodium-Sulphur	1,000 – 3,000 [143], [151], [12]	300 – 500 [143], [151], [12]	Commercial [143], [12]
Nickel-Cadmium	500 – 1,500 [151], [12] 400 – 2,400 [152]	800 – 1,500 [151], [12]	Commercial, mature [12]
Vanadium RFB	600 – 1,500 [143], [151] 1,200 – 2,000 [150]	150 – 1,000 [143], [151] 350 – 800 [150]	Demonstration [143], [12]
Lead-acid	300 – 600 [12] 300 – 800 [150]	200 – 400 [12] 150 – 500 [150]	Mature [12]
Lithium-ion	1,200 – 4,000 [143] 400 – 1,000 [150]	600 – 2,500 [143] 500 – 1,500 [150]	Demonstration [143] Commercial [12]

2.3.3 Battery Storage

Batteries are rated based on their energy and power characteristics. It is important to point out that energy and power are not independent battery variables but usually fixed during the battery design phase. Besides the basic properties of ESS, as presented earlier in Table 2.3, batteries have one additional parameter which is vital towards their operation and lifetime. The Depth of Discharge (DOD) refers to the extent to which a battery can be discharged and is represented by a percentage value. Discharging the battery completely (DOD = 100%) or above the recommended DOD value by the manufacturer can affect its lifetime significantly [153]. The relationship between the cycles to failure and DOD is reflected, in Figure 2.20, for several battery technologies. It is clear that battery lifetime is reduced when DOD increases.

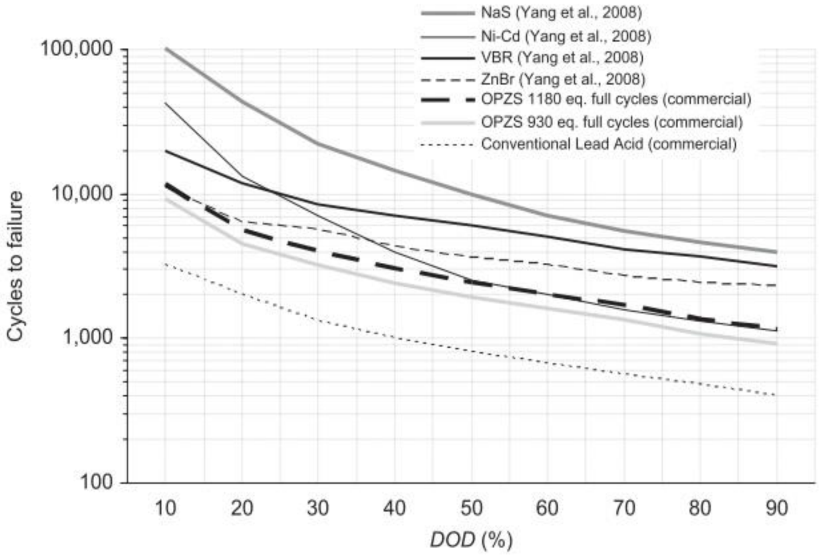


Figure 2.20 – Cycles to failure versus DOD for several battery electrochemistries. Reproduced with permission from [154]. Copyright 2009, Elsevier.

BES also requires a number of additional components, besides the battery which constitutes the storage device of the system. These components include monitor and control systems, commonly referred together as the battery management system (BMS), whose purpose is to make sure that the safety standards are enforced and maximise the overall performance. Therefore, BMS keeps cells from overcharging by monitoring and controlling the charge and discharge status of the battery. The critical parameters differ from battery to battery, for example in li-on systems, BMS gives a special priority in thermal monitoring, as there is an inclination towards overheating. Furthermore, a power conversion system is present and usually comprises of a bi-directional converter, which has the ability to convert DC to AC power and vice versa. This is unavoidable because batteries deliver DC while all modern conventional electric and electronic systems utilise AC. Therefore, a two-way conversion of electricity is required, depending on the source and the destination [155].

As mentioned above, there is a number of different battery chemistries some of which are mature and commercial while others are still in their R&D phase. However, the Pb-A battery is the oldest and the most mature battery technology; therefore, it has been used in the majority of power system applications [153].

Finally, according to [155], there are several factors when deciding which battery chemistry to use. As shown in Figure 2.21, it is clear that the energy density of the battery has to be considered along with potential space limitations while the policy and the regulatory treatment of the battery application also have to be taken into account. Considerations include operational, performance, maintenance and grid requirements, technical characteristics and the associated costs. The rest of the chapter presents important background information on certain major battery chemistries that include Pb-A, Li-ion, NaS, RFB and finally Ni-Cd batteries.

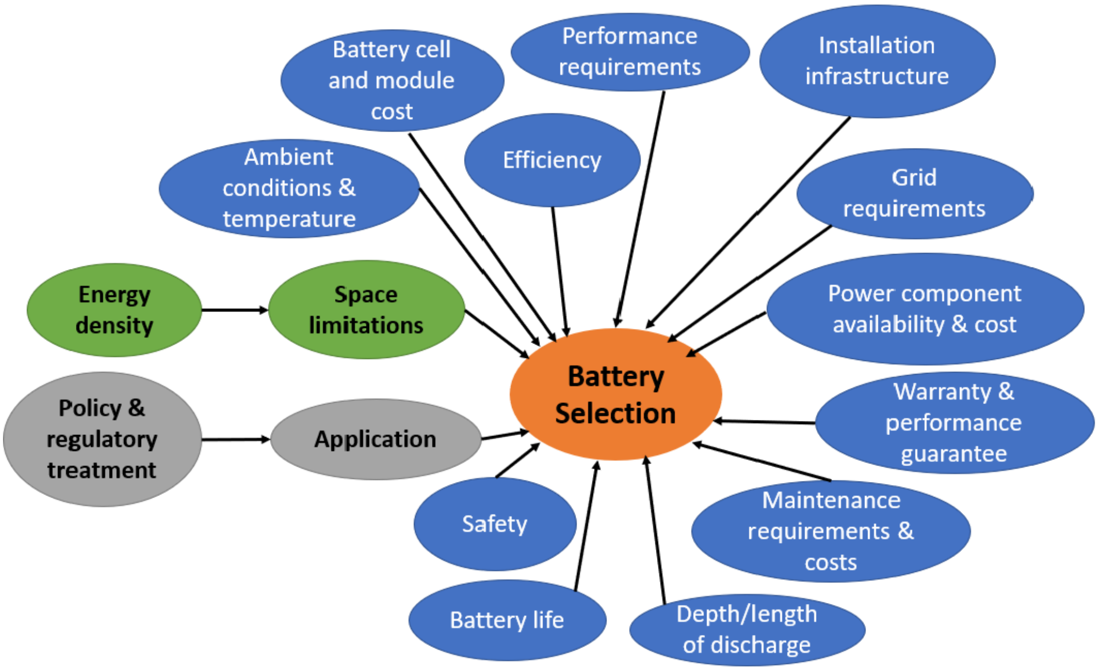


Figure 2.21 – Considerations for battery selection (Adapted from [155])

2.3.3.1 Lead-acid (Pb-A)

Pb-A batteries constitute an old technology, invented back in the 1860's and therefore they are one of the most mature, affordable and popular batteries worldwide. Its technical properties have been researched for decades and more specifically their plate and case design, the electrolyte and active material composition, as well as the separator materials. While the battery is generally considered to be cheap and technically mature, downsides include low energy density and limitations concerning their lifetime in cycles. Improvements have been introduced through additives, but the basic design includes sulphuric acid as the electrolyte, a lead-oxide positive plate and metallic lead as the negative electrode.

Pb-acid batteries have been mostly used for heavy cycling applications, supporting the grid through peak shaving or as uninterruptible power supplies (UPS). In terms of energy and power capacity, one of the biggest Pb-A battery in the world is located in Chino, California with an output of 10 MW and 40 MWh and used for various balancing services, such as peak shaving, load-leveling, load following, frequency and voltage control. Another significant Pb-A system, worth mentioning, is the BEWAG facility in Germany, rated at 17 MW and 14 MWh, and used for frequency regulation and spinning reserve. Finally, the Puerto Rico Electric Power Authority is also using a lead-acid battery (20 MW, 14 MWh) to provide ancillary services to the grid [156].

Zhang et al. [157] noted that Pb-A batteries have been used as backup batteries in power plants and transformer substations. However, the specific battery chemistry suffers from low power density, energy density and cycle life as well as long charge times and high parasitic losses. Combining these characteristics with environmental concerns around potential pollution that could be caused from their components and especially lead, Pb-A batteries have been used rarely in the power market, in the recent years, despite their relatively low cost.

2.3.3.2 Lithium-ion (Li-on)

Li-ion is a relatively new technology in the battery area, whose popularity is expected to significantly increase and replace a percentage of the lead-acid market share. Li-ion is used in EVs and hybrid vehicles, in electric bikes, while it has been receiving an increasing penetration in other sectors, such as the electronic industry, the army and medicine. Its future growth can potentially lead to a 'booming effect' and consequently lead to a more affordable price, making li-ion an even more suitable technology for RES and energy storage. Among the benefits of its unique electrochemistry, Li-ion has higher energy and power densities, longer lifecycle and therefore it is ideal for portable and consumer electronics, like mobile phones, laptop computers, cameras etc. While the Li-on battery faces financial and safety issues, these are likely to be resolved in the near future by the mass utilisation of the battery chemistry in EVs. There are great concerns regarding the sustainability of the Li-on battery as it will highly depend on its recyclability. It is worth noting that replacing the batteries of 1 billion future electric and hybrid cars could use up to 30% of lithium's world reserves [158].

According to [159], lithium appears to be the most promising metal available for battery chemistry due to its wide availability, non-toxicity and light weight. A Li-on battery cell consists of four main parameters: cathode, anode, electrolyte and separator. During the charging phase of the cell, the lithium ions move from the cathode to the anode, through the electrolyte while the reverse movement takes place during discharging. Commercial Li-on batteries are named after the Li-ion donator in the cathode, the main parameter that determines the cell properties. Several Li-ion metal oxides are used, including lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). The selection between the materials mentioned can highly affect battery performance and characteristics. The most common anode material is graphite; however, some manufacturers choose to use lithium titanite instead. The electrolyte used is a mixture of lithium salts and organic solvents while polyethylene and polypropylene are the most common separator materials.

Table 2.7 summarises the most important parameters for popular Li-on chemistries along with their qualitative analysis, advantages and disadvantages. It is clear that there is no perfect Li-on battery chemistry; compromises have to be made depending on the application, the available budget, safety requirements and other criteria, previously mentioned in Figure 2.21. Special mention should be given to the safety issues of the technology, caused by the thermal instability of some metal oxide electrodes as they can degrade at high temperature and release oxygen, making way for a thermal runaway. In the recent years, manufacturers took extra steps to avoid such phenomena, by using a monitoring unit to prevent overcharging and overdischarging. Checking the voltage of each cell in order to avoid variations is also critical, by deploying a voltage balance circuit [160].

One characteristic example of those issues was reported in 2013, when multiple incidents, including onboard and ground electrical fires and smokes, were reported in Boeing 787 aircrafts. Dreamliner was the first civil aircraft of its size that has ever used Li-ion batteries for electric power source. Due to the safety concerns, all 50 aircrafts of the same type were grounded in order to discover the cause of the problem. It was concluded that there were major issues between the Li-on batteries and the electrical systems, resulting in thermal runaways of the batteries. After the appropriate investigation, modifications and tests, the problem was resolved but it is a reminder that battery technologies need extra care, attention and frequent inspections, especially when used for new applications [161].

Table 2.7 – Comparison of lithium-ion chemistry properties [162]

Parameter	**Lithium nickel manganese cobalt oxide**	**Lithium manganese oxide**	**Lithium nickel cobalt aluminium**	**Lithium iron phosphate**	**Lithium titanate**
Abbreviation	NMC	LMO	NCA	LFP	LTO
Cathode	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	$LiFePO_4$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety	3/4	3/4	2/4	4/4	4/4
Power density	3/4	3/4	4/4	3/4	3/4
Energy density	4/4	3/4	4/4	2/4	2/4
Cell costs advantage	3/4	3/4	2/4	3/4	1/4
Lifetime	3/4	2/4	4/4	4/4	4/4
System performance	2/4	2/4	2/4	4/4	4/4
Advantages	• Good properties combination • Can operate at high voltages • Can be tailored for high power or energy	• Low cost due to manganese abundance • Very good thermal stability and power capability	• Very good energy and good power capability • Good cycle life in newer systems. • Long storage calendar life	• Very good thermal stability, cycle life and power capability • Low costs	• Very good thermal stability. • Long cycle lifetime • High rate discharge capability • No solid electrolyte interphase issues
Disadvantages	• Patent issues in some countries	• Moderate cycle life insufficient for some applications • Low energy performance	• Moderate charged state thermal stability can reduce safety • Capacity can fade at 40-70°C	• Low energy density due to lower cell voltage	• High cost of titanium • Reduced cell voltage • Low energy density

2.3.3.3 Sodium-sulphur (NaS)

The NaS battery includes liquid sulphur at the positive electrode and liquid sodium at the negative electrode, which are separated by a solid electrolyte. The roundtrip efficiency is satisfying, varying between 70 – 90%, and relatively cheap and non-toxic materials are used. On the other hand, NaS is mostly suitable for large-scale stationary applications, as the operating temperatures are high and the sodium is corrosive. The produced heat has an average temperature of 300 – 350°C [163]. The capacity of the installed sodium-sulphur batteries has increased, from 10 MW in 1998 to 305 MW (2,000 MWh) in 2008 and 530 MW (3,700 MWh) in 2014, in over 190 locations.

One of the biggest systems in the world is located in northern Japan, with a capacity of 34 MW and 245 MWh and used for integration and stabilisation of a 51 MW wind farm. The system was built by the only NaS battery supplier in the world, NGK Insulators. As the company supports, NaS batteries are designed for bulk energy storage, they can come at very large sizes (10 to 100s of MW) and they have a long lifetime, of approximately 4,500 cycles, which is equivalent to 15 years, assuming 300 cycles per year [164], [165].

Additionally, electricity can be delivered within 1 millisecond, needs less space compared to other battery technologies and is reliable and safe by design. Applications include RES integration, generation management, investment deferral and ancillary services. NaS can have a discharge duration between 0 and 7 hours, with a respective power capacity of 1-20 MW [165].

2.3.3.4 Redox Flow Batteries (RFB)

RFBs have some unique characteristics, when compared to conventional battery technologies. Except for their design flexibility, energy and power capacity are independent of each other, the same materials are used in both half-cells; therefore, the risk of cross contamination is eliminated, and the electrolytes can theoretically have unlimited lifetime and cycles. As their energy density is relatively low, RFBs are suitable for large scale stationary energy storage, assuming the overall volume and weight of the system is not an issue. They can be used for peak shaving, load-leveling, UPS and RES integration. They are capable of rapid response and can provide both power quality and energy management services, with low maintenance.

A typical RFB includes two liquid electrolytes (anolyte and catholyte), stored in two external tanks and transferred into the cell through a pumping system to produce energy, by an electrochemical reaction that takes place. There are different types of RFB systems, depending on the solutions used on the external tanks of the battery. The Vanadium Redox Flow Battery (VRFB) is a classic example and mentioned often in the literature. It takes advantage of the different oxidation states of Vanadium, which are diluted in an acid solution, such as sulphuric acid. The energy capacity of the system can be increased by adding more volume of the electrolyte solution, while adding more cells will increase the overall power output of the system. The typical components of a VRFB unit are shown below, in Figure 2.22, connected to the electrical grid through a DC/AC inverter. Other components include the electrolyte tanks, pumps and the BMS [147], [166], [167].

Additionally, it is worth mentioning the differences and properties between existing RFB configurations. Table 2.8 lists some critical RFB parameters such as energy and specific energy density, nominal voltage and energy efficiencies. The All-Vanadium battery has the highest reported efficiency around 80 – 85% and one of the highest energy densities as well, between 20 – 33 Wh/L. Both the design and electrochemistry flexibilities, along with the capacity to put cells in series or in parallel provides a great opportunity to create and use an RFB battery for the desired application [147], [166].

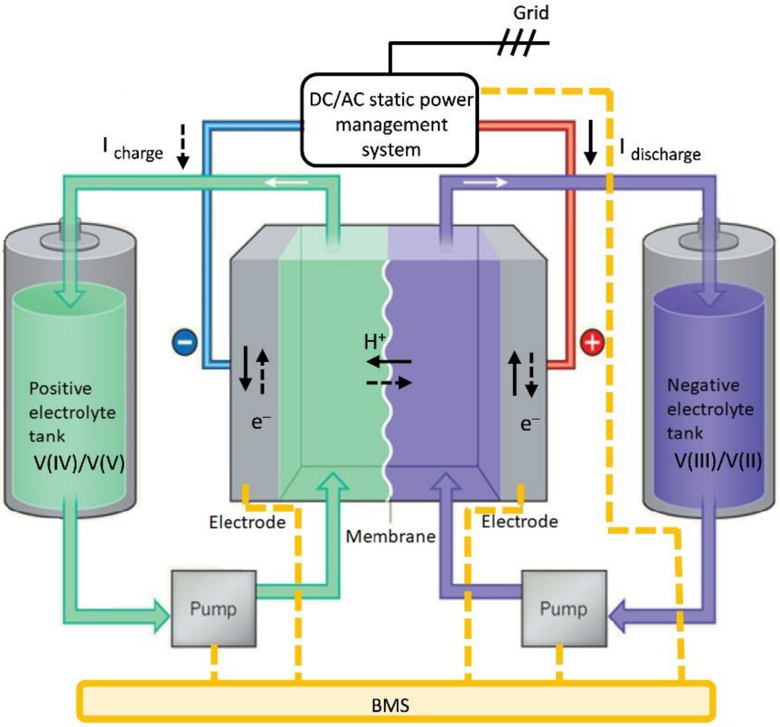


Figure 2.22 – Components of a typical VRFB connected to the electrical grid. Reproduced with permission from [167]. Copyright 2020, Elsevier

Table 2.8 – Characteristics of Redox Flow Battery Types [166]

Parameter	**All-Vanadium**	**Vanadium Bromide**	**Zinc-Bromine**	**Cerium-Zinc**	**Regenesys**	**Fe-Cr**
Energy Density (Wh/L)	20-33	35-70	50	12-20	20-30	-
Specific energy density (Wh/kg)	15-25	25-50	65-70	-	20	<10
Nominal voltage	1.4 V	1 V	1.8 V	2.1 V	1.35 V	1.18 V
Operational temperature	5-40°C	0-50°C	20-50°C	20-60°C	20-40°C	65°C
Reported Energy Efficiency	80-85%	60-70% at 40°C	75%	75%	60-65%	70-80%

2.3.4.5 Nickel-Cadmium (Ni-Cd)

Ni-Cd batteries share some similarities with Pb-A, regarding their physical structure. More specifically, instead of lead, the plates consist of nickel hydroxide (positive) and cadmium oxide (negative). Additionally, instead of sulphuric acid, an alkali, potassium hydroxide, is used as electrolyte. Ni-Cd are considered to have an important advantage, when compared to Pb-A, as sulphation is not an issue and therefore, they can get overcharged or left discharged, without any damage to the plates. Also, temperature does not affect their charging and any methods or available chargers can be used for this purpose. On the other hand, measurement of their state of charge (SoC) is not a simple process as the voltage and specific weight variations are insignificant when discharging takes place. This adds some inconvenience for the battery users as it is not possible to identify the moment it reaches full discharge. Finally, battery residues can potentially lead to the formation of cadmium blocks and the battery being unable to fully charge, an issue often called “memory effect”. The first-generation Ni-Cd batteries make use of vented pocket plates where folded steel stripes are pierced on both sides to increase by 30% the useful area to the plate and consequently the maximum charging capacity of the battery. Sintered plate second-generation Ni-Cd batteries perform better in low temperatures due to lower internal resistance and the required maintenance is minimal. However, larger amounts of nickel are needed leading to higher manufacturing costs that are not viable for a cell more than 100 Ah [168].

Regarding their applications, Ni-Cd batteries are used in devices, such as phones, toys and hand tools. They are considered to be excellent solutions for long-term storage while having a long cycle life as well as good durability and charge retention. Disadvantages of the battery technology include low energy density and higher costs when compared with Pb-A. It should be mentioned that cadmium is a highly toxic metal and therefore Ni-Cd batteries must be treated accordingly after the end of their life. Significant amounts of cadmium detected in municipal waste originate from Ni-Cd batteries [169].

2.3.4 Energy Storage Applications

Conventional grid infrastructure is designed to meet the peak loads of electricity as supply and demand are coupled. However, peak loads only take place for a limited number of hours during the year as electricity varies significantly on a daily and seasonal basis. Peak power plants which are usually overdesigned and their operation expensive are used to keep the system balanced. However, by using ESS to perform specific services, system planners can use the right amount of generating capacity to meet the average loads instead, therefore decoupling supply and demand. Some ES applications have already been mentioned occasionally, in both the current and previous chapter, including peak-shaving and load-leveling. The electrical loads and the impact of the EES utilisation are shown in Figure 2.23. Regarding peak-shaving, ESS is charged during the early hours of the day, when the electrical demand is relatively low. Later in the day, when the electrical loads reach their peak values, the electricity stored in the ESS is discharged to meet part of the electrical demand. In this way, the electricity purchased from the electrical grid to meet the remaining loads is reduced, compared to the base scenario without the operation of ESS. Load-leveling follows a similar approach but the discharging process has a slightly different objective and more specifically to cap the remaining loads that need to be purchased by the grid at a specific power limit in terms of kW [144].

Arbitrage, also referred to as time-shifting of loads, is just one of the energy storage revenue streams; however, it is considered to be the main mechanism that renders the operation of ESS financially sustainable. It can be primarily found in the day-ahead energy market while the rest of the ES applications are offered in different markets which offer balancing actions and frequency regulation services. Participation in such services is still profitable but the energy volume of the auctions in question is comparatively smaller [170].

The idea behind arbitrage is simple as it includes buying electricity when prices are cheaper and later using that electricity to meet electrical loads or selling it at a higher price to take advantage of the price difference. In deregulated power markets, supply and demand determine the electricity prices. Other parameters that affect the market price are RES generation, coal and gas prices, emission prices and energy prices in neighbouring countries. The amount of potential revenues for providing arbitrage highly depend on the operation frequency of the ESS and more precisely on the daily number of the full charge-discharge cycles. BES in particular can be flexible and provide arbitrage by performing services in other markets as prices of balancing services are more volatile than the day-ahead market [171].

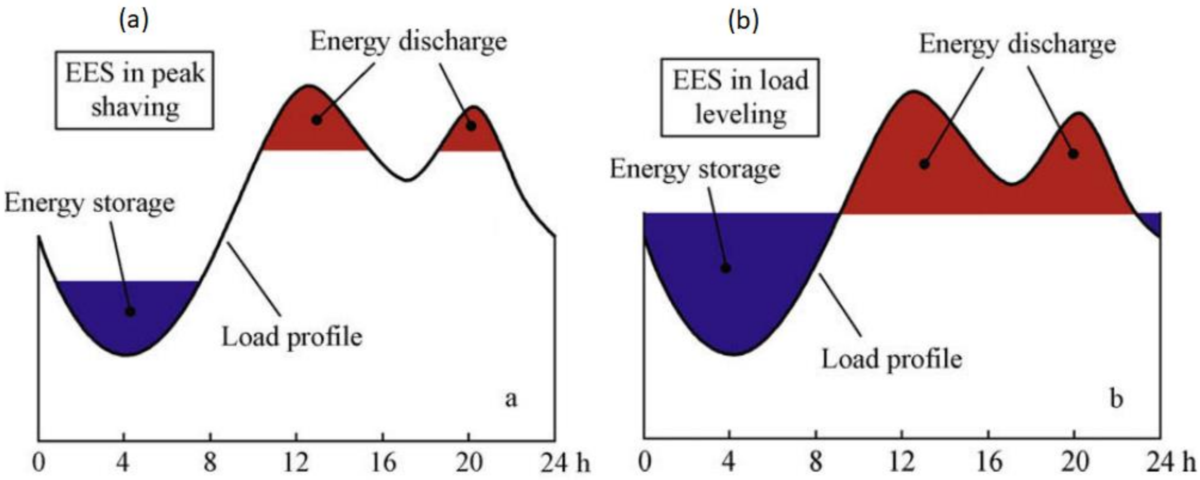


Figure 2.23 – Electrical Energy Storage (EES) performing (a) peak-shaving and (b) load-leveling. Reproduced with permission from [144]. Copyright 2009, Elsevier.

Wankmüller et al. [172] supported that "*arbitrage represents the largest profit opportunity for BES in the electric power grid*" while highlighting that there are several studies which investigate the profitability of different charging and discharging profiles when utilising batteries to conduct arbitrage. Battery lifetime and degradation constitute one of the most important assumptions when evaluating the cost-effectiveness of an arbitrage scheme. Finding the most suitable operational strategy can be thought of as an optimisation problem with assumptions, known data (e.g. electricity prices), constraints and finally assumptions.

Arcos-Vargas et al. [173] reviewed several publications related to electric arbitrage through storage utilisation. Grid tariffs and more specifically transmission access tariffs can particularly impact arbitrage's cost-effectiveness and the profitability of the ESS operation regardless of its size. The ESS operation profile is not affected by that impact itself; on the other hand, the volume of the traded electricity is indeed affected. Furthermore, another publication pointed out that costs, properties and efficiencies of storage technologies have improved significantly during the recent years. The Li-on battery constitutes a characteristic example with its capital costs having been reduced by approximately 90% due to the mass utilisation of the technology in EVs. Therefore, several existing papers which examined the cost-effectiveness of energy storage schemes, especially systems based on Li-on batteries, need to be revised to reflect the current economic costs.

According to [173], a 2019 Swiss study showed that shared ownership of community energy storage between an aggregator and a DNO can lead to profitability for conducting energy arbitrage-peak shaving, when utilising Li-on batteries and VRFBs. Finally, a study on the electricity market of Alberta in Canada showed that PHES has a clear advantage over NaS batteries when it comes to arbitrage. Table 2.9 summarises the main publications reviewed by [173] and their main contributions. While the conclusions may vary, regarding arbitrage, there is a clear interest on its techno-economic optimisation, operational dispatch strategies as well as the impact of using different storage technologies and sizes. The authors concluded that batteries are not currently attractive for conducting arbitrage; nevertheless, their participation in the balancing/ancillary services market has the potential to improve their profitability and bring benefits to the electrical network due to their flexibility and easy configuration.

Table 2.9 – Existing research on electric arbitrage evaluations [173]

Market(s)	Energy Storage Technology	Contribution
Alberta, Canada	Not specified	Impact on benefits and battery design of grid access tariffs
New York Independent SO	CAES, PHES	Arbitrage benefits in day-ahead, intraday, and ancillary services
United States	PHES, CAES, Li-on, ZEBRA, Ultra capacitors, Liquid-air	Maximum configuration of hours for each technology
11 different countries	PHES	Optimal configuration and operational strategies
UK	Li-ion	Arbitrage and renewable penetration
California Independent ISO	CAES	Grid benefits, Wind penetration and pay back
Iran	VRFB	Optimal sizing for improving distribution network performance
Alberta, Canada	NaS, PHES	PHES has a clear advantage over NaS batteries
California Independent ISO	BES	Optimal bidding strategies
Germany	Not specified	Arbitrage profitability and sustainability conditions
Alberta, Canada	PHES	Optimal sizing and strategies for maximum benefit
Australia	PHES	Parameters influence on profitability
Switzerland	Li-ion, PHES, CAES, NaS, Liquid-air, VRFB	Comparison of technologies
New York	NaS, FES	Relevant factors in profitability
China	Not specified	Optimal sizing for a non-competitive market
Turkey	CAES	Optimal arbitrage
Finland	PHES, CAES, NaS, Liquid-air, VRFB	Optimal sizing

Figure 2.24 provides a detailed list of services that can be provided by energy storage, classified by their scale: Bulk Energy, Balancing, Transmission & Distribution Infrastructure and finally Customer Energy Management Services. Certain services, shown in grey background, directly support the integration of stochastic RES by matching their supply with the respective demand, providing or removing power to keep the system balanced and generally optimising the RES feed-in to the electrical grid. These services include arbitrage (both at bulk and customer levels), frequency regulation and power reliability [155].

A similar classification of services provided by ESS is reported by [174] with some minor differences; arbitrage and electric supply capacity constitute separate categories due to their importance while transmission and distribution (T&D) deferral and relief are listed as sub-services of the electric supply capacity. The authors also classified further the energy storage applications based on the physical locations of the systems as part of the grid and the scope of the provided services (Table 2.10). It can be observed that energy storage deployed in the lower hierarchical levels of the grid can theoretically provide services for the higher grid levels as well; however, in practice, requirements and constraints set by the utility could make certain services unavailable.

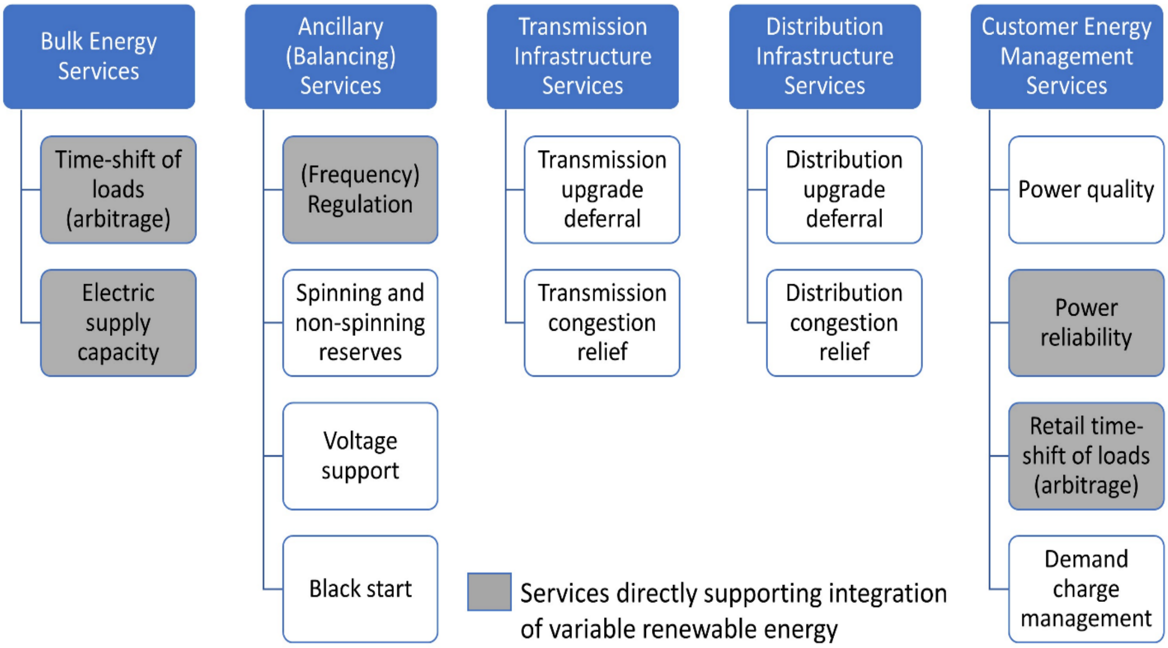


Figure 2.24 – Services provided by Energy Storage (Adapted from [155])

Table 2.10 – Classifications of Energy Storage Applications based on the physical locations in the grid and the scope of services [174]

			Grid Domain		
			Transmission	**Distribution**	**Customer**
		Power Rating (MW)	10 ~ 100	0.010 ~ 10	0.002 ~2
Service Scope	**Wholesale (Bulk)**	Energy arbitrage	✓	✓	✗
		Frequency Regulation	✓	✓	✓
		Reserve	✓	✓	✓
		Resource adequacy	✓	✓	✓
		Demand Response	✗	✗	✓
	Transmission	Transmission Deferral	✓	✓	✗
		Voltage support	✓	✓	✓
		Inertia	✓	✓	✓
		Frequency response	✓	✓	✓
		Black start	✓	✓	✓
	Distribution	Distribution Deferral	✗	✓	✗
		Voltage support	✗	✓	✓
		Reliability service	✗	✓	✓
		Microgrid	✗	✓	✓
	Customer	Bill reduction	✗	✗	✓
		Increase PV consumption	✗	✗	✓
		Backup power	✗	✗	✓

Additionally, at the customer-level, energy storage has the potential to reduce the total costs for the end user, increase consumption from photovoltaics and also serve as backup power in case of an emergency. Certain grid applications can take advantage of the rapid bidirectional power exchange capabilities of ESS, especially providing frequency response, voltage control and reducing/deferring the need for potential costly infrastructure upgrades. The uncertainty of electricity prices is also an important factor when considering the profitability of arbitrage provided by ESS as storage utilisation might have an impact on the determination of the prices themselves. If that is the case, the profitability of ESS conducting arbitrage may be reduced. Finally, in market terms, small-scale ESS conducting arbitrage can be considered as price-takers while large-scale ESS can act as price-makers in the wholesale market and use strategic bidding to increase their profits.

The locations of ESS are showed inside the electrical grid that consists of high-voltage (110 kV), medium-voltage (20 kV) and low-voltage (0.4 kV) sections, in Figure 2.25. ESS can be seen next to variable RES, conventional power plants, large residential, large industrial as well as residential consumers. The applications vary depending on the location and the accompanying entity, but it can be observed that the same applications can indeed take place in different parts of the network, with the characteristic examples of arbitrage, power quality and power reliability. The services present in the figure are also in accordance with the content of Table 2.10, further reinforcing the fact that can provide certain services from the lower to the higher hierarchical levels of the electrical grid. Regarding the individual suitability of ESS for specific services, batteries constitute a reliable storage category that is capable of contributing towards the majority of grid applications, as shown in Table 2.11. While batteries are generally an appropriate storage technology to provide balancing services, integrating RES is also possible through time shift and capacity firming. On the other hand, batteries are not considered to be suitable for arbitrage and peak-shaving at the wholesale/bulk scale due to their smaller size and the higher capital costs per kWh. For bulk energy applications, PHES is the leading storage technology with CAES being a possibility as well.

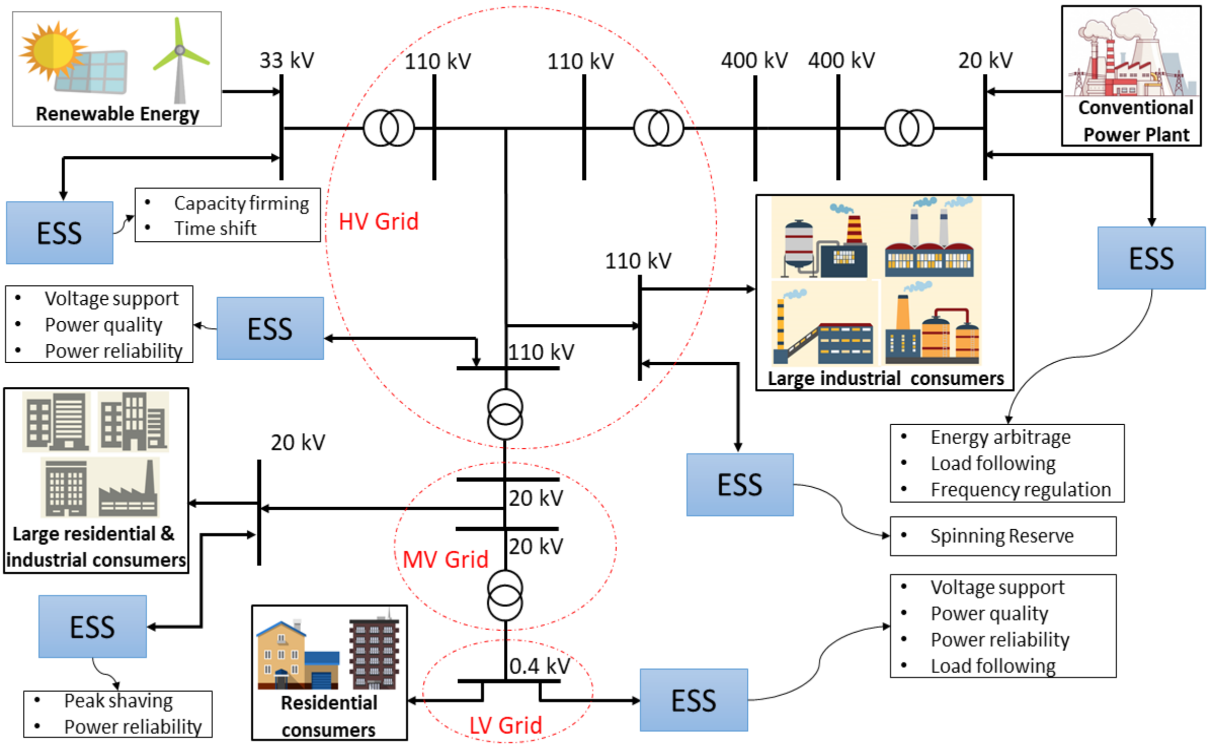


Figure 2.25 – Location of ESS in the power network and their applications (Adapted from [175])

The suitability of storage technologies towards applications was also reviewed by [176]; their output is generally in accordance with Table 2.11, with some minor differences. Gür [177] highlighted that T&D systems around the world are very old but legal, socioeconomic and environmental obstacles render their upgrade a rather challenging issue. The deployment of distributed ESS can contribute towards the decentralisation of the power network that needs long and costly T&D networks where power losses take place by providing local control and improving energy security. When considering energy storage applications, the economics of storage are as important as the performance, round-trip efficiency, and the discharge duration of the system. It is argued that each technology has its special advantages, disadvantages and challenges while "*there is no silver bullet for electrical energy storage*" and "*one size does not fit all*". The authors presented the example of using batteries of different sizes for grid applications. While a megawatt-scale battery is appropriate for certain grid applications when deployed at a high voltage (e.g. 10 kV) near a utility transformer, this configuration would be more complicated as several step-down transformers to reduce the voltage as well as other controls would be needed. On the other hand, smaller batteries (e.g. 10 kW) could be used on the 100 V side of the transformer to simplify the entire process.

Table 2.12 lists the characteristic performance requirements for the most common storage applications, including the properties mentioned above that affect the suitability of certain technologies. Applications such as seasonal storage, bulk-energy arbitrage and load-following have the widest ranges of discharge times while the majority of the remaining services have a maximum discharge time of some hours.

Table 2.11 – Energy Storage Technologies versus Applications [175]

	Technologies	**Electrochemical**				**Mechanical**
Applications		Pb-A	Li-ion	NaS	VRFB	PHES
Bulk Energy	Energy Arbitrage	✗	✗	✗	✗	✓
	Peak-shaving	✗	✗	**P**	**P**	✓
Ancillary (Balancing) Services	Load-following	✓	**P**	✓	✓	**P**
	Spinning reserve	**P**	✗	**P**	✗	**P**
	Voltage support	✓	✓	✓	**P**	✗
	Black Start	✓	✓	✓	✓	**P**
	Primary FR	✓	✓	✓	✓	**P**
	Secondary FR	✓	✓	✓	✓	✓
	Tertiary FR	✓	✓	✓	**P**	✓
Customer Energy Management	Power quality	✓	**P**	**P**	**P**	✗
	Power reliability	✓	✓	✓	✓	✗
RES integration	Time shift	**P**	**P**	**P**	**P**	✓
	Capacity firming	**P**	**P**	**P**	**P**	✓

*FR: Frequency Response, P: possible

Table 2.12 – Characteristic performance requirements for EES applications [177]

Application	Size (MW)	Discharge duration	Cycles (topic)	Response time
Seasonal storage	500 to 2,000	Days to months	1 to 5 per year	Day
Arbitrage (bulk trading)	100 to 2,000	8 to 20 hours	0.25 to 1 per day	>1 hour
Frequency regulation	1 to 2,000	1 to 15 minutes	20 to 40 per day	1 min
Load-following	1 to 2,000	15 minutes to 1 day	1 to 29 per day	<15 min
Voltage support	1 to 40	1 second to 1 minute	10 to 100 per day	milisec. to second
Black Start	0.1 to 400	1 to 4 hours	<1 per year	<1 hour
T&D congestion relief	10 to 500	2 to 4 hours	0.14 to 1.25 per day	>1 hour
T&D investment deferral	1 to 500	2 to 5 hours	0.75 to 1.25 per day	>1 hour
Load-shifting & peak-shaving	0.001 to 1	Minutes to hours	1 to 29 per day	<15 min
Off-grid	0.001 to 0.01	3 to 5 hours	0.75 to 1.5 per day	<1 hour
Variable RES integration	1 to 400	1 minute to hours	0.5 to 2 per day	<15 min
Spinning reserve	10 to 2,000	15 minutes to hours	0.5 to 2 per day	<15 min
Non-spinning reserve	10 to 2,000	15 minutes to hours	0.5 to 2 per day	<15 min

2.3.5 Current and Future Trends

Regarding the popularity of EES, their global grid capacity is increasing and was estimated to be around 140 GW, back in 2014, with 99.6% of the energy stored being in the form of PHES. Only four years later, in 2018, the capacity value increased to 176 GW, 96.44% of which was attributed to PHES while the rest of EES technologies constituted the remaining 3.56% of the capacity. According to the IEA, the worldwide EES capacity is expected to reach 450 GW by the year 2050 [178]. While 372 MES projects were considered to be operational in 2020, including PHES, CAES and FES, there were also 695 operational projects with electrochemical ESS of a 2.03 GW combined capacity. In this category, Li-on batteries were considered to have the highest market share. Regarding future expansion of the technologies, a further number of 136 electrochemical projects of 0.63 GW capacity have been announced while 10 projects of 0.70 GW are under construction. The respective values for the announced mechanical systems are 26 projects of 11.26 GW, with 7 projects of 5.95 GW being under construction [179].

Regarding future battery costs, the battery's levelised cost of electricity (LCOE) is expected to drop by one-third by 2030 and 50% by 2050 with Li-on being regarded to become the most competitive battery technology by 2030. Along with the reduction of costs, lifetime of the systems will be extended as well with improvements in materials and efficiency [179]. Projections for the future lifetime and costs of certain technologies, including the different Li-on electrochemistries, can be seen, in Table 2.13, for the year 2030, where the worst, reference and best scenarios are shown [162].

The cycle life of CAES and PHES are not expected to improve further while all PHES properties remain static, further evidence of the advanced maturity of the technology. Regarding the differences expected in the reference values, energy costs for flooded Pb-A batteries are predicted to drop from $147/kWh in 2016 to $74/kWh in 2030. The values for the same years, for VRFBs, are 347 and $119/kWh, respectively. Regarding the Li-on group category, a wide range of values can be observed depending on the electrochemistry. LTO, which constitutes the most expensive subcategory, is expected to drop from $1,050 to $478/kWh while the most affordable NCA will be reduced from $352 and $145/kWh. Despite the wide range of the prediction values, it is clear that an energy cost reduction of at least 50% is anticipated for BES systems, for all three scenarios. The reference energy cost values for the years 2016 and 2030 are shown in Figure 2.26, using data from [162]. While differences exist between technologies, all BES are expected to see major cost reductions. At the same time, with the exemption of VRFB, the lifetime of all BES systems is predicted to increase significantly, both in terms of cycles and calendar years. For example, the cycle life for the LTO battery will be expanded from 10,000 to 19,000 cycles and from 15 to 23 years while the life cycle of LFP battery will increase from 2,500 to 4,774 cycles and from 12 to 18 years. Detailed projections can be seen in Table 2.13.

Table 2.13 – Projections for the Characteristics of Energy Storage Technologies [162]

			Energy Installation Cost Unit: $/kWh			**Cycle Life Unit: Equivalent full cycles (years)**		
Type	**Technology**	**Year**	**worst**	**reference**	**best**	**worst**	**reference**	**best**
Battery	VRFB	2016	1050	347	315	12,000 (5)	13,000 (12)	14,000 (20)
		2030	360	119	108	12,000 (8)	13,000 (19)	14,000 (32)
	NaS	2016	735	368	263	1,000 (10)	5,000 (17)	10,000 (25)
		2030	324	162	116	1,500 (14)	7,500 (24)	15,000 (36)
	Flooded Pb-A	2016	473	147	105	250 (3)	1,500 (9)	2,500 (15)
		2030	237	74	53	538 (4)	3,225 (13)	5,375 (21)
	VRLA	2016	473	263	105	250 (3)	1,500 (9)	2,500 (15)
		2030	237	132	53	538 (4)	3,225 (13)	5,375 (21)
	LFP	2016	840	578	200	1,000 (5)	2,500 (12)	10,000 (20)
		2030	326	224	77	1,910 (8)	4,774 (18)	19,097 (31)
	LTO	2016	1,260	1,050	473	5,000 (10)	10,000 (15)	20,000 (20)
		2030	574	478	215	9,549 (15)	19,097 (23)	38,194 (31)
	NCA	2016	840	352	200	500 (5)	1,000 (12)	2,000 (20)
		2030	347	145	82	955 (8)	1,910 (18)	3,819 (31)
	NMC/LTO	2016	840	420	200	500 (5)	2,000 (12)	4,000 (20)
		2030	335	167	79	955 (8)	3,819 (18)	7,639 (31)
Mechanical	PHES	2016	100	21	5	12,000 (30)	50,000 (60)	100,000 (100)
		2030	100	21	5	12,000 (30)	50,000 (60)	100,000 (100)

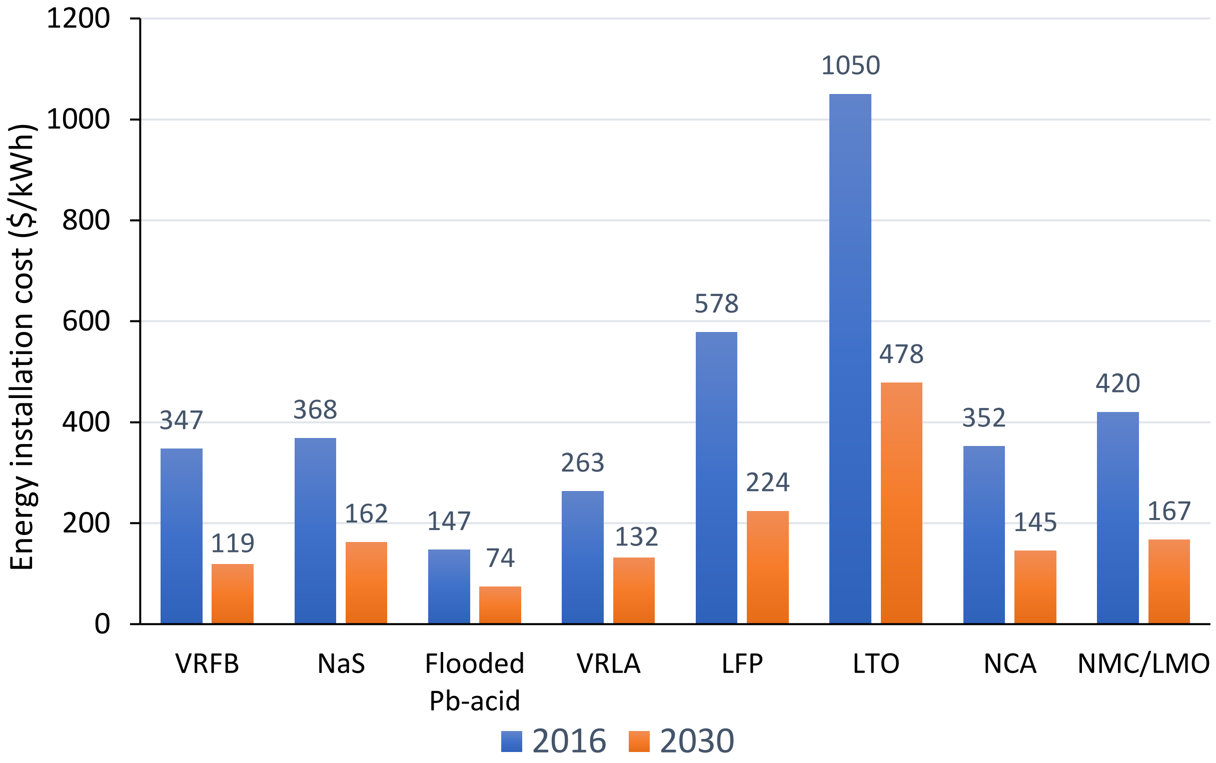


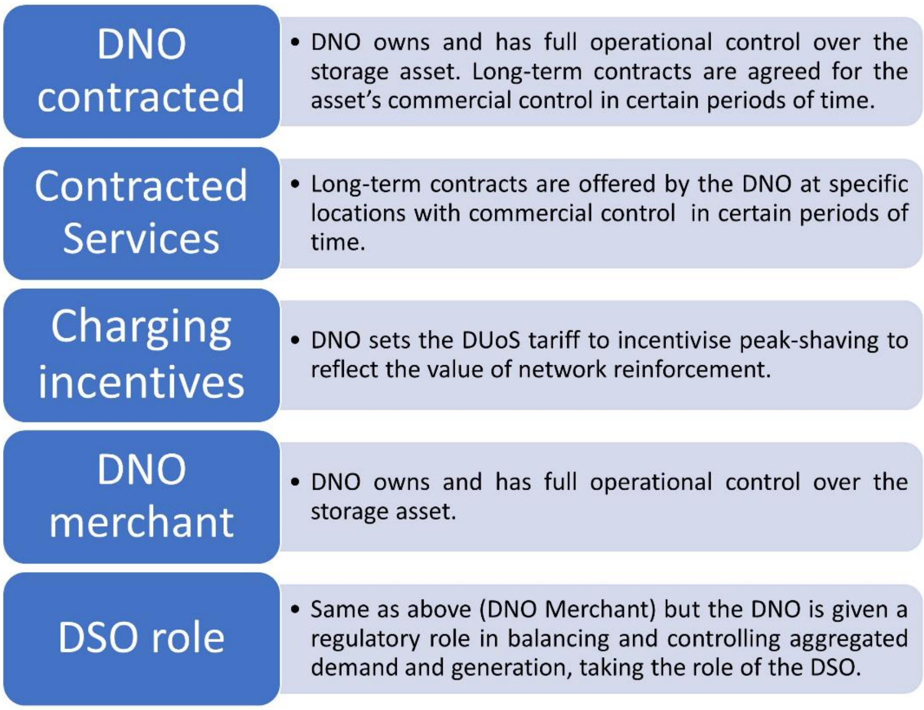
Figure 2.26 – Energy installation cost ($/kWh) for BES. Reference values adapted from [162]

2.3.6 Policy and Regulations

Before presenting and discussing energy storage projects of different scales, it is important to briefly mention the regulations and policy that are relevant to energy storage in the EU and the UK. EU Directive 2019/944 on common rules for the internal market for electricity replaced the older 2017/27/EU Directive. Its aim is to "*establish common rules for the generation, transmission, distribution, energy storage and supply of electricity*" for a fully integrated, fair, transparent and competitive electricity market inside the Union [180]. It is clear that energy storage is considered as a vital component of the electricity network along with T&D and supply. Additionally, it is mentioned 43 times in the directive, a fact that highlights that it is regarded by the European Commission as a key technology. More specifically, the directive supports that electricity markets in Europe need to be organised more flexibly to integrate all the market players, including RES, new energy service providers, energy storage and flexible demand. Regulatory authorities shall facilitate cross-border transactions that involve electricity originating from new electricity suppliers, providers, energy storage and DR. Technically, consumers are able to consume, store and sell self-generated electricity by utilising energy storage. However, it is recognised that important legal and commercial barriers do exist that prevent consumers to engage in a bidirectional exchange of power. It is stated that "*system operators should not own, develop, manage or operate energy storage facilities*", referring to TSOs and DNOs. The directive argues that these restrictions are placed in order to endorse and promote a competitive market without any discriminations and make sure that fair access to storage facilities is given to all the market players in order to be used efficiently and effectively.

Further recognising the importance of energy storage for the continent, in 2020, the European Commission published a study on storage and its contribution to the security of the electricity supply [181]. The absence of viable business cases for most storage projects is considered to be the most significant barrier. As the relevant costs and performance are improving, business cases are anticipated to become much more cost-effective in the long term. However, the issues remain and must be resolved through the prioritisation of appropriate policy measures. More specifically, policymakers should provide "*an enabling environment and level playing field to storage*". Positive externalities and environmental benefits, provided by energy storage, must be appropriately valued while it must be ensured that fair network charges and suitable taxation regulations apply.

Furthermore, energy storage should be defined by the EU member states in their national legislative framework. This is of the essence, especially since the majority of the countries do not currently have a clear definition in place. Additionally, double charging of energy storage grid tariffs, during charging and discharging, must be eliminated by the member states. Finally, dynamic electricity prices and ToU grid tariffs must be offered to consumers in order to promote responsiveness and the usage of behind-the-meter energy storage such as electric vehicles. Currently, the tariff options given to residential users are limited. Additionally, net metering should be phased out in the nine remaining countries as it constitutes a significant barrier for the deployment of small-scale storage. This will allow to account separately for the amount of electricity exported to the grid and consumed by the grid [181].



DNO contracted	• DNO owns and has full operational control over the storage asset. Long-term contracts are agreed for the asset's commercial control in certain periods of time.
Contracted Services	• Long-term contracts are offered by the DNO at specific locations with commercial control in certain periods of time.
Charging incentives	• DNO sets the DUoS tariff to incentivise peak-shaving to reflect the value of network reinforcement.
DNO merchant	• DNO owns and has full operational control over the storage asset.
DSO role	• Same as above (DNO Merchant) but the DNO is given a regulatory role in balancing and controlling aggregated demand and generation, taking the role of the DSO.

Figure 2.27 – Proposed business models for ownership and operation of Energy Storage by DNOs (Adapted from [182])

Nevertheless, [182] highlighted that storage is still classified as a generation asset in the majority of the electricity markets, including the UK where there is no separate asset class or activity, related to storage. This is problematic as the definition for generation is vague as it refers to any technology generating or being able to generate electricity, according to the UK Electricity Order 2001. Therefore, as ESS also generate electricity, they fulfil the requirements and fall into the generation asset category. The authors noted that despite their being capable of providing such services, ESS are not used to provide balancing services towards reducing peak loads, in many countries including the UK. As in many other countries, in the UK, one of the reasons are the associated costs and more specifically, the Transmission Network Use of System (TNUoS) costs as well as the Distribution Use of System (DUoS) costs. As ESS need first to charge and discharge at a later time, storage providers have to pay double TNUoS charges for the dual role of energy storage, as a generator and consumer of electricity, on top of the DUoS costs. If the storage facility has a capacity below 100 MW, the DUoS charge does not apply but there are still double DUoS tariffs. Finally, the authors summarised suggested business models for storage assets, for DNOs ownership and operation (Figure 2.27). It is mentioned that in Italy and Belgium, DNOs are allowed to own and operate BES with no evidence that this affects negatively the competitiveness of the generation and supply markets.

Finally, regarding the TSOs and their ability to own and operate storage, three business models are suggested: ownership bundling (separation) to guarantee the independence of the network ownership, the establishment of an Independent System Operator (ISO) or an Independent Transmission Operator (ITO) [182].

Zame et al. [60] suggested the introduction of short-term policies to counter the high capital costs of storage, focusing on investment tax credits which have the potential to bring the capital costs down and at the same time increase the storage capacity utilised towards balancing services such as frequency regulation. The authors mentioned that research regarding energy storage the USA has shown that federal investment tax credits of 20% over ten years could increase the storage capacity by 300% when compared to a scenario without tax credits. Therefore, appropriate investment tax credits can promote storage expansion in the short term while reducing capital costs in the long term. Finally, it is pointed out that deregulated electricity markets offer the best potential for the development of energy storage services.

Figure 2.28 shows the projected energy storage capacity for the UK, based on the four scenarios studied by the 2019 National Grid Future Scenarios which have been presented in the previous chapter. It can be seen that the capacities vary depending on the scenario and the assumptions made. For example, the range of the installed capacity for the year 2050, in the UK, is between 14 and 28 GW, approximately. Low-carbon power generation, including variable RES, will increase the electrical grid needs for flexibility. This is the case for the Community Renewables and Two Degrees scenarios, where the increasing amount of RES leads to an important expansion of the storage capacity, as a solution towards providing the required grid flexibility [183].

Furthermore, [183] noted that National Grid might not have considered certain policy implications when developing the scenarios, such as contract for difference (CfD) which aims to stabilise revenues in the long term, for new low-carbon initiatives. Other parameters will also affect the expansion of the storage capacity as new business models and electricity pricing tariffs are anticipated to show up in the energy storage market. It is concluded that policy mechanisms promoting low-carbon technologies could impact negatively the adoption of energy storage; therefore, regulatory policies need to be introduced to protect the energy storage market accordingly. In this direction, a price floor mechanism for energy storage would enable the government to control the price limit or establish a lower boundary (£/MWh) on payments made to storage facilities and operators (e.g. TSOs) for storing electricity when its wholesale price is low and sell it later when the price reaches a higher value (arbitrage). A second policy to support the energy storage market would be to provide an upfront subsidy towards the ESS capital expenses.

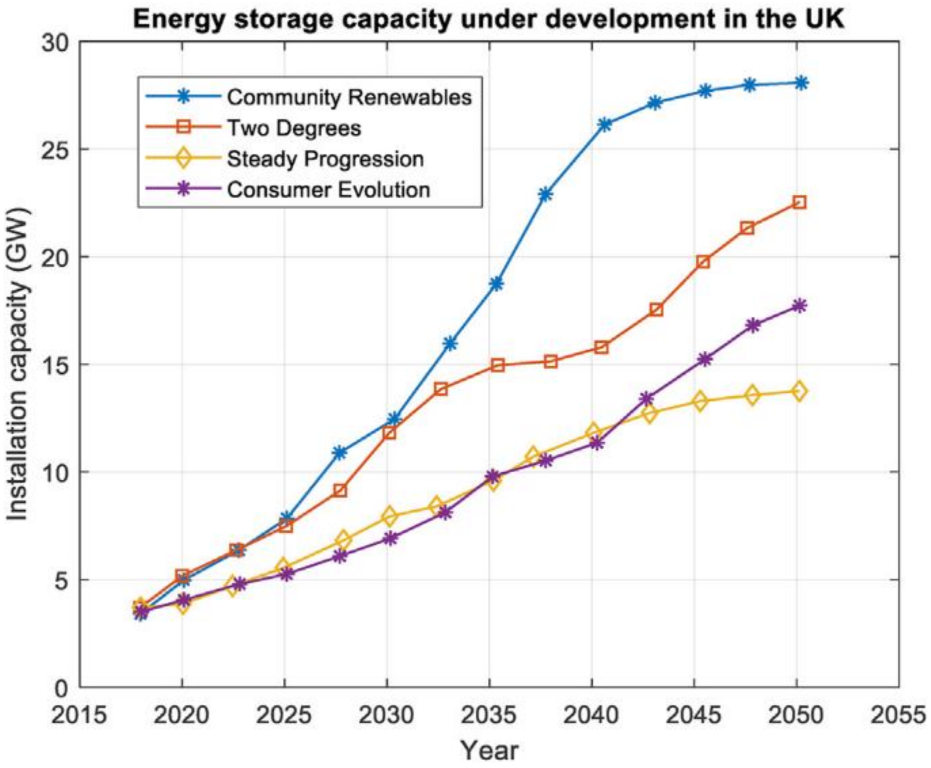


Figure 2.28 – Predicted energy storage Capacity in the UK based on the 2020 National Grid Future Scenarios [183]

Sani et al. [184] summarised the policy tools that can be used for the promotion of ESS, according to the Energy Storage Association, which belong to three categories: value, grid and market access and finally competition. Incentives programs, the establishment of deployed targets and the creation of energy storage markets aim on increasing the value of storage while energy storage must have fair, non-discriminatory and easy access to the electrical grid through interconnection processes and established codes and standards that will allow grid interconnection with storage. Procurement practices must also be improved in order to guarantee a level playing field for energy storage whose importance have been previously mentioned, at the EU level. All the above must be taken into careful consideration when designing and implementing policy tools that specifically target energy storage as a technology.

Forrester et al. [185] concluded that electrical grid assets around the world are classified as generation, transmission, or distribution, not giving the possibility to energy storage to be characterised as a separate, discreet asset class. This constitutes a significant barrier towards maximising the storage benefits within and across electricity markets. Consequently, it is of paramount importance to redefine and refine market rules to remove market barriers and biases while also eliminating any regulatory uncertainties.

Finally, [186] reviewed the policy framework for utilising energy storage in the UK electricity markets. DBEIS does not have policy incentives, aiming specifically on storage technologies. On the other hand, there are market-based incentives for storage owners. In more detail, Electricity Market Reform was adopted as government policy, being part of the Energy Act 2013. The legislation in question established the Capacity Mechanism to reinforce the security of electricity supply, minimising the associated costs that are passed to the consumer. The

Capacity Mechanism rewards providers with an annual payment for providing a certain amount of generating capacity for emergencies and other events which put pressure on the grid infrastructure. The payments are determined through competitive auctions either four years (T4) or one year before (T1) the actual provision of services. Nevertheless, the Capacity Mechanism payments (£/MW) are less than 50% of the respective values provided for other services, such as FFR and STOR while they constitute only a small fraction of the Fast Reserve payments. Therefore, it is clear that the Capacity Mechanism cannot be the exclusive revenue source for an energy storage owner, making necessary the participation in other markets. It should be noted that the mechanism itself is technology neutral and therefore all asset classes can participate, including DR, storage, interconnectors and generation.

2.3.7 Energy Storage Projects

There are several energy storage projects that are either in operation or planned for the near future. Lie et al. [174] summarised a number of battery-related field projects, the vast majority of which have been active since 2015 with a minimum capacity of 1 MWh and various power outputs. A total of 14 battery projects are listed in the Table 2.14 including Li-ion, Pb-A and VRFB batteries; nevertheless, the majority refer to the Li-ion electrochemistry due to its decreasing costs. The energy storage applications vary from project to project

It is worth mentioning the grid-connected Li-ion battery of the Hornsdale Power Reserve in South Australia which was considered, in 2020, as one of the biggest BESS in the world with a power rating of 150 MW and a capacity of 194 MWh. It is used to provide power system security while a part of its overall capacity participates in the local power market. The initial project cost has been estimated to be around $56m with benefits of £17.4m in 2018. Additionally, as the Californian electrical grid has significant amounts of integrated RES, their energy generation is occasionally higher than the respective demand, resulting into particularly low or even negative electricity prices. In this direction, the Li-ion battery of the Escondido energy storage project provides balancing services to the grid including arbitrage and peak shaving.

Regarding the economics of the field projects, the Pomona Energy Storage facility (20 MW/ 80 MWh) had an investment cost between $40-45m with estimated annual revenues of $5.6m and more specifically, $2.85m from provision of resource adequacy, $1.62m from energy and ancillary services and $1.62M from participating in frequency response. Finally, the Marengo project (20 MW/ 10 MWh) has annual benefits of $5.6m against a total investment cost of $20m. Despite the fact that there is extensive research on the grid applications of energy storage, as previously presented in Chapter 2.3.6, their respective CBA is rarely studied and in many cases it is not disclosed. For example, there is information on the associated costs and benefits for only 5 out of the 14 projects of Table 2.14.

As the projects in question are considered large-scale and consist of relatively big battery sizes, they are owned either by a non-utility independent power producer (IPP) or utilities. The authors highlighted the fact that batteries deployed behind the meter are usually smaller in terms of their scale (<1 MW) and owned by the final consumers who can be domestic, commercial or industrial. It is supported that all BES projects can be cost-effective regardless of their ownership and scale with the potential exception of domestic batteries that currently do not offer the same financial opportunities [174].

Table 2.14 – Energy Storage field projects [174]

Project name	Year	Storage Technology	Ownership	Power rating/ Capacity	Applications
Hornsdale Power Reserve (Southern Australia)	2017	Li-ion	IPP	150 MW/ 194 MWh [187]	Initially: 70MW / 10MWh for power system security 30MW/ 119MWh participating in the power market
Pomona Energy Storage (California, USA)	2016	Li-ion	IPP	20 MW/ 80 MWh	Providing resource adequacy Participating in energy and ancillary service market
Marengo (Chicago, USA)	2018	Li-ion	IPP	20 MW/ 10 MWh	Participating in frequency regulation market
Rabbit hill	2019	Li-ion	IPP	10 MW/ 5 MWh	Energy arbitrage Participating in regulation market
Sterling	2016	Li-ion	Utility	2 MW/ 3.9 MWh	Reliability service/Peak shaving/Energy arbitrage
Stafford hill	2015	Pb-A Li-ion	Utility	4 MW/ 3.4 MWh	Participating in energy and ancillary service markets Demand peak shaving
Punkin Center Service Market	N/A	Li-ion	Utility	1 MW/ 4 MWh	Replacing transmission line & Participating in ancillary. Cost of BES is less than it of transmission upgrade.
Snohomish PUD MESA 2	2017	VRFB	Utility	2.2 MW/ 8 MWh	Peak shifting & Energy arbitrage
Escondido (California, USA)	2017	Li-ion	Utility	30 MW/ 120 MWh	Peak shaving, Providing reliability service Participating in energy and ancillary service markets
Ideal Energy MUM Project	2019	VRFB	Utility	350 kW/ 1.05 MWh	Peak shaving & Improve solar self-consumption
MidAmerican Energy Storage pilot project	2019	Li-ion	Utility	1 MW/ 4 MWh	Peak shaving Enhancing renewable energy's reliability
SCE LM6000 Hybrid EGT	2017	Li-ion	Utility	10 MW/ 4.3 MWh	Spinning reserve/Frequency regulation Load following
Convergent-SCE pilot University of Arizona	2019	Li-ion	Utility	35 MW/ 140 MWh	Electric supply capacity credits
Science and Technology	2017	Li-ion	Utility	10 MW/ 5 MWh	Electric bill management & Demand response Reliability service

2.3.8 Energy Storage in Buildings and Local Communities

In the previous section 2.3.7, large-scale ESS, the vast majority of which had a power rating higher than 1 MW, and owned by either utilities or IPP have been discussed while it was mentioned that batteries behind the meter are smaller and owned by the end users. In this direction, this chapter discusses briefly small-scale energy storage deployed for use by the final consumers which can be domestic, commercial or industrial buildings, also named in the literature as community energy storage. It is clear that energy storage technologies that occupy significant amounts of space and have specific geographic and topographic limitations cannot be considered as suitable for buildings. Therefore, suitable systems mostly include batteries, hydrogen or a hybrid configuration that includes both with some characteristic case studies presented in Table 2.15, as published in [9].

Storage is used either on its own or in combination with RES, especially photovoltaics. Applications vary and can include optimisation of the operational dispatch strategy, provision of balancing services to the grid, minimisation of the associated costs and increasing the building's self sufficiency.

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Figure 2.29 – System configuration of grid-connected buildings with energy storage and photovoltaics [188]

The system configuration of grid-connected buildings with deployed energy storage and photovoltaics can be seen, in Figure 2.29. DC loads and AC loads can both be met, if present, and the inclusion of the solar panels is optional [188]. Hydrogen appears to be a technology with significant potential, even at the building-scale. However, its role in the future energy system has been discussed in detail, in Section 2.2.2, including the difficulties of storing large amounts of hydrogen and setting up the related infrastructure as well as the problematic lower overall efficiency. Therefore, the rest of the present chapter will focus on the utilisation of batteries for local projects in buildings and community energy storage (CES).

Table 2.15 – Utilisation of Energy storage in Buildings [9]

Technologies	Application(s) in the Buildings and/or the grid	Comments/Conclusions
Batteries	Peak shaving	Residential Battery energy storage systems can reduce peak electricity loads by >40%.
	ToU Energy management	Medium-scale batteries can reduce the electricity bills of consumers through ToU energy management. They are economically beneficial for medium-scale buildings if there is an important difference between the maximum and the minimum electricity prices
	Balancing Services, RES Integration, Customer Energy Management	Batteries can provide several services, including balancing services, such as voltage support, black start and load following, as well as customer energy management (power quality/reliability). RES Integration can be achieved through time-shifting and capacity firming.
	Optimisation of energy dispatch schedule in a PV/storage system	Batteries are important for providing peak-shaving and load shifting. The cost-effectiveness of the system depends on the electricity rates and battery technology used (Li-ion, Pb-A etc.).
Hydrogen	Self-sufficient energy buildings and cost minimisation	There is an increasing interest in combined battery and hydrogen storage. Domestic hydrogen storage can render a building self-sufficient for an annual premium of 52% when compared to buying electricity from the grid by 2030. It can also lead to annualised cost reductions of 72–80% for the supply of heat and electricity when compared to Li-ion batteries.
	Integration of RES and balancing of the grid	Electrochemical and mechanical storage are not sufficient to balance the grid; therefore, hydrogen is expected to play a major role in the energy transition. Evaluating hydrogen is very challenging while a detailed techno-economic assessment is required on a case-to-case basis.
Hybrid System	Meeting loads, minimisation of costs and emissions	Considering several energy systems (wind turbines, PVs, hydrogen storage, batteries), many optimal combinations include high levels of solar and wind power. As high costs are associated with hydrogen storage, priority is given to batteries.

Khezri et al. [189] reviewed the optimal planning of solar panels and battery storage for use in domestic buildings. It was supported that batteries can mitigate certain key challenges as FITs are gradually phased out in several countries and RTP is used instead. By using BES, buildings could absorb any excess electricity through the battery and meet the load at a later time of zero generation. Batteries could be used in buildings to provide energy arbitrage, resilience and time-shifting of electricity. When the system contains only the battery, without RES, the authors highlighted a number of relevant studies for the optimal planning of the system. For the majority of the studies, the decision variable included the battery capacity and the objective function was either the net present value or the total annual cost. The electricity tariffs taken into account were either flat or ToU with various optimisation methods, including several MATLAB-developed tools. Power balance, battery's SoC, bidirectional power flow, discharging power, peak shaving limit and the lifetime of the battery in cycles were among the most popular design constraints.

According to [190], CES is installed near the energy consumption centres which can also include renewables owned by the end users. CES are able of supporting the integration of distributed generation by enabling the final consumers to shift excess generation and use it later (energy arbitrage), contribute towards the stability of the grid by maintaining supply and demand and bring additional revenue streams by participation in power markets. Therefore, CES can bring significant social and economic benefits to the local community and the final energy consumers. It is connected to the local distribution network and its energy storage capacity can only provide tens or hundreds of kWhs to the surrounding community. Therefore, it can be of service to small-scale users, from single dwellings up to a small community. As technologies such as capacitors and flywheels are appropriate, they are very limited due to their small energy capacity and could only be components of hybrid solutions. The authors pointed out that only "*a few tens of consumers at most*" had participated in CES projects in order to demonstrate the novel properties and the benefits that storage could potentially bring at the local level.

Table 2.16 provides a list with ongoing CES projects around the world. It is clear that these projects are of comparatively small size, especially when compared to ESS facilities owned by utilities or IPP as previously shown in Table 2.14. More specifically, the range of their energy capacity varies between 25 kWh to 1.1MWh while the respective power range is between 25 KW and 550 kW depending on the number of battery units used. Unsurprisingly, the vast majority of the projects mentioned by the authors consist of batteries on their own and in certain cases in combination with hydrogen; nevertheless, the majority of the ESS are Li-on batteries. Applications again vary depending on the presence of distributed generation (i.e. photovoltaics) and can include DSM, frequency response, arbitrage, reduction of peak loads or costs [190]. Finally, it is concluded that CES due to its local character can address the issues of energy affordability, energy security and efficiency/sustainability which constitute the three main elements of the energy trilemma, as presented in Chapter 2.1.5. CES can bring important opportunities and benefits to the residents of the local community, especially when combined with renewables.

Table 2.16 – Current Community Energy Storage projects [190]

Project name	Starting Year	Storage Technology	Location	Power rating/ Capacity	Applications
Storage trial at Alkimos Beach residential development	2016	Li-ion	Alkimos, Australia	250 kW/ 1.1 MWh	PV and demand management; grid stability
CES for Toronto Hydro	2013	Li-ion	Toronto, Canada	550 kW/250 3 units	Grid stability, deferral of distribution costs and demand load shifting
gridSMART project	2009	Li-ion NaS	Ohio, USA	25 kW/ 25kWh; up to 80 units 1 MW/ 6MWh (NaS)	Microgrid/ Smart Grid management; maximisation of self-consumption; peak demand management
CES for Grid Support	2013	Li-ion	Detroit, USA	25 kW/ 50kWh; up to 20 units	Back-up power; Peak demand management; voltage control; real/reactive power control
Kelsterbach	2014	Li-ion	Kelsterbach, Germany	50 kW/ 135kWh	Maximisation of self-consumption; optimisation of Combined Heat and Power (CHP)
Slough Zero-Carbon Homes (SSE)	2012	Li-ion	Chalvey, UK	25 kW/ 25kWh; 3 units	Peak demand management; voltage control; real/reactive power control
S&C HQ CES	2014	Li-ion	Chicago, USA	25 kW/ 25kWh; 6 units	Aggregation for Frequency Response
Local Energy System project (E.On)	2016	Li-ion	Aston, Sweden	500 kW/ 300kWh	Microgrid management, maximisation of self-consumption
Ergon	2015	Li-ion	Queensland, Australia	25 kW/ 100 kWh; 20 units	Upgrade deferral/ constraint management
Creative Energy Homes	2014	Li-on Hydrogen	Nottingham, UK	Li-on: 24 kWh Hydrogen: 155 kWh	PV and demand side management; load shifting
SENSIBLE project (Siemens)	2015	Li-ion Pb-A	Nottingham, UK	X20 3kWh Li-ion and x2 20 kWh Pb-A	PV and demand side management; grid stability; load shifting; cost reduction
FALCON project (Western Power)	2011	Sodium Nickel Battery	Milton Keynes, UK	X5 50 kW/100 kWh	Improved capacity margins, RE penetration, T&D deferral, power and frequency control
McAlpine Circuit CES System	2011	Li-ion	Charlotte, USA	50 kW / 50 kWh	transformer-level peak shaving by integrating with residential level distributed resources/ loads

2.4 The Building Sector

2.4.1 Introduction

In 2013, IEA published a report regarding the transition to sustainable buildings, focusing on strategies and opportunities, for the building sector, to 2050 [191]. Table 2.17 shows these priorities for seven major countries and the EU, classified into technological and policy priorities. The major parameters influencing the priorities are the local climate and the resources available in each country. For example, the advanced envelope has a high priority for Russia due to the cold climate while solar thermal is a reliable technology option for India, Brazil and South Africa thanks to the high potential of solar power. Appliance and equipment standards, including the promotion of advanced appliances, lighting, efficient cooling and heat pumps, constitute the most common high priority while building codes with supporting infrastructure is shown as the second most frequent priority. Regarding the EU, the deployment of heat pumps for water and space heating/cooling and the deep renovation of the existing building stock via advanced building envelopes and energy-efficient equipment are among the high priorities for the continent while advanced envelopes also constitute a second priority in cold climate countries (e.g. high-insulation windows, airtightness).

Table 2.17 - Priorities in the building sector (✓ indicates second priority) [191]

Technology	**Brazil**	**China**	**EU**	**USA**	**Russia**	**India**	**Mexico**	**S. Africa**
Advanced envelope (cold climate)		High	✓	High	High			
Reduced cooling loads (hot climate)	✓						✓	
Heat pumps		✓	High	✓	✓			
Solar thermal	High					✓	High	High
More efficient use of biomass						High		✓
Policy								
Building codes with supporting infrastructure	✓	✓			✓	High	✓	✓
Appliance and equipment standards	High	High				✓	High	High
Deep renovation of existing buildings			High	High	High			
Zero Energy new buildings			✓	✓				

2.4.2 Building Energy Performance

Regarding the key parameters affect the buildings' energy performance, [192] summarised them and a brief version can be seen, in Figure 2.30. Other parameters that affect the building's energy demand include the number of storeys and the building type with the latter determining its energy consumption and profile through the activities that take place. The building envelope physically separates the conditioned interior with the unconditioned environment of a building and mainly consists of the external walls and the roof. Its two critical components are insulation, including the insulation level, material and position, while glazing refers to the area covered by windows (often called window-to-wall-ratio). Finally, a building's HVAC configuration highly affects its energy demand. Ventilation can be natural, mechanical or mixed while heating may be based on the combustion of conventional fossil fuels (e.g.

natural gas) or fully electric through the usage of heat pumps and electric radiators. The deployment of renewable systems is also possible at the building level through a variety of RES, such as photovoltaics and solar-thermal. The parameters that have to be considered for building planning and design are also described briefly in [193]. In the northern hemisphere, a southern orientation should be chosen, when possible, in order to take advantage of the solar energy towards heat gains and daylight while ventilation needs and heat losses through the building's envelope must be taken into account.

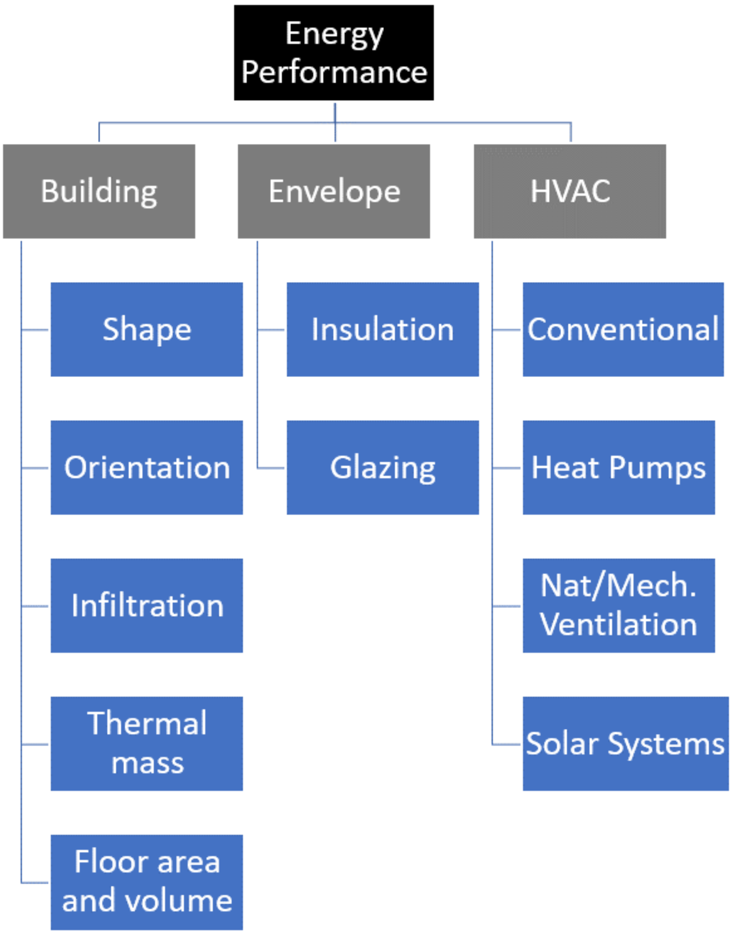

Figure 2.30 – Key building variables affecting its energy performance (Adapted from [192])

The level of the building's responsiveness to internal and external heat inputs is dependent on the thermal conductivity of its materials, its thermal mass (also called heat capacity) and the admittances of its construction elements. The admittance has the same units as the U-value, one of the most important parameters in construction and thermal comfort, and expresses the amount of energy that can enter the element surface per degree of temperature change outside, the surface. Its units are in $W/m^2 \cdot K$ and admittance also depends on the material's thermal conductivity ($W/m \cdot K$), thickness, specific heat and the rate at which heat is put into it. Buildings are said to be thermally heavyweight when they experience small temperature rises despite receiving large amounts of heat; therefore, they have high admittances and thermal mass, often requiring ventilation during the night period to eliminate any thermal discomfort issues. On the contrary, lightweight buildings have the opposite characteristics regarding their response to heat, admittance and thermal mass. A buildings' heat inputs from the outside are considered to be cyclical with the sunrise and sunset times constituting key daily events. Thermal mass is used in order to compensate for the temperature variations by delaying the heat transfer inside the building, during the summer period, and consequently the time of day when the temperature reaches its highest value. However, it is important to make appropriate use of thermal mass as "*there can be a limit to its usefulness*" [193]. Heavyweight buildings are recommended in cold climates with continuous occupation due to their ability of keeping a stable temperature and provide thermal comfort. On the other hand, using a lightweight insulated construction for buildings with intermittent usage and a heating system would be more appropriate [194].

Furthermore, windows are recognised to be the weakest elements of the building envelope with their overall U-value being the result of glazing (single, double etc.), the frame materials (wood, metal etc.), the frame thickness and the exposure (normal, exposed, sheltered). The window elements have to be carefully considered, taking into account its five main functions: provide a view, admit daylight, reduce heat loss, admit solar heat (in cold climates) and allow a controllable ventilation. Therefore, other parameters such as the glass quality, position and orientation of the windows, the closing mechanism and potential use of internal blinds are important towards choosing a suitable type of windows and glazing, which often includes a compromise that considers both the U-value and emittance requirements [194].

Chen et al. [195] reviewed the internal and external factors that affect the energy efficiency design of buildings. It is noted that the individual consideration of one building characteristic will not necessarily lead to the optimal energy consumption which is dependent on the combination of several building characteristics. Regarding the building shape, shape factor (SF) is the ratio of the building surface area to the conditioned floor area, compactness factor (CF) is the ratio of the building surface area to the conditioned space volume and finally relative compactness (RC) evaluates the impacts of the building's shape and geometry on its energy performance by comparing its compactness with a reference building; SF, CF and RC are among the most studied shape parameters. In extreme cold climates, increasing SF can lead to an increase of the heating demand while in severe cold conditions, the energy demand is inversely proportional to the compactness. On the other hand, in locations with non-extreme weather conditions, the building's shape has less impact on its energy demand. A review of the key building parameters affecting energy performance can be seen in Table 2.18 along with their characteristics.

It is important to point out strategies to limit the heat inside buildings and expel it in the atmosphere through natural processes, commonly known as passive cooling strategies (Figure 2.31). The efficiency of a passive cooling system depends on the nocturnal and diurnal outside temperature gradient as well as the temperature peak values. Advanced natural ventilation refers to buildings that make use of the stack effect where the air flow is driven by the temperature and density differences. Nocturnal convective cooling is usually utilised in regions with high day temperatures and minimum night temperatures of less than 20°C. It has the capacity to drop the indoor temperature by 3°C. Radiant cooling can be achieved by using highly conductive material as part of the roof construction combined with insulation. In this way, the cooled roof behaves as a heat sink by absorbing heat through the ceiling. With evaporative cooling, the water in the fresh air is evaporated either directly or indirectly to cool down the building e.g. installing wetted pads near the windows. Finally, earth-air cooling refers to buildings located partially or completely underground which make use of the earth's thermal inertia [196].

Table 2.18 – Building Characteristics and Energy Performance [195], [197]

Parameter	Comments
Shape	• The shape is more significant in buildings located in extreme weather conditions. • The optimal shape depends on WWR, SHGC, RC and other parameters. • Oval-shaped buildings can minimise the construction costs and the energy consumption. • Regular pentagon-shaped buildings have lowest life cycle cost but the highest environmental impact. Symmetrical pentagon-shaped buildings have the opposite results. • Compact buildings need less energy as higher surface area leads to higher heat losses and therefore a higher energy demand.
Orientation	• The building's life cycle cost should be considered when optimising the building's orientation. • The optimum orientation depends on the building’s shape. • In the northern hemisphere, buildings should have a south-faced orientation or 20-30° to the south. • Rooms with intermittent occupation (e.g. bedrooms) or no heating should be placed in the non-solar-oriented face. Living spaces should face the sun. • The building’s orientation is critical to climate-responsive architecture and it affects the solar shading requirements.
Insulation	• A range of 10-25% of Window-to-Wall-ratio is recommended. • Low-emissivity and gas filling (usually argon) constitute the most common insulation materials for windows. • Double glazing is a good option for domestic buildings. • The location of the wall insulation layer varies, depending on the building scenario.
Glazing	• Glazing properties are critical, especially its U-value and g-value, as they are responsible for heat losses and heat gains, respectively. • Overheating during the summer must be avoided. External shading devices are recommended for solar-oriented windows
Thermal mass	• Heavyweight buildings have a slow response time as the peak indoor temperature takes place in the early hours of the morning (flywheel effect). Lightweight buildings respond much faster as they can heat up and cool down slightly more slowly than the outdoor conditions. • In temperate climates, using thermal mass can result to a stable internal thermal environment as it reduces the diurnal temperature variations. • Thermal mass is the opposite of insulation as insulation does not store heat but resists its flow. A suitable combination of thermal mass and insulation can lead to satisfactory thermal comfort conditions e.g. due to storing heat and minimising heat losses.

Table 2.18 (Contin.) – Building Characteristics and Energy Performance [195], [197]

Parameter	**Comments**
Thermal mass	• Night ventilation might be required in heavyweight buildings after a full day of absorbing heat to guarantee thermal comfort. • The selection between a heavyweight and lightweight building depends on the climate and the functions of the building (e.g. domestic, commercial). Lightweight buildings are recommended for either hot-humid conditions or intermittent occupation but elsewhere both configurations can be found. A heavyweight construction is recommended for buildings with continuous occupation such as hospitals.
Shading	• Internal and external shading devices are recommended for solar-oriented façades in the summer.
Daylight	• Daylight can be used in order to reduce the building's lighting loads.
Air temperature	• Air temperature is the most important meteorological parameter.
Relative humidity	• The HVAC's coefficient of performance is affected by the outside ambient temperature and relative humidity. • A value of less than 40% is recommended. • The efficiency of the HVAC system can be reduced by 25% due to the Heat Island Effect.
Solar radiation	• Solar radiation can affect the building's cooling demand, especially in tropical and subtropical conditions. • Solar radiation can be maximised with an optimal 15^o azimuth angle of a surface in a building.
Wind speed	• Wind speed is much less important for buildings with a central HVAC system. • Wind speed can affect the design of natural ventilation.

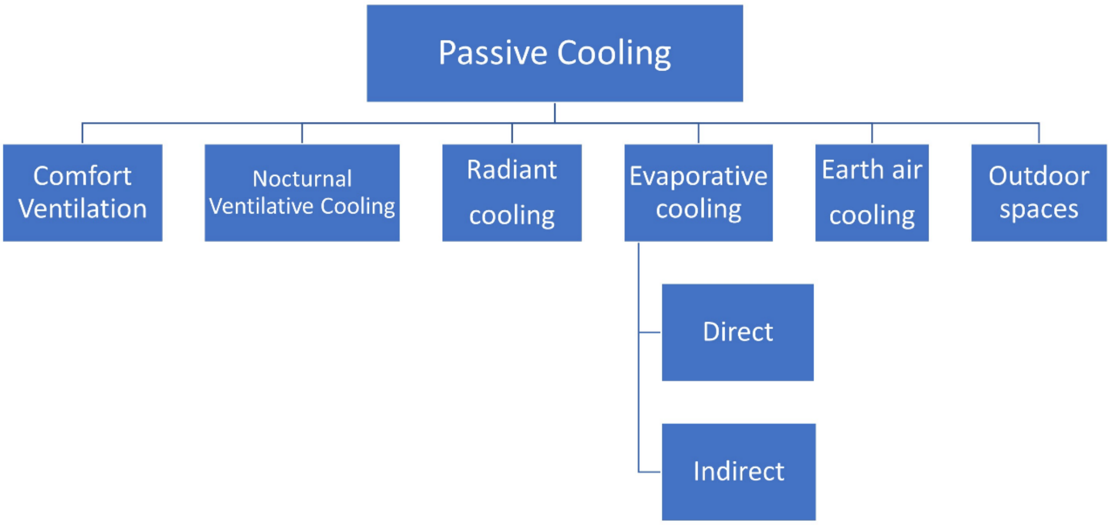

Figure 2.31 – Passive cooling strategies in buildings [196]

2.4.3 Thermal Comfort and Satisfaction

Thermal comfort is closely related to building design and its objectives. According to [198], it constitutes the subjective feeling of satisfaction over the local thermal environmental. Fanger's Predicted Mean Vote (PMV) – Predicted Percentage of Dissatisfied (PPD) and ASHRAE's comfort criteria in its 55 standard on thermal environmental conditions for human occupancy are mentioned as the leading comfort models, with the latter constituting a recognised industry guidance standard. Personal factors that affect thermal comfort are the occupant's (metabolic) activity and clothing while the key environmental factors include air temperature, radiant temperature, air velocity and humidity. While thermal comfort can be improved by adjusting the environmental factors, energy efficient building design is expected to take into account and evaluate the thermal comfort mechanisms working in the background in order to choose the appropriate building system which will deliver the desired results, also achieving the lowest energy consumption. The importance of the personal factors is highlighted as thermal comfort will vary depending on the climate and the activity that takes place. In this direction, the selection of reference thermal comfort standards is necessary towards establishing baseline values. For most cases and buildings, ASHRAE Standard 55 is deemed to be suitable; however, it should be noted that several guidelines are included within the standard.

The operative temperature is of fundamental importance towards establishing a range of acceptable environmental conditions for thermal comfort, based on ASHRAE 55 and as seen in Figure 2.32. For normal metabolic rates between 1 – 1.3 met, where clothing is assumed to provide thermal insulation of 0.5 and 1 clo and air velocity does not exceed a value of 0.20 m/s, the 80% acceptability range can be specified based on the operative temperature, wet bulb temperature, relative humidity and the humidity ratio values. It should be pointed out that clo is the unit referring to the thermal insulation provided by garments and clothing ensembles (1 clo = 0.155 m^2 °C/W) while met is the unit describing the energy generated inside the body due to metabolic activity (1 met = 58.2 W/m^2). The humidity ratio is defined as the ratio of the water vapour mass to the dry air mass, in a given volume while relative humidity is the ratio of the water vapour's partial pressure to the water vapour's saturation pressure, at the same temperature and total pressure. 10% of the dissatisfaction is based on the PMV/PPD index criterion with an extra 10% added to account for local thermal discomfort [199].

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Figure 2.32 – Acceptable range (80% of occupants) of operative temperatures and humidity for spaces [199]

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Figure 2.33 – Acceptable operative temperature ranges for naturally conditioned spaces (Adaptive model) [199]

Specifically for naturally conditioned spaces where ventilation takes place through operable windows, the determination of acceptable thermal conditions can be conducted by using Figure 2.33, for 80% and 90% acceptability limits. This figure also takes into account the clothing adaptation of the occupants; therefore, the clothing's thermal insulation values are not required to be considered. This method is often mentioned to be an adaptive model as it connects the indoor operative temperature with an outdoor meteorological parameter [199].

Table 2.19 – Fanger model specifications for different building categories [200]

Building Category (EN 15251)	Description	Fanger model		ΔT
		PPD (%)	PMV	
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons.	≤ 6	-0.2 ≤ PMV ≤ 0.2	± 2
II	Normal level of expectation, it should be used by new buildings and renovations	≤ 10	-0.5 ≤ PMV ≤ 0.5	± 3
III	An acceptable, moderate level of expectation and may be used for existing buildings	≤ 15	-0.7 ≤ PMV ≤ 0.7	± 4
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.	> 15	PMV > 0.7 or PMV < -0.7	> 4

After reviewing the different thermal comfort models, [200] supported that the adoption of the Fanger model is agreed by all standards regarding mechanically cooled/heated buildings (Table 2.19). On the other hand, ASHRAE Standard 55 is suitable for buildings with natural ventilation through its adaptive comfort model. The rise in the deployment and use of air-conditioning in buildings led to the development of an appropriate determination of the acceptable thermal comfort conditions; in this direction, the PPD/PMV model is widely used, especially when designing sealed air-conditioned office buildings [199], [200], [201].

2.4.4 Building Types and Relationship with the Electrical Grid

Regarding the several building types mentioned in the literature, [202] investigated the design optimisation of nearly/net zero energy buildings (nZEBs) which constitute an innovative category of sustainable buildings that has recently received attention. Three main steps are needed to be adopted in order for a building to be classified as a nZEB: passive design, energy efficiency and energy generation. In 2015, the authors [202] reviewed the academic literature on the nZEBs' design optimisation with the majority of the publications including the utilisation of photovoltaics and wind turbines for local electricity generation combined with batteries to take advantage of their energy storage capabilities. It is concluded that the inclusion of a combined heat and power (CHP) system or energy storage, combined with automated intelligent control, could reduce the peak loads of the building, purchased by the grid, and allow the buildings to respond quickly to dynamic electricity prices.

According to [203], there is lack of clarity in the terminology used in the building sector which often creates issues and challenges to decision-makers, clients, designers as well as researchers. While intelligent buildings have been researched thoroughly in the past 30 years and included in the literature and reports, smart buildings appeared relatively recently and there is still confusion regarding the distinction between the two building categories, also used interchangeably. The authors [203] defined smart buildings as intelligent buildings with three extra integrated elements that are adaptable: materials & design, enterprise and control.

Enterprise refers to the methods adopted in order to collect building usage data and ameliorate occupant performance. It was recognised that the drivers behind building performance resulting in the sector's evolution are energy and efficiency, longevity and finally comfort and satisfaction. Table 2.20 provides an overview of the building sector's evolution with the characteristics of primitive, simple, automated and finally intelligent/smart buildings [203].

Table 2.20 – Evolution of Building Types [203]

Building Parameter	**Building Type**			
	Primitive Building	**Simple Building**	**Automated Buildings**	**Intelligent/ Smart Buildings**
Control Flow	Uncontrolled	Manually controlled	Local feedback (centralised feedback)	Interactive
Comfort & Efficiency Information Input	None	Controllable comfort variables	Thermostat, humidistat etc. (BMS system)	Systems and data integration
Occupant Interaction & Efficiency	No control	Full control, low efficiency	Less control, higher efficiency	More control, higher efficiency
Materials & Construction	Basic	Electrical supply and basic materials	More advanced materials, sensors, displays (automated feedback loop systems)	IP backbone used to integrate building service systems. Adaptable building structure with reactive features
Interaction of Operation with Occupants	None	Manual input	Defined occupancy times (Zoned occupancy data)	Real-time integration and optimisation of building systems with building use

Bulut and Wallin [204] introduced the concept of Active Buildings, clarifying that it constitutes a new building type even for the people working in the energy and building sectors. While it is vital for future buildings to provide demand response in order to balance the electricity supply originating from variable RES, the bidirectional exchange of energy with the grid per se is not a priority for Active buildings; on the other hand, the focus is on "*trading the right amount of energy in the right time*". More specifically, users could respond to signals such as dynamic electricity prices and emissions, helping utilities cope with peak loads and in return receive financial rewards for the provided services. However, regulations are needed for the development and adoption of the active buildings concept through the support of relevant business models which will bring benefits to all the involved parties and guarantee their cooperation and active participation in the electricity market.

According to the 2015 – 2016 studies published in [205], [206], the Swedish government and the Swedish Energy Agency funded a project involving Active Buildings as part of a sustainable city, referring to buildings with smart energy and smart grid features. Active Buildings are considered to have a strong relationship with the grid and they are not passive elements of the network; on the contrary, they are assumed to have multiple roles by acting as consumers, producers and suppliers of energy by changing their energy demand to accommodate the intermittent RES generation. Several stakeholder groups were interviewed, regarding their view on Active Buildings, with different definitions being provided based on the sector that interviewees belonged to. In descending order, the most popular active building characteristics for respondents working in the electricity retail and distribution sectors were the automation of energy activities, flexible electricity usage, environmental friendliness, self-generation, interaction with the energy system, local energy storage, user response to electricity prices and emissions. The respondents recognised high investment costs, the current regulatory framework and low energy prices as the most important barriers that affect negatively the development of Active Buildings. In more detail, the required active building components are considered to be expensive while there is there is lack of appropriate business models which could both reduce the risks for end-users and support investments in active building technologies. Additionally, as tariffs offered to the end-users must be uniform in order to ensure the energy equity of customers belonging to the same category, no special rewards can be provided to demand response schemes which would technically be more promising in terms of electricity demand flexibility. It is also mentioned that low energy prices in countries with high GDP per capita like Sweden result in a lack of interest from the public for such schemes.

Vahidinasab et al. [207] highlighted the role of Active Buildings as network service providers regarding the provision of DSM and ancillary services. Concerning their market-based operation and because of the relatively small amount of transactions and their size, it is argued that they might need to participate in the energy market through an aggregator. Nevertheless, as SG3.0 is expected to include P2P energy trading, they are conceptually permitted to trade their electricity directly with other energy peers. Furthermore, they are also anticipated to contribute towards the integration of other energy vectors, including distributed generation, energy storage and EVs. They could potentially rectify significant network issues in times of emergencies and improve the resilience of the energy system. It is concluded that the future role of active buildings needs to be properly assessed by policy-makers.

It is clear that buildings are gradually evolving and are expected to adopt several characteristics of smart and active buildings in the near future, especially as components of the smart grid, and have a strong and interactive relationship with the grid. This has already been discussed in Chapter 2.2 where buildings, as the final end-users of the network, are expected to have an increasing amount of bi-directional exchanges with the grid.

Kolokotsa [3] reviewed the role of the smart grid in the building sector, highlighting that distributed RES, smart buildings and other local generators are expected to be integrated through the smart grid, enabling the reliable and efficient delivery of electricity via demand response while the final consumers, including buildings, will have the capacity to control their electricity consumption and become active components of the network by participating actively in the electricity market. This is also in accordance with the concept of Active Buildings and their expected role within the grid, as presented in the previous subchapter. Specific requirements are mentioned in order for smart buildings to be fully functional and interconnected with the smart grid: smart metering, demand response, distributed architecture and interoperability.

More specifically, demand response offers the opportunity to buildings to change their energy consumption profile and respond to the dynamic nature of electricity prices, resulting in this way in reduced energy demand during the peak hours of the day, increased system reliability while wider adoption of demand response could serve as an alternative to additional generation capacity that would otherwise be necessary to meet the peak loads. Finally, the beneficial character of the smart grid for the building sector is highlighted in terms of improving its power quality and energy reliability while investments could then target the building envelope and the building's energy efficiency instead of growing the transmission part of the electricity network. Several building types can be seen, in Figure 2.34, as components of the smart grid, including Smart Buildings and ZEBs with energy storage, distributed generation, smart metering infrastructure, building integrated RES and other sustainable forms of electricity such as hydroelectric power stations constituting vital parts of the network [3].

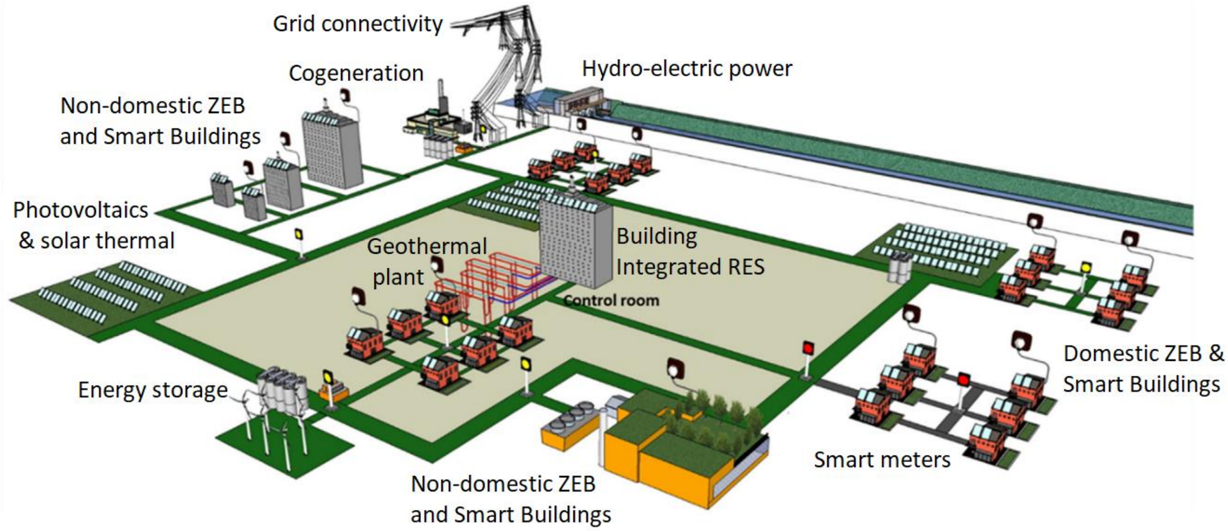

Figure 2.34 – Buildings as components of the Smart Grid [3]

In a technical article by Siemens, it is claimed that smart grids unavoidably require smart buildings which are called as the "*protagonists of the smart grid*", helpings towards a secure and safe power supply. It is recognised that in order for a conventional building to transition to a smart building, accurate predictions of its energy demand are needed. Afterwards, a comparison between the consumption profile and the energy availability will reveal the interventions that need to take place energy-wise; for example, an office building could be preheating during the night period by using cheap energy in order to be thermally comfortable for the following day. Building occupants must be able to adapt their behaviour in order for smart buildings to be successful. In this direction, local generation is of fundamental importance as it will allow users to schedule and balance production and consumption. A smart energy management system is required while buildings should be able to respond to dynamic electricity prices and buy a suitable amount of electricity, at the appropriate time. It is concluded that smart buildings should be considered as intelligent and autonomous systems of the wider smart grid environment. Their integration into the smart grid will provide an opportunity for massive energy savings whilst conducting an essential and critical balancing function [208].

The significance of understanding how quickly a building can change its energy consumption is highlighted as linking demand and supply system can bring benefits to all the players involved with current research focusing on a fully automated participation of a building in a dynamic DR event, with no human involvement. The participation of grid-aware smart buildings in DR events is shown in detail, in Figure 2.35, where it can be seen that continuous energy efficiency constitutes the first priority for the majority of the year. When moving to the right, there is an increasing amount of interactions with the grid, speed of telemetry and granularity of control; therefore, building service levels in DR periods are reduced, DR systems are getting quicker with day-ahead (slow) DR, real-time DR and finally spinning reserve (fast) DR. Apart from DR, [209] discussed the term of demand side flexibility (DSF), defined as the ability of an energy user to manage the local generation and demand, according to the occupants' needs as well as the local climate and power network conditions. Definitions found in the literature may vary but they all concentrate on the capacity to keep the power network stable during periods of uncertainty [210].

According to [211], commercial buildings are the "*major loads on the demand side*". Therefore, buildings have the potential to provide balancing services to the grid by participating in the frequency regulation market with the appropriate management and control of their HVAC systems. This is of vital importance as such a participation would require neither additional equipment nor investments. Additionally, as energy purchasers, buildings could receive compensation for their energy transactions as a reward for the provision of their services to the grid.

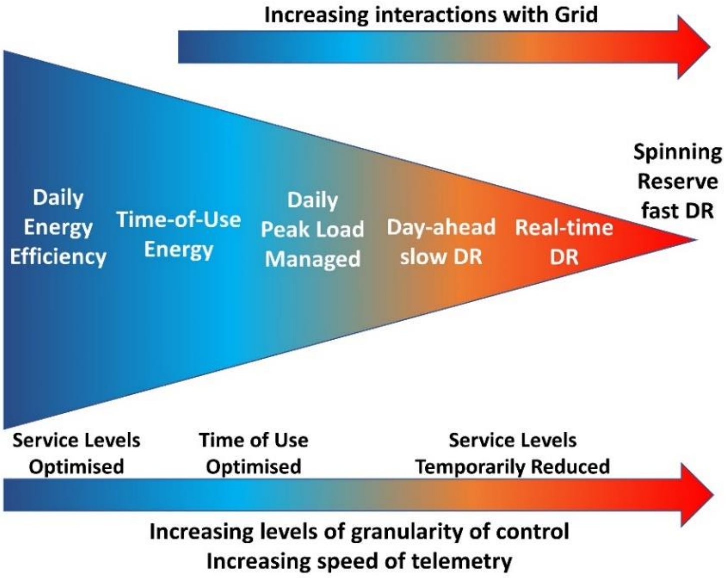

Figure 2.35 – Demand Response, service levels and controls in grid-aware Smart Buildings (Adapted from [210])

Lawrence Berkeley National Laboratory published a report, summarising field data from 28 non-domestic buildings, located in California and New York, that participated in DR events. It was concluded that the HVAC system constitutes an excellent resource for DR schemes due to the high amount of the associated electric loads that need to be met, especially in commercial buildings. Thermal mass and the thermal flywheel effect allow the building's HVAC loads to be reduced for a short amount of time without compromising the occupants' thermal comfort. Peak demand can also be reduced by incorporating lighting loads into the DR scheme, particularly in daylit and over-lit buildings to introduce demand savings. However, it is pointed out that any changes on the building's lighting profile should be chosen carefully, taking into account any safety implications. If a specific strategy appears to be successful, it should be treated as a permanent opportunity for DR and should also take place in non-DR days [212].

Aduda et al. [213] argued that due to their high levels of energy consumption, buildings have the potential to play a major role in terms of operational flexibility which is needed by the power grid by taking part in DSM events. Flexibility is classified by source, load type and strategy, as shown in Figure 2.36. The motive for buildings and other market players to participate in DSM can be either incentive/reliability or price based; the former refers to regulation-based services that take place due to the "*deterioration in overall power quality*" while in the latter, final users participate in the scheme to reduce their electricity cost.

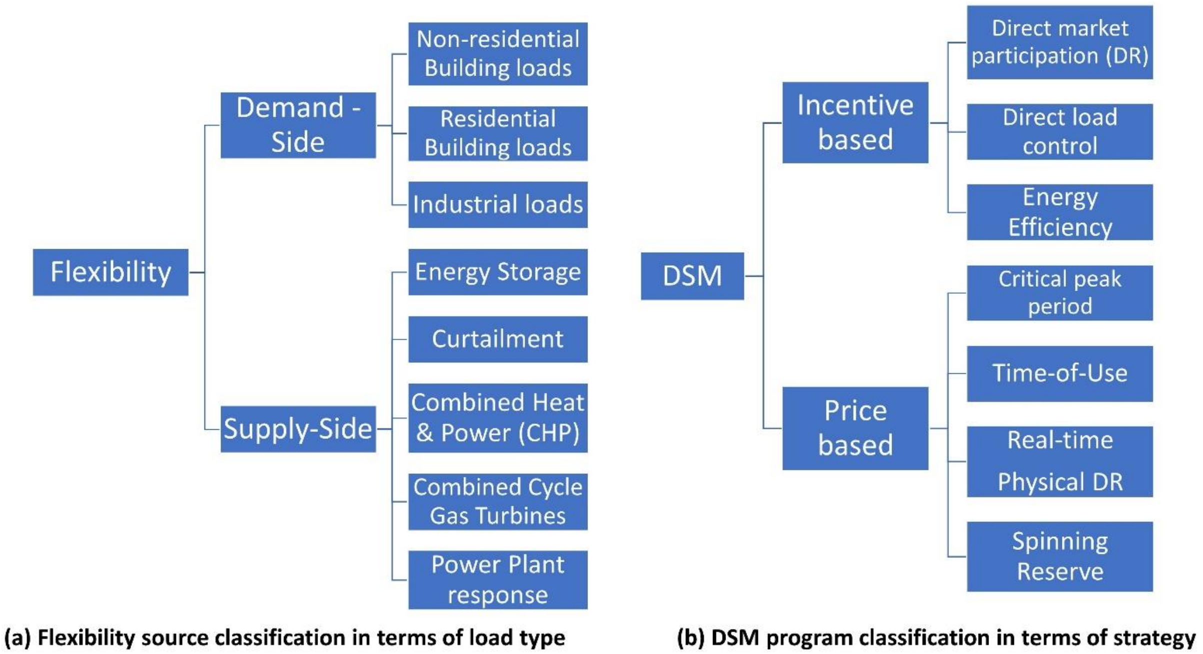

Figure 2.36 – Flexibility sources in electricity power networks by (a) source/load type and (b) DSM strategy. DSM also includes DSF events (Adapted from [213])

Having reviewed the literature for the power flexibility characteristics, [213] pointed out the shed-ability of certain building loads originating in office buildings, referring to the theoretical potential for load-shedding or load-shifting. This has been found to be 41 – 58% for cooling, 46 – 64% for heating, 46 – 59% for ventilation, and finally 26 – 28% for lighting loads. The response time needed are between 1 – 15 minutes for all HVAC loads while lighting only requires 30 – 40 seconds. Finally, existing DSM program strategies for buildings towards providing support to the grid are mentioned. In more detail, strategies for both heating and cooling systems include set-point temperature reset and fixed operational schedule or modulated operation. Additional strategies for cooling include the implementation of pre-cooling as well as operating at partial load conditions. It is concluded that future work is required to create cost-effective business models for participation of buildings in DSM events.

Chen et al. [214] investigated measures to improve DSF in buildings. It is recognised that the ability of buildings to participate in DR events and provide flexibility to the power network is relatively recent while a DR mechanism enabled by buildings is considered to be vital for the future smart (power) grid, consisting of significant amount of stochastic renewables. Additionally, a four-part framework for quantifying the DSF capacity of a building was suggested: (a) local energy generation, (b) building thermal mass as passive heat storage due to its heat absorption/release rates and thermal inertia, (c) ESS with its charging and discharging rate and finally (d) appliances. Several energy storage technologies are mentioned such as batteries, flywheels and compressed-air for electricity storage. It is highlighted that BES constitute flexible energy resource for a number of hours that can be charged during off-peak periods and discharged during periods of the day when peak loads normally take place. On the other hand, the lifetime and the associated investments costs are considered to be important barriers for the deployment of BES at the building scale. Nevertheless, energy storage is considered to be an "*indispensable*" technology for buildings towards energy flexibility and management [213], [214]. A list of DR/DSF projects in buildings can be seen in Table 2.21.

Table 2.21 – DR potential of DSF in buildings based on state-of-the-art research [214]

Year	Building Energy Systems description	DR type	Load flexibility results
2014	Thermal energy storage	Price based	Max. 18.7% total peak load shifting to valley time
2014	Space heating with thermal storage	Price based	Reduction of energy payments and indirectly of market power
2015	Fast DR strategy with active and passive building cold storage	Incentive based	Up to 35% chiller power reduction
2016	PVs and ice storage in building	Price based	Maximum peak load reduction of 90%
2016	Ventilation system in residential building	Price based	During DR, a single ventilation system can either increase power by 4.5 kW or decrease it by 1 kW.
2016	Smart Building cluster with PV systems	Price based	Shiftable loads can reach 25% of the total building loads.
2016	Compressed-air energy storage	Price based	Shifting 10% of the loads to other hours
2016	Fast DR of HVAC system	Incentive based	39% power reduction
2016	HVAC system and smart appliances	Incentive based	Reduction of daily peak loads by 26%
2016	Electric Vehicles in residential, commercial and industrial areas	Price and inventive based	20% reduction of peak loads and 40% reduction of aggregate costs
2017	Home Energy Management System in residential building	Price based	Reduction of peak loads and reduction of daily electricity costs up to 20%

2.4.5 Smart Grid Optimised Buildings

It is expected that buildings will establish a very strong relationship with the grid and the future smart grid, being engaged in frequent bidirectional exchanges, participating in DR schemes and generating electricity using local RES. SGOBs have built on the description and the characteristics of smart and active buildings with the addition of external drivers (e.g. direct requests) that invite buildings to become part of the wider SGOB community, engage in schemes that can be beneficiary for both themselves and the energy network by taking advantage of financial rewards. Presented for the first time in [4], a SGOB is thought of "*as meeting its service obligations to its occupants and minimising its operational cost and footprint to its owner, while actively engaging with the electricity provider and enabling best use of the resources available*". This is also reflected in Figure 2.37 where the service relationships among the occupants, SGOB and the electricity provider can be seen.

In more detail, a SGOB can make use of its embedded intelligent systems to make a decision regarding the potential participation to a DR event and its extent. If the response provided by the building to a formal request from the grid is positive, then the SGOB has to adapt its building loads based on the agreed terms and conditions, both temporally (within seconds, minutes or hours) and energy-wise (kWh or/and kW constraints). The SGOB concept can be applied to both existing and new buildings through economic incentives; it is assumed that the building's design can be optimised in order to take full advantage of the offered incentives and maximise the potential revenue stream [4].

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Figure 2.37 - Service relationships between building occupants, SGOB and electricity provider [4]

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Figure 2.38 - Electricity usage pattern and effect of Smart Grid requests for modification (a)-(d) [4]

Figure 2.38 shows how the electricity profile of an SGOB could be modified after receiving a notification from the Smart Grid. The building could then use all the available resources to adapt its loads and comply with the request made by the grid operator. Three temporal types of requests are visible in the figure and more specifically, a request for a planned modification could take place a day in advance (day-ahead) in order for the building to prepare its systems accordingly, such as electricity generation from solar panels as well as passive systems. Additionally, imminent requests would be sent to the building in case of unpredicted changes in consumption to adapt its profile within the same day (intra-day) [4].

Moreover, an immediate request for modification of the SGOB's electricity demand would be used as an urgent measure to tackle unplanned and unpredictable incidents, including generation or transmission system failures. It should be pointed out that SGOBs are assumed to be fully electric, making use of heat pumps for both heating and cooling purposes, in order to maximise the potential of bidirectional exchanges of electricity with the grid. Using electricity storage, SGOBs are able to become fully active elements of the smart grid, changing their electricity profile on demand.

The ideal characteristics and the perceived barriers for SGOBs are presented in detail, in Table 2.22. More specifically, the participation of SGOBs in DR-type grid events must not have any ramifications regarding its operation and productivity while the building should be able to predict with very high levels of certainty its building loads across all timescales. It is pointed out that conventional buildings are already capable of decreasing their energy demand, but the respective timescales are not taken into account. Finally, the authors argued that an SGOB can utilise its ESS to participate in the energy market as a storage vector; however, the establishment of a proper regulatory framework and the adoption of dynamic electricity pricing are of major importance in order for buildings to be allowed to act as "*energy-related entities and prosumers*" and work towards the objectives of the Smart Grid [4].

2.5 Summary and Conclusions

Originally designed to be a monodirectional system with centralised generation and limited control, the electrical grid faces decarbonisation with an increasing amount of bidirectional power exchanges that take place. It has become an increasingly complex system and faces significant challenges towards its transformation to the future smart grid.

The intermittent and stochastic nature of renewables introduce stability issues and imbalances between supply and demand, affecting the reliability of the grid. Electrification of the heating sector will affect the future energy consumption profiles with heat pumps, such as ASHP and GSHP, already receiving a growing popularity in the recent years and expected to contribute to the energy transition. Similarly, the increasing popularity of EVs will contribute towards the electrification of the transport sector. Distributed generation from RES, buildings as power plants, energy storage and the smart grid are considered to be the four necessary pillars of the new post-carbon society.

Regarding energy storage technologies, they have several grid applications such as providing balancing services, enabling participation in arbitrage schemes and therefore deferring the need for potential costly infrastructure upgrades. They can be placed and utilised in different parts of the network while several energy storage projects, the vast majority of which are Li-ion batteries, are planned at the utility-scale as well as for buildings and communities.

Table 2.22 – Characteristics and perceived barriers for SGOBs [4]

Element of SGOB hypothesis	Ideal SGOB characteristic	Perceived barriers
Capability to reduce grid-connected load on demand.	Diverse and resilient methods to achieve load reduction across all timescales.	Conventional buildings may already include demand reduction characteristics, but diversity, resilience, and timescales are not known to be objectively considered at all.
Capacity to increase grid-connected load on demand.	Diverse and resilient methods to achieve load increase across all timescales.	Conventional buildings may not include any deliberate means to increase load in response to external instructions.
Acceptability of impact arising from reduction or increase in grid-connected load.	No impacts upon normal operation, productivity, or energy being to put to a useful purpose without wastage, when participating in load modification.	Conventional buildings may exhibit a direct link between connected load and internal control measures, which would mean that reduction in load could be achieved but with compromised level of service, and increased energy use could result in energy wastage.
Notice required to make a change to grid-connected load.	Capability to predict with certainty the ability to participate in events across all timescales.	Conventional buildings are not known to predict the quantity of energy that will be taken from the grid at any point in time, and in-use data has shown significant variation from design predictions.
Response time between request for change (event) and change being evident.	Capability to reliably deploy methods to achieve the predicted change (event) within an acceptable tolerance of the required timescale.	Conventional buildings are not known to have demonstrated reliable deployment of load modification activities across all potential vectors.

3. Methodology

At the beginning of this chapter, a brief overview of the methodology used id presented. Afterwards, its methodology section explained in detail, for its three main elements: Buildings, the electrical grid and battery storage.

3.1 Methodology Overview

There are three main components in the research project. In terms of energy storage, technologies that are not able to be physically placed in a building or in its vicinity have not been considered, such as PHES and CAES that have significant geographical limitations. Additionally, as the utilisation of storage is needed for both power and energy applications, other technologies such as SMES, flywheels and supercapacitors have been excluded as inappropriate for energy applications. Therefore, batteries have been selected as the energy storage technology of the project and in particular Li-on batteries as they constitute the most promising battery electrochemistry with rising popularity, declining capital costs, wide availability and non-toxicity (Section 2.3.3.2). The most import ESS characteristics are battery capacity (kWh), bi-directional converter capacity (kW), lifetime (years/cycles) as well as the operational (dispatch) strategy followed.

The key building characteristics have been identified and discussed in Section 2.4.2. For the needs of the current research, six key building characteristics are taken into account: the building envelope, glazing, HVAC, shape, orientation and thermal mass. The interaction of buildings utilising battery storage with the electrical (smart) grid results in the operation of SGOBs, as illustrated in Figure 3.1 and published in [9]. Real-time electricity prices (£/kWh) are required as an input while the output includes electricity costs and detailed results on the modification of the building's electricity profile. For the current project, the energy services provided by the SGOB to the grid are limited to arbitrage, in other words load-shifting of electricity which also has the potential to lead to peak-shaving. Buildings are assumed to be fully electric through the utilisation of heat pumps for both heating and cooling purposes; this strategy maximises the potential of bidirectional power exchanges between the SGOB and the electrical grid, including electricity exports.

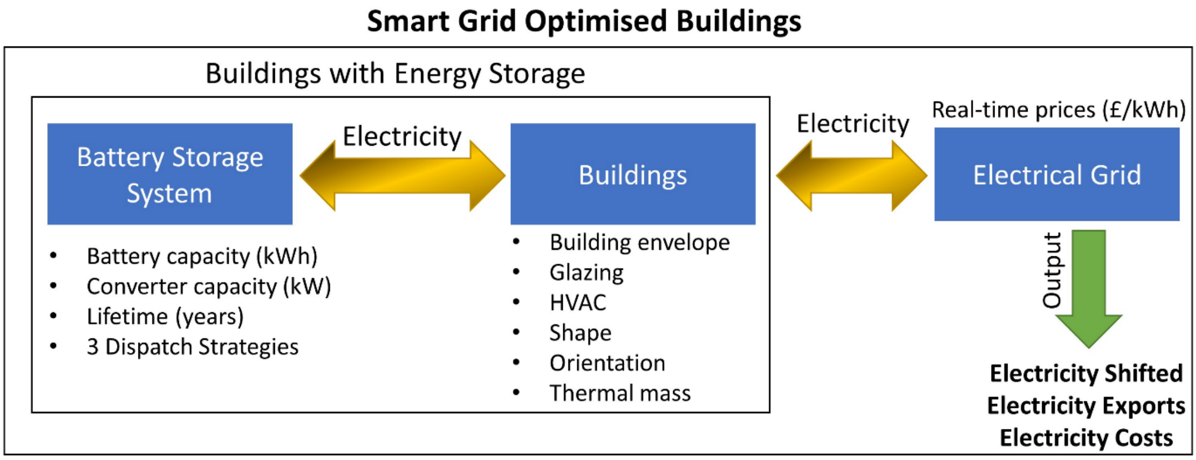


Figure 3.1 – Main research elements and their characteristics [9]

The simulation tools and software used for the needs of this research are presented in Figure 3.2. More specifically, DesignBuilder is used to draw the geometry of the buildings and run the energy simulations, using the integrated EnergyPlus engine. The input provided to the software is detailed and includes construction & materials for the entire building envelope and internal building elements (e.g. floors), activity (e.g. occupation density) and the HVAC configuration. The output of the DesignBuilder simulation is then fed into the custom MATLAB BES model along with real-time electricity prices; therefore, MATLAB has a total of two inputs, one containing the necessary building data and the second the required electricity prices. After the MATLAB simulation is completed, the combined results are obtained and can either be analysed and plotted internally or exported in a different software, such as Microsoft Excel. A variety of grid modelling tools are presented in Section 3.2.2. However, as the focus of SGOBs is concentrated on the local building scale instead of larger and more complicated industrial, transport or community energy systems, it was decided that customised code would be the most flexible approach with MATLAB being chosen as the programming language.

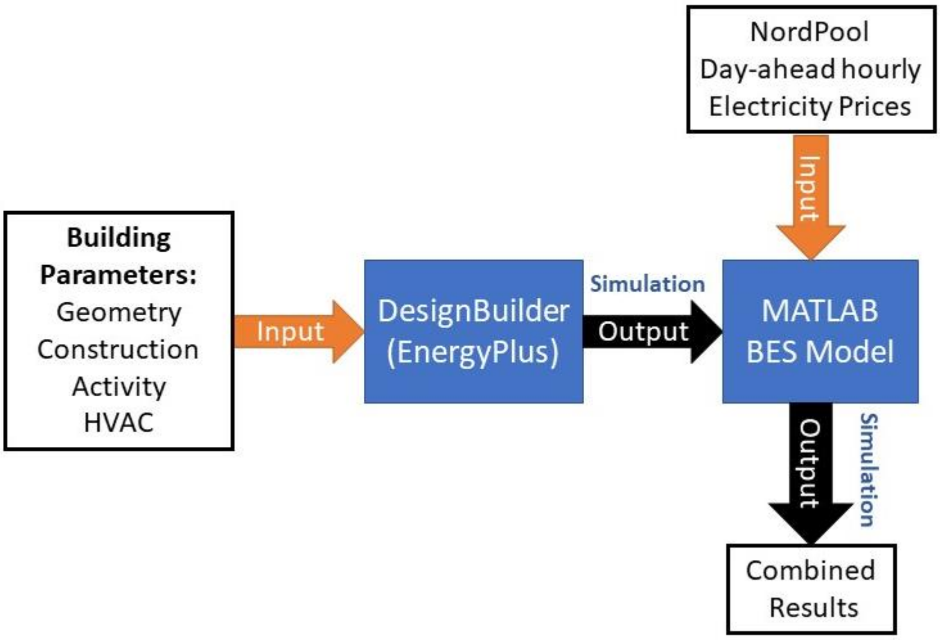


Figure 3.2 – Modelling tools used in the current research [9]

3.2 Review of Existing Modelling Tools

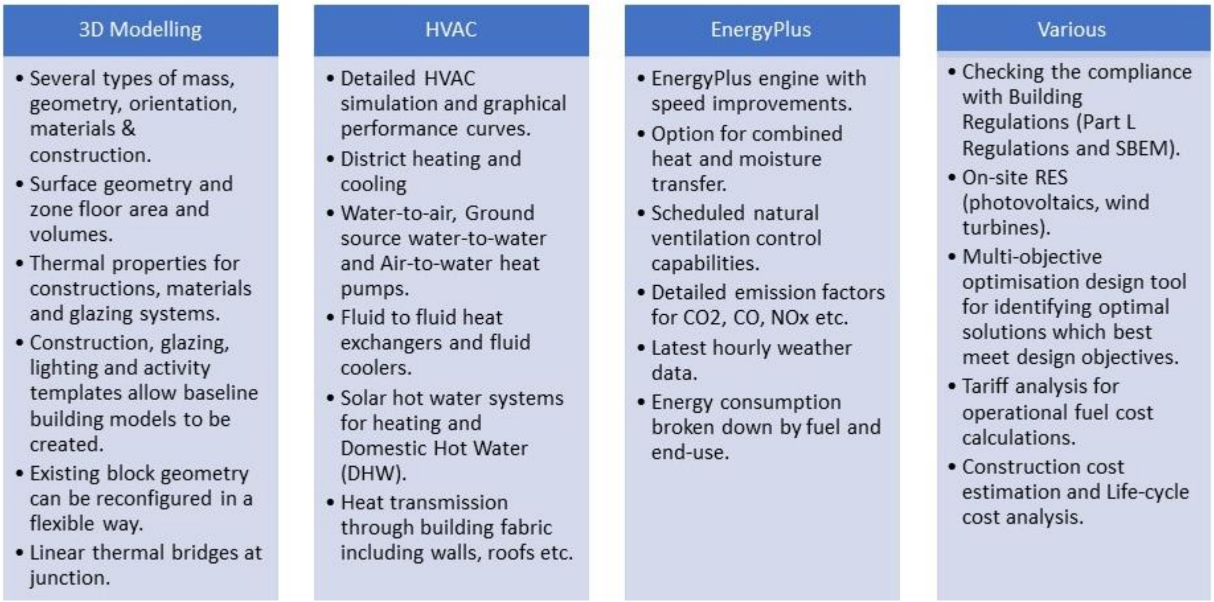
3.2.1 Energy and Buildings

There is a range of available dynamic thermal simulation tools that have the capacity to predict a building's energy demand over a typical year. Many building energy tools are based on either the EnergyPlus or the DOE2 simulation engines, there is also a number of independent tools, such as Ecotect, TRNSYS and IDA ICE. Certain data which are necessary for the building's energy simulation input are taken from readily available templates, based on several ASHRAE standards and therefore do not require input from the user [215].

EnergyPlus is a free open-source energy simulation engine, created by the US Department of Energy for predicting the building energy and water consumption. For calculation purposes, thermal zones are used by the software while a time-step methodology is followed which can lead to either lower or higher simulation times, depending on the accuracy needed. It is noted that EnergyPlus does not have its own graphical user interface (GUI), a significant disadvantage of the simulation engine. However, appropriate solutions are available, such as OpenStudio and DesignBuilder, with the latter being a commercial CAD software that can be used to draw the geometry of the building and import data from other Building Information

Modelling (BIM) tools. Afterwards, DesignBuilder makes use of the integrated EnergyPlus engine to conduct the simulation and present its results. Autodesk Revit is another commercial CAD software than can be used to continue a BIM project with the Insight 360 plugin being required for energy simulations, utilising the EnergyPlus Engine [216], [217].

In this project, DesignBuilder is used to model buildings. The software can import construction templates with components such as glazing, materials, textures, local shading, window blinds, vents, and others. A database of typical hourly weather data is included with the main software for different locations in many countries, including the UK and Ireland. Furthermore, a variety of templates are included, such as activity templates for occupancy and equipment usage, lighting, location as well as HVAC templates. A summary of the most important modelling characteristics of DesignBuilder are shown in Figure 3.3, in categories. Calculation of the building's emissions, as well as its construction and life-cycle cost analysis are also possible while solar panels can also be included in the simulation, located either on the roof or on the ground. Finally, it is capable of simplifying the EnergyPlus Simulations, importing existing BIM and CAD design data and optimising the building at any design stage; therefore, it is suitable to meet the needs of engineers, architects and energy assessors [218] [219].



3D Modelling	HVAC	EnergyPlus	Various
• Several types of mass, geometry, orientation, materials & construction. • Surface geometry and zone floor area and volumes. • Thermal properties for constructions, materials and glazing systems. • Construction, glazing, lighting and activity templates allow baseline building models to be created. • Existing block geometry can be reconfigured in a flexible way. • Linear thermal bridges at junction.	• Detailed HVAC simulation and graphical performance curves. • District heating and cooling • Water-to-air, Ground source water-to-water and Air-to-water heat pumps. • Fluid to fluid heat exchangers and fluid coolers. • Solar hot water systems for heating and Domestic Hot Water (DHW). • Heat transmission through building fabric including walls, roofs etc.	• EnergyPlus engine with speed improvements. • Option for combined heat and moisture transfer. • Scheduled natural ventilation control capabilities. • Detailed emission factors for CO2, CO, NOx etc. • Latest hourly weather data. • Energy consumption broken down by fuel and end-use.	• Checking the compliance with Building Regulations (Part L Regulations and SBEM). • On-site RES (photovoltaics, wind turbines). • Multi-objective optimisation design tool for identifying optimal solutions which best meet design objectives. • Tariff analysis for operational fuel cost calculations. • Construction cost estimation and Life-cycle cost analysis.

Figure 3.3 – Modelling capabilities of DesignBuilder [218], [219]

3.2.2 Electrical Grid and Energy Storage

Ringkjøb et al. [220] reviewed and presented a total of 75 models that are used for energy and electricity systems, focusing on software capable of modelling renewables. The availability of the software differs from package to package as 24 are open-source, 7 are provided free of charge, 16 are commercial while others are available upon request. Table 3.1 presents below the general logic and the spatiotemporal resolution of ten selected modelling tools, including their purpose, approach and adopted methodology. It can be seen that most models follow either a bottom-up or hybrid optimisation while their purpose is to provide decision support regarding investments and operation. Their coverage can also vary significantly, from one system/project to an entire continent and finally the world. Additionally, the modelling horizon can be user-defined in the majority of the models flexibly with a broad range between 1 and 100 years.

More detailed economic and technical information on the selected 10 models is presented in Table 3.2. In more detail, the models support all sources of conventional power generation, with the exception of nuclear power for energyPro and HOMER, while the vast majority of packages include a variety of ES Technologies. It should be highlighted that BES is the only storage technology which is supported by all models present. Regarding grid (power) modelling, most models take into account imports and exports with OpenDSS and PRIMES including more sophisticated options on multiphase AC power flows and DC linearised optimal flows, respectively. The two most popular options for market modelling are simple supply/demand and spot (merit-order) electricity market modelling. The authors noted that only a few of the rest 65 models are able to provide day-ahead and intra-day modelling [220].

Table 3.1 – Logic & spatiotemporal resolution of modelling tools for energy and electricity systems (Adapted by [220])

Model/Tool	Purpose	Approach	Methodology	Temporal Resolution	Modelling Horizon	Coverage
COMPOSE	ODS, SCE	ACC, MIP	ACC, MIP	UD (hourly)	UD	Single-Project/System
EnergyPLAN*	SCE, IDS	BU	SIM	Hourly	1 year	Local to Continental
energyPro	IDS, ODS	BU	AO	Minutes	Max. 40 years	Local to Regional
HOMER	IDS, ODS	BU	SIM	Minutes	Multi-year	Local
MARKAL	SCE	BU	LP/MIP, PE	Multiple years, UD within a year	Long-term (UD)	Local to Regional
MESSAGE	SCE, IDS	HYB	LP	UD (Multiple years)	Long-term (50-100 years)	Global (11 regions)
OpenDSS*	PSAT	BU	SIM	UD (1s to 1h)	UD	Distribution areas
PRIMES	IDS, SCE	HYB	PE	Yearly	Long-term	National (Europe)
RETScreen*	IDS, SCE	HYB	SIM	Daily/Monthly /Yearly	Max. 100 years	Single-system to Global
TIMES	IDS, ODS	HYB/BU	LP/MIP, PE	Multiple years, UD within a year	Long-term (UD)	Local – Global

* The model is either open-source or provided for free.

Table Abbreviations - **Purpose**: IDS = Investment Decision Support, ODS = Operation Decision Support, PSAT = Power System Analysis Tool, SCE = Scenario, **Approach**: BU = Bottom-up, TD = Top-down, HYB = Hybrid, **Methodology:** ACC = Accounting, AO = Analytical Optimisation, LP = Linear Programming, MIP = Mixed Integer Programming, PE = Partial Equilibrium, SIM = Simulation, **Temporal Resolution**: UD = User-defined.

The importance of energy storage, DSM and grid expansion for the integration of the variable RES is highlighted as most studies have taken the approach to assess the individual impact of these features instead of their combination. Moreover, the importance of the available demand sectors is paramount in order to match the appropriate model to the application in question. More specifically, it is clear that there are several tools capable of modelling

Table 3.2 – Technical and economic parameters of modelling tools for energy and electricity systems* [220]

Model	RES	Energy Storage	Grid	Commodity	Demand Sectors	Demand elasticity	DR	Costs	Market
COMPOSE	All	All	None	Electricity, Heat & Fuels	Buildings, Transport & Industry (UD)	Inelastic	No	INV, O&M, FU, TA, BC	Spot, BAM
EnergyPLAN	All	All	Import/ Export	Electricity, Heat, H_2, Fuels	Buildings, Transport & Industry	Elastic	No	INV, O&M, FU, TA, CO_2	Spot
energyPro	All	PHS,CAES TES	None	Electricity & Heat	AG	Elastic	No	INV, O&M, FU, TA, CO_2, BC	Spot
HOMER	All	CAES, B, H	Import/ Export	Electricity & Heat	AG	Inelastic	No	INV, O&M, FU, CO_2	Supply/Demand
MARKAL	HP, WP, SP, GT	PHS	NTC	Any	Buildings, Transport & Industry	Elastic	Yes	INV, O&M, FU, CO_2, TA	Supply/Demand
MESSAGE	All	All	Import/Export	Any	Buildings, Transport & Industry	Elastic	Yes	INV, O&M, FU, CO_2, TA	Supply/Demand
OpenDSS	SP	All	Full AC Load Flow	Electricity	AG	Inelastic	Yes	NA	NA
PRIMES	All	All	DC linearised Optimal Flow	Electricity, Heat & H_2	Buildings, Transport & Industry	Elastic	Yes	INV, O&M, FU, CO_2, TA	Supply/Demand
RETScreen	All	B	Central/ Isolated/ Off-grid	Electricity & Heat	Buildings & Industry	Inelastic	No	INV, O&M, FU, CO_2, TA	Supply/Demand
TIMES	All	All	NTC	Any	Buildings, Transport & Industry	Elastic	Yes	INV, O&M, FU, CO_2, TA, BC	Supply/Demand

***Table 3.2 abbreviations: RES:** HP = Hydropower, ROR = Run-of-river, SP = Solar Power, WP = Wind Power, ST = Solar Thermal, WaP = Wave Power, GT = Geothermal, CSP = Concentrated Solar Power, TP = Tidal Power; **Energy Storage**: PHS = Pumped Hydro Storage, CAES = Compressed Air Energy Storage, B = Batteries, H = Hydrogen, TES = Thermal Energy Storage; **Grid**: NTC = Net Transfer Capacity; **Demand Sectors**: AG = Aggregated, UD = User-Defined **Cost**: INV = Investment, O&M = Operation & Maintenance, FU = Fuel, CO2 = Carbon cost, TA = Taxes, BC = Balancing costs; Market: BAM = Balancing Markets.

buildings, industry and transport while others follow a different approach by aggregating all the demand sectors. Finally, DR can be found as an option in half of the modelling tools while the authors recognised that none of the 75 existing models can be used to tackle all the challenges and issues encountered in the present energy system. Nevertheless, a compromise has to be found by selecting the software with the most appropriate characteristics.

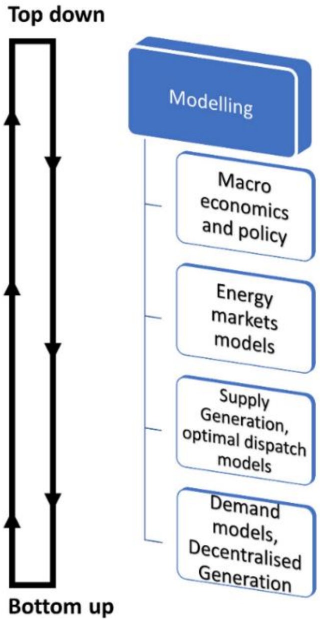


Figure 3.4 – Layers of the Energy System and modelling approaches (Adapted from [221])

Granado et al. [221] discussed the challenges of modelling the energy system and its several layers towards energy transition. The economy creates demand for energy services, such as heat and electricity, through a top-down financial perspective that captures any interactions between national and global markets. Afterwards, demand leads to the adoption of certain bottom-up technology options that serve as infrastructure in the energy sectors which constitute once more input to the economic top-down decisions (Figure 3.4). Therefore, it is important to understand the different modelling approaches and the reasons why certain elements of the energy network are intentionally either included or omitted, depending on the objectives of the modelling tool. Top-down approaches make use of computable general equilibrium, in order to model macroeconomic and microeconomic behaviours, and they include agents of the economy as well as markets for goods and factors. An equilibrium between supply and demand can be achieved through the adjustment of energy prices while the addition of taxes is also a possibility. One of the advantages of these models is the inclusion of all the interactions between the different agents and feedbacks that take place through the entire economy. Econometric top-down models follow a different approach by focusing on the statistical relationships between the model variables and adopting higher levels of aggregation; they are often used for predictions and analysis of different scenarios. Regarding bottom-up models, MARKAL is considered as a detailed tool that incorporates many technologies; however, interactions with the energy system are not taken into account. The simple MARKAL model uses linear programming where energy supply and demand are represented based on the associated costs and technical characteristics of the involved technologies. In this direction, the model aims to minimise the overall supply costs for the respective energy demand as well as the required capital and operational costs.

Additionally, the TIMES model improves and extends the capabilities of MARKAL as it adds scalability from local to global systems, flexible time slices including daily load profiles and a flexible long-term modelling horizon. On the other hand, both tools have been criticised for the adopted simplifications, especially when representing supply-demand operations of high temporal resolution, while the absence of energy system feedbacks and local generation led certain authors to question the quality and the validity of the tools' results. Most issues can be rectified by using a combination of TIMES and EnergyPLAN and an hourly time resolution for the integration of the increasing amounts of variable RES. The authors concluded that while all models can be proved to be useful, they all appear to be lacking at least one of the following elements: integration of distributed RES, grid security assessments, modelling details of the power grid and long-term outlook [221].

Hall and Buckley [222] reviewed the energy systems modelling tools used in the UK, identified more than 100 different modelling tools, mentioned in the literature from a total of 423 publications between 2008-2016, and focused on 22 of them. MARKAL and its variations was the most popular tool, with a total of 86 appearances, followed by MESSAGE and its 15 appearances while the rest of the tools appear between 1-9 times. The vast majority of the modelling tools, included in Tables 3.2 and 3.3, are also present in this review. Furthermore, regarding the appearance of renewables in the literature, wind power was the most popular technology (78), followed by energy storage (75), biomass (65) and solar (55).

For the needs of the current research, Homer Pro was evaluated as the most appropriate modelling tool to be used at the building-scale. However, a lack of customisation was noticed in terms of the operational dispatch strategies offered. While newer versions of the software offer more flexibility through importing MATLAB scripts, it was decided to implement the desired algorithms, exclusively in MATLAB without using any additional software.

3.3 Building Simulations

3.3.1 Geometry and Considered Scenarios

As mentioned above, DesignBuilder is a building energy modelling tool that consists of two parts, a GUI and the integrated EnergyPlus simulation engine that works in the background. The GUI is used to develop the geometric model of the buildings and provide all the necessary information as an input while it is also used to view and export the simulation output results. The interoperation between DesignBuilder and the EnergyPlus engine is shown below, in Figure 3.5. The buildings are considered to be non-domestic commercial with a total of two zones: the main zone consists of open-plan office area and the secondary zone constitutes a small generic area for the lobby, stairwells and the lift, located in the center of the floor.

The key geometry characteristics are summarised in Table A1 of the Appendix, where it can be seen that a total of three storeys are taken into account, besides the ground floor. The exact dimensions of the Zones depend on the building shape which is either square or rectangular; nevertheless, for all cases, the total floor area is 625 m^2/floor and 2,500 m^2 for the entire building. A typical building geometry is shown in Figure 3.6 through DesignBuilder's visualization function where both Zones 1 and 2 are visible. The exact appearance of each building varies based on its design characteristics while the buildings are designed with the northern hemisphere in mind. Floor plans for both the square and rectangular buildings can be seen in Appendix A along with the building exteriors, as seen within the DesignBuilder interface (Figures A1-A4). Critical information for this chapter has been taken from DesignBuilder's documentation and user manual which can be found in [223].

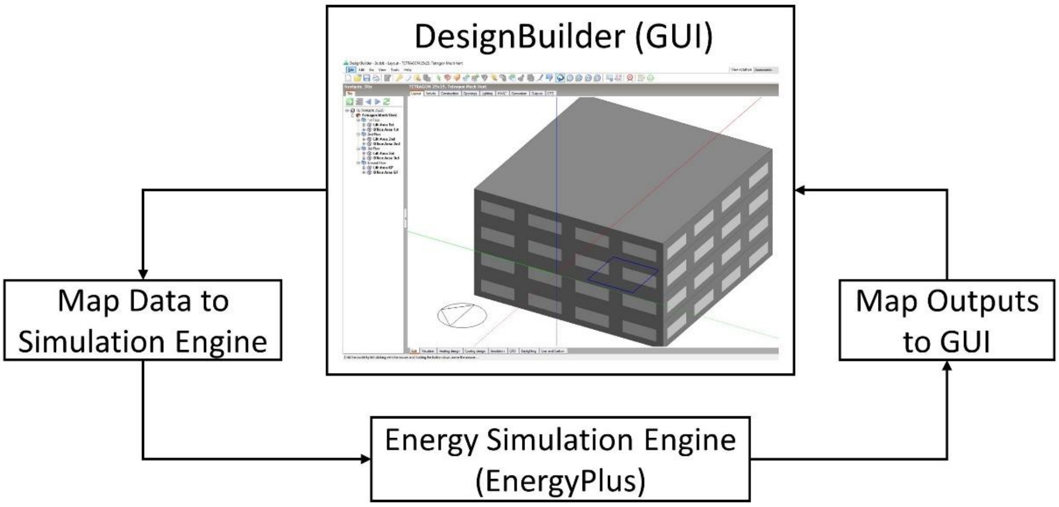


Figure 3.5 – Interoperation between DesignBuilder GUI and EnergyPlus [9]

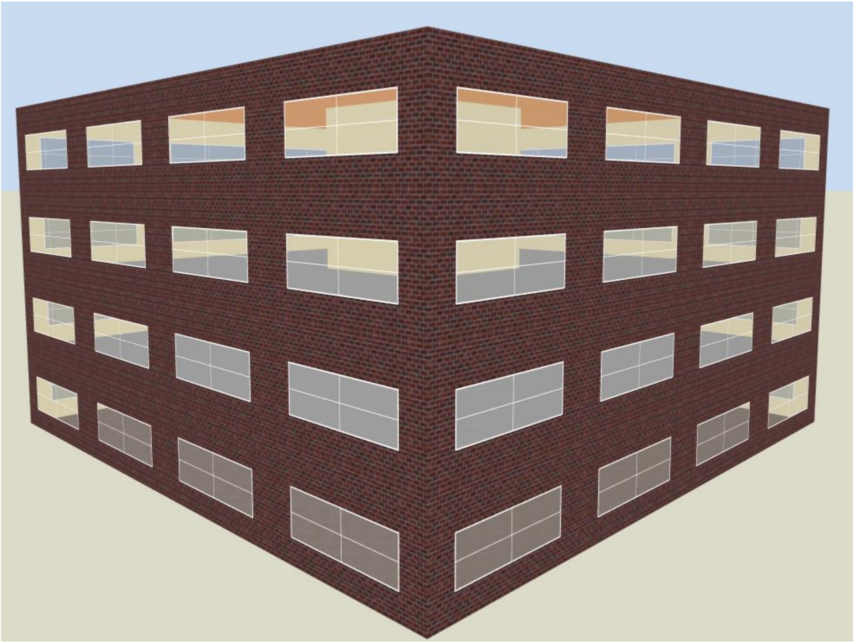


Figure 3.6 – Building's visualisation in DesignBuilder. Zones 1 and 2 can be distinguished. Appearance of the building varies depending on its shape, glazing, construction and materials.

The combination of building characteristics leads to the formation of unique building scenarios, as shown in Figure 3.7. These will be discussed in more detail at later stages of this chapter; however, it is important to briefly present the design elements and the respective options taken into account:

a. **Thermal mass**. Its importance has been highlighted in the previous chapter and the two options (heavyweight, lightweight) are set to include varying thermal response times. It significantly affects the thermal response (lag) of the building and it falls under the category of “construction and materials”.

b. **Energy Efficiency**. This refers to the fabric’s thermal performance. Thermal insulation aims to slow the heat transfer through the building’s envelope and decrease heat losses. Appropriate materials have been chosen to result into two respective U-values: the first option (Part L) meets the UK Building Regulations while Best Practice uses a smaller U-value to further improve energy efficiency, based on the UK notional building specifications. Insulation is also considered to be part of “construction and materials”.

c. **Shape**. Self-explanatory with two options, square and rectangular buildings.

d. **Orientation**. As the options depend on the building’ shape, square buildings can have either a southern (symmetrical) orientation or within ± 45°, resulting in a south-western or south-eastern orientation. On the other hand, rectangular buildings have the additional option of the eastern orientation.

e. **Ventilation & Air-conditionning (VAC)**. This component refers to the HVAC configuration except for heating which is the same for all building cases. In naturally ventilated buildings, operable windows are used to bring in fresh air and cool down the indoor temperature when necessary while the second option includes the utilisation of both mechanical ventilation and cooling through heat pumps to meet the same objectives. An economiser is used to transfer outside air to the building’s interior through mechanical ventilation. Square buildings are assumed to be only mechanically ventilated as natural ventilation is not considered sufficient to meet thermal comfort standards for their geometry.

f. **Glazing.** This is also called the Window-to-Wall ratio (%) and refers to the percentage of the external wall covered by glazing. Two cases are considered, a medium value of 30% and an extreme value of 80% for highly-glazed buildings with the latter not being used for naturally-ventilated buildings due to thermal confort issues.

3.3.2 Construction & Materials

In this subchapter, the materials used for the building envelope are presented in detail. As shown in Figure 3.7, there are two cases considered regarding the energy efficiency of the buildings: Best Practice and Part L compliant with the former having lower U-values. The values used in Best Practice are based on the notional building specifications of the UK Building Regulations. The latter makes use of less insulation in order to marginally meet the Part L requirements, resulting in higher thermal energy losses. As expected, Best Practice buildings have a higher thermal insulation thickness than Part L for all envelope elements. A variety of insulation materials is used, including extruded polystyrene, urea-formaldehyde and glass wool. For example, external walls in Part L compliant buildings have a U-value of 0.35 with the respective value being reduced at 0.25 $W/m^2{\cdot}K$ in Best Practice buildings. The values can be found, in detail, in Tables A2 – A3 of the Appendix.

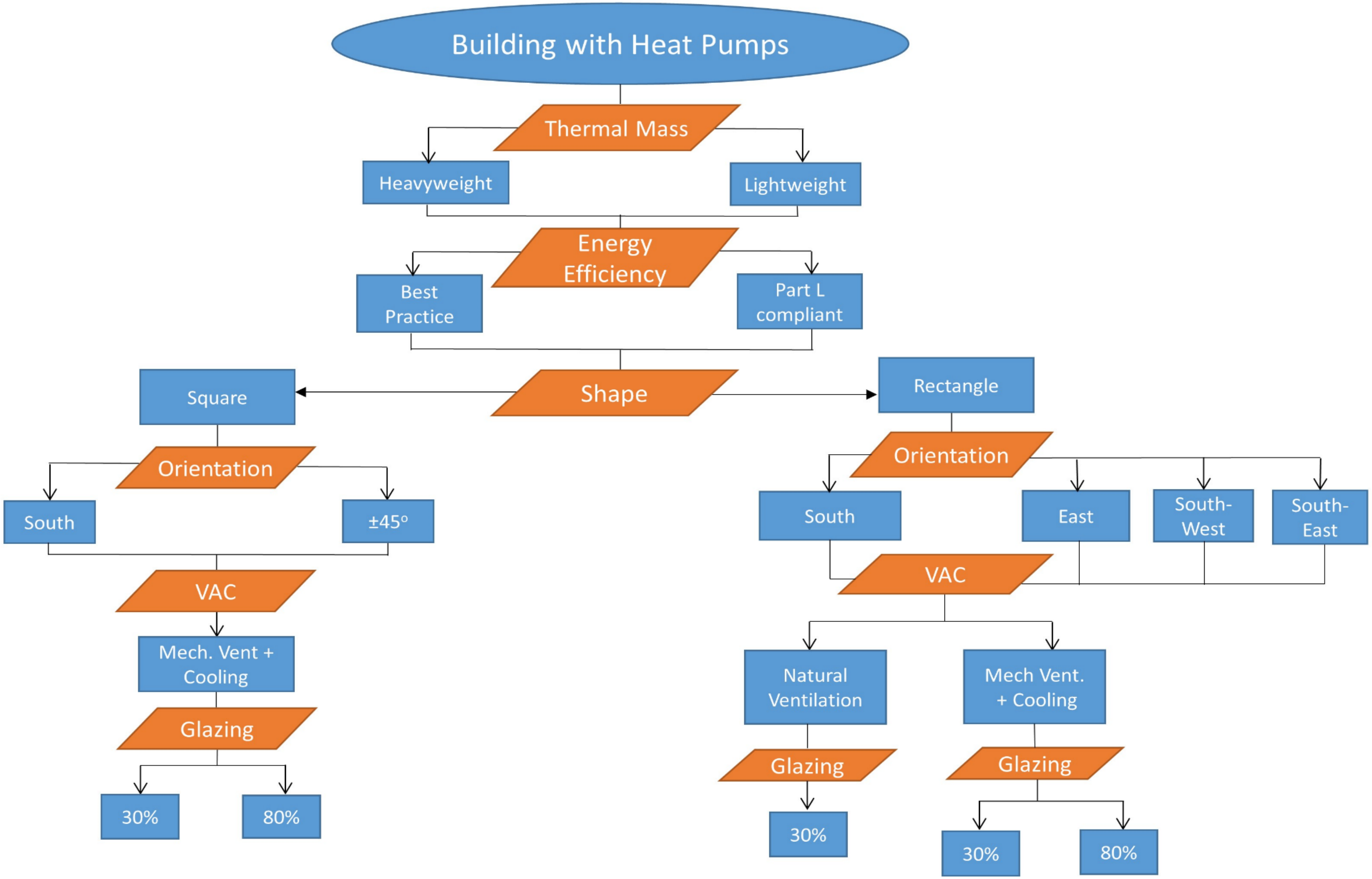


Figure 3.7 – Building Characteristics Considered for Energy Simulations

The building envelope consists of the ground floor, roof and the external walls. As thermal mass is also one of the building design characteristics taken into account for the current project, two scenarios have been selected: heavyweight and lightweight buildings. When combined with the two energy efficiency options, there is a total of four scenarios regarding construction and materials. The construction elements are shown in Tables A4 - A5 for heavyweight buildings and Tables A6 – A7 for lightweight buildings.

In terms of thermal mass, heavyweight buildings' external walls consist of brickwork and concrete block with a combined thickness of approximately 200mm while in lightweight buildings a thin 6 mm layer of metallic cladding is used. In terms of internal floors, the same material, cast concrete is used for both building types; however, a thickness of 300 mm has been selected in heavyweight buildings instead of 100 mm used in lightweight. With the exception of the ground floor composition which remains the same for both thermal mass scenarios, all envelope elements are fundamentally different. The roof in heavyweight buildings includes an asphalt layer of 190 and 130 mm of fibreboard while a thin 10 mm layer of asphalt along with 200 mm of air gap cavity are used as roof materials in lightweight buildings. Cross sections of the external walls and roofs that demonstrate the material layers and thicknesses used can be seen in Figures A5-A6.

3.3.3 Glazing

Glazing has been classified in two categories depending on the vertical fenestration percentages: 0 – 40% for medium-glazed and 60-80% for highly-glazed buildings. Similarly to the methodology followed for the building envelope values, two scenarios have been considered: Best Practice and Part L compliant, always related to their energy efficiency. Regarding the U-values for 0 – 40% vertical fenestration, the notional building specifications have been used for the Best Practice scenario while the limiting factor from Part L2A (buildings other than dwellings) has been chosen for the Part L scenario.

Originally, different glazing properties were chosen for each energy efficiency and vertical fenestration percentage scenarios, as shown in Table A8. However, light and solar transmission were modified and the respective values of 55% and 38% were adopted for all scenarios. This was deemed to be necessary as the mentioned glazing properties highly affect the simulation results. Therefore, using different values would undermine the comparison between Part L and Best Practice in terms of insulation (U-values) as it would also render the comparison a ''glazing properties competition', especially in relation to the thermal transmission percentage value'. Generally, each building has a unique set of suitable glazing options that depend on several factors including location, climate, orientation and many others; ergo, there is no standard best practice or Part L compliant glazing components. Regarding the 0 – 40% glazing scenario, the Part L limiting factor was used (2.2) for the Part L scenario and the notional building's U-value (1.6) was chosen for the Best Practice model. As the UK Building Regulations provide only an area-weighted average window U-value, the respective value for the Best Practice 60-80% glazing scenario was lowered to 0.8, in order to guarantee that the building regulations are still met, and a value of 1.3 W/(m^2·K) was finally adopted for the Part L scenario.

Regarding shading strategies, originally internal blinds with high reflectivity slats were chosen to be activated if the solar radiation is higher than the solar setpoint of 150 W/m^2, the default option in DesignBuilder. Other shading strategies were considered such as the activation of the blinds when there is a presence of cooling loads during the previous time step (i.e. one hour before). Both options were evaluated and despite constituting reliable solutions, it was decided not to include any shading strategies as the overall modelling results would be affected. For example, deployment of the blinds would lead to higher lighting loads during the summer period regardless of the activation method. The revised glazing construction elements, considered for the building simulations, are shown in Table 3.3. The solar heat gain coefficient (SHGC) chosen value of 38% is very close to the notional building specifications (40%) and at the same time constitutes the mean value of the initial glazing construction g-values; therefore, it represents a suitable base value for all scenarios.

Table 3.3 – Glazing Construction Data parameters

Glazing Parameter	Unit	Part L Compliant		Best Practice	
Vertical fenestration	%	**0 – 40%**	**60 – 80%**	**0 – 40%**	**60 – 80%**
Total solar transmission (SHGC or g-value)	%	38	38	38	38
Light transmission	%	53	53	53	53
U-value	$W/(m^2 \cdot K)$	2.2	1.3	1.6	0.8
Shading	N/A	No shading			
Frame and dividers	N/A	The divider elements project out from the outside and inside surfaces of the glazing and divide the glazing into individual lites. The window frame is painted wooden.			

3.3.4 Natural Ventilation

Natural ventilation takes place through the window openings and is used to supply air and therefore towards meeting two objectives. The first one is to provide cooling, especially in the summer period using a setpoint temperature, and the second is to provide fresh air to the building occupants (10 L/s/person). There are two simulation options in DesignBuilder/EnergyPlus, regarding natural ventilation: scheduled and calculated. The former assumes a constant amount of air changes per hour (ac/h) for the outside air or constant air supply based on the minimum air requirements for the occupants, both taking place under a specified schedule (e.g. 1 pm to 5 pm). The latter option of calculated natural ventilation is used in the simulations. It is significantly more CPU demanding and realistic as it calculates the amount of air coming from outside into the building through the operable window area, taking into account all the necessary information such as the discharge coefficient and wind pressure. The characteristics of natural ventilation and external windows selected for the simulations for cooling purposes are summarised in Table 3.4. Any operable windows are opened if two conditions below are both met:

a) $T_{zone} > T_{out}$
b) $T_{zone} > T_{set}$

Table 3.4 – Natural Ventilation and external windows configuration for cooling purposes

Natural Ventilation/Openings Parameter	Value/Characteristic
External Windows Opening position	Top
Percentage of glazing area that opens	20%
Wind Factor	1
Discharge coefficient for holes	0.65
Discharge coefficient for external windows	0.60
Control mode for modulation	Temperature
Cooling Setpoint Temperature	23°C
Lower value of T_{in} -T_{out} for modulation	5
Upper value of T_{in} -T_{out} for modulation	15
Limit value of opening modulation factor	0.01

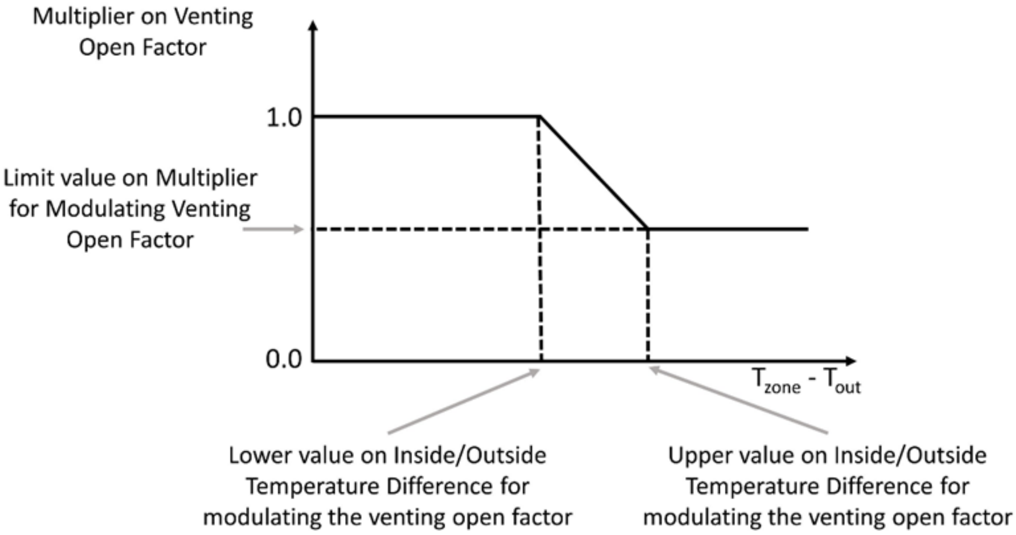


Figure 3.8 – Modulation in External Windows (Adapted from [224])

T_{out} represents the outdoor air temperature, T_{zone} is the zone's air temperature in the previous time step, i.e. the previous hour, and finally T_{set} is the natural ventilation's setpoint temperature, 23°C. The windows are also modulated when certain conditions allow it in order to consider the difference between the outside and the inside temperature. For example, the opening of the window is expected to be reduced if T_{out} is significantly lower than T_{zone} as the air in question will drop the indoor temperature below $T_{set.}$ Figure 3.8 demonstrates the principle of the windows modulation operation which his clearly based on the difference of the indoor/outdoor air temperatures $T_{zone} – T_{out,}$ with an upper and lower value used for modulating the venting open factor.

Additionally, the minimum amount of ac/h can be calculated for the fresh air supply that is required, taking into account the dimensions of one story and the maximum occupancy density (12 m^2/person, as discussed in section 2.4.5). The zone has a volume of 25 m x 25 m x 3.5 m (2,187.5 m^3) and a maximum number of occupants equal to (25 x 25)/12 = 52. Therefore, the required fresh air is 52 x 10 = 520 L/s = 0.52 m^3/s or 0.85 ac/h. It should be pointed out that this is the maximum amount of required ac/h as the occupation density varies throughout the day; consequently, lower values will also be sufficient depending on the time period. Increased infiltration through the building's windows is used to provide the necessary supply of fresh air, exclusively for buildings where natural ventilation is used for cooling purposes. The details are presented in the next section.

3.3.5 Infiltration

Infiltration is the uncontrolled exchange of air between the building interior and outside through cracks, porosity and other unintentional/accidental openings, usually created by pressure difference effects of the wind and the stack effect. Infiltration is never constant as its value depends on several parameters such as wind speed and pressure differences. DesignBuilder offers two methods to set the building's external infiltration, scheduled and calculated, similarly to natural ventilation modelling. The latter option has been selected for more realistic results as a constant infiltration rate at the building is required under the former. DesignBuilder calculates the infiltration by using crack templates; under this configuration, infiltration takes place in two instances:

1. Airflow through the surface itself due to cracks or by the general porosity of the fabric.

2. Cracks between the windows and the main wall or roof surface area.

The flow of air through gaps and cracks into the building fabric is transitional and can be calculated in Equation 3.1. The flow coefficient refers to the size of the opening while the flow exponent is used to evaluate the flow regime (0.5 for fully turbulent to 1 for fully laminar flow.)

$Q = C\ \Delta P^{n}$, where: (3.1)

C = flow coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

n = flow exponent

ΔP = pressure difference across the opening (Pa).

The full methodology and calculations adopted regarding infiltration can be found in detail in [225]. However, it was deemed that the included Excellent and Good templates have insignificant infiltration values, resulting in minimal thermal losses and consequently very low heating demand. Therefore, the default templates were removed from the models and replaced with the Medium and Poor crack templates. More specifically, after test simulations, the Excellent crack template was able to introduce an infiltration rate of 0 – 0.01 ac/h while the Good crack template an infiltration varying between 0.01 and 0.07 ac/h. Therefore, the Medium and Poor crack templates were chosen, for the Best Practice and Part L models, respectively. The test results can be seen in detail, in Table A9. It should be noted that as the infiltration rate is not given as a simulation output, the only way calculate it indirectly is to observe the values of the total fresh air (Mechanical Ventilation + Natural Ventilation + Infiltration) outside the working hours when there is no scheduled outside fresh air to enter the building, with the exemption of summer night cooling for the heavyweight building models. The infiltration values are indicative and can be used for comparison purposes between the different crack template models, providing a better understanding of the infiltration scale/extent but they should not be used as accurate values to calculate an airtightness value in $m^3/(m^2{\cdot}h)$ @ 50 Pa. The crack template characteristics for all construction elements along with the respective calculated infiltration rates for the mechanically-ventilated buildings can be found in Tables A9 – A10.

Infiltration through external windows is also used to model the amount of fresh air required for the building occupants in naturally ventilated buildings which are consequently designed to have higher external infiltration. Consequently, the flow coefficients and exponents for windows were revised for naturally-ventilated buildings, as shown in Table A11. The average infiltration values, 0.98 ac/h and 1.08 ac/h for the Medium and Poor crack templates respectively, are considerably close to the required 0.85 ac/h vale for fresh air supply.

3.3.6 Mechanical Ventilation

Mechanical ventilation is used for supply purposes, to transfer outside air inside the building and has the same objectives as natural ventilation: the provision of 10 L/s/person for the building occupants and cooling; however, the air is not brought into the building through window openings but with the help of the appropriate mechanical ventilation system components. Mechanical ventilation can be modelled in DesignBuilder either through the Room Ventilation method or the Ideal loads method. The former makes use of the EnergyPlus ZoneVentilation:DesignFlowRate data, separately from the main HVAC system, which allows the fan energy and heat pickup to be included in the simulation; however, heat recovery, economisers and humidity controls are not included. The latter option utilises the EnergyPlus ZoneHVAC:IdealLoadsAirSystem data with the inverse capabilities as economisers, heat recovery can be modelled. For the needs of the project, an economiser is considered as essential towards introducing free cooling into the building. Consequently, the ideal loads method has been implemented and as this approach cannot model the fans' energy consumption, this has to be manually set in the simulation input options. Heat recovery is not considered as it cannot be modelled under Ideal Loads.

In more detail, economisers are deployed to provide free cooling when the indoor temperature is higher than the outdoor temperature. They are basically damper openings that can draw up to 100% of the outside air, leading to a reduction of the cooling loads, especially during the summer period. The economiser's operation is set to 2 – Different Dry Bulb as this modelling option uses the economiser to increase the outside air flow rate above the minimum outdoor air flow provided that two conditions below are met. The first one is identical to the natural ventilation operation condition while the second refers to the presence of cooling loads and therefore the operation of the cooling system

a. $T_{zone} > T_{out}$
b. Cooling loads > 0

Regarding energy consumption due to fans/pumps and controls, it should be highlighted that the energy simulation results are produced for comparison purposes between different buildings and therefore as long as there is consistency on the assumptions made for all the models, using the same value for all scenarios (in kWh/m^2) is a reasonable assumption. In simulation terms, this value translates to a constant but insignificant auxiliary load that is present 24 hours per day, 365 days per year. Finally, night ventilation is used only for the heavyweight buildings in order to cool down the building during the night and make it thermally comfortable at the early hours of the following day when occupancy is scheduled to begin. Night ventilation takes place between 1st of June to 30th of September to mitigate overheating in the summer months. It should be clarified that only one method of ventilation is used per building; therefore, a building can have either natural or mechanical ventilation but not both.

3.3.7 Auxiliary Loads

Auxiliary loads refer to energy consumption due to fans, pumps and controls, also known as parasitic energy. For the naturally ventilated buildings, values were identified from the literature and more specifically from the Scottish Government, for several northern European countries [226]. An average value of 3 kWh/m^2 was selected for the naturally ventilated buildings as supply air passes into the buildings through the windows. However, finding an acceptable value for mechanically ventilated buildings proved to be a more complicated issue. Additionally, case studies use different methodologies to define and calculate auxiliary loads while frequently there are not considered as a separate entity as fans & pumps energy consumption can be included within the heating and cooling loads. Benchmark values for office buildings were identified on CIBSE Guide F; nevertheless, these values originate from an outdated Energy Consumption Guide which was published more than 20 years ago. Therefore, it is doubtful if they can be representative of modern office buildings.

A specific methodology was followed to calculate reasonable values for auxiliary loads in kWh/m^2 by correlating mechanical ventilation to power and energy through the Specific Fan Power (SFP) variable. SFP is a useful parameter which represents the ratio of the total electric power required to drive the fans to the amount of circulated air:

$$\mathrm{SFP} = \frac{\Sigma \mathrm{P}}{\mathrm{q_v}}\text{, where:} \tag{3.2}$$

ΣP = sum of all fan powers (kW)

q_v = gross amount of circulated air (m^3/s)

The units of SFP are:

$$[\text{SFP}] = \frac{\text{kW}}{\text{m}^3\text{s}} = \frac{\text{W}}{\text{l}\cdot\text{s}} = \frac{\text{kJ}}{\text{m}^3} = \text{kPa}$$

SFP can be expressed in units of pressure as it also constitutes the ratio of energy per cubic meter of air. In the ideal case of a fan system with 100% efficiency, SFP is equal to the fan pressure rise and the total pressure loss in the mechanical ventilation system. However, in reality, fans have an overall efficiency less than 100%. This efficiency refers to the percentage of the electrical power that results in useful driving pressure that transfers the air inside the ventilation system. It should be pointed out that the SFP and the overall fan efficiency are not constant but vary with air flowrate and the fan pressure rise [227]. Consequently:

$$\text{SFP} = \frac{\Delta \text{p}_{\text{total}}}{\eta_{\text{total}}}, \text{ where:} \tag{3.3}$$

Δp_{total} = the fan pressure rise, equal to the total press loss in the ventilation system

η_{total} = the overall fan efficiency (between 0 and 1)

The DB simulation output includes total fresh air in air changes per hour (ach^{-1}) and by turning off external infiltration, it is guaranteed that the value represents only the air supplied by mechanical ventilation. Based on that value, the respective total auxiliary power and energy can be calculated, assuming that the overall fan efficiency and SFP values remain constant.

$$\text{Mechanical Ventilation rate } (m^3/s) = \frac{\text{Mechanical Ventilation } (ac/h) \text{ x Total Volume } (m^3)}{3600}$$

$$\text{Auxiliary Power } (kW) = \text{Mechanical Ventilation } (m^3/s) \text{ x SFP } \left(\frac{kW}{m^3\cdot s}\right)$$

$$\text{Total Auxiliary Power } (kW) = \frac{\text{Power } (kW)}{\text{Fan Efficiency } (\%)}$$

$$\text{Total Auxiliary Power } (kW/m^2) = \frac{\text{Total Power } (kW)}{\text{Total Surface area } (m^2)} \tag{3.4}$$

Given the fact that DesignBuilder uses hourly periods for simulation purposes, power and total power are also equal to energy and total energy, respectively. The UK Part L Regulations include an SFP value of 1.8 kW/($\text{m}^3\cdot\text{s}$) regarding specifications for buildings other than dwellings [228]. CIBSE Guide A refers to the relationship between the SFP value and Part L compliance while it is stated that, for volumetric flowrates lower than 1 m^3/s, SFP has a minimum value of 1 due to fan inefficiencies [229]. The Non-Domestic Building Services Compliance Guide includes specifications regarding the maximum SFP of several mechanical ventilation systems, in detail, with a range of values between 0.5 and 1.9. Central balanced mechanical ventilation systems in new buildings have recommended SFP values of 1.1, 1.5 and 1.6 depending on the configuration and presence of heating and cooling. A comparative office building simulation case study which included three climate zones, including London, considered SFP values of 0.75 and 1 and fan efficiencies between 0.6 and 0.78 [230]. It is therefore clear that the auxiliary/fan loads are a function of the HVAC configuration, climate, ventilation set-points and other variables. Using the methodology and assumptions described in this chapter, a reasonable value can be calculated in kWh/m^2. For the calculation needs, SPF values of 1 and 1.2 will be used, along with an overall fan efficiency of 70%.

A number of different building models were simulated in DesignBuilder for testing purposes, assuming perfect airtightness and therefore zero external infiltration. Then, the mechanical ventilation rate was used to calculate the fan loads, following the equations shown above.

Using a total floor area of 2500 m^2 and total volume of 8,750 m^3, the fan loads were then normalized per square meter. The fan loads simulation results had a range between 3.01 and 7.71 kWh/m^2, with an average value of 5.36 kWh/m^2. It should be noted that this range only corresponds to six building scenarios and results will vary depending on the building characteristics. Finally, as the values in question represent only the energy consumed by the fans, an estimation for the pumps and controls loads has to be added in order to formulate the auxiliary energy loads. Given the fact that the auxiliary energy has been considered to be 3 kWh/m^2 for the naturally ventilated buildings where there are no fan loads present, a value of 9 kWh/m^2 is assumed for all mechanically ventilated buildings.

3.3.8 Environmental Control

All the necessary environmental control parameters for the simulations are summarised in Table 3.5. The setpoint temperature refers to the target operative temperature when the building is occupied during working hours while the setback temperature constitutes the target operative temperature when the building is vacant. In this way, it is guaranteed that the building will maintain reasonable temperature values during prolonged periods of closure, for example from Friday night until Monday morning in the wintertime. Initially, following CIBSE/ASHRAE guidelines, different values had been selected for each Zone with the lift/stairwell area having less requirements and more specifically lower heating setpoint/setback temperatures as well as higher cooling values. However, this led to a small amount of discomfort hours specifically for the smaller zone. Consequently, temperatures were then revised and the same setpoint and setback temperatures were chosen for both the main office and stairwell zones.

Table 3.5 – Environmental Control Properties for the DesignBuilder Simulations based on CIBSE Comfort

Environmental Control Parameter	Required Value(s)	
	Setpoint Operative Temperature	**Setback Operative Temperature**
Heating	22°C	12°C
Cooling	23°C	27°C
Natural Ventilation	23°C	N/A
Mechanical Ventilation	N/A. The economiser operates and provides free cooling when $T_{zone} > T_{out}$ and cooling loads are present.	
Mechanical Ventilation Air Supply	10 L/s/person	
Target Illuminance	500 lux for office area 200 lux for stairwell/lift area	

Regarding temperature control, DesignBuilder documentation mentions that there is a lot of debate amongst building simulation experts on whether an ambient or an operative temperature thermostat is the most suitable option. Using an ambient temperature thermostat ignores any radiant effects; on the other hand, real-life thermostats do not sense in practice more than 20% radiant heat transfer as they tend to measure the temperature of the nearby air. Using operative temperature control with a radiant fraction of 50% can be beneficial for the building's environmental conditions as HVAC systems will continue conditioning the space (heating or cooling) in order to fulfill the thermal comfort criteria.

This is not the case when it comes to an ambient air thermostat as maintaining the ambient temperature does not necessarily translate to a thermally comfortable environment, depending on the internal radiant temperatures. However, it should be noted that operative control also comes with downsides as start-up loads can be unreasonably high due to the thermal response lag of the building's envelope. If the flywheel effect is dominant, the design cooling and heating loads along with the total cooling and heating energy consumption could be potentially overestimated. In conclusion, both options present advantages and disadvantages but the importance of the operative temperature control is reflected by its presence in multiple guides published by CIBSE and ASHRAE in regards to thermal comfort, including the ASHRAE 55 Standard [231]. Therefore, it has been chosen as the environmental control parameter in the current research.

3.3.9 Metabolic Activity and Occupancy

The details regarding the metabolic activity, occupancy and the days during which the building is not considered to be operating are summarised in Table A12 and largely based on ASHRAE Fundamentals. The metabolic activity that takes place is assumed to be filing/standing with a value of 144 W/person. The British Council for Offices suggests a workplace density between 8 – 13 m^2/person [232] while CIBSE recommends 12 – 16 m^2/person in its Concise Handbook [233]. For this research, the occupancy density has been set to 0.0833 people/m^2 or 12.01 m^2/person. Additionally, the daily occupancy profile for a working day is shown in Figure 3.9 with the occupancy factor being a fraction between 0 and 1, with 0% and 100% representing the values for zero and full building occupancy, respectively. It can be seen that occupancy reaches its maximum value as early as 10am while there are subsequent drops with the passing of time, a characteristic example is the lunch break that starts at midday.

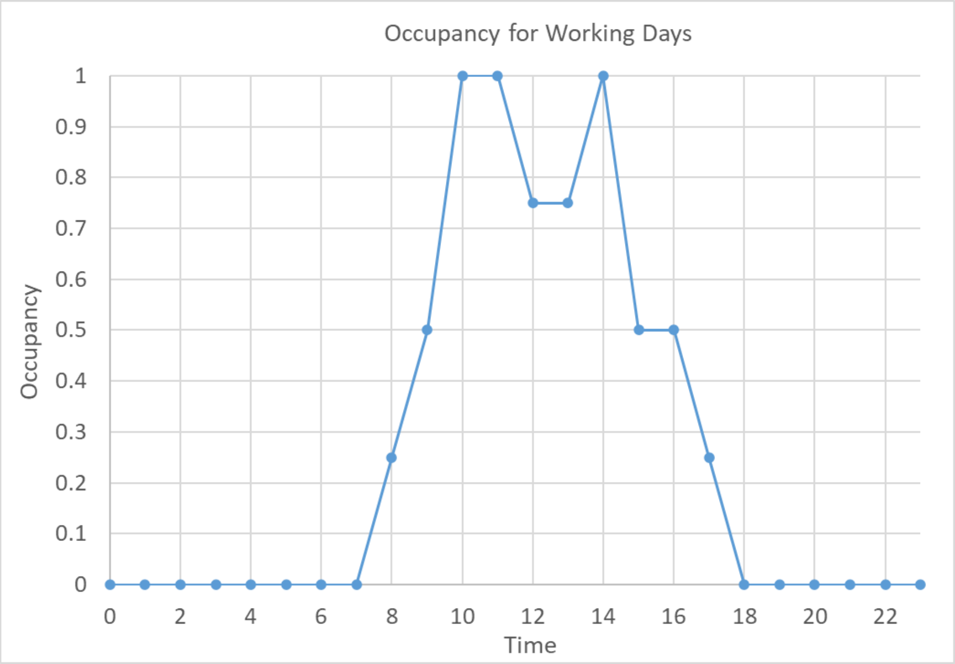


Figure 3.9 – Building Occupancy profile during a working day (0-100%)

3.3.10 Activity and Schedules

This subchapter presents the schedules of all the HVAC components as well as lighting and Domestic Hot Water (DHW). Firstly, the heating system is active between 7am – 6 pm, trying to meet the heating setpoint temperature; therefore, there is one hour of pre-heating that takes place before the building starts operating. Similarly to heating, one hour of pre-cooling also takes place and consequently the cooling system is active between the same hours, 7am to 6pm, meeting the cooling setpoint temperature. The operation of heating and cooling is shown in Figure 3.10. When operation is set to 1, the system operates in order to meet the setpoint temperature(s) while under the 0.5 value the system keeps meeting the less demanding setback temperature(s).

The operation value is constantly set to 0.5 for all non-working days such as weekends. Furthermore, Figure 3.11 demonstrates the working day schedule of lighting for all building models and the mechanical ventilation system that applies to all lightweight buildings for the entire year as well as heavyweight buildings between 1 January – 31 May and 1 October – 31 December. As heavyweight buildings utilise night cooling during the summer (1 June – 30 September), mechanical ventilation has continuously a fraction value of 1 (100%) for the entire period in question, including non-working days. Moreover, as consumption of DHW is closely related to the building occupancy, its schedule is exactly the same as in Figure 3.9. Finally, the computers schedule is very similar to lighting with one difference: during non-working hours, the fraction is set to 5.394% instead of 0 as computers are assumed to be idle (hibernation/sleep mode). The complete schedules, as used in DesignBuilder, can be found at the end of Appendix A.

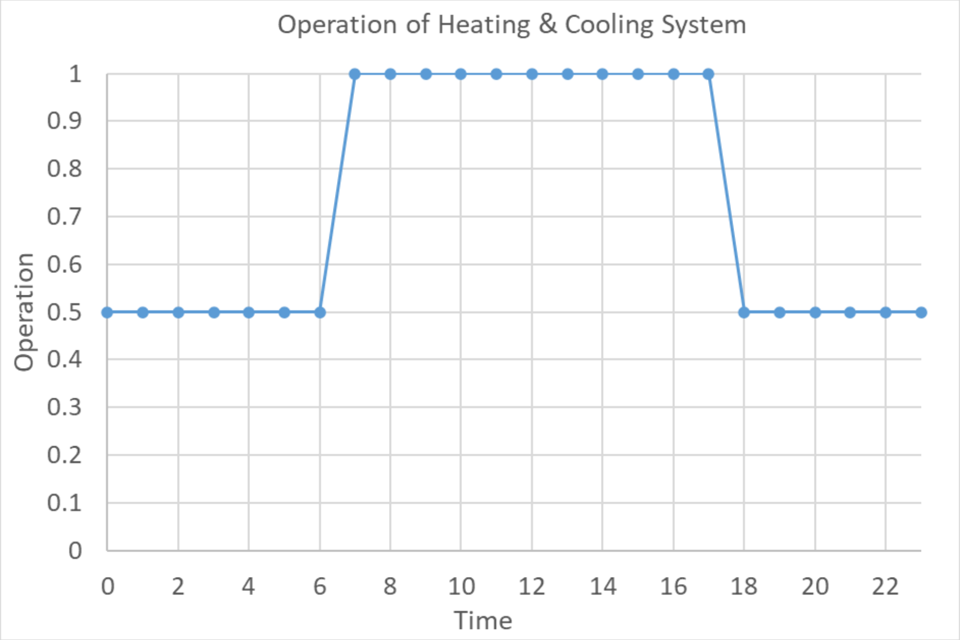


Figure 3.10 – Operation of the Heating and Cooling System during a working day. 0.5 represents the Setback temperature and 1 the Setpoint temperature.

3.3.11 HVAC and Building Loads

For modelling the building model’s HVAC system, EnergyPlus’ simple autosizing function constitutes part of the main simulation. In more detail, a heating design margin is used to give a recommended size for the heating system. This extra amount of heat allows the building to increase its temperature during a brief pre-heat period and provides more certainty that thermal comfort conditions will be met. The default standard design margin is 1.25 resulting in an oversized heating system by 25%. Similarly, the cooling design margin is used to provide additional cooling capacity when the temperature needs to be decreased in a brief pre-cool period, ensuring that thermal comfort is satisfactory even during extreme summer conditions. The cooling design margin is set to 1.15 leading to an oversized cooling system by 15% which is also the recommended value by ASHRAE. There is no humidity control or heat recovery mechanism taken into account for the simulations.

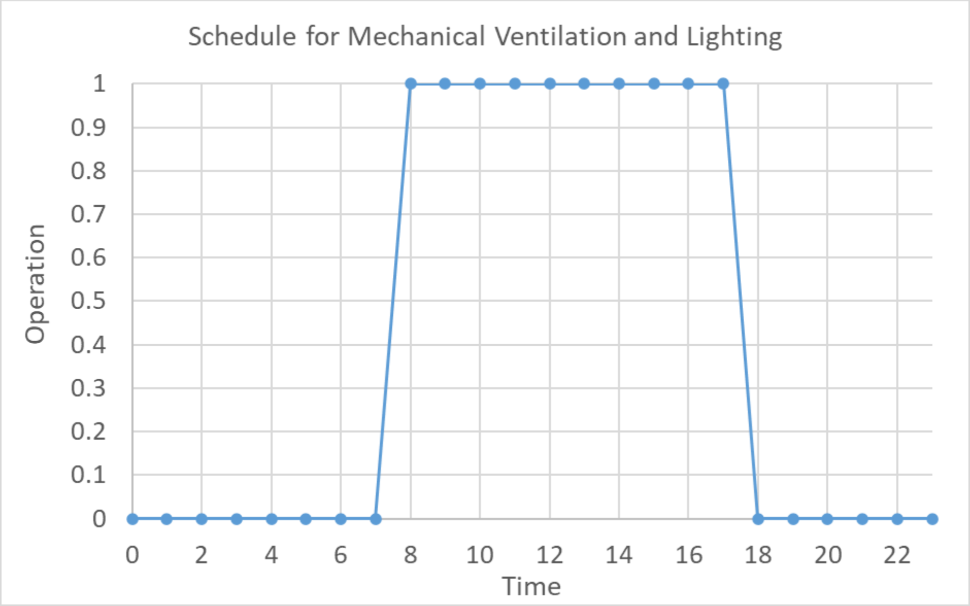


Figure 3.11 – Schedule of Lighting and the Mechanical Ventilation system during a working day. The ventilation schedule applies to all lightweight buildings for the entire year as well as heavyweight buildings between 1 January – 31 May, 1 October – 31 December.

Regarding heating and cooling, GSHPs are deployed and therefore all the building loads are fully electric. As supported by [234], GSHPs have significant advantages as they have relatively small ground area requirements, they are in contact with the ground where the temperature variations are insignificant while lower amounts of pumping energy and pipes are needed. Their characteristics and configuration lead to higher system performance; nevertheless, it should be noted that the expensive equipment and the requirements for drilling boreholes also result in high costs [234].

In order to assume reasonable performance standards and calculate the electricity consumption attributed to heat pumps, the appropriate CoPs and SCoPs have to be considered in accordance with the UK Part L Regulations and ASHRAE 90.1. For simplification purposes, the coefficient of performance (CoP) values are considered equal to the respective seasonal values (SCoPs), resulting in constant CoP values throughout the year. The definitions of all CoPs and SCoPs for both heating and cooling are found below, in Equations 3.5 – 3.8 [235]. The cooling CoP is often mentioned in the literature as Energy Efficiency Ratio (EFR).

$$\mathrm{COP_H} = \frac{\text{Rate of Heat delivered (kW)}}{\text{Power Input for heating(kW)}} \tag{3.5}$$

$$\mathrm{COP_C} \text{ or EER} = \frac{\text{Rate of cooling energy delivered (kW)}}{\text{Power Input for cooling (kW)}} \tag{3.6}$$

$$\text{SCOP}_H = \frac{\text{Annual quantity of heat supplied (kWh)}}{\text{Annual electrical energy consumed for heating (kWh)}} \tag{3.7}$$

$$\text{SCOP}_C = \frac{\text{Annual cooling energy supplied (kWh)}}{\text{Annual energy input for cooling (kWh)}} \tag{3.8}$$

For this research, CoPs of 3.5 and 5 have been selected for heating and cooling, respectively as they meet the values set in the UK Regulations, follow the CIBSE guidance as well as the ASHRAE recommendations. These values means that the consumption of 1 electrical kWh by the GSHPs is translated to 3.5 thermal kWh in regard to the building's thermal environment when the heat pumps operate in heating mode and 5 kWh in cooling mode.

For heating, the maximum supply air temperature and maximum supply air humidity ratio have been set to 35°C and 0.016 g/g, respectively. Additionally, for cooling, the minimum supply air temperature and the minimum supply air humidity ratio are 12°C and 0.008 g/g, respectively. These values are DesignBuilder's default settings.

In terms of the Ventilation loads, these are assumed to be constant throughout the day and year. For mechanically-ventilated buildings with a total of 9 kWh/m^2 of parasitic energy per annum, there is a continuous hourly load of 2.57 kW while the value drops to 0.86 kW for naturally-ventilated buildings with a total of 3 kWh/m^2 of auxiliary energy consumption per annum.

In terms of the lighting system for the main office area, LEDs with a recessed luminaire type have been selected while the lighting power density has been set to 10.6 W/m^2 in accordance with ASHRAE 2017 Fundamentals [236] values for an open-plan office. For the smaller zone, a lower value of 7.4 W/m^2 has been assigned (surface mount) as the target illuminance is decreased from 500 to 200 lux. At the building level, the lighting density translates into a maximum hourly lighting load of 26.04 kW. Linear control is applied and therefore lights will dim continuously and linearly if conditions allow it, as demonstrated in Figure 3.12 [237]), with the minimum light output fraction and maximum input power fraction values set to 0.1 (10%). Finally, concerning the radiant fractions of lighting, the default values of DesignBuilder are used which follow the ASHRAE 90.1 Standard: 0.37 for the office area and 0.72 for the smaller lift/stairwell zone.

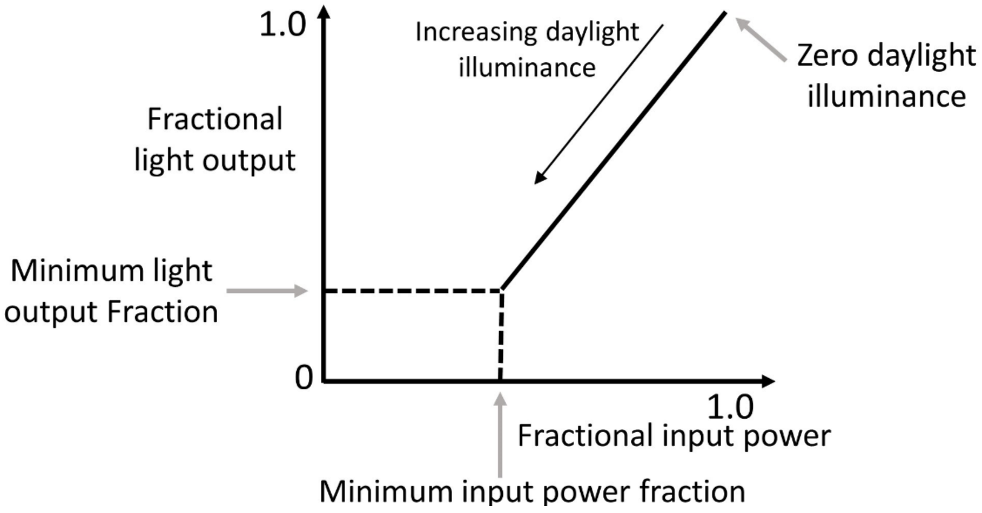


Figure 3.12 – Linear control of the Lighting System (Adapted from [237])

As computer equipment is assumed to be utilised in the building as part of its commercial operation, the relevant building loads for the office area have been set to 9.06 W/m^2 which corresponds to the ASHRAE guideline value for a 11.6 m^2/workstation, all laptop use with two screens, 1 printer per 10 people as well as a radiant fraction of 0.3 [236]. There are no computer loads present in the smaller lift/stairwell area of the building. The computer equipment density leads to a constant hourly load of 21.35 KW during building occupancy while the value drops to 1.15 kW during non-working hours due to sleeping/hibernation mode of the computer equipment. The DHW requirements are based on the 14 L/person value recommended by CIBSE [233] while the resulting annual electricity consumption of 5.13 kWh/m^2 is in accordance with the benchmark values mentioned by the Scottish Government [226]. All the key information provided in this subchapter are summarised in Table 3.6.

Table 3.6 – HVAC and Building Loads Simulation Summary

Building Parameter	**Value**
Heating & Cooling System	GSHP
GSHP CoP (Heating mode)	3.5
GSHP CoP (Cooling mode)	5
Auxiliary Energy/Power	Nat. Vent. Buildings: 9 kWh/m^2 per annum, 2.57 kW hourly load Mech. Vent. Buildings: 3 kWh/m^2 per annum, 0.86 kW hourly load
Lighting (LED) Energy/Power	Main Office Area: 9.06 W/m^2 Lift/stairwell area: 7.4 W/m^2 Maximum total hourly load: 26.04 kW Linear control
Computer Loads	Main Office Area (only) : 9.06 W/m^2 Maximum hourly load: 21.35 kW
DHW	14 L/person or 1.166 L/m^2 during occupancy hours Annual electricity consumption of 5.13 kWh/m^2

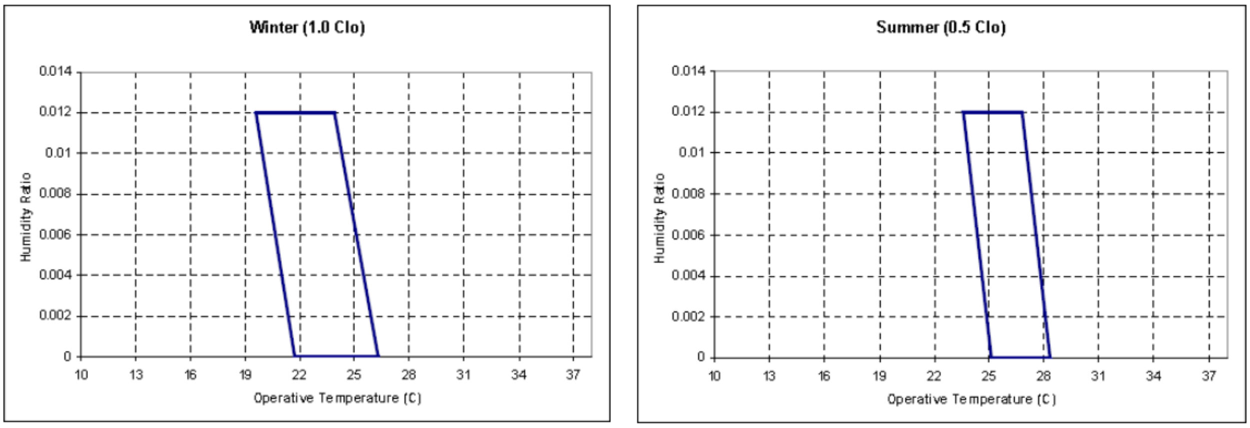
3.3.12 Thermal Comfort

Concerning thermal comfort, DesignBuilder makes use of the Simple ASHRAE 55 thermal comfort criteria to calculate the number of hours during which discomfort takes place for the building occupants. When the humidity ratio and operative temperature values are outside the designated comfort areas, shown in Figure 3.13, the hour is considered to create thermal discomfort. The operative temperature calculation is simplified and it is equal to the mean value of the air and radiant temperatures, as shown in Equation 3.9. The comfort areas are dependent on the period of the year as different values of clothes insulation are taken into account and the range of the acceptable operative temperatures is higher for the summer period. Additionally, DesignBuilder uses a different methodology than EnergyPlus to calculate discomfort hours at the building level. More specifically, the size of the area (m^2) where discomfort takes place is now considered.

The comfort data are calculated for blocks by utilising floor area weighted averages of the zones, as seen in Equation 3.10 while the same principle applies to discomfort hours which are essentially normalised per floor area [238]. Discomfort hours are also divided by the total number of occupancy hours in order to calculate discomfort as an annual percentage (Equation 3.11). A predicted percentage of persons dissatisfied (PPD) with the building's thermal comfort of 5% is considered to be satisfactory according to CIBSE [239].

$$T_{Operative} = 0.5 \cdot T_{ambient} + 0.5 \cdot T_{radiant} \qquad (3.9)$$

$$T_a = \frac{A_1 \text{ x } Ta_{Z1} + A2 \text{ x } Ta_{Z2}}{A_1 + A_2} \quad (3.10)$$


(a)

(b)

Figure 3.13 – Definition of Discomfort hours in DesignBuilder according to the ASHRAE 55 Standard for the (a) winter and (b) summer periods [238]

Where :

T_a is the Block average Air temperature (°C)

A_1, A_2 are the floor areas (m^2) of Zones 1 and 2, respectively.

Ta_{Z1}, Ta_{Z2} is the air temperatures (°C) in Zones 1 and 2, respectively.

$$\text{Discomfort (\%)} = \frac{\text{Amount of Discomfort hours (hours/annum)}}{\text{Amount of Occupancy hours (hours/annum)}} \quad (3.11)$$

Furthermore, DesignBuilder is able to calculate the Fanger PMV values at the building level. Any occupancy hours during which PMV > 0.7 or PMV < -0.7 are considered to induce discomfort to the building occupants, in accordance with EN 15251 and as presented in Section 2.4.3. The percentage of discomfort hours under Fanger PMV are also calculated by dividing with the total number of occupancy hours, similarly to the approach followed above in Equation 3.11. However, Fanger PMV results are only generated for verification purposes and discomfort hours are going to be primarily based on the ASHRAE Standard 55. A custom PMV of 0.75 was selected for the needs of the project to avoid including marginal values close to the initial 0.70.

3.3.13 Weather and Location

The location chosen is Birmingham Airport, Solihull, West Midlands, England, United Kingdom. The respective weather data file was used from IWEC, the result of an ASHRAE project that provides typical weather files in EnergyPlus format for building energy simulation purposes. All the information is listed in Table A13. Additional UK locations have been selected and used in simulations for the sensitivity analysis which is presented later in section 3.7.

Daylight Saving Time (DST) is not observed in the building simulations and the time is assumed to remain constant throughout the year without any changes taking effect. The primary reason for this decision is that enabling DST results in changes to the building's electricity profile, which is moved by one hour after the last Sunday in March when clocks are turned forward, to be restored to its original pattern in the last Sunday of October. This decision has been taken into account very carefully when matching building energy data with electricity prices in order to ensure that both types of data are in accordance and refer to the same time period.

3.4 Real-time Electricity Pricing Data

Data from NordPool, the biggest electricity market in Europe, were used and more specifically the wholesale hourly prices of the day-ahead market, the main arena for trading power. As Ofgem reported, 33.63% of the total domestic electricity bill in 2017 was attributed to the wholesale cost of domestic electricity [240], with the percentage remaining almost constant to 33.87% as of January 2021 [241]. Other parameters include operating costs, transportation, network costs, environmental and social obligation costs and Value Added Tax (VAT). The wholesale percentage is based on the annual reports published by the six biggest UK electricity suppliers, and more specifically their Consolidated Segmental Statements [242]. These data include both domestic and non-domestic usage for electricity and dual-fuel consumers. In order to convert wholesale costs to the final retail prices, it is assumed that the wholesale percentage of the bill is constant for the entire year. Therefore, Equation 3.12 is used for the calculation of the non-domestic retail electricity price.

$$\text{Retail Electricity Price (£/kWh)} = \frac{\text{Wholesale Electricity Price (£/kWh)}}{\text{Direct Fuel Cost Percentage (\%)}} \qquad (3.12)$$

Regarding non-domestic electricity, the contribution of each section was calculated and is presented, in Figure 3.14. It is worth noting that while the reduced VAT rate of 5% applies for domestic electricity, consuming non-domestic electricity is taxed at the standard rate of 20% [243]. The wholesale contribution to the non-domestic electricity price, described in the reports as “direct fuel costs”, was calculated to be 36.63% in 2017, approximately 3% more than the respective value for domestic electricity. Using the same data and methodology for 2018, it was calculated that the wholesale percentage for the non-domestic electricity bill remained approximately the same at 35.79% for the year 2018. As the difference is insignificant, only the 2017 direct fuel cost percentage of 36.63% has been considered in this research, as published in [9].

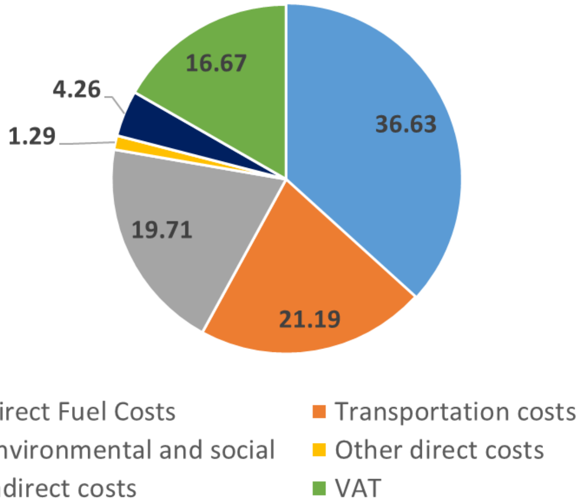


Figure 3.14 – Breakdown (%) of the 2017 non-domestic electricity bill based on the Electricity Companies’ Annual Consolidated Segmental Statements [9], [26]

Finally, in the case of zero or near-zero wholesale prices, a minimum value is set to avoid a consequent zero or near-zero retail price. This is necessary as the distribution costs as well as the other added taxes always result in a positive retail price. Therefore, any wholesale prices below £0.004/kWh are automatically corrected to 0.004 through Equation 3.13 which consists of a MATLAB code assignment.

$$RTP\_wholesale(RTP\_wholesale \leq 0.004) = 0.004 \qquad (3.13)$$

Assuming a wholesale percentage of 36.63%, the respective minimum retail price is £0.0119/kWh. The resulting synthetic hourly retail electricity prices are shown in Figure 3.15 and it is clear that the prices vary both on a daily and on a seasonal basis, with a broad range of data between 0.01 to £0.41/kWh. Figure 3.16 presents the maximum, minimum and average values per day for the same year; the daily difference between the lowest and the highest prices (red and orange lines) constitute the foundations of electricity arbitrage.

The difference between the daily maximum and the minimum price is shown separately in Figure 3.17. The potential for conducting arbitrage and taking advantage of the price differences is present throughout the year. It is important to recognise the fact that certain months appear to be more promising than others such as January, February and March especially since the price difference reach a higher range when compared with other months of the year. However, price spikes are often observed to take place during several months and only the complete annual results are capable of representing quantitively the full arbitrage potential.

Finally, the same data and figures have been generated for the 2018 year, following the same methodology and using raw data from the NordPool day-ahead market, which can be seen in Appendix B. The majority of the simulations utilise 2017 data which are of fundamental importance to meet the objectives of this project while the 2018 data are used complimentarily for one simulation. Figure 3.18 demonstrates the minimum, maximum and average electricity prices per day for the 2018 year. It is evident the hourly prices change from year to year depending on a number of different factors, including demand levels, supply issues, weather etc. Therefore, each set of annual data generates unique results with a different profile.

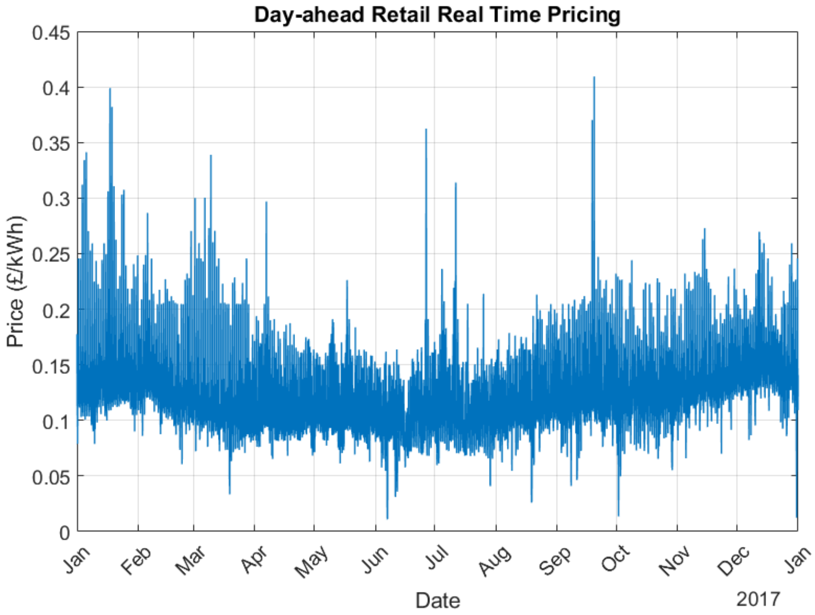


Figure 3.15 – Synthetic real-time retail electricity prices based on the NordPool 2017 day-ahead data. The wholesale percentage is assumed constant throughout the year at 36.63%.

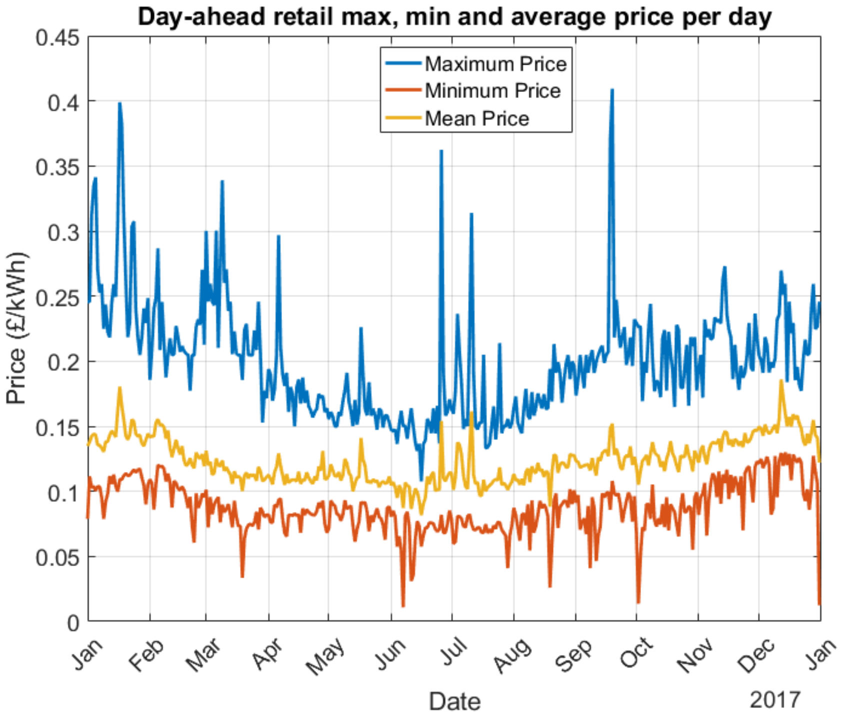


Figure 3.16 – Minimum, maximum and average daily values for the synthetic real-time retail electricity prices based on the NordPool 2017 day-ahead data of Figure 3.15 [9]

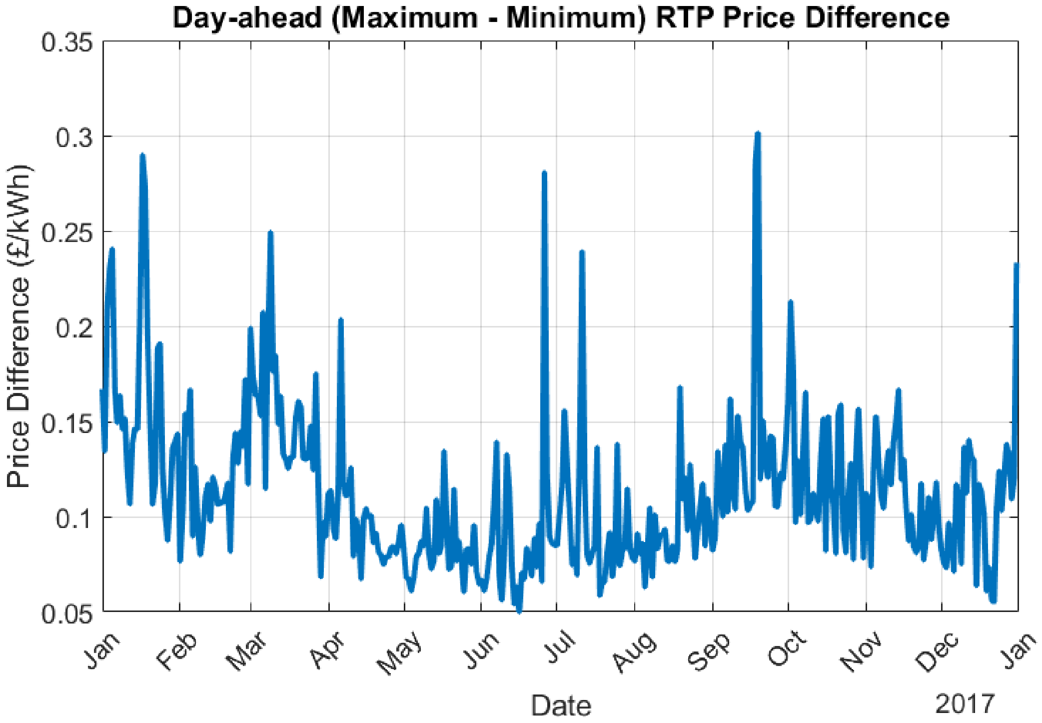


Figure 3.17 – Maximum price difference per day for the synthetic real-time retail electricity prices based on the NordPool 2017 day-ahead data of Figure 3.15. The difference is calculated by subtracting the daily minimum price from the daily maximum price.

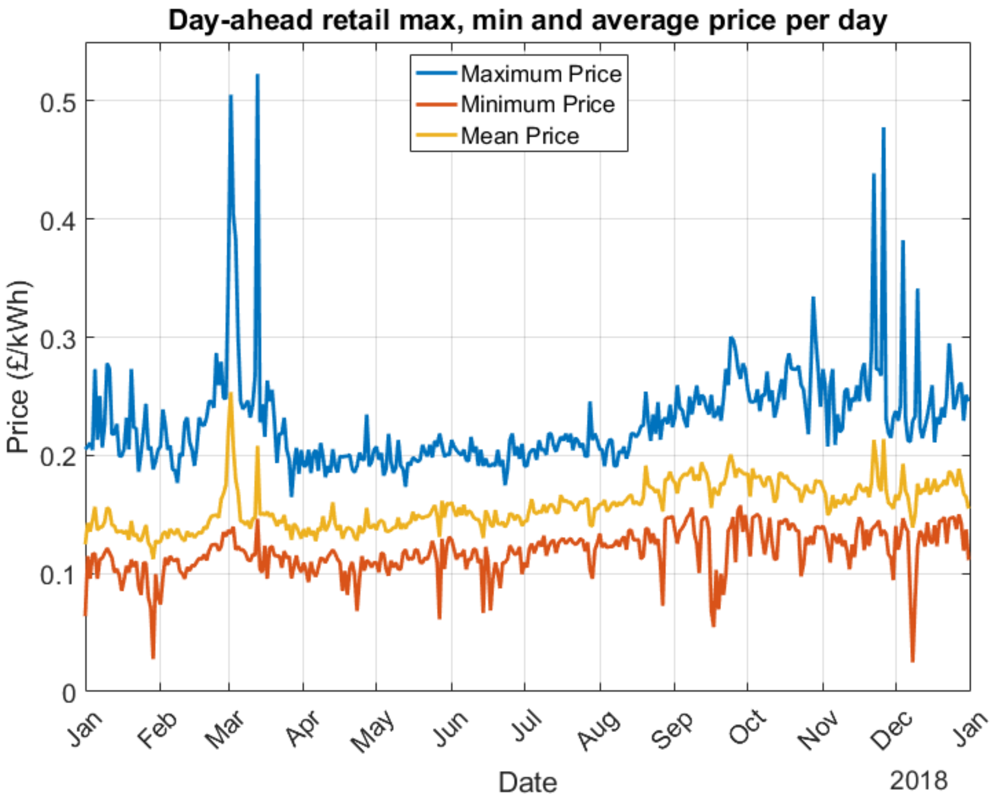


Figure 3.18 - Minimum, maximum and mean daily values for the synthetic real-time retail electricity prices based on the NordPool 2018 day-ahead data of Figure B1

3.5 Battery Storage & Arbitrage Modelling

3.5.1 Introduction to the Arbitrage Model

The technical side of the battery storage system can be seen below, in Figure 3.19. The system components include the battery bank, one inverter, one rectifier and the controller. More specifically, the battery bank may include a number of several modules, connected in series or in parallel, depending on the required values of power and voltage. The inverter is used to convert the battery's DC to the grid's AC allowing the battery to be used to meet building loads or export electricity back to the grid, while the rectifier is used to convert AC to DC in order to charge the battery. Often, the rectifier and inverter are combined in a bi-directional inverter, also called bidirectional converter [244].The control system receives information from the MATLAB model and manages accordingly the electronic switches S1, S2 and S3, depending on the algorithm used and based on the values of the building loads and electricity prices. It should be noted that electricity can flow bidirectionally while information flow is only transferred one-way from the MATLAB model to the control system and from the control system to the three switches. All the possible scenarios can be seen in Table 3.7. It is clear that for every configuration, power can only flow in one of the possible two directions, at the same time.

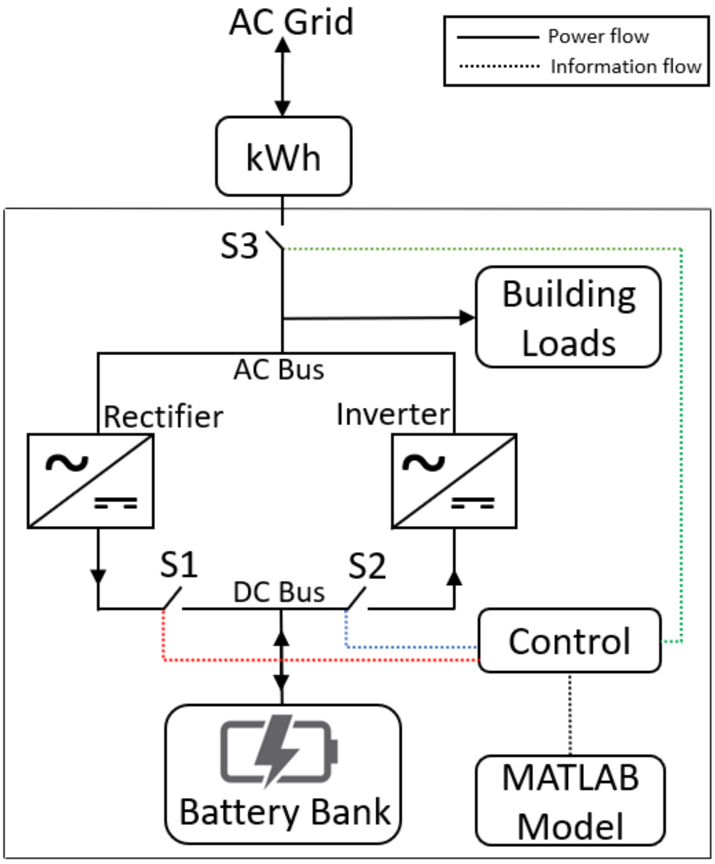


Figure 3.19 – Power and information flow between system components (Inspired by [245])

Additionally, as the inverter and rectifier cannot be operational simultaneously, configurations #1 and #2 are not applicable, while switching off all switches would result in total power loss. Therefore, a total of four BSS configurations are possible. The schematic was inspired by [245] but modified and adapted for the needs of this research. Regarding the sizing of the BSS components, a reasonable rule of thumb was used in order to be able to discharge the total usable battery capacity in a maximum of 2 hours and charge it under 3 hours. Battery sizes between 40 and 220 kWh were considered, with a 20-kWh step.

The basic idea of the arbitrage model is relatively simple: charging the battery when prices are cheap, usually during the night and early hours of a day, and discharge later when prices are more expensive. Discharging can only take place when building activity and loads are present while it's also possible to export any excess electricity back to the grid depending on the operational (dispatch) strategy used. A total of three different operational strategies are modelled and explored.

Table 3.7 – Switches and BSS Operation

Configuration #	Switches Operation			Description
	S1	S2	S3	
1	ON	ON	ON	N/A
2	ON	ON	OFF	N/A
3	ON	OFF	OFF	N/A
4	ON	OFF	ON	Battery charging
5	OFF	ON	ON	Battery discharging to meet building loads and export excess electricity back to the grid
6	OFF	OFF	ON	Battery idle, loads are met only by the grid.
7	OFF	ON	OFF	Battery discharging to meet building loads

3.5.2 Basic Model Variables

As the model operates on an hourly basis, the amount of power (kW) and energy (kWh) are always equal. Also, as there are four efficiencies in total that take place and affect the energy transactions amongst the building, the battery and the AC grid, it is important to explain how these efficiencies are reflected in the variables used. This is shown in Figure 3.20 with two sets of energy exchange variables:

- The first set refers to the amount of energy that an imaginary observer, located outside the battery, would identify. Therefore, battery_charge_REAL is the total amount of electricity purchased from the AC grid with the purpose of charging the battery. Similarly, battery_discharge_REAL is the amount of usable electricity discharged by the battery with the purpose of meeting the building loads or exporting back to the grid.

- The second set includes energy variables that an imaginary observer, located inside the battery, would identify. Consequently, battery_charge is the amount of energy that manages to enter the battery while battery_discharge is the total amount of energy leaving the battery when the battery discharges.

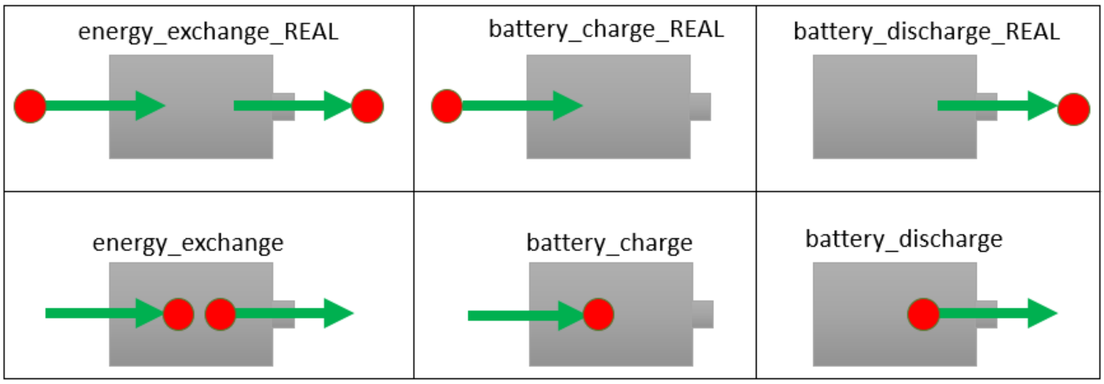


Figure 3.20 – Energy exchange variables used by the Battery Storage MATLAB model

Table 3.8 - Battery Storage Model key variables in MATLAB

Model variable	Unit
annual_energy_cost	Annual cost of electricity purchases [£/year]
annual_net_cost	Annual electricity net cost [£/year]
annual_OM_cost	Annual Operation and Maintenance cost for the BSS [£/year]
annual_revenues	Annual revenues from electricity exports [£/year]
battery_cost	Capital cost of the battery including cabling and other hardware [£]
bottleneck	Capacity to operate the battery based on conditions [kW]
converter_cost	Capital cost of the bi-directional converter [£]
DOD	Battery's Depth of Discharge [%]
energy_demand	The building's hourly electricity demand without storage [kWh]
energy_from_the_grid	Total amount of hourly electricity purchased by the grid [kWh]
energy_shifted	Hourly building loads shifted due to the utilisation of the battery [kWh]
exported_energy	Net annual amount of electricity exported back to the grid [kWh/year]
financial_reward	Financial reward required to provide the service (arbitrage) [£/kWh]
inflation_rate	Annual inflation rate
interest_rate	Annual interest rate
LCOE_with_storage	Levelised cost of electricity with storage for the study period [£/kWh]
LCOE_without_storage	Levelised cost of electricity without storage for the study period [£/kWh]
MC_{charge}	Marginal operational cost of charging the ESS [£/kW]
$MC_{discharge}$	Marginal operational cost of discharging the ESS [£/kW]
maxHourIndex	Period of maximum electricity price [index]
maxHourPowerLimit	Power limit below which discharging is not allowed [kW]
maxHourPrice	Electricity price for the maxHourIndex period [£/kWh]
maxRangeIndex	Latest period during which the battery can discharge [index]
minHourIndex	Period of minimum electricity price [index]
minHourPowerLimit	Power limit above which charging is not allowed [kW]
minHourPrice	Electricity price for the minHourIndex period [£/kWh]
minRangeIndex	Earliest period during which the battery can charge [index]
nbattch	Charging efficiency
nbattd	Discharging efficiency
ninverter	Inverter efficiency
nrectifier	Rectifier efficiency
NPC_with_storage	Net Present Cost using storage for the study period [£]
NPC_without_storage	Net Present Cost without using storage for the study period [£]
OM_cost	Total Operation and Maintenance BSS costs for the study period [£]
$replacement\_cost_j$	Cost of the replacement of BSS component j of the system [£]
RTP_retail	Calculated hourly retail electricity price [£/kWh]
RTP_wholesale	Hourly wholesale electricity price [£/kWh]
SOC	Battery's State of Charge [%]

Regarding the key variables used in the MATLAB model, Table 3.8 provides a detailed summary of these variables along with a brief description and the units involved. This list does not constitute an exhaustive list as dozens of variables are used for the simulation purposes.

Except for the technical variables that are relevant to the exchange of electricity among the three main players, there are also several economic variables related to the electricity costs, revenues from exports etc. Their associated units also vary as there are variables used to describe hourly (kWh, £/kWh etc.) and annual parameters (£/year, kWh/year etc.) while index and logical variables are also utilised to identify the order of a certain variable's values and if a specific event/condition takes place or not, respectively.

3.5.3 Operational Dispatch Strategies

As the algorithm takes into account day-ahead real-time electricity prices, it is assumed that the prices of the following day are announced one minute before midnight. In reality, the prices are published at noon during the previous day, but this does not affect the way the model operates. More specifically, the MATLAB model receives as input the hourly electricity prices and the buildings' hourly electricity demand and based on the model algorithm, specifications, constraints and the operational strategy followed, it determines the best possible daily operation of the BSS and generates the electricity profile of both the battery and the building. Therefore, a perfect prediction of the building's energy demand is assumed every time the algorithm runs.

This routine takes place 365 times, each covering one day of the year. It is worth noting that the algorithm preschedules charging and discharging always in pairs; therefore, charging cannot take place without discharging and vice versa. Finally, as mentioned above, the examined real-time prices and building loads are hourly, any power variables are equal to the respective energy variables and therefore both units (kW and kWh) can be used. The original version of the algorithm for utilisation of large scale PHES was presented in detail and used in [246], [247], [248] and [249]. However, for the needs of the current research, significant changes and additions have been made to scale down the algorithm and adjust it at the building level and reality; the algorithm now considers the building's activity and consequent electricity loads to decide on the operation of the BSS.

When the battery is discharged, the stored electricity can be used to either meet the local building loads or to get exported back to the grid, resulting in an additional revenue stream. This potential dual nature of the discharging phase led to the formulation of three operational dispatch strategies with each strategy including at least one of the two discharging operations. More specifically, strategy E7 uses the battery to meet local building loads while any excess electricity left in the battery is sent back to the grid. Additionally, during the weekends when there is no building activity, the battery is still charged and discharged in order to get additional revenues from the exports. Furthermore, strategy E5 is very similar to E7 with the difference that the battery does not operate on weekends and public holidays while the BSS operation remains identical during working days. Finally, under strategy E0, the battery is only discharged to meet the building loads and no exports are allowed. The three operational dispatch strategies and their key characteristics and differences are summarised below, in Table 3.9.

The total cost of the BSS operation is dependent on the electricity price used to buy electricity and the four efficiencies that are present for charging and discharging along with the rectifier and inverter efficiencies. The model ensures that using the electricity which is stored in the battery and used to meet the local loads is cheaper than buying electricity directly from the grid. For the current research, the marginal operational costs of charging and discharging the system, often cited and used in PHES arbitrage research, are considered to be insignificant.

Table 3.9 - Overview of the Operational Strategies [9]

Activity	**Operational Strategy**		
	E7	E5	E0
Battery is allowed to discharge to meet building loads on working-days	✓	✓	✓
Exports can take place on working-days	✓	✓	×
Exports can take place on non-working days	✓	×	×
Charging takes place when electricity prices are cheap and building loads insignificant.	✓	✓	✓
Discharging takes place when electricity prices are expensive and building loads significant	✓	✓	✓

Therefore, $MC_{charge} = MC_{discharge} = 0$. Finally, operational bottlenecks also apply, ordering the BSS to charge or discharge with a specific power in mind depending on the percentual state of charge (SOC) of the battery. More specifically, constraints will apply in order to prohibit the battery to charge more than the maximum allowed SOC (100%) or discharge less than the minimum allowed SOC (10%). The storage content of the battery is then updated and the modelling process is complete only when all time periods have been evaluated for a day and finally for the entire year. The operational dispatch strategies have been used and published in [9].

3.5.3.1 Arbitrage – Exports allowed with retail revenues (E7)

The first operational strategy identifies the cheapest and most expensive hours of the day and schedules the BSS to take advantage of the price difference, considering specific technical and economic conditions. The process refers to a day and is repeated until the end of a calendar year and until all periods have been examined for their suitability. No distinction is made between working and non-working days and therefore the algorithm will try to operate the battery as many times as possible. The steps are as follows:

1a) Identify the highest price of the series as maxHourIndex, assigning an index number to that period, and priority is given to try and discharge the battery during that hour. The variable maxHourPrice is assigned as its respective price.

1b) If the respective building loads exceed a specific value, maxHourPowerLimit, then remove the hour in question from the time series and proceed to the next iteration to identify the next suitable maxHourIndex. This is necessary in order to avoid discharging the battery during hours where the building loads are insignificant. This threshold is calculated as the average value of the building loads of the first day, which is always a non-working day, plus an optional margin of 5 kW to allow for error.

2) Determine the range around maxHourIndex where charging might occur. The earliest hour the battery can charge is after the most recent period to maxHourIndex when the battery was full (minRangeIndex). Likewise, the latest hour when charging can happen after maxHourIndex is the hour before the battery has reached its minimum SOC (maxRangeIndex).

3a) Identify the minimum electricity price between minRangeIndex and maxRangeIndex. The index of the minimum price is named minHourIndex and the respective price maxHourPrice.

3b) Similarly to 1b, if the building loads that take place during minHourIndex exceed a specified limit, minHourPowerLimit, which is set as equal to maxHourPowerLimit, then the period is removed from the price series and the next iteration starts again to identify a new maxHourIndex and minHourIndex. This ensures that charging does not take place during the building's operation as doing so would result in higher peak loads.

4) Calculate the marginal operating cost based on the buying electricity price and the roundtrip efficiency (Equation 3.14). If the maximum electricity price, identified in step1, is found to be higher than the marginal cost of production, the calculations proceed to step 5. Otherwise, remove maxHourIndex from the series and return to step 1. Equation 3.15 constitutes a simplified version of Equation 3.14, taking into account that the marginal operational costs of charging and discharging are insignificant.

$$MC_{production} = MC_{discharge} + \frac{\text{minHourPrice} + \text{MCcharge}}{n_{battch} \cdot n_{battd} \cdot n_{inverter} \cdot n_{rectifier}} \tag{3.14}$$

$$\text{maxHourPrice} > \frac{\text{minHourPrice}}{n_{battch} \cdot n_{battd} \cdot n_{inverter} \cdot n_{rectifier}} \tag{3.15}$$

5) Determine the "operational bottlenecks". The bottlenecks will instruct the BSS with the exact amount of power to charge and discharge at depend on the amount of the energy stored in the battery, during minHourIndex and maxHourIndex. Constraints will also apply to avoid charging above a SOC of 100% and discharging below the minimum SOC required (10%). Therefore, the first bottleneck is the available discharging capacity during maxHourIndex (bottleneck1) and the second bottleneck is equal to the available charging capacity during minHourIndex (bottleneck2). Concerning the third bottleneck (bottleneck3), there are two subcases in total:

- If charging takes place before discharging (minHourIndex<maxHourIndex):
  The third bottleneck is the minimum free storage space, calculated by subtracting the maximum amount of the energy stored in the battery, between minHourIndex and maxHourIndex, from the battery rated capacity. This will prevent the battery from charging over a SOC of 100%.

  bottleneck(3) = storageFree = bat_cap - max(energy_stored)

- If charging takes place after discharging (minHourIndex>maxHourIndex):
  The third bottleneck is the minimum storage content, calculated by subtracting the minimum battery capacity allowed from the minimum energy stored between maxHourIndex and minHourIndex. This constraint prevents the battery from discharging below the minimum SOC allowed.

  bottleneck(3) = storageLeft = min(energy_stored) - SOC_min · bat_cap

The final bottleneck used for each iteration is equal to the minimum of the three values, mentioned above. Therefore:

final bottleneck = min(bottleneck1, bottleneck2, bottleneck3).

6) Discharge the battery at maxHourIndex and charge the battery at minHourIndex by the capacity determined in Step 5, through the appropriate bottleneck.

7) Update the storage content to reflect the charging and the discharging phases that take place.

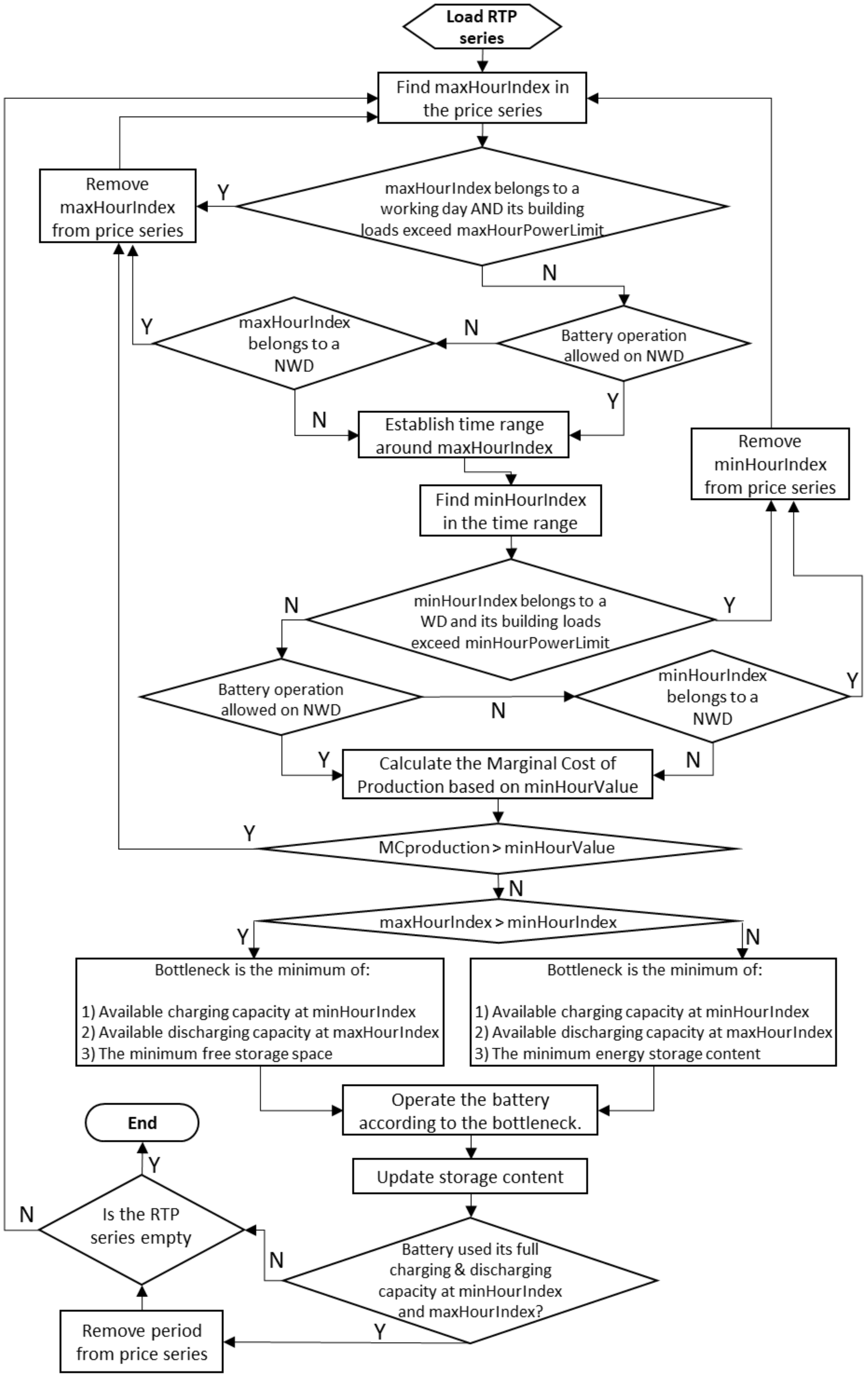


Figure 3.21 – Flow chart for Arbitrage with Exports (E7 and E5) [9]

8) If the battery has used all its charging capacity during minHourIndex, remove minHourIndex from the price series. Similarly, if the battery has used all its discharging capacity during maxHourIndex, then remove maxHourIndex from the price series.

9) Iterate back to Step 1 until all time periods are evaluated.

3.5.3.2 Arbitrage - Exports allowed only on weekdays (E5)

This version of the algorithm does not introduce any significant changes when compared with the algorithm presented in 3.5.3.1. The only difference is that non-working days (NWDs) are excluded from the battery operation. Therefore, any hours that belong to NWDs and have been identified as potential maxHourIndex and minHourIndex candidates are removed from the series and the algorithm iterates back to Step 1. Regarding maxHourIndex candidate hours, their elimination takes place between steps 1b and 2 while minHourIndex eliminations between steps 3b and 4. Despite the fact that this additional constraint is minor, structurally and code-wise, its impact is significant as NWDs include 52 weekends and 3 UK public holidays, a total of 107 days, the equivalent of 2,568 hours and 30% of the entire calendar year during which the battery is not allowed to charge or discharge.

When also considering the fact that the BSS is able of cycling more than once during a single day, it can be concluded that this exclusion can have significant consequences on the electricity exports and the respective revenue streams which are expected to be greatly reduced. On the other hand, as the battery is utilised less frequently under the E5 strategy, this also leads to a higher batter life. The combined flowchart for both strategies E7 and E5 is presented in Figure 3.21.

3.5.3.3 Arbitrage – No Exports allowed (E0)

Algorithms E7 and E5 make use of all the available battery and inverter capacities, trying to discharge as much as possible during the most expensive hour(s) of the day, with excess electricity being exported back to the grid. The third version of the algorithm introduces one additional constraint to ensure that all the discharged energy from the battery is only used locally to cover building loads, eliminating in this way all exports. Two subcases are introduced for the first bottleneck, comparing the building loads at maxHourIndex and the inverter's rated power capacity.

In this way, the algorithm decides whether to proceed with the former or the latter, as the energy amount assigned to the first bottleneck. This leads to a generation of four possible bottleneck sets, depending on the conditions. As most of the core algorithm remains the same, only the steps that differ are presented below. Similarly to Operational Strategy E5, hours belonging to NWDs are eliminated from the series as minHourIndex and maxHourIndex candidates.

5) The final bottleneck used for each iteration is equal to the minimum of the three values, presented below in Steps 5a, 5b and 5c.

a) The second bottleneck is the available charging capacity at minHourIndex.

b) If discharging takes place after charging (minHourIndex<maxHourIndex), the third bottleneck is the minimum free storage space, calculated by subtracting the maximum amount of the energy stored in the battery, between minHourIndex and maxHourIndex, from the battery rated capacity. This will prevent the battery from charging over a SOC of 100%.

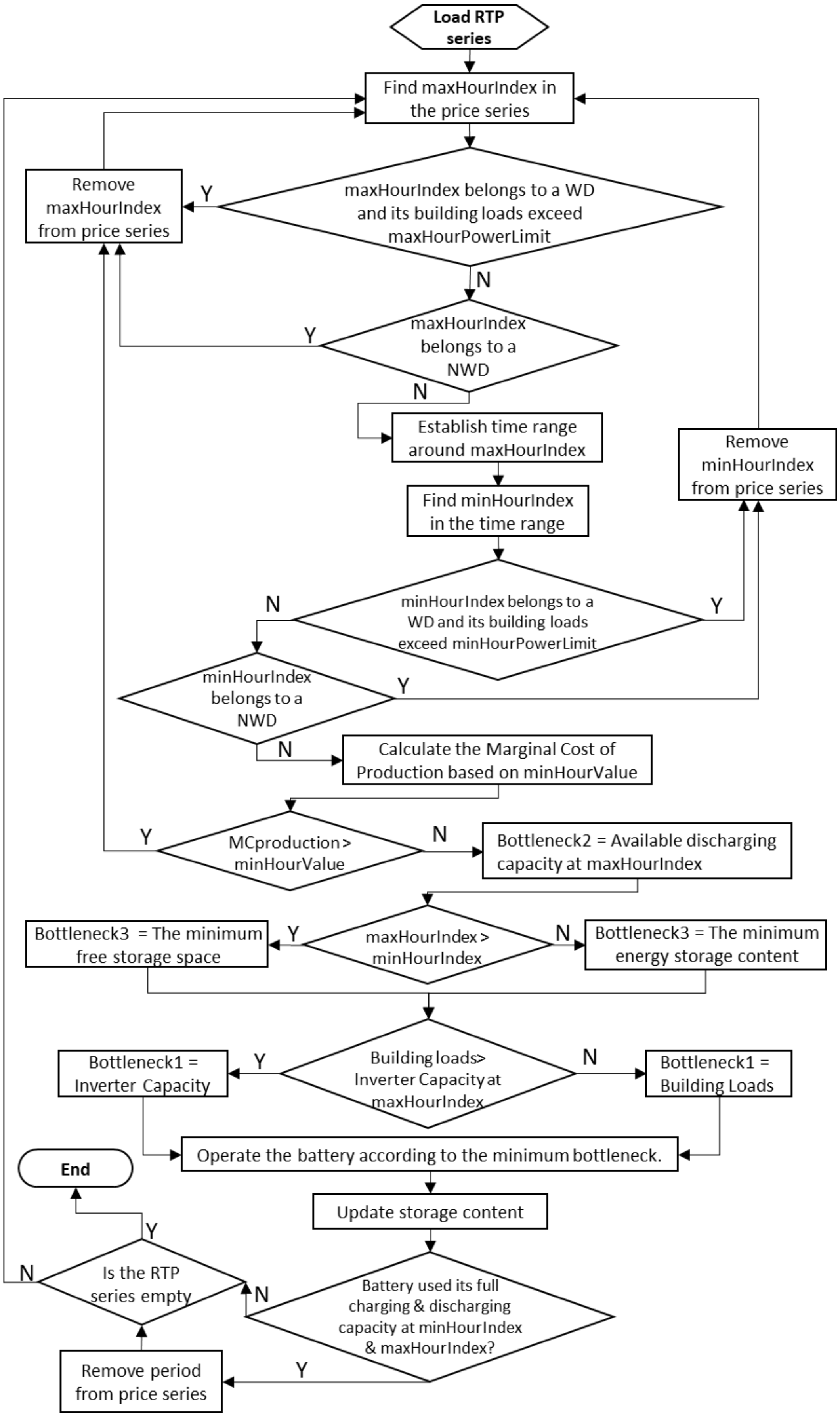


Figure 3.22 – Flowchart for Arbitrage without exports (E0) [9]

bottleneck(3) = storageFree = bat_cap - max(energy_stored)

If charging takes place after discharging (minHourIndex>maxHourIndex), the third bottleneck is the minimum storage content, calculated by subtracting the minimum battery capacity allowed from the minimum energy stored between maxHourIndex and minHourIndex. This constraint prevents the battery from discharging below the minimum SOC allowed.

bottleneck(3) = storageLeft = min(energy_stored) - SOC_min · bat_cap

c) The last bottleneck is the available discharging capacity at maxHourIndex. If the building loads at maxHourIndex are greater or equal to the inverter's rated power capacity, the third bottleneck is equal to the building loads. Otherwise, it is equal to the inverter's rated power capacity.

8) If the battery has used all its charging capacity during minHourIndex, remove minHourIndex from the price series. Similarly, if the battery has used all its full discharging capacity during maxHourIndex, then remove maxHourIndex from the price series. The amount of the full discharging capacity differs, depending on the relationship between the building loads and the invert's rated power capacity, as described previously in Step 5c. The flow chart for the operational strategy E0 is presented in Figure 3.22.

3.5.4 BSS Sizing

The sizing of BSS is based on the "three hours to charge" and "two hours to discharge" rules of thumb [9]. Nevertheless, for the largest systems exceeding a battery capacity of 160 kWh, initial results suggested that the inverters' power capacity were oversized when compared with the mean or even the peak hourly building loads. Consequently, under the E7 and E5 scenarios, significant amounts of the electricity stored in the battery would be exported back to the grid during the discharging phase instead of meeting the local building loads. Initial results for all systems using a battery bank larger than 160 kWh would result in the same amount of peak loads shifted, rendering the additional battery capacity useless for the building. Therefore, the sizing criteria were revised for the larger systems and consistent sizes were adopted. More specifically, a maximum power capacity of 65 kW was selected for the inverter while a value of 45 kW was selected for all the inverters as it was deemed that sufficient amount of time is provided to the battery to fully charge. The initial and revised BSS components can be seen below, in Table 3.10. The biggest battery size of 220 kWh (45 kW/ -65 kW) is used for the main results while the rest of the sizes (40-200 kWh) are examined as part of the sensitivity analysis.

Table 3.10 - BSS Components Sizing based on the roundtrip efficiency (86.7%) and minimum SOC (10%) [9]

Battery Size (kWh)	Initial Inverter & Rectifier Rated Power (kW/-kW)	Revised Inverter & Rectifier Rated Power (kW/-kW)
40	15 / -20	15 / -20
60	20 / -30	20 / -30
80	30 / -40	30 / -40
100	35 / -45	35 / -45
120	40 / -55	40 / -55
140	45 / -65	45 / -65
160*	55 / -75	45 / -65
180*	60 / -80	45 / -65
200*	65 / -90	45 / -65
220*	70 / -100	45 / -65

*Revision needed for the respective inverter and rectifier sizes.

3.5.5 Battery Lifetime and Cost-Benefit-Analysis (CBA)

The battery used was based on a nominal Li-ion lifecycle of 5,000 cycles with a minimum SOC of 10%, resulting in the equivalent of 4,500 full cycles [250]. For dispatch strategies E7 and E5 under which exports are allowed to take place, the respective revenue streams are calculated on an annual basis by multiplying the hourly wholesale prices with the amount of the respective exported electricity. The annual net costs of electricity are calculated by subtracting the export revenues from the electricity grid purchases. The annual electricity cost is given in Equation 3.16 while the respective revenues and net cost are calculated through Equations 3.17 and 3.18, respectively. O&M costs for the BSS are calculated through Equation 3.19 with the lifetime referring to the duration of the study period in years. The replacement costs are calculated in Equation 3.20 with $Nrep_j$ representing the number of the replacements needed for a component j, such as the battery and the converter, and $life_j$ referring to the estimated lifetime of a component j. The last part of the equation is used to consider the revenues due to the remaining lifespan of the components but considered to be zero for the 10-year period [9].

The BSS prices used have been calculated per kWh and kW, based on a high-end commercial power pack [251]. The exact capital costs have been calculated to be approximately £371/kWh and £162/kW [252], [253]; slightly higher values of £390/kWh and £170/kW are considered to adjust for error and inflation. The costs of cabling and other hardware are included in the total battery cost and are estimated to be around £28/kWh [9].

Table 3.11 – BSS Technical and economic parameters used for modelling purposes [9]

Parameter	Value	Comments
Battery cost	£390/kWh	Based on [252], [253]
Bi-directional converter cost	£170/kW	Based on [252], [253]
O&M cost	£100 per annum	Based on [245], [169]
Battery lifecycle	5,000 cycles at DOD 90% (4,500 full equivalent cycles)	Based on [251]
Estimated battery lifetime	10.5 years (E7) 19.5 years (E5, E0)	E7: 1 cycle per day for working days 2 cycles per day for NWDs. E5 and E0: 1 cycle per day for working days only
Estimated converter lifetime	10 years (E7, E5, E0)	Based on [254]
Inflation rate	2%	Based on [244], [245], [254] Efficiencies are assumed to be constant.
Interest rate	5%	
Charging efficiency	97%	
Discharging efficiency	97%	
Inverter efficiency	96%	
Rectifier efficiency	96%	
Roundtrip efficiency	86.7%	Calculated
Minimum SOC	10%	Assumed
Maximum SOC	100%	

An annual inflation rate of 2% and an interest rate of 5% were taken into account, for 10-year and 20-year periods (Equations 3.21 – 3.22) to calculate the net present costs (NPCs) for each scenario. The levelised costs of electricity (LCOE) were calculated by dividing each NPC value by the respective amounts of electricity, as shown in Equations 3.23 and 3.24, excluding any battery losses for charging and discharging. Finally, the financial reward required is given in Equation 3.25 to reflect the financial benefit that a building must earn per kWh shifted to make the two NPCs equal and therefore make the scheme cost-effective, for the entire project lifetime.

The battery lifetime differs based on the dispatch strategy followed, as shown in Table 3.11 along with key technical and economic parameters considered in the modelling process. For strategy E7, the estimated battery lifetime is approximately 10 years while the lifetime is almost doubled to around 20 years, for dispatch strategies E5 and E0. The bidirectional converter lifetime is considered to be 10 years for all scenarios. Finally, the CBA for the current research is considered over 10 and 20-year periods; therefore, while there are no replacements needed for the former period, an additional battery and converter is required under strategy E7 while E5 and E0 require only the addition of a replacement converter, for the 20-year period.

$$\text{annual\_energy\_cost} = \sum_{t=1}^{8760}(\mathrm{RTP}_{\mathrm{retail}} \cdot \mathrm{energy\_from\_the\_grid}) \tag{3.16}$$

$$\text{annual\_revenues} = \sum_{t=1}^{8760}(\mathrm{RTP}_{\mathrm{wholesale}} \cdot \mathrm{exported\_energy}) \tag{3.17}$$

$$\text{annual\_net\_cost} = \text{annual\_energy\_cost} - \text{annual\_revenues} \tag{3.18}$$

$$\text{OM\_cost} = \sum_{k=1}^{lifetime}\left[\mathrm{annual\_OM\_cost} \cdot \left(\frac{1+\mathrm{inflation\_rate}}{1+\mathrm{interest\_rate}}\right)^{k}\right] \tag{3.19}$$

$$\text{replacement\_cost}_j = \sum_{k=1}^{Nrep_j}\left[\mathrm{component\_cost}_j \cdot \left(\frac{1+\mathrm{inflation\_rate}}{1+\mathrm{interest\_rate}}\right)^{k \cdot life_j}\right] - \text{component\_cost}_j \cdot \frac{\left[\frac{(\mathrm{Nrep}_j+1)\cdot \mathrm{life}_j-\mathrm{lifetime}}{\mathrm{life}_j}\right]\cdot(1+\mathrm{inflation\_rate})^{\mathrm{lifetime}}}{(1+\mathrm{interest}_{\mathrm{rate}})^{\mathrm{lifetime}}} \tag{3.20}$$

$$\text{NPC\_without\_storage} = \sum_{k=1}^{\mathrm{lifetime}}\left[\mathrm{annual\_energy\_cost} \cdot \left(\frac{1+\mathrm{inflation\_rate}}{1+\mathrm{interest\_rate}}\right)^{k}\right] \tag{3.21}$$

$$\text{NPC\_with\_storage} = \text{battery\_cost} + \text{converter\_cost} + \text{replacement\_cost} + \text{OM\_cost} + \sum_{k=1}^{lifetime}\left[\mathrm{annual\_net\_cost} \cdot \left(\frac{1+\mathrm{inflation}_{\mathrm{rate}}}{1+\mathrm{interest}_{\mathrm{rate}}}\right)^{k}\right] \tag{3.22}$$

$$\text{LCOE\_without\_storage} = \frac{\mathrm{NPC\_without\_storage}}{\mathrm{lifetime} \cdot \sum_{t=1}^{8760}\mathrm{energy\_demand}} \tag{3.23}$$

$$\text{LCOE\_with\_storage} = \frac{\mathrm{NPC\_with\_storage}}{\mathrm{lifetime} \cdot \sum_{t=1}^{8760}(\mathrm{energy\_demand} + \mathrm{exported\_energy})} \tag{3.24}$$

$$\text{financial\_reward} = \frac{\mathrm{NPC\_with\_storage} - \mathrm{NPC\_without\_storage}}{\mathrm{lifetime} \cdot \sum_{t=1}^{8760}(\mathrm{energy\_shifted})} \tag{3.25}$$

Unlike the rest of the simulations, the CBA is conducted for a smaller number of scenarios, shown in Table 3.12. The smaller battery systems have been removed in order to investigate only two bigger battery sizes, 120 and 240 kWh. The bidirectional converter capacities have been adjusted accordingly, including three scenarios for the former battery and five for the latter. In the current thesis, only two BSS scenarios are presented: 120 kWh (40 kW/-60 kW) and 240 kWh (80 kW/-60 kW) as published in [9]. Finally, as Li-on battery costs have been continuously decreasing in the recent years, a sensitivity analysis has been conducted to allow for an overall BSS capital cost reduction of 15%, 30% and 45%. No new building simulations have been necessary for this scenario. The same BSS sizes have been used as in the initial CBA, as previously shown in Table 3.12.

Table 3.12 – BSS Sizing Scenarios for the CBA

Battery Size (kWh)	Rectifier (kW)	Inverter (- kW)
120	40	- 40
120*	40*	- 60*
120	40	- 80
240	80	- 40
240*	80*	- 60*
240	80	- 80
240	80	- 100
240	80	- 120

*Presented in the current thesis

3.6 Selection of Models for further investigation

The building models and the BSS scenarios that are investigated in this research are summarised in Appendix C. Each building has a case number as well as a case ID for quick referencing. The case referencing system consists of two elements, a numerical value to demonstrate the order under which the buildings have been simulated and a letter to indicate the building's shape (r for rectangular, s for square). One additional letter (N) follows the previous letter if the building in question is naturally-ventilated. Scenario ID is more descriptive as it includes all the major building design characteristics: thermal mass, energy efficiency and window-to-wall-ratio. If the building is not rectangular, additional information is provided at the beginning of the ID while a different that Southern-Northern orientation is included at the end. For example, HwBP80-SW is heavyweight, Best Practice, 80% glazed and has a southern-western orientation. It is clear that the simulations involve 56 building models and 10 different BSS sizes, numbering a total of 560 scenarios. As it would be highly impractical to present all results, focus is given on the biggest battery size (220 kWh) to allow for quick comparisons between the building models. It should be noted that any comparison made is based not only on the building energy simulation results but on the BSS MATLAB results as well. This allows for more transparent and thorough analysis of the results as for example buildings with similar electricity consumption profiles could in theory perform much differently when it comes to the Arbitrage Model. After presenting the results for the 2017 calendar year, a sensitivity analysis follows using the 2018 RTP data while the rest of the sensitivity analysis chapter is conducted for a limited amount of 8 building models. The building models in question consist of the most and least efficient cases, based on their combined DesignBuilder and MATLAB results. The CBA is also performed only for the final 8 building models.

The MATLAB code, used in this project, can be found in Appendix D and consists of three parts: the first file (data_analysis_oneyear.m) imports DesignBuilder's data generated from the building energy simulations, assigns them in variables and makes quick calculations. The second file (RTP_NEW_ONEYEAR.m) imports NordPool's real-time pricing data to carry out the same objectives along with a quick statistical analysis, while the third and largest part consists of three files, each for every operational strategy, making up the MATLAB BSS Arbitrage Model. Appendix D also includes a detailed validation of the model.

3.7 Sensitivity Analysis

The selected building models are further investigated by changing one or two major simulation parameters, either related to the Building Simulation or the Battery Arbitrage Model. The building energy simulation results are then exported to the MATLAB model which then runs for only the 220 kWh (45 kW / - 65 kW) BSS, with the exception of sections 3.7.6 – 3.7.7. A total of six parameters are included in the sensitivity analysis in order to understand how the results are affected. Sections 3.7.2 – 3.7.3 make use of additional weather data while the rest use the initial Birmingham IWEC TRY weather data.

3.7.1 RTP Electricity Data (Birmingham IWEC)

As the initial simulations use the 2017 day-ahead NordPool data (N2EX), the prices of one additional calendar year (2018) is considered as the RTP input of the arbitrage model.

3.7.2 Location and Weather Data

As mentioned, all initial simulations have been based on the Birmingham IWEC weather data that consist of "typical year" data. Birmingham is located in Central England and the weather file in question contain data which are derived from up to 18 years (1982-1999 for most locations) [255]. Therefore, it is important to investigate different UK locations as well as real weather data recorded from a weather station. In this direction, the simulations below have been conducted:

a) Typical year weather data files (TRY) have been purchased by CIBSE for Southampton (Bournemouth Airport) and Edinburgh, located in Southern and Northern England respectively.
b) Real weather data for the 2017 Calendar Year have been also purchased for Manchester Airport, located in North West England.

Both weather files have received appropriate modifications in order for DesignBuilder to graphically output the results and allow external transfer of the data. More specifically, all hourly timestamps have been changed to the year 2002, as required by DesignBuilder.

3.7.3 Extreme Weather Conditions – Overheating

This category is closely related to the previous subchapter as it includes the usage of additional weather data to investigate how extreme hot weather conditions affect the results. In more detail, Design Summer year 3 (DSY3) have been used for London based on the 1976 data when a prolonged period of sustained warmth took place [255]. The following simulations are considered:

a) DSY3 weather data with no further modifications to evaluate the building in terms of thermal comfort, energy demand, the performance of heat pumps in cooling mode and Arbitrage.
b) DSY3 weather data – No Free Cooling. As above with the additional assumption that no economisers are used and therefore cooling is only provided by the GSHP. This combined scenario is expected to evaluate the economiser contribution in terms of electricity consumption reduction as well as thermal comfort, on top of what is included in (a).
c) DSY3 weather data – Reduced CoPs. Same as (a) with the additional assumption that the heat pumps performance is reduced by approximately 36% and 40% for heating and cooling, respectively. The new CoP values are 2.25 and 3, down from the original values of 3.5 and 5. This combined scenario is expected to evaluate how the GSHP CoPs affect the building's electricity consumption results on top of what is included in (a).

3.7.4 Reduced Equipment Loads (Birmingham IWEC)

The only parameter that changes are the Equipment (computer) loads, which are reduced by 1/3. No new building simulations have been performed for this scenario and it has been assumed that there are no changes regarding the internal heat gains or thermal comfort. This allows to investigate how the constant loads of the building throughout a working day affect the Arbitrage results.

3.7.5 Inverter Sizes (Birmingham IWEC)

10 inverter sizes have been selected to investigate if and how the final Arbitrage results are affected without any new building simulations being necessary. Only one battery size has been used for this sensitivity analysis (220 kWh). The rectifier capacity is the same for all cases (45 kW) while the inverter sizes follow: 30, 45, 65, 85, 105, 125, 145, 165, 185 and 195 KW.

3.7.6 Battery Sizes (Birmingham IWEC)

10 battery sizes are used in the arbitrage model without any new building simulations being necessary, similarly to Section 3.7.5, starting from a relatively small capacity of 40 kWh. The bidirectional converter capacity is the same for all considered scenarios (45 kW/-65 kW) with a 20 kWh step increase for the batteries: 40, 60, 80, 100, 120, 140, 160,180, 200 and 220 kWh.

3.8 Arbitrage Model Validation

3.8.1 Introduction

Regarding the nature of the MATLAB variables used, introduced in section 3.5.2, it should be noted that energy_exchange and energy_exchange_REAL have negative values during the discharging phase and positive values for the charging phase. The variables battery_charge and battery_discharge are in essence the absolute values of the energy_exchange variable, during the charging and discharging phase, respectively.

Battery operation: *energy_exchange* ≠ 0

energy_exchange_REAL ≠ 0

Charging phase: *battery_charge* = *energy_exchange*

battery_charge_REAL = *energy_exchange_REAL*

Discharging phase: *battery_discharge* = – *energy_exchange*

battery_discharge_REAL = – *energy_exchange_REAL*

3.8.2 Validation with Synthetic RTP Data

In this section, the arbitrage model is validated by using different types of RTP electricity data to ensure the correct operation of the BSS, including a constant price for the entire year, one daily peak and one daily off-peak price, prices following a sine distribution and finally using a C-rate higher than 1 (or 1C).

a) Constant price for the entire year.

RTP_wholesale(:,:) = constant_price;

As expected, the battery will never charge or discharge as there is no financial motive for its operation (Figure 3.23). More specifically, the economic condition of the model, presented below is not met. MCproduction also takes into account all the four efficiencies of the battery and the converter. Therefore, even if the prices were marginally different during the day, the battery would still not charge.

if (MCproduction + MCmargin) < (RTP_retail(maxHourIndex))

&&(minHourIndex ~= maxHourIndex)

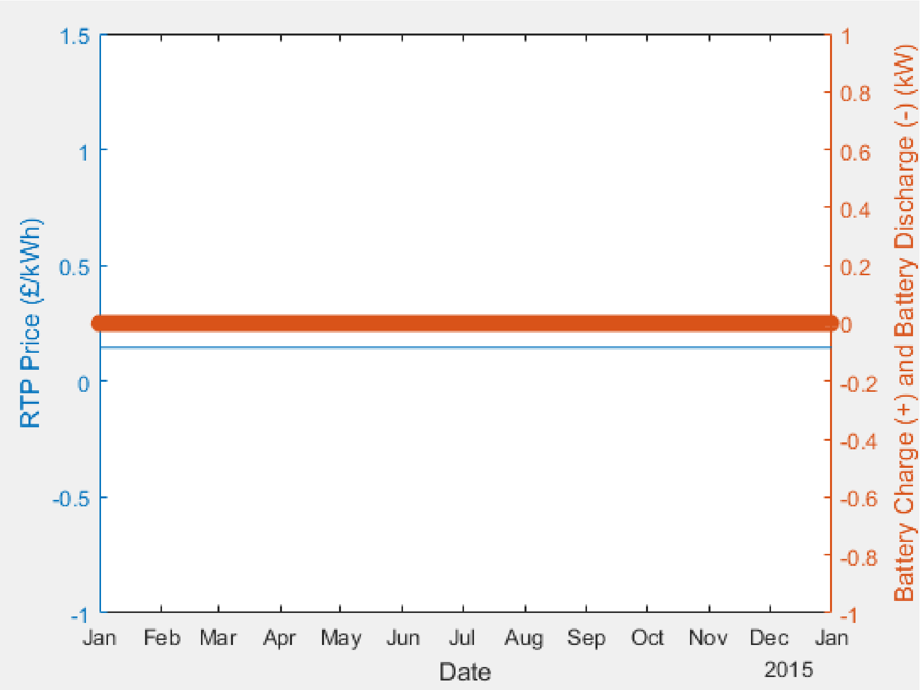


Figure 3.23 – BSS Operation for constant RTP prices

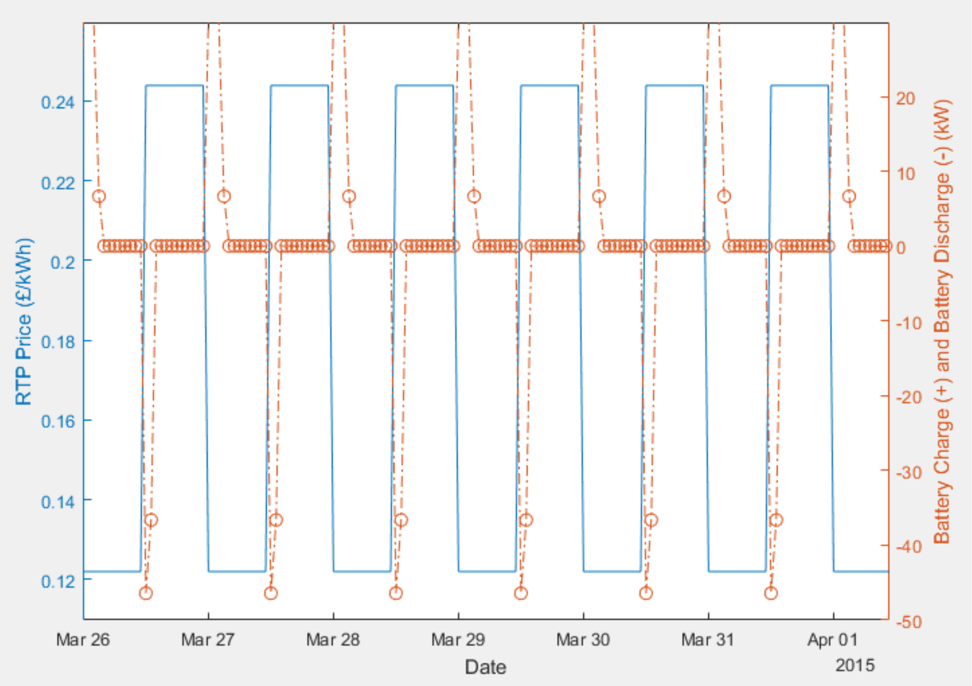


Figure 3.24 – Battery Operation for price-step RTP data

b) Peak and off-peak price

In this case, only one lower price is present during the first twelve hours of a calendar day and a more expensive (peak) price follows for the rest of the day.

RTP_wholesale(1:12,:) = off_peak_price;

RTP_wholesale(13:24,:) = peak_price;

As soon as the price drop takes place at t=1, the battery charges utilising the rectifier's full rate until it reaches its full capacity. Later, when the peak price is in effect, the battery is discharged at the full inverter rate until it reaches the minimum SOC (Figure 3.24). However, it is important to examine the reversed case, i.e. when the expensive price comes first in the day and the cheaper rate follows. While this does not reflect a realistic scenario, it is worth examining it to further validate the model.

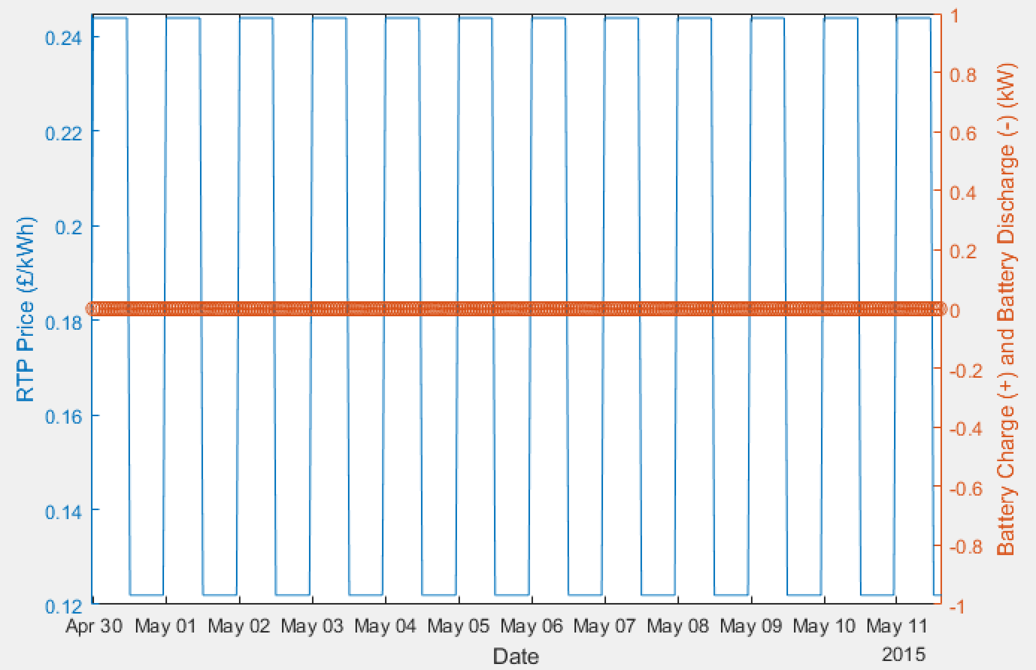


Figure 3.25 – Battery Operation for reversed price-step RTP data

RTP_wholesale(1:12,:) = peak_price;
RTP_wholesale(13:24,:) = off_peak_price;

As shown in Figure 3.25, in this case, the battery remains inactive and never charges or discharges. While this seems at first unexpected, it is exactly what the arbitrage model is asked to simulate, as it optimises the charge/discharge pairs, not the charging or discharging process on their own. It should be reminded that the model optimises the schedule every 24 hours and as it is cost-effective to charge the battery only during the second half of the day, the battery is always at its minimum SOC at the beginning of the 24-hour period; therefore there is no energy stored to be discharged and it remains inactive. In conclusion, when *maxHourIndex* takes place before the *minHourIndex*, the battery does not operate.

c) Price series following a sine distribution (1 full cycle per day)

*RTP_wholesale = sine_price * sin(2*pi*ttt / 24);*

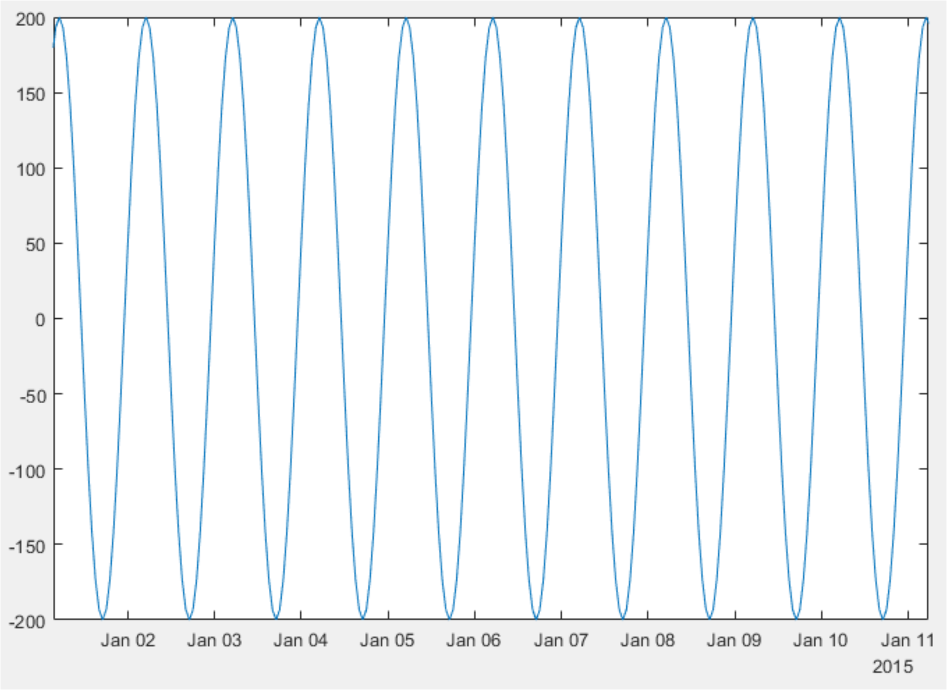


Figure 3.26 – Synthetic RTP data following a sine distribution (1 cycle per day)

The RTP distribution can be seen in Figure 3.26, where one full cycle is conducted daily, and negative electricity prices are also included. As the price series enter an increasing sine trend at the beginning of the day, the battery charges during the first hours until the SOC reaches 100% and then it immediately discharges to take advantage if the biggest price difference, before the end of the increasing price period; later in the day, the battery is idle until the lowest price(s) are observed (negative peak), resulting in the battery charging again, for a second time in the day (Figure 3.27).

In this case, the results highly depend on the frequency of the sine distribution. In Figure 3.28, different price series can be seen as only 2 cycles take place per year. The battery operates for a very small part of the year, exclusively when there is an increasing trend in the prices. This can be explained by carefully looking at the RTP price range for every 24-hour period (Figure 3.29).

The difference between the maximum and the minimum price per day is relatively insignificant and therefore the financial condition is not met, when considering the roundtrip efficiency of the BSS. Even in the most optimistic scenario, assuming all efficiencies having a value of 97%, the roundtrip efficiency of the system is equal to 88.5%, resulting in the battery being inactive as the marginal cost of production will marginally exceed the electricity price during maxHourIndex.

```
MCproduction = MCdischarge + (RTP_retail(minHourIndex)+
MCcharge)/(pbidi_eff_RECTIFIER * nbattch * pbidi_eff * nbattd);

if (MCproduction + MCmargin) < (RTP_retail(maxHourIndex))
 &&(minHourIndex ~= maxHourIndex)
```

To confirm this, the efficiencies were removed from the financial condition and new results were generated (Figure 3.30). It is clear the battery operates wherever the price follows an increasing trend. By including the efficiencies to calculate the marginal cost of production, the days when the battery operates are narrowed down to the results earlier shown in Figure 3.28. Therefore:

MCproduction = MCdischarge + (RTP_retail(minHourIndex)+ MCcharge

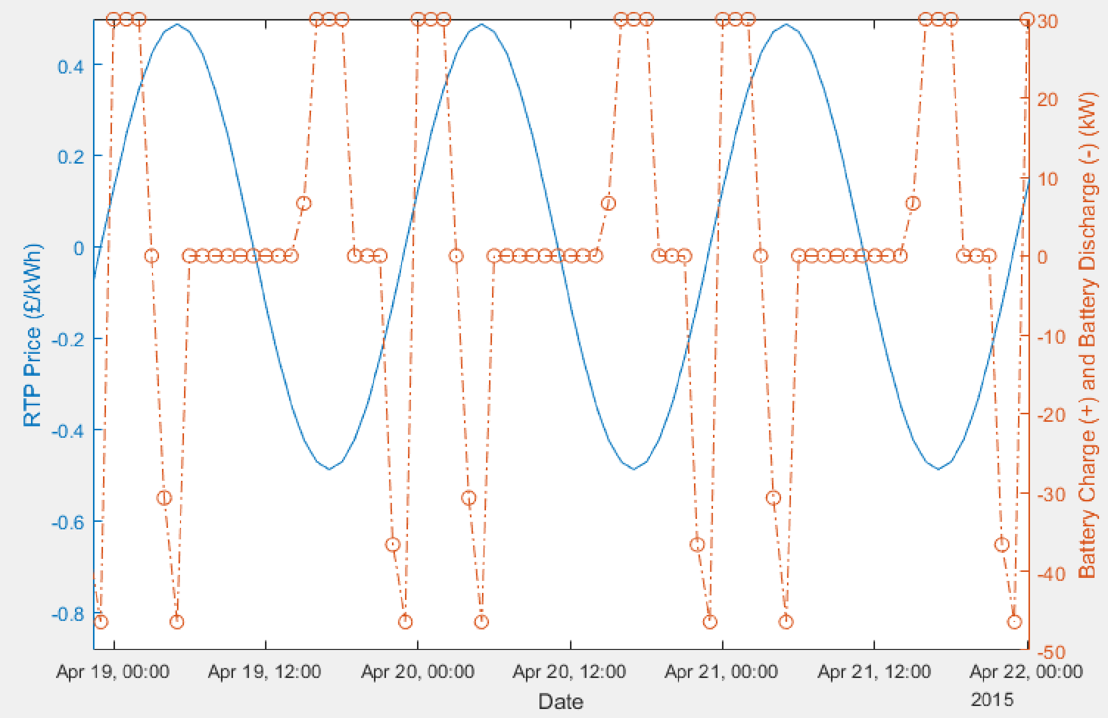


Figure 3.27 – Battery Operation under sine RTP data (1 cycle per day)

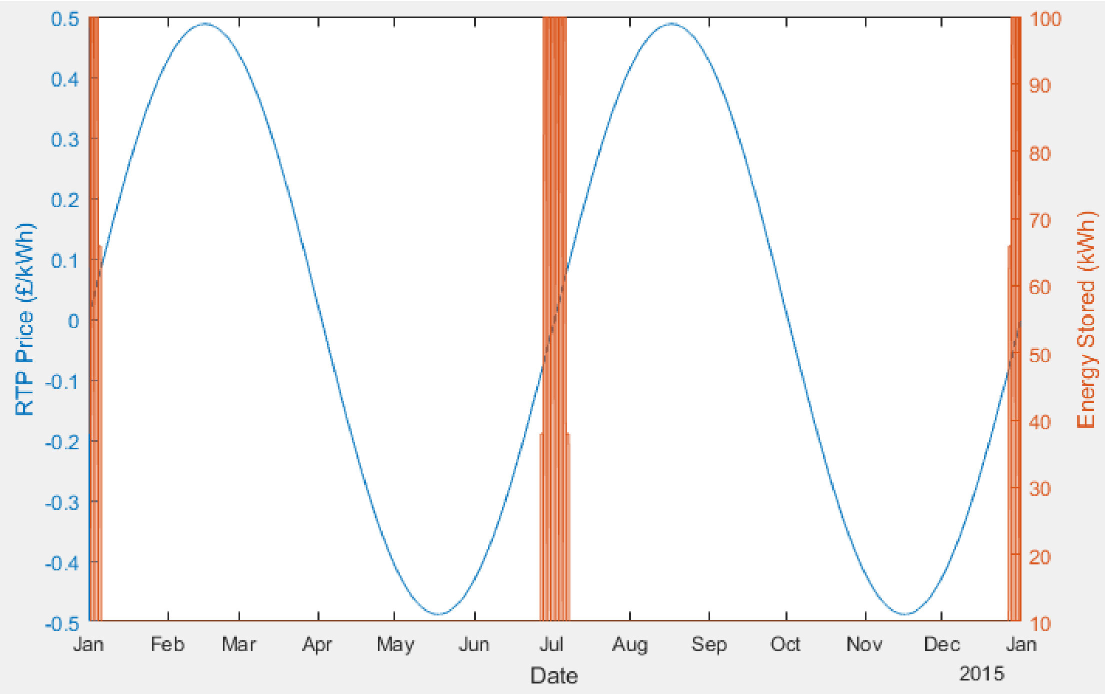


Figure 3.28 – Battery Operation under sine RTP data (2 cycles per year)

Regarding the reason why there is no battery activity during the rest of the year when the prices drop, this is based on the same principles, as in Figure 3.26, where *maxHourIndex* comes before *minHourIndex*. Similarly, in the decreasing part of the sine price series, there cannot be optimisation of the charge/discharge pairs.

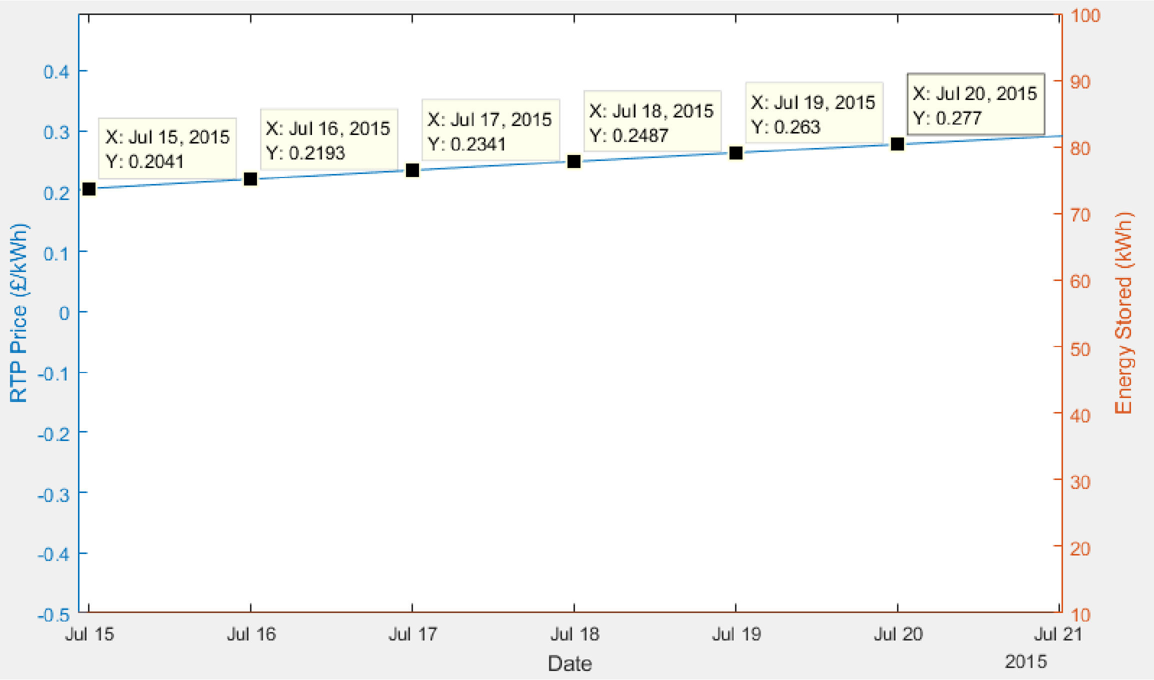


Figure 3.29 – Battery inactive during sine RTP data (2 cycles per year)

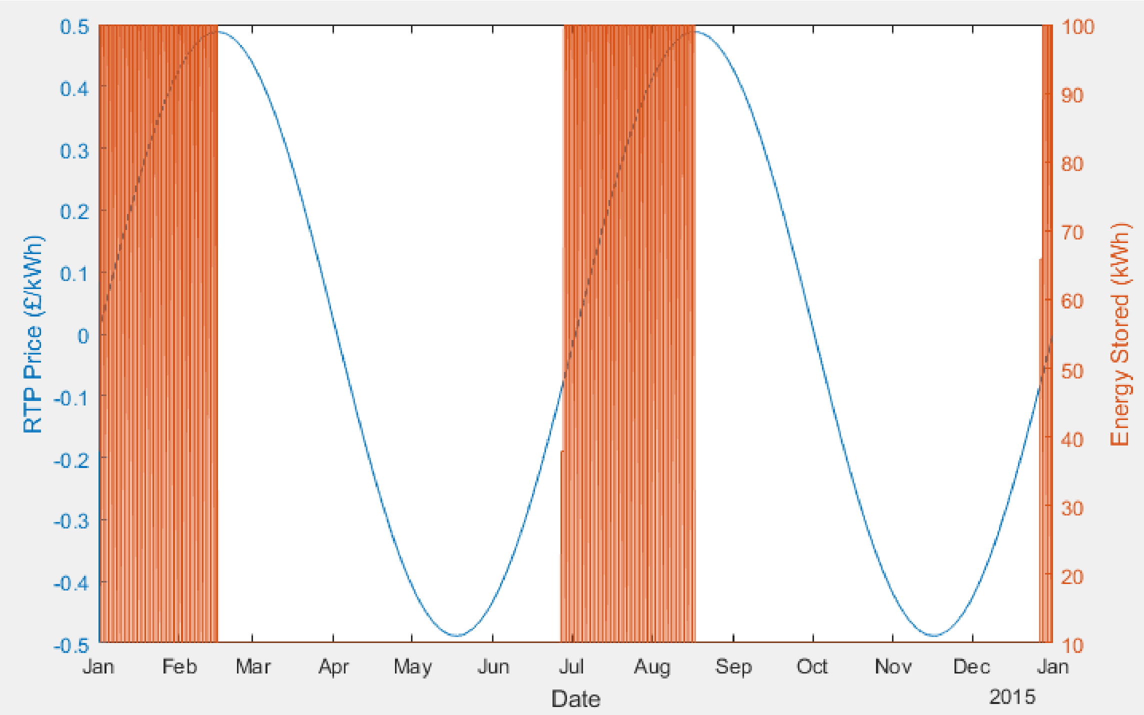


Figure 3.30 – Battery under sine RTP data with efficiencies removed

d) Validation using C-rates higher equal or higher than 1

To further test the validity of the model, C-rates equal and higher than 1 were applied (Figure 3.31). It was discovered that the battery's SOC violated the initial constraints, acquiring of a value higher than 100% when charging and a value less than 10% (in this case, the acceptable minimum SOC). This immediately indicated that the calculation of the third bottleneck, which is responsible to guarantee that the battery's SOC will not exceed 100% is incorrect.

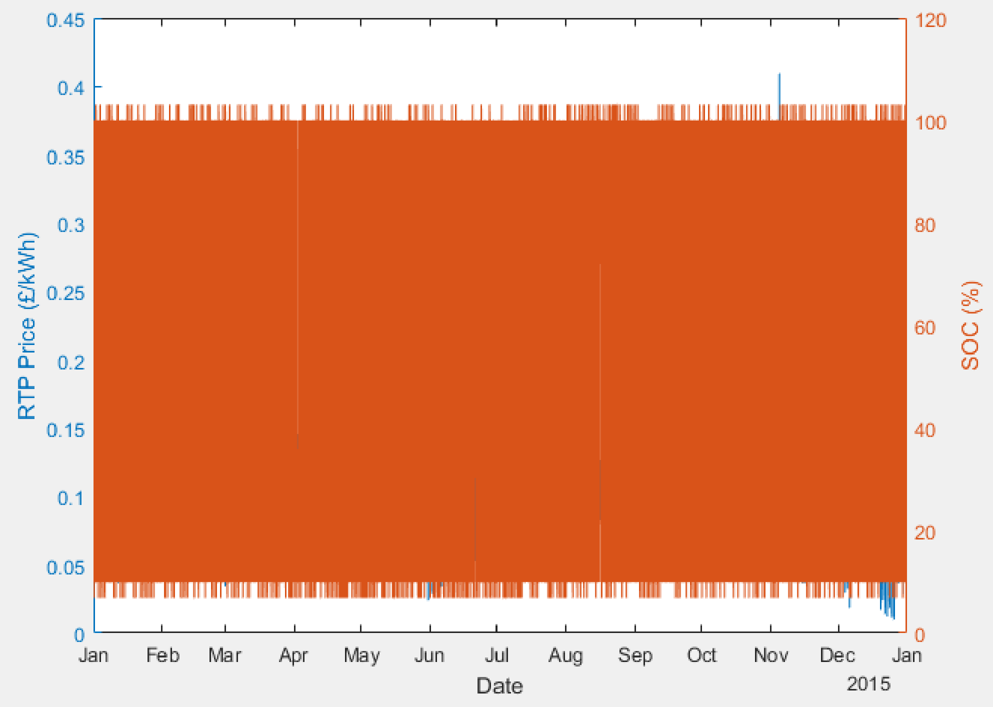


Figure 3.31 – Battery SOC when using a C-rate of 1 (DOD = 90%)

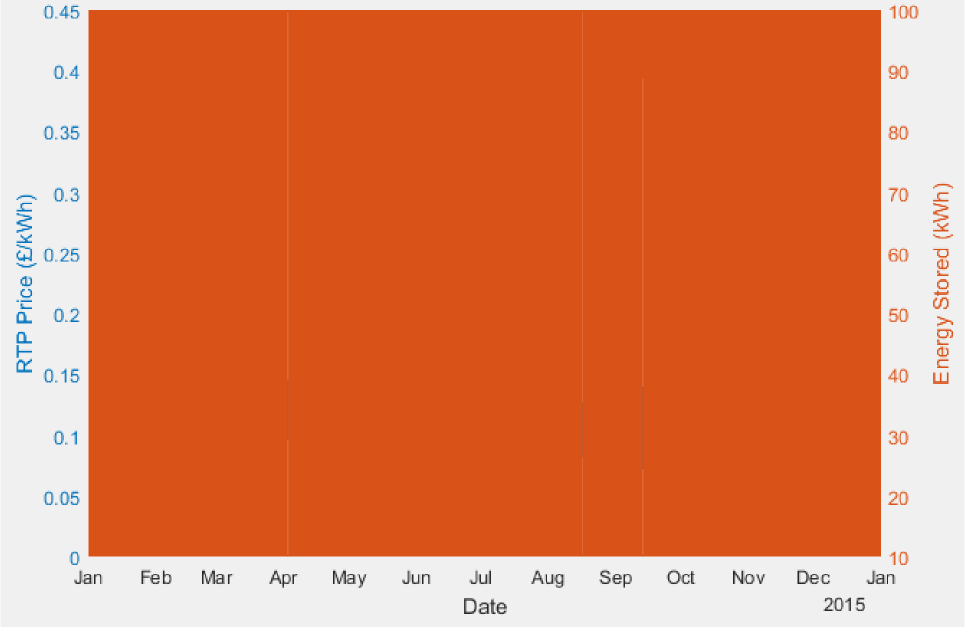


Figure 3.32 – Energy Stored when using a C-rate of 1 (Corrected version)

The same results were generated for any C-rate higher than 1. Indeed, it was found out the inclusion of the charging and the rectifier efficiencies are not required for the bottleneck calculation, as inverter & discharging efficiencies are applied to the battery activity post-loop, while the rectifier & charging efficiencies are introduced at the beginning of the model, assuming the real *pbidi_cap_ch* instead of the nominal one. The old and the correct equations are listed below.

*bottleneck(3) = storageFree/(batch*pbidi_eff_RECTIFIER)*
bottleneck(3) = storageFree

After the efficiencies were removed, the simulation of the model revealed that the battery now obeys to the bottlenecks and the SOC constraints (Figure 3.32) regardless of the C-rate applied.

3.8.3 Marginal Cost of Production

The model incorporates both positive and negative prices, therefore the formula calculation the marginal cost production must have two cases. For non-negative values, according to the literature:

*MCproduction = MCdischarge + (RTP_retail(minHourIndex)+ MCcharge)/(pbidi_eff_RECTIFIER * nbattch * pbidi_eff * nbattd);*

The buying price (plus the operating cost for charging) is divided by the charging efficiencies as the battery is charged less due to the charging/rectifier losses and therefore more energy must be purchased. In this way, the MCproduction increases. Also, as there are also energy losses while discharging, from the battery and the inverter, less energy is used, resulting into a lower profit and a lower energy potential. Therefore, the buying price must be divided by the discharging efficiencies as well. However, in the case of negative electricity prices, the formula has to change regarding its discharging element as the discharging efficiencies increase the marginal production cost, similarly to the first scenario of positive pricing.

*MCproduction = MCdischarge + ((RTP_retail(minHourIndex) + MCcharge) * nbattd * pbidi_eff)/(pbidi_eff_RECTIFIER * nbattch);*

3.8.4 Electricity Exports

a) When exports are allowed by the battery storage model, they are calculated simply by subtracting the building loads from the total battery discharged energy. It is important to point out that *energy_exchange_REAL* represents the real electricity imports after losses, considering the inverter and the battery discharging efficiencies. As the hours with insignificant building loads are excluded from discharging due to the qualitative constraints explained above, the exported energy is minimised.

However, when the battery is oversized or when the building's electricity consumption during the most expensive hour(s) of the day is lower than the inverter capacity, exports will take place on weekdays. Furthermore, as the qualitative restraints do not cover weekends, the battery storage system is able to charge and the vast majority of the discharged energy (excluding auxiliary loads) is exported back to the grid. The variable *remaining_loads* refers to the electricity that has to be purchased from the grid when the energy discharged by the battery is not sufficient to meet 100% of the building loads during *maxHourIndex*.

```
for ee = 1:length(RTP_retail)

if battery_discharge_REAL(ee) >= totalenergyLIFE(ee)
   remaining_loads(ee) = 0;
   exported_energy(ee) = battery_discharge_REAL(ee) - totalenergyLIFE(ee);
else
   remaining_loads(ee) = totalenergyLIFE(ee) - battery_discharge_REAL(ee);
   exported_energy(ee) = 0;
end
end
```

b) Electricity exports are not allowed in the second version of the battery storage model in order to maximise the building's self-reliance by using 100% of the battery discharged energy to only meet the building loads. This has also a significant effect on the total battery lifecycles and consequently on the overall battery life. To eliminate exports from the model, its core has to be changed and more specifically the bottlenecks. As it can be seen for the code below, an *if statement* was introduced that checks the relationship between the building loads of *maxHourIndex* and the inverter capacity. If the building loads value is higher than the inverter capacity, in terms of absolute values, the first bottleneck remains the same as in the first version of the model. However, if the building loads are higher than the inverter capacity, they will take its place at bottleneck(1).

```
if totalenergy(maxHourIndex) >= -pbidi_cap_disch
  bottleneck(1) = energy_exchange(maxHourIndex)- pbidi_cap_disch ;
else
 bottleneck(1) = energy_exchange(maxHourIndex) + totalenergy(maxHourIndex);
end
```

One more change, closely connected with the *if-statement* above, is also needed at the very end of the battery storage model in order to eliminate the hours investigated for discharging from the time series. This change is implemented also by two additional *if-statements* that compare the relationship amongst the energy discharged by the battery, the building loads and the inverter capacity.

```
if totalenergy(maxHourIndex) <= -pbidi_cap_disch
  if (energy_exchange(maxHourIndex) <= -totalenergy(maxHourIndex))
     HourIndexExamined(maxHourIndex) = 0;
  end
else
  if (energy_exchange(maxHourIndex) <= pbidi_cap_disch)
     HourIndexExamined(maxHourIndex) = 0;
  end
end
```

Finally, the modelling issues regarding DST can be found at the end of Appendix D.

3.8.5 Deterministic nature of the model

Regarding its nature, the BSS model operates deterministically as there is no randomness involved; therefore, the same input always results into the generation of the same exact output. In more detail, after providing the necessary input to the model, the algorithm is followed and no hardcoded results are generated, including key output parameters such as the relationship between shifted and exported electricity that also affects consequent calculations, including the financial motive required. In this direction, it is important to demonstrate that the ratio between the annual shifted electricity and exports varies from scenario to scenario. In Table 3.13, exported and shifted electricity can be seen for a selection of buildings, for Operational Strategy E7 and a battery size of 220 kWh. It is clear that due to the deterministic nature of the BSS model, the ratio between the two parameters varies per building case and has a range of 0.80 – 0.97. Similarly, Table 3.14 presents the results for the same buildings, for a slightly smaller battery of 180 kWh for the same buildings where the respective range is comparatively higher between 0.86 – 1.02. Because of the smaller battery size and the prioritisation of load-shifting, the remaining battery capacity available for exports is also smaller and therefore the ratios are higher when compared to the initial values of Table 3.13.

Table 3.13 – Relationship between shifted and exported electricity under Operational Strategy E7 and BSS of 220 kWh (45/-65 kW) for a selection of buildings

Building ID	Electricity Shifted (kWh)	Exported Electricity (kWh)	Ratio
2r	39492.02	40841.72	0.97
5r	34970.89	45188.37	0.77
8r	38659.94	41662.63	0.93
29r	35554.72	44604.53	0.80
1rN	37125.97	43176.69	0.86
2rN	39991.22	40339.73	0.99

Table 3.14 – Relationship between shifted and exported electricity under Operational Strategy E7 and BSS of 180 kWh (45/-65 kW) for a selection of buildings

Building ID	Electricity Shifted (kWh)	Exported Electricity (kWh)	Ratio
2r	34421.42	33712.26	1.02
5r	31477.92	36596.17	0.86
8r	33873.13	34260.55	0.99
29r	31778.64	36295.45	0.88
1rN	32433.16	35700.53	0.91
2rN	34342.82	33790.86	1.01

3.8.6 Expected and actual BSS operation

In this section, the actual output of the model is compared against the expected operation of the BSS. For Operational Strategy E0 that does not allow exporting back to the grid, the battery is expected to operate one cycle per working day. Considering the fact that the BSS does not operate on weekends and the set non-working days, this translates into a total of 256 cycles per year. For a BSS of 240 kWh (80/-60 kW) and taking into account the minimum SOC of 10% and the discharging efficiencies of 97% and 96% for the battery and the inverter, respectively, the theoretical maximum BSS discharge is approximately 51491.64 kWh per year. Therefore, for validation purposes, it is important to investigate the actual BSS output of the models, compare them with the value in question and calculate the annual BSS utilisation rate (%). It should be pointed out that the actual BSS utilisation rate depends on the RTP data as well as the temporal distribution of the buildings' loads. Additionally, certain conditions need to be met in order for the BSS to operate, as explained earlier in Section 3.5.3. More specifically, the electricity prices during the buildings' operating hours need to be higher than the marginal cost of production (Equations 3.14 – 3.15). Furthermore, the amount of hours during which charging takes place has to be equal to the number of discharging hours and charging cannot take place without discharging and vice versa, as dictated by the algorithm and the operational dispatch strategy. The BSS outputs and utilisation rates are presented in Table 3.15, for a selection of buildings.

Table 3.15 – Annual BSS Utilisation rates for Operational Strategy E0 and BSS of 240 kWh (80/-60 kW)

Building ID	Electricity Consumption without storage (kWh)	Battery output (kWh)	BSS Utilisation Rate (%)
2r	161124.04	50740.15	98.54
5r	131416.75	48608.10	94.40
26r	163685.87	50549.94	98.17
29r	136035.60	48465.14	94.12
1rN	145614.41	50620.45	98.31
2rN	168390.74	50731.75	98.52
3rN	140367.66	50663.99	98.39
4rN	159129.84	50789.32	98.64

In more detail, the BSS rates for the majority of the buildings are very close to the maximum theoretical value of 100%. With the exception of Buildings 5r (HwBP80) and 29r (HwBP80-E), the rest of the building cases have achieved high utilisation rates between 98.31 – 98.64%; therefore, the model works as expected while it is important to investigate the lower rates of Buildings 5r and 29r. The two buildings in question belong to the Best Practice group and their electricity consumption is among the lowest of all the building scenarios investigated in the current thesis. This is also clear when comparing their consumption values (131416.75 and 136035.60 kWh, respectively) with the rest of the scenarios, whose range is between 140367.66 – 168390.74 kWh. Consequently, it is worth comparing the electricity profile of two buildings, one with a high utilisation rate (2r – 98.54%) and one with a relatively lower value (5r – 94.40%).

Looking at the arbitrage E0 results for the 13th March of 2017, for Building 2r, the BSS output reaches its maximum daily discharge value of 201.14 kWh while for Building 5r, the respective BSS daily output is smaller, at 141.42 kWh, a difference of approximately 60 kWh. The electricity profile of Building 2r can be seen below, in Figure 3.33 and it is clear that for that particular day, electricity prices are not significantly cheaper during the early hours of the day. Therefore, there is only a small window of 4 hours (8-10am and 4-6pm) during which the conditions are met and the BSS can discharge its capacity. In this specific case, the BSS discharges 55.87, 46.60, 42.80 and 55.87 kW/kWh for the four specific time periods. However, this is not the case when looking at the electricity profile Building 5r, in Figure 3.34, which has comparatively lower electric loads during its occupancy hours due to its higher thermal efficiency and improved airtightness. Despite that fact the BSS does discharge during the same 4 hours, the amounts of power/energy are smaller (31.83, 31.49, 33.56 and 44.54 kW/kWh) as all local loads are successfully met by the BSS. Therefore, the combination of low building loads and high electricity prices during the early (8-10am) and late (4-6pm) opening hours of the building as well as the absence of cheap electricity prices during several early hours of the day (midnight – 7am) resulted in a slight underutilisation of the battery, for Building 5r.

Summing up, the arbitrage model works as expected and the BSS utilisation rates are generally very high and close to the theoretical maximum. However, for limited cases of very efficient buildings that have smaller building loads throughout the day, utilisation can drop by up to four percentage points.

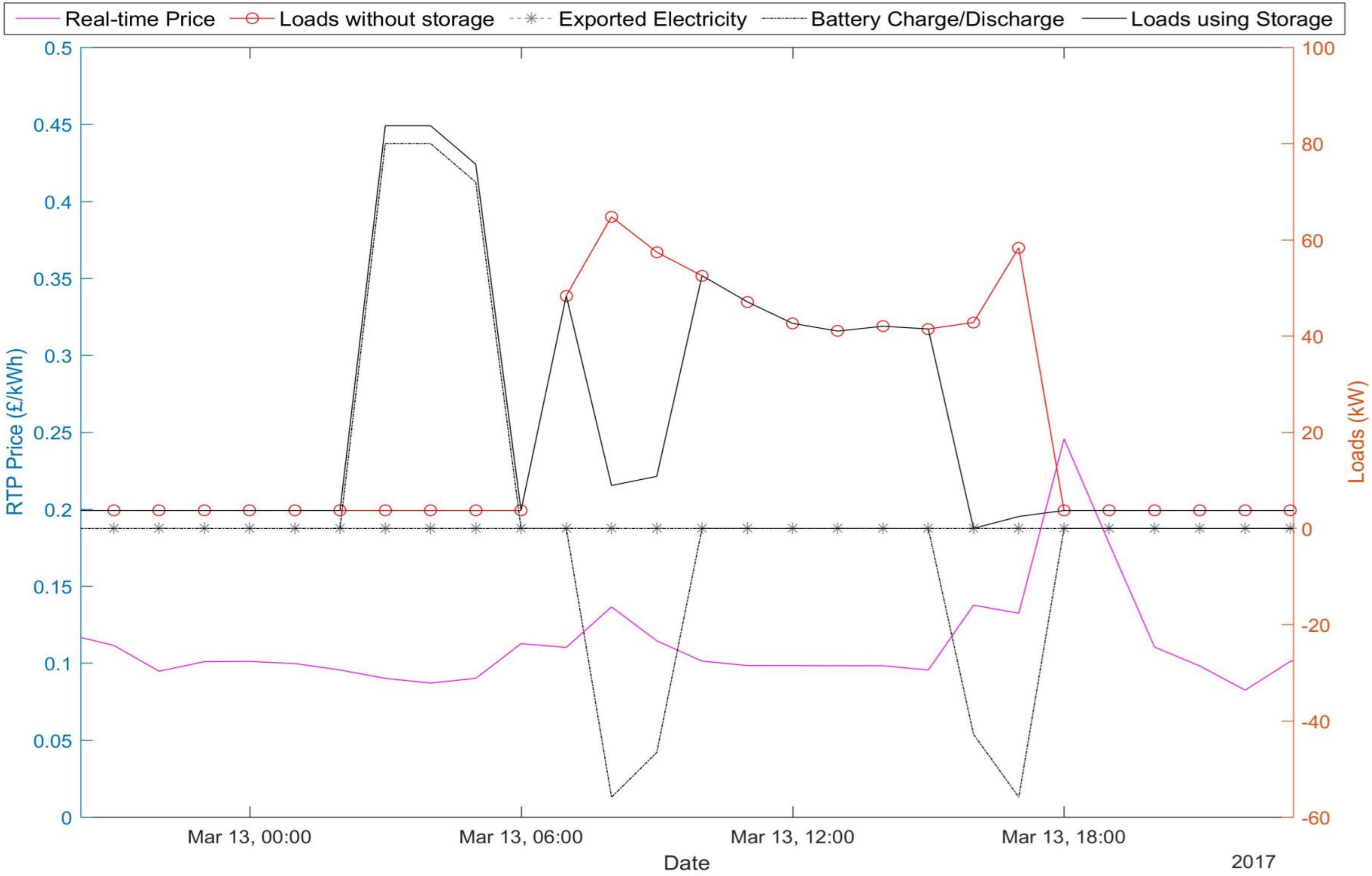


Figure 3.33 – Battery Operation (240 kWh, 80/-60 kW) on the 13th of March 2017 for Operational Strategy E0 and Building 2r (HwPL30)

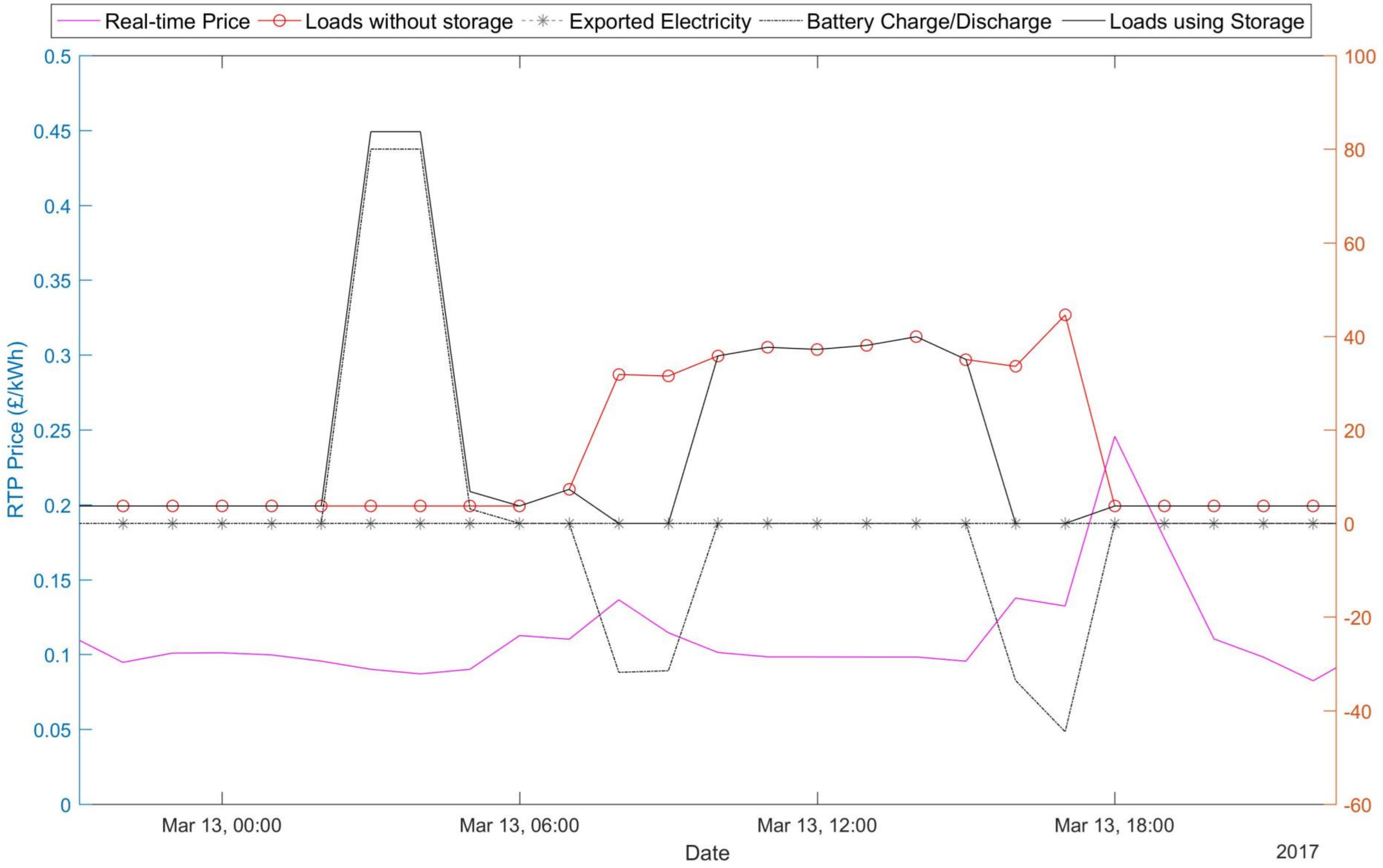


Figure 3.34 – Battery Operation (240 kWh, 80/-60 kW) on the 13th of March 2017 for Operational Strategy E0 and Building 5r (HwBP80)

3.8.7 Precision of the model input/output and data

Finally, this section presents more information regarding the precision and accuracy of the reported values in Chapters 4 – 7. More specifically, the arbitrage model receives two major types of input data, the hourly wholesale electricity prices and the building's hourly electricity consumption, for 1 year. Both these types of raw data have 2 decimal places and used by MATLAB in the consequent calculations of the model. All MATLAB variables of numeric nature used are double-precision arrays that include up to 15 decimal places. The majority of financial parameters, that constitute part of the arbitrage results and are presented in the current thesis, have been rounded to 4 decimal places for practicality and presentation purposes. It should be noted that electricity suppliers also use 4 decimal places for the definition of their unit rate. For example, the variable-flexible tariff offered by Octopus Energy in the last quarter of 2023 was £0.2652 or 26.52p/kWh [256].

Key input and output variables can be seen below, in Table 3.16, along with their units and precision and rounding specifications. When results are normalised in terms of the building's area, such as electricity consumption, net cost etc., rounding in 2 decimal places takes place, e.g. 3.55 kWh/m^2.

Table 3.16 – Precision of input/output data and rounding of the values as presented in the current thesis

Parameter	Source	Precision	Rounding	Example & Unit
Building's hourly Electricity Consumption & Power	DesignBuilder Simulation output	2 decimal places	N/A	45.12 kW (power) 45.12 kWh (electricity)
Wholesale Electricity Price	NordPool	2 decimal places	N/A	56.65 £/MWh
Wholesale Electricity Price	MATLAB Calculation	4 decimal places	N/A	0.5665 £/kWh
Retail Electricity Prices	MATLAB calculation	double-precision max. 15 decimal places	4 decimal places	0.0155 £/kWh
Financial Motive	MATLAB calculation	double-precision max. 15 decimal places	4 decimal places	0.1565 £/kWh shifted (Presented as 15.65p/kWh shifted)
LCOE	MATLAB calculation	double-precision max. 15 decimal places	4 decimal places	0.1122 £/kWh (Presented as 11.22p/kWh)
NPC	MATLAB calculation	double-precision max. 15 decimal places	0 decimal places	245,555 £

4. Building Simulation Results

In this chapter, the energy and thermal comfort results are presented for all 56 building models, 40 out of which are mechanically ventilated while natural ventilation is deployed in the remaining 16 models. The weather data for Birmingham, West Midlands, UK is used for all the simulated building cases. Firstly, the annual results for three building cases are shown for demonstration purposes, followed by a detailed comparison between key building characteristics follows, such as shape, orientation and ventilation strategy, for all building scenarios. Finally, the evaluation of buildings' thermal comfort is presented according to the ASHRAE Standard 55 and Fanger's PMV to ensure that the simulated building cases work correctly and are comparable in terms of performance.

4.1 Model Results Demonstration

In this chapter, the monthly results per building sector are presented for thee specific buildings in order to demonstrate the output of DesignBuilder models and the fact that each building's profile is unique. The daily building electricity consumption includes 6 different types of building loads that are listed below and have been presented in detail, in Chapter 3 and the end of Appendix A through the DesignBuilder schedule profiles used.

- Auxiliary loads (parasitic energy) due to fans, pumps and controls. Their hourly value is assumed to be constant for the entire simulation period. It should be noted that the relevant electricity consumption differs slightly on a monthly basis due to the unequal number of days included in each month.
- DHW loads to provide hot water to the building occupants during the opening hours. The same value is assumed for all occupancy hours. Slight variations can be seen from month to month due to the different number of working days contained in each month.
- Heating and cooling loads consumed by the GSHP to meet temperature set-point and set-back requirements (°C). These can vary on an hourly basis based on the environmental conditions.
- Lighting loads to achieve a satisfactory illuminance value (lux) which can vary on an hourly basis as well.
- Room Electricity refers to the loads required by the building equipment whose value is constant throughout the occupancy hours. A significantly lower power consumption is present, approximately 5% of the working-hours value , to account for the needs of the equipment's hibernation/sleeping mode.

Before discussing the individual results presented in Figures 4.1 – 4.3, it is important to note that these values represent the electricity amount consumed on a monthly basis, per building sector. The actual output of the models includes detailed building loads on an hourly basis; however, for presentation purposes, monthly values are discussed in the current chapter. Therefore, the amount of working days included within each month affect the results. For example, hourly equipment loads are always constant during occupancy and therefore the electricity consumed for equipment is the same on a daily basis.

However, as mentioned above, variations can be seen regarding the monthly electricity consumption values do fluctuate from month to month. The lowest values take place in February, April and December due to either a low total number of days included in the month in question (e.g. 28 days in February) or the inclusion of public holidays, such as Easter and Christmas, which result into a lower amount of working days.

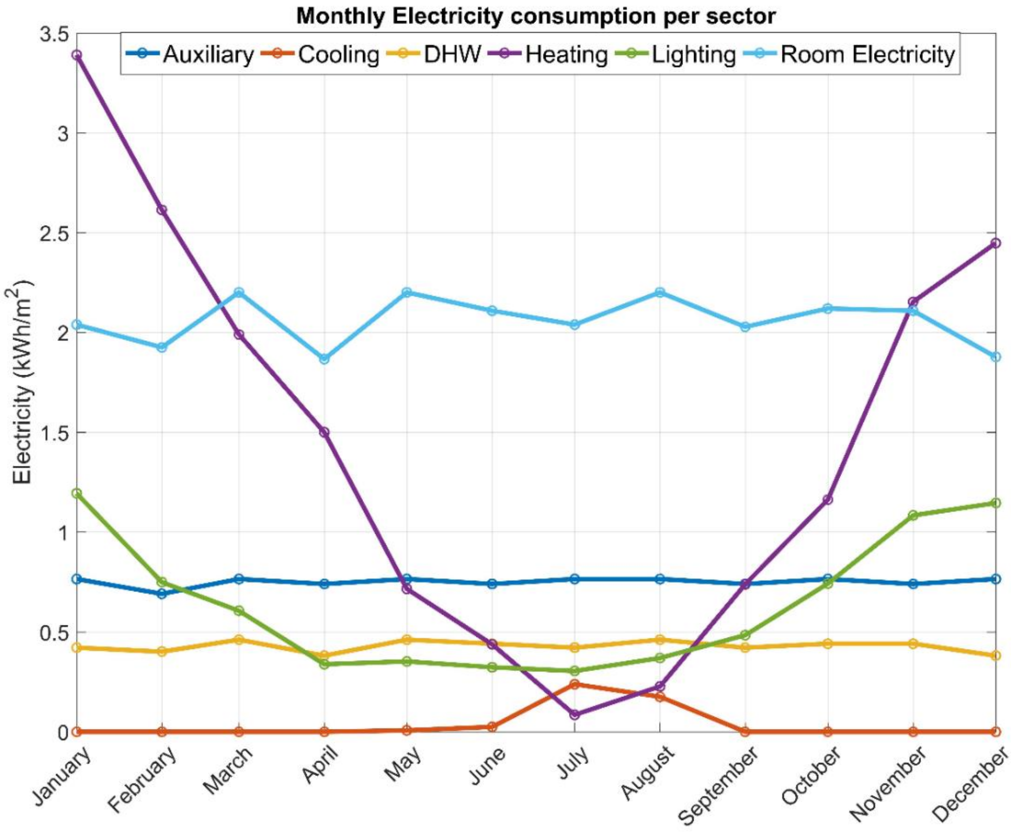


Figure 4.1 – Annual Electricity Consumption results per sector for Building HwPL30 (2r)

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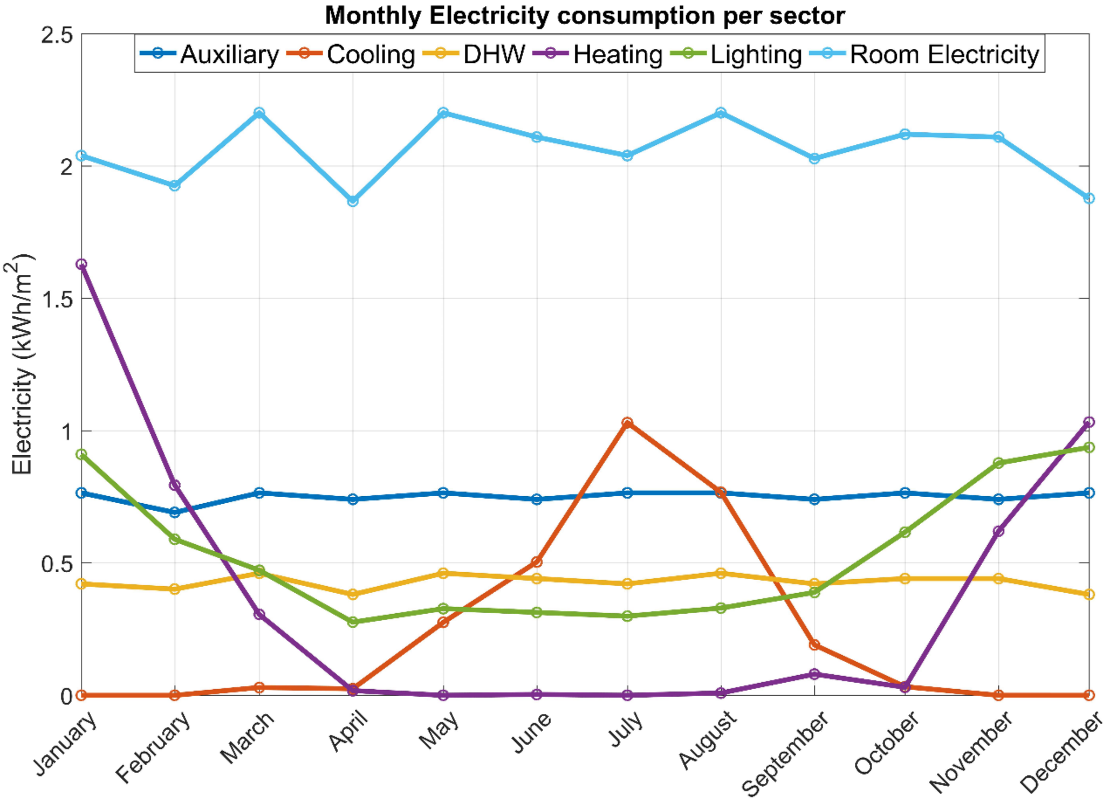

Figure 4.2 – Annual Electricity Consumption results per sector for Building HwBP80 (5r)

Regarding Building HwPL30/2r (Figure 4.1), auxiliary and equipment loads are largely constant throughout the year. Cooling loads are virtually non-existent for the majority of the year with the exception of the summer period; however, the respective peak value is approximately 0.25 kWh/m^2 in July, indicating that free cooling deployed through the economisers is sufficient for the cooling needs of the building. Heating is of particular interest as it appears to be the building's loads type with the highest variations, not only in monthly terms but seasonally as well. The highest heating loads take place in the winter time, reaching a peak value of around 3.4 kWh/m^2 in January. However, heating loads can be seen to continuously dropping between February and July when the lowest value of 0.1 kWh/m^2 is recorded. Finally, lighting loads remain in the same levels between April and August, around 0.35 kWh/m^2 with the values increasing during the autumn and winter periods due the lower amounts of daylight; a peak lighting consumption of 1.2 kWh/m^2 can be seen for January.

It is essential to briefly compare the monthly results per sector for different buildings in order to demonstrate the validity of the DesignBuilder model and its input. For example, Figure 4.2 illustrates the electricity consumption results for Building HwBP80 (5r) that differs in two key characteristics when compared with the previously presented and discussed building of Figure 4.1: higher energy efficiency for the fabric and higher window-to-wall-ratio. To begin with, the auxiliary, equipment and DHW loads are consistent and virtually identical in both building cases, as expected. On the other hand, major differences can be seen for the rest of the load types. Electricity consumption for cooling is now present for five months of the year and reaching a peak of 1 kWh/m^2 in July, an increase of three months and 300%, respectively when compared to Building HwPL30. This is due to the additional solar heat gains that take place due to the higher glazing percentage (80% instead of 30%) that leads to a total annual consumption of 2.85 kWh/m^2, an overall increase of 550%. Additionally, while lighting can be seen to follow a very similar profile, the lighting loads are generally slightly lower both in a monthly and annual basis.

Similarly to cooling, the extra solar heat gains have also affected the electricity profile for heating purposes as lower amounts of electricity are now required to condition the building and control its internal temperature to the required values. It is important to point out that heating needs are insignificant or even zero between April and October, a significant change when compared to Building HwPL30 (2r), with the total annual heating demand being reduced from 17.46 to 4.52 kWh/m^2 (-74%). Summing up, due to the extensive electricity savings on heating as well as the additional savings on lighting, Building HwBP80 (5r) has proven to be the most energy efficient of all 56 building models due to the combination of its key characteristics, mentioned and discussed above. While cooling loads have increased, their contributions are deemed to be trivial when compared to heating and the total electricity consumption savings.

Finally, it is important to discuss the results of a naturally-ventilated building, HwPL30* (Figure 4.3), which is identical to the building case presented in Figure 4.1 (HwPL30) with the ventilation strategy constituting the only change. More specifically, electricity consumption for auxiliary loads is 66% smaller due to the lower needs for fans, pumps and controls while there are no cooling loads. The lighting needs remain exactly the same and no differences can be seen either on a monthly or an annual basis. Nevertheless, heating's electricity profile is now structurally and quantitatively different because of the significant external infiltration entering the building. Therefore, it is clear that there are heating loads present during all the months of the year with the only exception of July. It can be observed that certain out-of-pattern heating variations take place between February and May. While some of them could be potentially explained by looking at the number of working days included in each month, May's heating loads indicate this might not be the reason as the differences are significant.

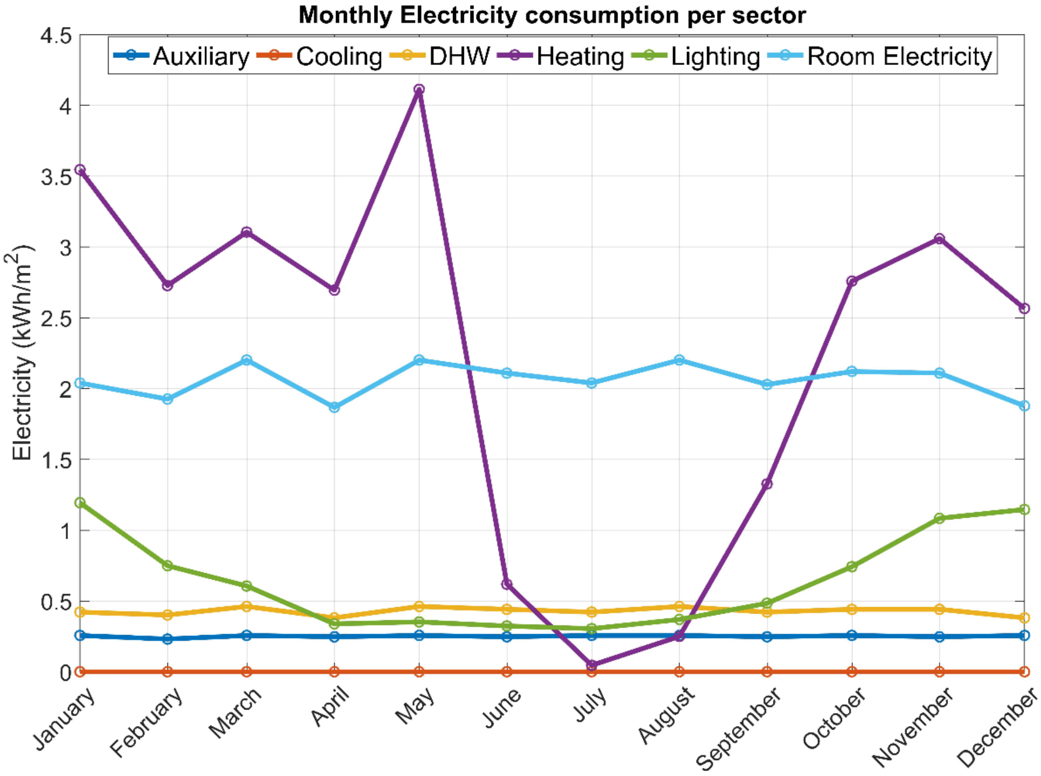

Figure 4.3 – Annual Electricity Consumption results per sector for Building HwPL30* (2rN)

It should be reminded that external infiltration now constitutes an additional parameter that affects the temperature balance of the building throughout the year. External infiltration varies and its values fluctuate based on several meteorological and weather factors such as pressure differences and wind speeds. The resulting thermal losses also fluctuate, as seen in Figure E1 of the Appendix, for the building model in question. The higher amounts of external infiltration for May and certain months support the heating fluctuations of Figure 4.3 and therefore the building model seems to be functioning well. Overall, it is clear that heating loads can be unpredictable and their pattern and values are now even more susceptible to the variation of external weather conditions. Nevertheless, Building HwPL30* consumes 67.36 kWh/m^2 per year which is 2.9 kWh/m^2 higher than the respective mechanically-ventilated building case.

4.2 Electricity Consumption

The electricity consumption results from the Building Simulations are presented in detail, in Tables E1 and E2 of the Appendix for mechanically-ventilated and naturally-ventilated buildings, respectively. All six building load types can be seen along with the total amount of electricity consumed by each building case, normalised by area, in kWh/m^2. Some quick observations can be made:

a) The DHW annual consumption of 5.13 kWh/m^2 is the same for all building cases regardless of ventilation type. This is expected due to the way DHW loads have been modelled.

b) Auxiliary loads are also the same in all building cases; however, the exact value depends on the ventilation strategy. More specifically, 9.01 kWh/m^2 per annum are consumed for mechanically-ventilated buildings per while the respective annual value is 3.01 kWh/m^2 for buildings using natural ventilation.

c) Room equipment requires the same amount of electricity for all building cases regardless of ventilation strategy with a value of 24.71 kWh/m^2 being required.

d) Cooling loads are non-existent for naturally-ventilated buildings; therefore, the respective column has only been added in Table E2 for completion purposes to demonstrate that fact.

e) Based on the above (a-d), the energy performance of the different building cases and their consequent comparison in this Chapter focuses on heating and lighting loads for naturally-ventilated buildings while cooling constitutes an additional factor for mechanically-ventilated buildings.

The annual consumption of electricity can be seen graphically for all building cases, in Figure 4.4. The separate consumption for heating, cooling and lighting purposes are shown in Figures 4.5, 4.6 and 4.7, respectively. First of all, it can be noticed that the results of Figure 4.4 can be further categorised in two groups. In more detail, the first group contains the Part L building cases and has a higher range of values between 61.24 – 68.39 kWh/m^2 while the second group includes the Best Practice cases with a lower range between 52.57 – 59.15 kWh/m^2. The respective mean values are 63.74 for the Part L building cases and 55.63 kWh/m^2 for Best Practice, an average difference of 8.11 kWh/m^2 which translates into 20,275 kWh of electricity consumption for a year. Therefore, the fabric's energy efficiency in terms of thermal insulation and airtightness constitutes the most important parameter in regard to its overall energy consumption. Its significance cannot be overstated as its impact is clear and consistent throughout all the building models regardless of the other building design characteristics including ventilation.

Furthermore, looking inside the Part L and Best Practice groups for mechanically-ventilated buildings, it can be observed each group is further divided into two subgroups based on the overall electricity consumption. The subgroup with the higher values consists of the building cases with 30% glazing while all 80% glazed buildings require comparatively lower amounts of electricity. This is also expected as higher window-to-wall ratio results in a larger amount of thermal solar gains while the glazing's low U-values keep the heating losses to very small levels. It should be noted that no such comparison can be made for naturally-ventilated buildings as only the glazing option of 30% was selected and simulated. Additionally, the building's shape does not seem to affect the results in any significant way when looking at Buildings 1s – 8s and 1r – 8r.

Regarding the thermal mass impact on the results, heavyweight buildings appear to be less energy efficient for all naturally-ventilated buildings and the Part L mechanically-ventilated buildings. However, they appear to consume slightly less energy when it comes to the Best Practice mechanically-ventilated buildings with the difference being marginal in some cases. Finally, it is evident that adopting natural ventilation leads to higher energy consumption for almost all building scenarios. Nevertheless, there is a limited number of Best Practice building exceptions with have either a south-eastern or an eastern orientation. In detail, Buildings 1r – 4r consume between 55.79 – 64.45 kWh/m^2; replacing mechanical with natural ventilation leads to the respective range of 58.25 – 67.36 kWh/m^2 for Buildings 1rN – 4rN. This is expected as the increased levels of external infiltration as well as the windows operation that results in significant thermal losses. The groups and subgroups, based on the building electricity consumption of Figure 4.4, can be seen in Figure E2 of the Appendix.

It is also worth examining the impact of thermal mass on the heating and cooling loads, separately. For buildings with mechanical ventilation, a heavy thermal mass results into a higher electricity consumption for heating by 0.91 kWh/m^2 while loads for cooling are smaller by 0.83 kWh/m^2, on average. It should be highlighted that this reduction of cooling loads is not generally considered to be significant and not as high as expected. This can be attributed to the fact the cooling loads of the buildings are generally small due to the relatively high efficiency of the GSHP. When natural ventilation is used, while there are no cooling loads present to make a comparison, heavyweight buildings require higher heating loads by 2.55 kWh/m^2, on average. This increase is higher than the respective value for the mechanically-ventilated cases due to the higher external infilitration.

Concerning the electricity consumption towards heating and Figure 4.5, a very similar pattern is present as results can still be divided in two groups based on the fabric’s energy efficiency. When mechanical ventilation is used, the Part L group has a range of electricity values between 12.33 – 17.84 while the respective values for Best Practice Buildings are 4.25 – 9.14 kWh/m^2. As mentioned above, 80% glazed buildings experience higher thermal solar gains which result into a reduction of the heating loads and the consequent required electricity for heating. Moreover, it should be pointed out that the results for the naturally-ventilated buildings follow a similar pattern when it comes to its groups and subgroups.

Regarding heating loads and ventilation strategy, Best Practice Buildings with natural ventilation are comparable to mechanically-ventilated Part L buildings. For example, Buildings 1r – 4r consume between 7.73 – 17.46 kWh/m^2 for heating while the respective range for Buildings 1rN – 4rN is 15.60 – 26.80 kWh/m^2. While it is clear that natural ventilation leads to higher overall building loads (Figure 4.4), comparing the heating loads separately reveals that significantly greater amounts of electricity are required to heat the exact same building. Regarding the shape’s impact on heating demand and consequent electricity, it can be noticed that square buildings do require slightly higher amounts of energy than the rectangular-shaped cases. The building groups based on the heating electricity consumption of Figure 4.5 can be seen in Figure E3.

It is important to note that, while heating demand plays a major role towards the total electricity used, it does not always reflect the building’s energy trends or overall energy needs. For example, thermal mass does affect the electricity consumption for heating purposes as discussed above; however, when taking into account the rest of the building sectors, the difference in the total consumption can be minimal depending on the scenario. Similarly, while it is clear that heating demand is particularly greater in naturally-ventilated buildings, it should be reminded that the auxiliary energy required for the HVAC system to operate in mechanically-ventilated buildings is 9 kWh/m^2 per annum, higher than the respective value of 3 kWh/m^2 for buildings with natural ventilation. Finally, it is important to highlight that heating demand is not equal to the respective electricity consumption; therefore, the amounts of thermal and electrical kWh are different and heating demand is 3.5 times higher due to the GSHP CoP value.

Cooling electricity consumption (Figure 4.6) constitutes a comparatively less important parameter as its range for all the mechanically-ventilated buildings is between 0.44 – 3.75 kWh/m^2. While there are some differences taking place based on the building design characteristics, it is clear that the most vital parameter in regard to cooling is the window-to-wall ratio. More specifically, Buildings 1r – 4r (30% glazed) have a cooling electricity consumption between 0.44 – 1.73 while increasing their glazing to 80% require 2.16 – 3.52 kWh/m^2 (Buildings 5r – 8r). Similarly to heating, the cooling demand is 5 times higher than the actual electricity consumption for cooling because of the heat pump performance.

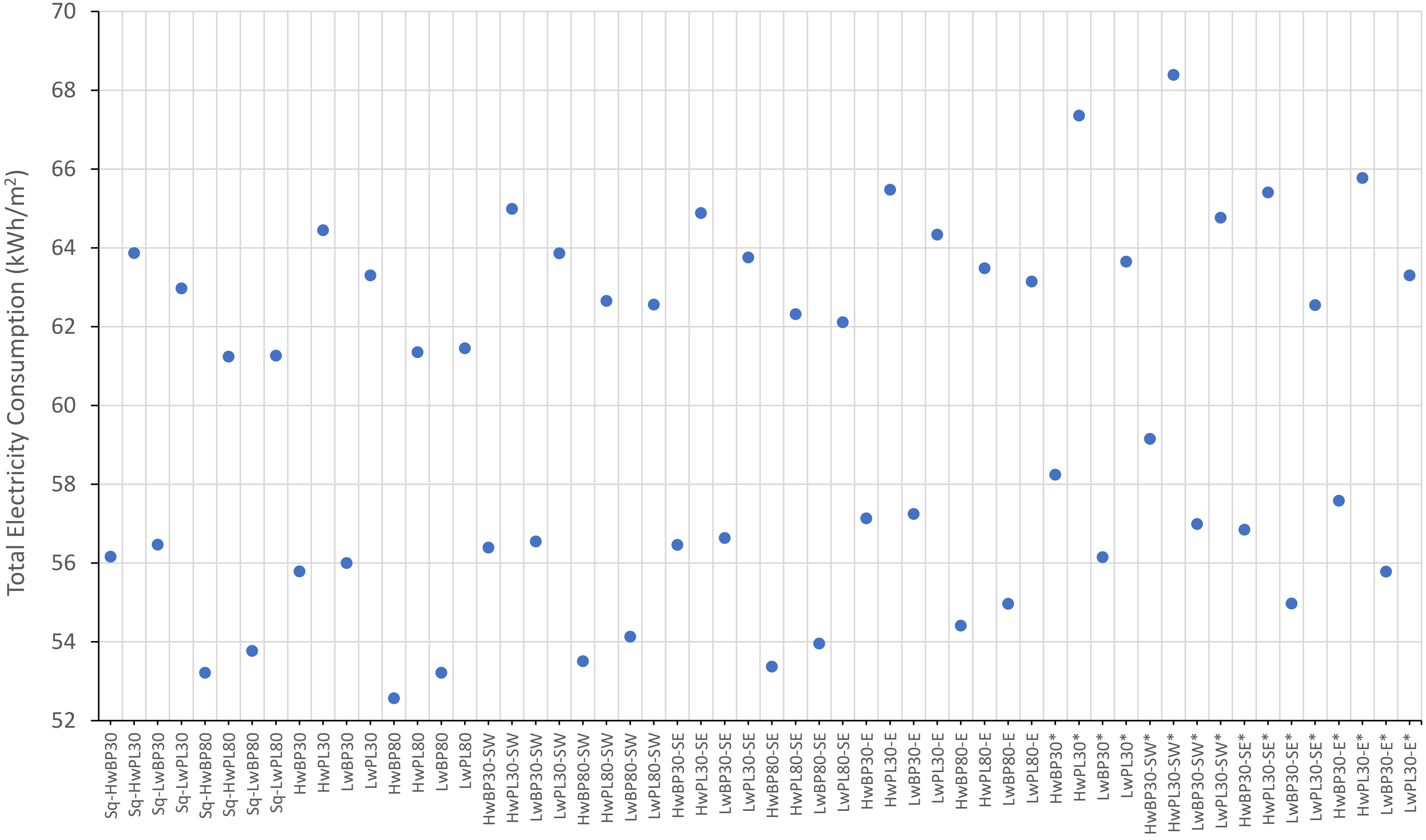

Figure 4.4 – Total Electricity Consumption (kWh/m^2) for all building models

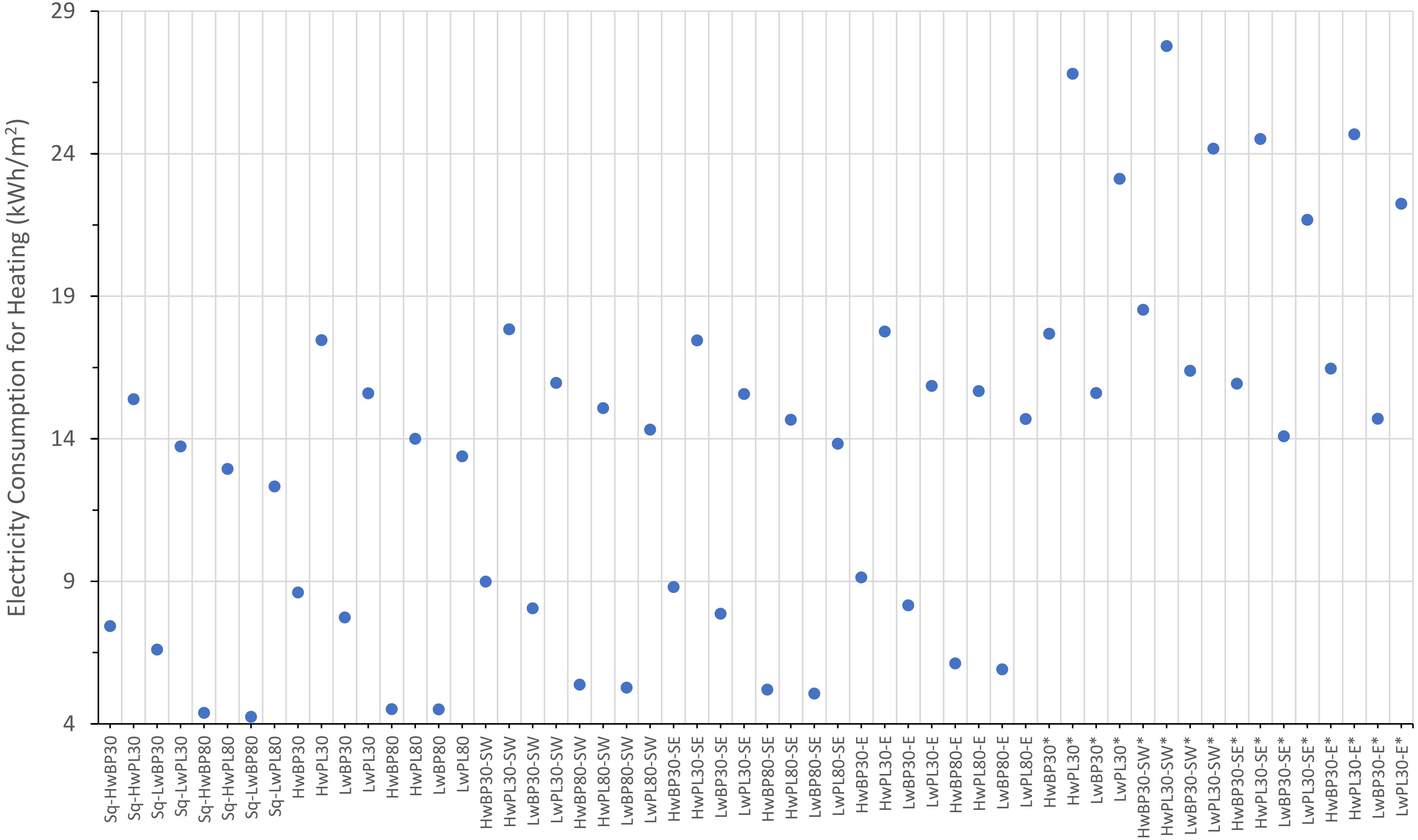

Figure 4.5 – Electricity Consumption for Heating (kWh/m^2) for all building models

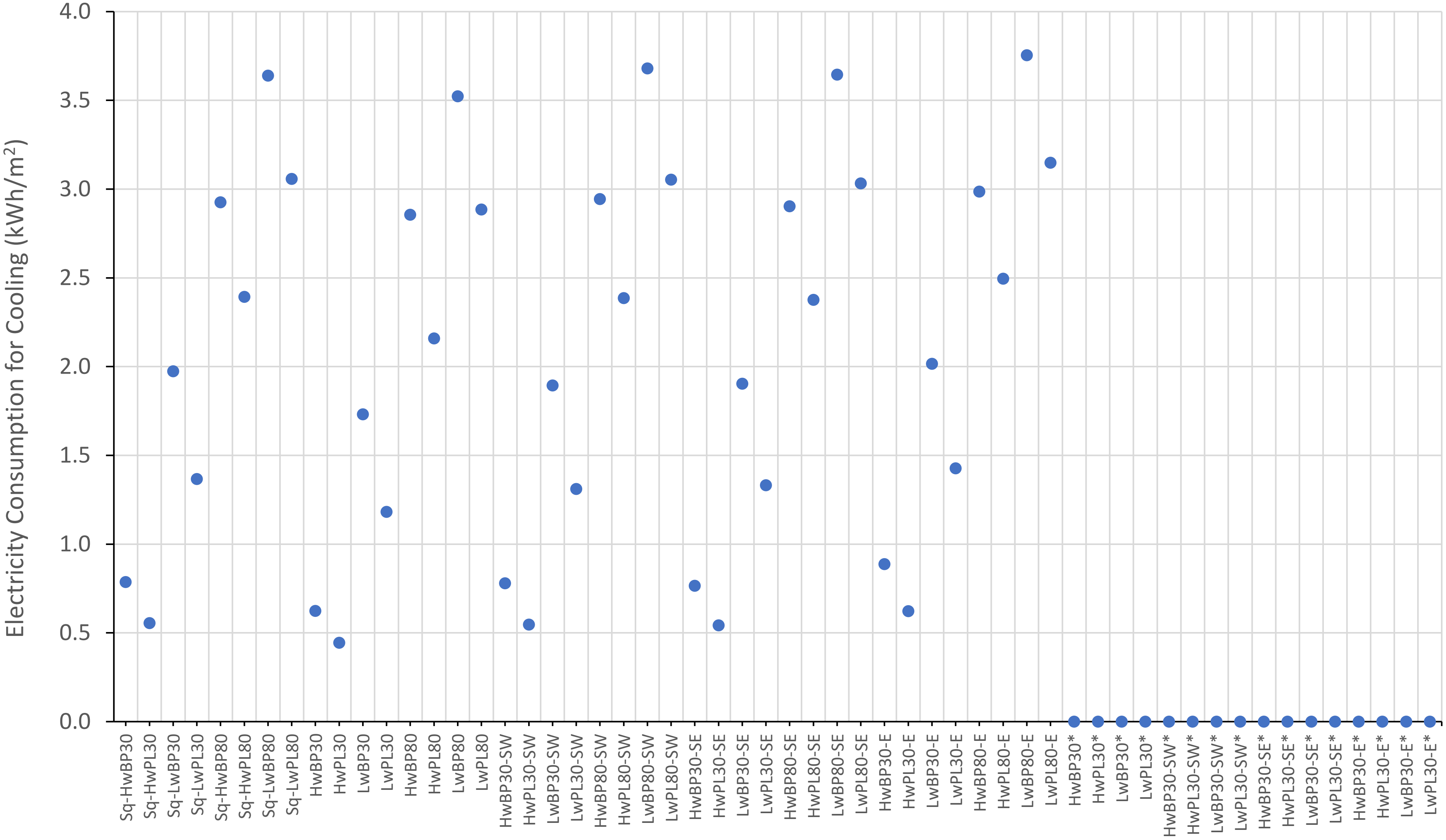

Figure 4.6 – Electricity Consumption for Cooling (kWh/m^2) for all building models

Focusing on the last remaining major type of building loads, lighting, the results can be seen along with a brief analysis in Figures E4 – E5. The building shape is a significant parameter as Square Buildings 1s – 4s consume approximately 9 kWh/m^2 while rectangular Buildings 1r – 4r have lower requirements, around 7.70 kWh/m^2. Ventilation strategy does not lead to any differences in lighting consumption while it is clear that when adopting different building orientations, the lighting consumption increases slightly when moving away from the Southern-Northern initial orientation.

Additionally, the second most major design parameter that affects lighting is the window-to-wall ratio as a higher glazing percentage is translated into increased levels of daylight. For a quick comparison, rectangular Buildings 1r – 4r which are 30% glazed consume 7.70 kWh/m^2 while Buildings 5r – 8r and the higher glazing setting need 6.33 kWh/m^2, resulting in an average difference of 1.37 kWh/m^2. Summing up, two parameters, glazing and shape, do have an impact on the electricity consumption needed for lighting. However, as the range of the observed values is between 6.33 and 9.09 kWh/m^2, the significance of this impact is debatable and potentially insignificant.

Summarising the electricity consumption results of the building simulations, the fabric's energy efficiency clearly constitutes the most significant building parameter as lower amounts of insulation and higher levels of external infiltration result in noticeably higher energy demand and therefore electricity consumption. Increasing the window-to-wall-ratio from 30% to 80% reduces the electricity needs for all building scenarios, by around 2.40 kWh/m^2 on average. Regarding thermal mass, results are inconclusive as the differences between heavyweight and lightweight buildings are not significant when mechanical ventilation takes place. However, when natural ventilation is adopted, it is evident that lightweight buildings perform significantly better than their heavyweight counterparts to the point that they are comparable to the respective mechanically ventilated building cases; however, lightweight buildings result into higher levels of discomfort as presented in Chapter 4.3. Finally, natural ventilation leads to higher electricity loads with a small number of exceptions belonging to buildings with Eastern-Western orientation. Lightweight buildings with natural ventilation achieve similar values with their mechanically-ventilated counterparts, as previously discussed.

4.3 Thermal Comfort

While the primary focus of this chapter and the current research is on the electricity consumption of the simulated buildings, it is also essential to assess if they are thermally comfortable to the occupants, based on the criteria set in Section 3.3.12 and more specifically Fanger PMV and ASHRAE 55 Standard. Evaluating thermal comfort also ensures that the simulated building cases are comparable in terms of performance which is important for battery deployment. The percentages of occupancy hours with thermal discomfort are presented in detail, in Figures E6 – E7 of the Appendix as well as in Tables E3 – E4. As mentioned in the methodology, a percentage of occupants dissatisfied with the building's thermal comfort of 5% is considered to be satisfactory and therefore it is vital to point out any building cases which exceed this value, if any.

Looking at the results, it is clear that the majority of the building cases have lower thermal discomfort percentages than the threshold value. In fact, 75% of the cases have a discomfort less than or equal to 2.5% following the ASHRAE procedure while that value increases to 3.5% for Fanger PMV. For both standards, only 4 building cases exceed the set limit: Sq-LwBP80, LwBP80-SW, LwBP80-SE and LwBP80-E. At the same time, LwPL80-E has a thermal discomfort value of 5.06% based on ASHRAE but the respective Fanger PMV is 4.30%.

Nevertheless, it is evident that all discomfort cases include variations of the same building in regard to its shape and orientation. This specific building is lightweight, Best Practice and 80% glazed and all the scenarios considered, which include a rectangular or a square shape as well as all four different orientations, lead to thermal discomfort beyond acceptable levels.

Based on ASRHAE 55, Building Sq-LwBP80 has achieved a thermal discomfort of 6.65% while its rectangular version has a respective value of 4.85% which is near the set limit. As long as the orientation of the building moves away from the original Northern-Southern direction, thermal discomfort intensifies and reaches approximately 10% for the Eastern-Western orientation. The combination of low thermal mass and the consequent insignificant thermal lag with high glazing and the increased amount of solar heat gains results into elevated levels of discomfort. While it may initially seem unexpected for a group of Best Practice Buildings to have uncomfortable levels of thermal comfort, much higher than the respective Part L Buildings that are characterised by lower energy efficiency, this can be easily explained when taking into account the differences between the two energy efficiency groups.

The envelopes of Best Practice Buildings do not only have lower U-values and thermal transmittances but also more effective airtightness, minimising the levels of external infiltration. On the other hand, this additional infiltration that takes place in Part L Buildings translates into significant heat losses during the winter, resulting in extra heating demand and electricity consumption. At the same time, it also provides extra cooling during the summer period by lowering the temperatures within the acceptable ranges, improving in this way the occupants' thermal comfort. Consequently, Best Practice Buildings can potentially become "airtight vessels" should certain building design characteristics are adopted and more specifically high window-to-wall-ratio and light thermal mass. This is clearly a design issue that can be rectified through the implementation of several strategies such as lowering the set-point temperature, and adopting a suitable shading strategy. However, this is considered to be outside the scope of the current project as it is important for all building cases to have the exact same simulation settings in order to be comparable with each other.

Besides this anomaly, it is shown that neither orientation nor the building shape affects the results in any significant way, for all mechanically-ventilated buildings. Several 80% glazed buildings seem to provide a higher thermal comfort when compared to their lower wall-to-ratio counterparts, indicating that that the increased amounts of solar heat gains in the winter result into better thermal comfort during the winter period whilst performing satisfactorily in the summer as well. Finally, it is clear that natural ventilation in combination with the problematic Easter-Western orientation can lead to elevated levels of thermal discomfort. Despite that, the thermal comfort of all naturally-ventilated buildings is within the set limits, providing very similar results to their mechanically-ventilated counterparts and in certain cases performing even better.

Finally, it should be noted that results from both standards are similar and while small numerical differences do appear due to the methodologies followed, they provide a consistent reflection of the thermal discomfort taking place in all building models. Despite the fact that Fanger PMV values include higher levels of variation, the differences are not significant and therefore the vast majority of the buildings meet the comfort criteria set in the methodology section. In fact, problematic buildings have been identified in both standards for the reasons explained above.

4.4 Summary

In this chapter, a demonstration and discussion of Building Simulation Results have been conducted in order to validate the DesignBuilder model and its input. Additionally, detailed results have been presented using several figures for all building scenarios while the impact of essential design characteristics has been discussed along with their thermal comfort performance. Summarising:

- The electricity consumption results differ from building to building in terms of heating, cooling and lighting as equipment and DHW loads are always the same. Auxiliary loads are the same for buildings with the same ventilation strategy.

- Monthly electricity results are affected by the number of working days included inside each calendar month. A higher number of weekends and public holidays can lead to false impressions that a building can be more energy efficient during specific month(s) of the year.

- The methodology followed to model natural ventilation adds the external infiltration, and therefore local weather conditions, as a parameter that leads to significant thermal losses.

- The fabric's energy efficiency constitutes the most important design characteristic as it leads to significant differences in the total electricity consumption, demonstrating the significance of the envelope's U-values and external infiltration.

- While some differences do take place, thermal mass does not affect the electricity results in any significant way for the mechanically-ventilated buildings. On the other hand, it is clear that lightweight buildings consume less electricity than their heavyweight counterparts when natural ventilation is in place.

- Window-to-wall-ratio is the second most important design characteristic. Generally, increasing glazing from 30% to 80% leads to a critical reduction of electricity towards heating and lighting while cooling consumption increases; nevertheless, this increase is deemed to be comparatively much smaller than the heating and lighting changes.

- Using natural ventilation instead of mechanical results in an overall increase of electricity consumption as the heating profile changes fundamentally due to the extra amounts of external infiltration.

- The vast majority of the building cases provide satisfactory thermal comfort to the occupants, based on both ASHRAE 55 and Fanger PMV.

However, as the current research evaluates the arbitrage potential of building cases with different design characteristics, using BSS, the annual and monthly electricity consumption results, while very useful, cannot provide a complete picture in this direction. Arbitrage and other balancing services provided by ESS take place on an hourly basis and therefore it is essential to include all building cases for the BSS simulations (Chapter 5) to be able to make the proper observations and reach the proper conclusions. Therefore, excluding building cases based exclusively on the results in the current chapter would not be appropriate.

5.Arbitrage Results

In this chapter, the Arbitrage Model results are presented for all building cases, considering the 2017 electricity prices and Birmingham IWEC as the weather climate data. While multiple battery sizes have been simulated, it was deemed impractical to introduce and analyse all results, especially since the performance of many buildings is very similar for the smaller battery sizes. Therefore, the results for the biggest battery size of 220 kWh, with a rectifier capacity of 45 kW and an inverter capacity of 65 KW (45 kW/-65 kW), are discussed in detail while the rest of the systems are presented as part of the Sensitivity Analysis chapter which includes several other parameters.

5.1 Introduction and Demonstration of the Model

The following parameters are used to compare the main output results of the model:

- Electricity shifted (% of peak loads) refers to the amount of electricity shifted from the peak periods to the off-peak periods of the day as a percentage of the building's peak loads. Any electrical loads which take place between 8am-6pm are considered to belong to the peak category in accordance with the building's activity profile, as set in Section 3.3.10.

- Electricity exports (kWh/m^2) is the amount of excess electricity stored in the battery and sent back to the electrical grid. Exports are allowed only under the E7 and E5 operational strategies.

- Electricity shifted (kWh/m^2). While this parameter seems to be quite similar in nature to the first, its unit is fundamentally different and refers to the total amount of electricity shifted from peak to off-peak periods of the day. It plays a minor role in the results, especially when compared with the shifted electricity as a percentage of the peak loads.

- Electricity Net Cost (£/m^2) is a financial variable that measures the net cost of electricity needed to cover all building loads considering the expenses as well as the revenue stream from the exports. Other expenditures (e.g. capital) are not considered in its calculation.

Regarding the CBA presented in Chapter 7, three additional key economic variables are used:

- Net Present Cost (NPC) includes all the negative and positive future cash flows over the entire life of the project, discounted to the present, taking into account interest and inflation rates. Capital and maintenance costs are included in its calculation.

- Levelised Cost of Electricity (LCOE) is often used to compare power generating technologies. It reflects the cost of electricity per kWh for the entire duration of the project and is calculated using the NPC value.

- Financial motive (£/kWh) needed is of paramount of importance as it constitutes the building reward required in order to make the NPC of the BSS arbitrage scheme equal to the no storage scenario, covering in this way all the additional expenses, such as capital and maintenance costs.

Before presenting and discussing the results for all building cases, it is essential to briefly demonstrate the concept of arbitrage for all three dispatch strategies and how its operation affects the electricity profile of a building. In this direction, Figure 5.1 presents in detail the arbitrage results for Operational Strategy E7 and Building HwPL30 (2r), including real-time electricity prices, electricity exports, building loads with and without the utilisation of storage as well as the battery charging/discharging operation. The results refer to the period between 19th – 21st of February 2017 which consists of one non-working day (Sunday) and two consecutive working days (Monday and Tuesday).

As E7 allows the operation of the BSS on non-working days, the battery charges during the early hours of Sunday (2 – 6am, 7 – 8am) and later the same afternoon (2 – 4pm) at times when particularly low electricity prices apply, reaching a minimum value of £0.095/kWh. The battery discharges at different periods during the day (noon – 1pm, 5 – 8pm) when prices are significantly more expensive, exceeding £0.20/kWh between 6 – 7pm. The operation of the battery consists of two activities:

- Meeting the auxiliary building loads which remain constantly at 3.72 kW. As the battery stands at a total capacity of 220 kWh, it can cover the entirety of these loads for the hours that it is active and at its discharging phase.
- Exporting the remaining of its capacity back to the grid. As an inverter of 65 kW is used, the vast majority of the electrical energy is returned back to the grid.

The following day is Monday, a working day; therefore, the battery charges between midnight and 5am and is later discharged during the working hours of the building, at various capacities, between 9 – 11am and 5 – 6pm. For the former time period, the building's electricity profile is reduced dramatically from 86 to 26 kW while for the latter the grid purchases decrease from 88 to 28 kW. As the building loads are constantly high during working hours, there is no electrical energy left in the battery to be exported back to the grid. For the final day shown, the BSS operates in the same way, exclusively covering the local loads; however, the exact time periods of charging and discharging as well as the power capacities utilised by the rectifier and the inverter are always unique as the hourly electricity prices are different on a daily basis.

The arbitrage results for Operational Strategy E5 are shown in Figure 5.2, for the same BSS configuration and building, between 8th – 10th of October 2017 that similarly includes one non-working day (Sunday), followed by two working days (Monday and Tuesday). It is evident that the battery remains idle for the first day as exports are not allowed and no significant building loads are present. For the rest of the days, building resumes its normal working operation and during the battery's discharging phase, purchases from the grid are again reduced and there is a time period (8 – 10am for Monday, 9 – 11am for Tuesday) when the electricity purchases from the grid are zero, making the building self-reliant during peak times. Furthermore, during these times of self-reliance, there is a small amount of electricity exported back to the grid, with its respective power varying between 5 – 9 kW. This key difference takes place because the building's energy demand for October is relatively lower when compared with the winter month of February, as shown in Figure 5.1, leaving additional energy stored in the battery to be used locally and even to be sent back.

Finally, Figure 5.3 illustrates the arbitrage results for the final Operational Strategy E0 that prohibits any exports, between 20th – 22nd of August 2017. Similarly to E5, there is no battery activity on the first day (Sunday) and any battery discharges are automatically translated to the reduction of the grid purchases through covering the local building loads.

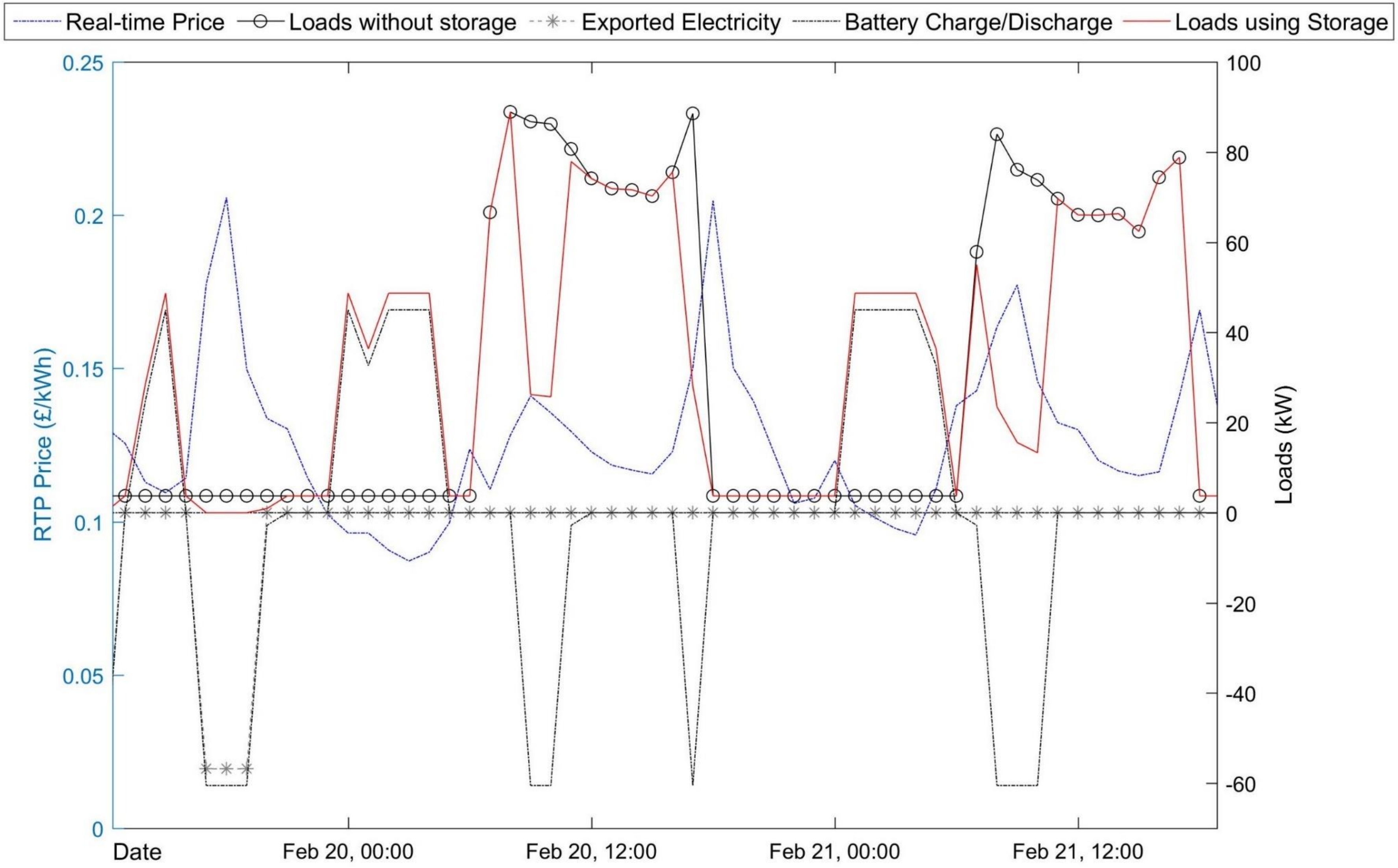

Figure 5.1 – Operation of BSS and its impact on the electricity profile of Building HwPL30 (2r) for Operational Strategy E7 (220 kWh, 45/-65 kW)

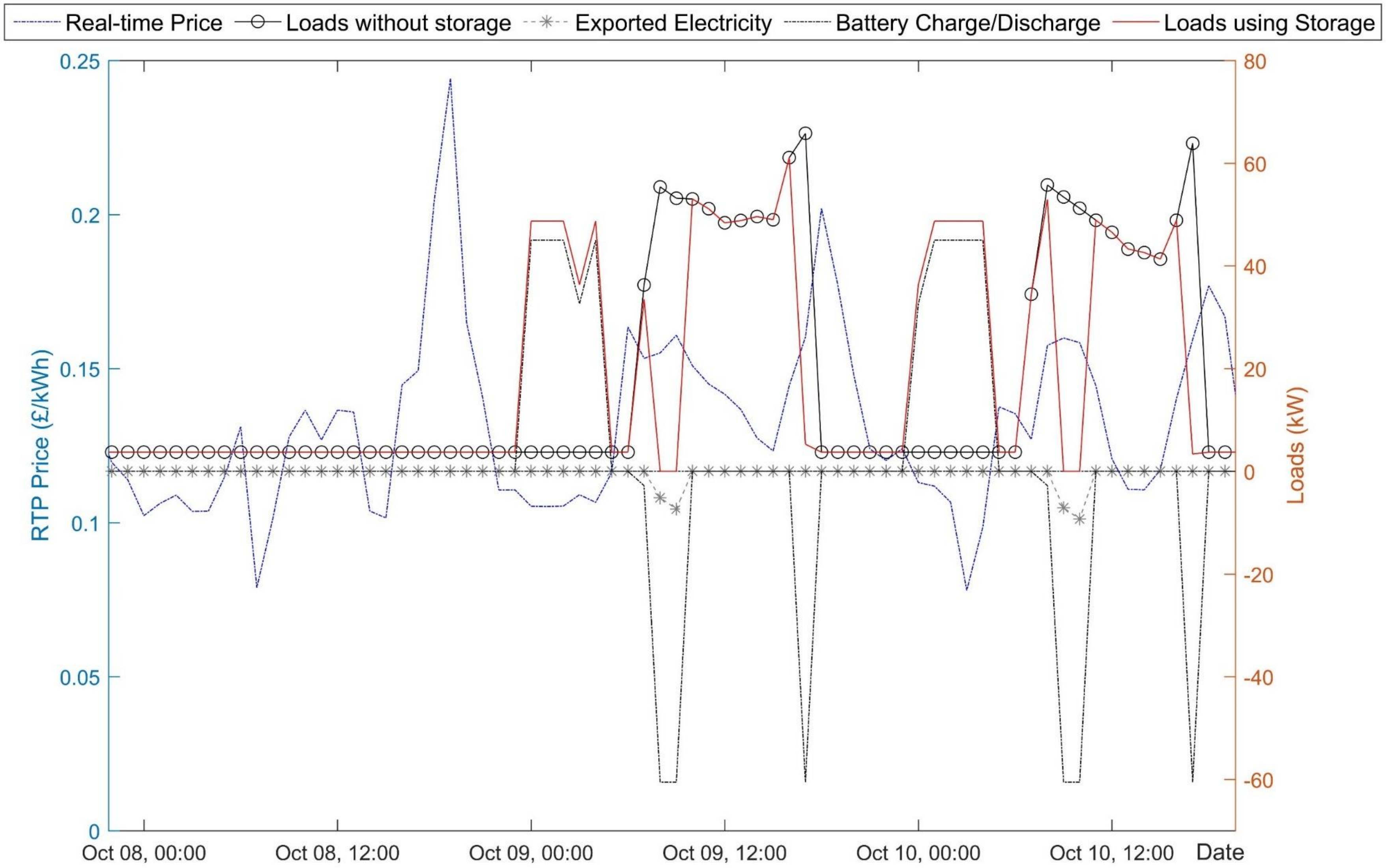

Figure 5.2 – Operation of BSS and its impact on the electricity profile of Building HwPL30 (2r) for Operational Strategy E5 (220 kWh, 45/-65 kW)

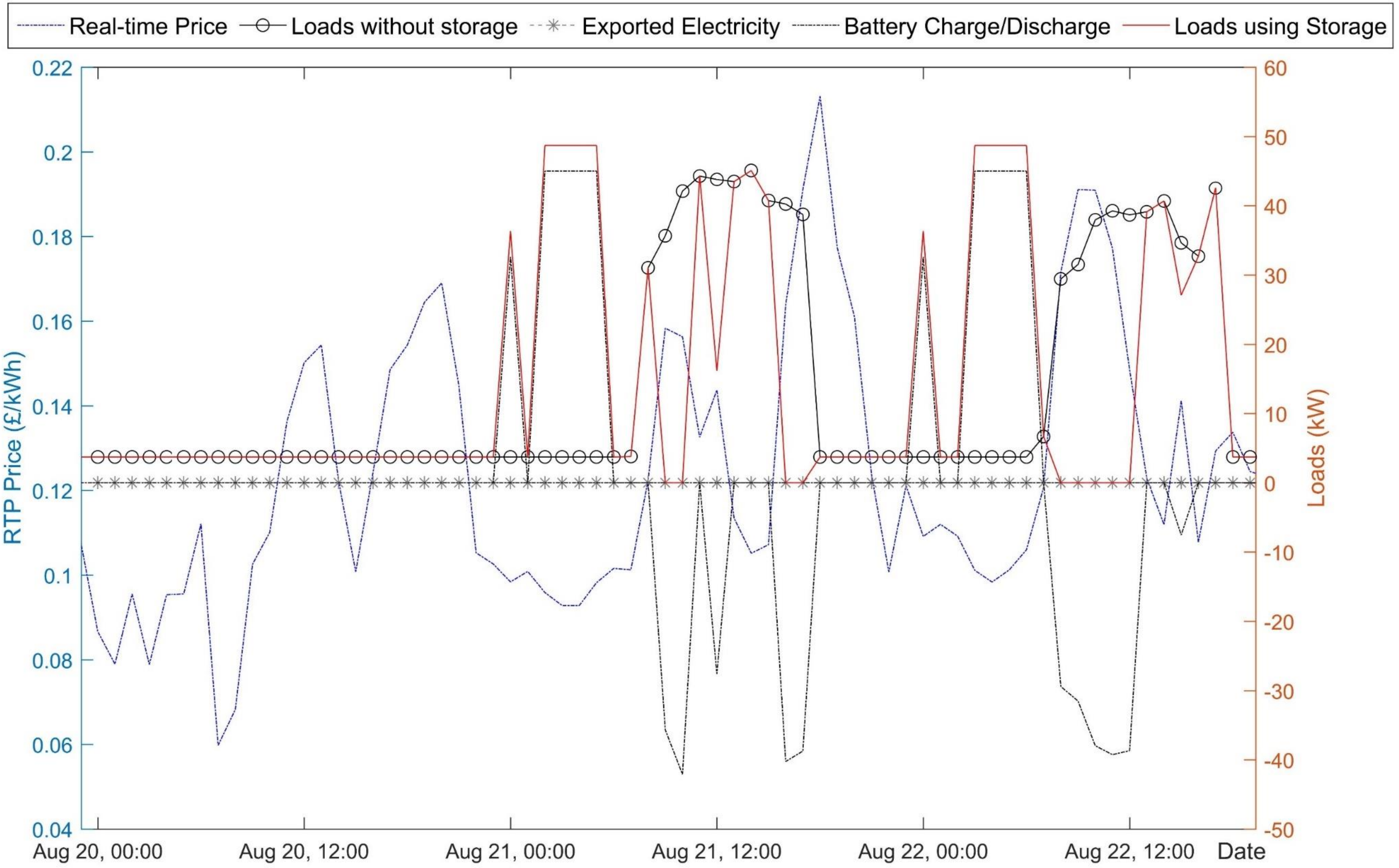

Figure 5.3 – Operation of BSS and its impact on the electricity profile of Building HwPL30 (2r) for Operational Strategy E0 (220 kWh, 45/-65 kW)

The battery is charged during the early hours of each working day and then discharged through the building's opening hours 8am – 6pm. It must be highlighted that for the final day shown, the operation of the battery allows the building to have zero electricity grid purchases between 8am – 1pm, which constitutes a peak period of 5 hours. This is also attributed to the lower energy demand of the building for the month of August and the minimal, if any, electricity consumption for heating. Overall, despite the lack of exports and the additional revenue stream, Operational Strategy E0 can transform a building's electricity profile should the conditions allow it, especially a beneficial distribution of building loads and electricity prices.

Regarding the total electricity purchased from the grid under E7, the amount varies between 75.56 – 89.49 kWh/m^2, for the 220 kWh battery. While the electricity used to cover the local needs always remain the same per building scenario, additional amounts are needed to charge the battery on a daily basis, including electricity to cover for the charging and discharging losses, with excess energy exported back to the grid. The electricity purchases from the grid are further augmented by the battery operation during the weekend when the local loads are trivial. Additionally, the ranges for operational strategy E5 are 60.94 – 74.50 kWh/m^2, significantly reduced due to the lack of exports during weekends. For E0, the respective range is further reduced to 55.24 – 71.19 kWh/m^2 because of the complete lack of exports. For comparative purposes, the total electricity consumption varies between 52.57 – 68.39 kWh/m^2 when no storage is operational.

The electricity shifted (% of peak loads) reaches its highest range for Strategy E0 (31.12 – 39.95%). With exports enabled during non-working days, the E5 range is reduced (26.09 – 30.83%) and reaching between 27.14 – 32.26% for E7 with exports enabled seven days a week. Concerning the exported electricity, significant differences can be seen between the two first operational strategies. More specifically, under E5 a narrow range of 3.22 – 5.53 kWh/m^2 takes place compared to the 16.09 – 18.08 kWh/m^2 E7 counterpart. The combination of time-shifting and exports has an impact on the electricity annual net cost. Taking into account the relevant revenue streams and the additional grid purchases, under E7, the buildings' electricity costs between 7.19 – 9.14 £/m^2 which constitutes the highest range of all strategies. The respective range for E5 is 6.59 – 8.51 £/m^2 which is similar to the E0 values, indicating that the E5 exports taking place are not significant. All the relevant figures for Operational Strategies E7, E5 and E0, are shown in Appendix F, for all building scenarios. Finally, Table 5.1 below summarises the information provided for all three Operational Strategies and the most important parameters for all the simulated building scenarios.

Table 5.1 – Arbitrage annual results for Operational Strategies for the 220 kWh BSS (45 kW/-65 kW) and No Storage

Parameter (Unit)	**Operational Strategy**			
	E7	**E5**	**E0**	**No Storage**
Electricity Shifted (% of peak loads)	27.14 – 32.26	26.09 – 30.83	31.12 – 39.95	N/A
Electricity Exports (kWh/m^2)	16.09 – 18.08	3.22 – 5.53	0	N/A
Electricity Net Cost (£/m^2)	7.19 – 9.14	6.59 – 8.51	6.20 – 8.28	N/A
Total Electricity Consumption (kWh/m^2)	75.56 – 89.49	60.94 – 74.50	55.24 – 71.19	52.57 – 68.39
Electricity Shifted (kWh/m^2)	13.99 – 16.04	13 – 15.38	17.42 – 18.29	N/A

5.2 Birmingham IWEC Results (2017 RTP Data)

In this chapter, the results have been categorised per design characteristic in order to assess the individual impact that each building element has on the arbitrage performance and economics. To demonstrate this, the differences between the values of two main Building Groups are presented in terms of the electricity shifted (% of peak loads and kWh/m^2), exports (kWh/m^2) and net cost (£/m^2) along with their overall mean value for each Operational Strategy. As exports are disabled under E0, the respective electricity shifted (% of peak loads) results can be used as the sole technical metric for comparing the buildings' arbitrage performance along with the net cost for the financial aspect of the scheme. The two main building groups have been selected in such a way that buildings belonging to one group differ only in one primary design characteristic from the buildings of the other group whose impact is to be assessed. Additionally, each main building group consists of several (secondary) subgroups, found in each line of the table(s). Buildings of each subgroup differ only in a secondary building element when compared to the respective building cases of other subgroups that belong into the same main building group.

In this way, instead of generating only a mean value for each main group, it is possible to identify if a major deviation from the mean value takes place between building subgroups due to the secondary building element. As both positive and negative values can be present for the several building subgroups, the mean value of the absolute differences is also given per parameter (column) in order to point out any significant variations which would otherwise be undetected by the mean value. While the mean value of the differences can point out which building category can shift more electricity, for example, the mean of the absolute differences can be used to classify the building design elements according to the average impact they have on the buildings' arbitrage performance. In the present chapter, the individual impact of several building elements is investigated and presented in the following order, separately for each operational strategy. It should be reminded that only annual results for the biggest BSS size of 220 kWh are shown:

a) Fabric's Energy Efficiency
b) Window-to-Wall ratio (glazing)
c) Orientation
d) Thermal mass
e) Ventilation method
f) Shape

5.2.1 Impact of Energy Efficiency

Regarding the impact of the fabric's energy efficiency (performance) in the arbitrage performance of buildings, results are shown in Table 5.2 for Operational Strategy E7. More specifically, the 1st Building Group consists of Best Practice buildings while the 2nd group of Part L compliant cases. Additionally, each subgroup of the Best Practice and Part L Buildings differ in the building orientation that constitutes the secondary building element. It is clear that since all values are positive for the shifted electricity (% of peak loads) and exports, Best Practice buildings are able to shift 1.48% more electricity as a percentage of their peak loads and export 1.14 kWh/m^2 more electricity back to the grid, in average. This can be observed for all secondary categories as the differences in electricity shifted gradually increases from 1.46 to 1.63% while moving away from the original southern-northern orientation, for the rectangular mechanically ventilated buildings (1r – 32r). Energy efficiency appears to have a slightly lower impact for naturally ventilated buildings with a mean difference of 1.24%. Differences in electricity exports appear to be consistent with very minor variations across the different secondary subgroups.

Table 5.2 – Impact of Energy Efficiency on different building groups for Operational Strategy E7 and the 220 kWh BSS

Building Category		Parameter (Unit)			
1st Building Group (Best Practice)	**2nd Building Group (Part L Compliant)**	**Differences in Electricity shifted (% of peak loads)**	**Differences in Exports (kWh/m^2)**	**Differences in Net Cost (£/m^2)**	**Differences in Electricity Shifted (kWh/m^2)**
1s, 3s, 5s, 7s	2s, 4s, 6s, 8s	1.39	1.05	-0.96	-1.08
1r, 3r, 5r, 7r	2r, 4r, 6r, 8r	1.46	1.20	-1.06	-1.23
9r, 11r, 13r, 15r	10r, 12r, 14r, 16r	1.56	1.19	-1.08	-1.22
17r, 19r, 21r, 23r	18r, 20r, 22r, 24r	1.58	1.12	-1.05	-1.15
25r, 27r, 29r, 31r	26r, 28r, 30r, 32r	1.63	1.10	-1.06	-1.13
1rN, 3rN, 9rN, 11rN, 17rN, 19rN, 25rN, 27rN	2rN, 4rN, 10rN, 12rN, 18rN, 20rN, 26rN, 28rN	1.24	1.18	-0.96	-1.17
Mean value		1.48	1.14	-1.03	-1.16
Mean value of the absolute differences		1.48	1.14	1.03	1.16

Table 5.3 – Impact of Energy Efficiency on different building groups for Operational Strategy E5 and the 220 kWh BSS

Building Category		Parameter (Unit)			
1st Building Group (Best Practice)	**2nd Building Group (Part L Compliant)**	**Differences in Electricity shifted (% of peak loads)**	**Differences in Exports (kWh/m^2)**	**Differences in Net Cost (£/m^2)**	**Differences in Electricity Shifted (kWh/m^2)**
1s, 3s, 5s, 7s	2s, 4s, 6s, 8s	1.15	1.04	-0.97	-1.08
1r, 3r, 5r, 7r	2r, 4r, 6r, 8r	1.21	1.19	-1.06	-1.22
9r, 11r, 13r, 15r	10r, 12r, 14r, 16r	1.31	1.18	-1.08	-1.21
17r, 19r, 21r, 23r	18r, 20r, 22r, 24r	1.32	1.11	-1.05	-1.14
25r, 27r, 29r, 31r	26r, 28r, 30r, 32r	1.38	1.09	-1.06	-1.12
1rN, 3rN, 9rN, 11rN, 17rN, 19rN, 25rN, 27rN	2rN, 4rN, 10rN, 12rN, 18rN, 20rN, 26rN, 28rN	1.29	1.08	-0.97	-1.07
Mean value		1.28	1.12	-1.03	-1.14
Mean value of the absolute differences		1.28	1.12	1.03	1.14

Regarding the economics, as Best Practice buildings perform better in terms of shifting and exporting, they are also cheaper overall to operate. More specifically, their electricity net cost is on average 1.03 £/m^2 lower to Part L Compliant buildings with minor variations again being present across the different subgroups. Finally, it is important to point out that while Best Practice buildings shift more electricity as a percentage of their peak loads, it is the less efficient Part L buildings that shift 1.16 kWh/m^2 more electricity and consequently a higher amount of shifted kWh. This is not surprising as generally, a building which is less thermally efficient requires and uses more electricity for the exact same functions and operations; therefore, it can potentially shift more electricity in absolute numbers through arbitrage when a BSS is deployed.

However, even if a less efficient building (Part L) shifts higher amounts of electricity than a more efficient building (Best Practice) in kWh, it still shifts less energy as a percentage of its peak loads which constitutes a clearly more appropriate metric of a building's arbitrage capabilities. Alternatively, giving priority to the total electricity shifted (kWh/m^2) would result in prioritising buildings with higher thermal losses to be considered as more appropriate arbitrage vectors, an end result which could be perceived as counterproductive. As this observation applies to all arbitrage results, electricity shifted (kWh/m^2) is therefore not considered a crucial parameter and its inclusion in the results section is for completion and verification purposes.

The respective comparison for Operational Strategy E5 is shown in Table 5.3. It can be seen that the higher energy efficiency of the Best Practice Buildings leads to a mean value of 1.28% more electricity shifted while 1.12 kWh/m^2 of extra energy is exported back to the grid. Moreover, Best Practice buildings are 1.03 £/m^2 more affordable in terms of their net cost. Similarly to the E7 results, the difference in electricity shifted (% of peak loads) slightly increases when moving away from the original southern-northern orientation, for the rectangular mechanically ventilated cases (1r – 32r). In addition, the values are again consistent across the secondary building groups with trivial variations. Finally, it is clear that the impact of energy efficiency is similar for both strategies E7 and E5 with only the mean difference in electricity shifted (% of peak loads) being slightly higher under E7 (1.48% instead of 1.28%).

On the other hand, this is not the case for Operational Strategy E0 due to its different nature and the lack of exports, as presented below in Table 5.4. More specifically, Best Practice buildings are able to shift on average 3.92% of their peak loads, significantly higher than the E7 and E5 values which are 1.48% and 1.28%, respectively; consequently, the fabric's' energy efficiency has its highest impact in energy shifting for E0. In terms of the economic output, the mean difference in net cost between Best Practice and Part L buildings is almost identical to the values achieved with the previous strategies (1.11 £/m^2) .

This is expected as the electricity net cost is always dependent on the combination of the shifting and exporting activities which is relatively constant as a sum for all operational strategies. Concerning the differences in electricity shifted (kWh/m^2), the less efficient Part L Buildings still consume and therefore shift more electricity; nevertheless, the difference between the two main building group under E0 is considerably smaller (0.33 kWh/m^2) when compared to the respective values for E7 and E5 (1.16 and 1.14 kWh/m^2) due to the strategies' different approaches and priorities.

Table 5.4 – Impact of Energy Efficiency on different building groups for Operational Strategy E0 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (Best Practice)	**2nd Building Group (Part L Compliant)**	**Differences in Electricity shifted (% of peak loads)**	**Differences in Exports (kWh/m^2)**	**Differences in Net Cost (£/m^2)**	**Differences in Electricity Shifted (kWh/m^2)**
1s, 3s, 5s, 7s	2s, 4s, 6s, 8s	3.64	N/A	-1.04	-0.33
1r, 3r, 5r, 7r	2r, 4r, 6r, 8r	4.04	N/A	-1.15	-0.37
9r, 11r, 13r, 15r	10r, 12r, 14r, 16r	4.06	N/A	-1.17	-0.37
17r, 19r, 21r, 23r	18r, 20r, 22r, 24r	3.96	N/A	-1.14	-0.35
25r, 27r, 29r, 31r	26r, 28r, 30r, 32r	3.87	N/A	-1.14	-0.38
1rN, 3rN, 9rN, 11rN, 17rN, 19rN, 25rN, 27rN	2rN, 4rN, 10rN, 12rN, 18rN, 20rN, 26rN, 28rN	3.95	N/A	-1.05	-0.13
Mean value		3.92	N/A	-1.11	-0.32
Mean value of the absolute differences		3.92	N/A	1.11	0.32

5.2.2 Impact of Window-to-Wall ratio (glazing)

Regarding the impact of glazing, the arbitrage performance of 30% and 80% glazed buildings is presented in Table 5.5 for Operational Strategy E7 and results are largely consistent across all parameters and secondary subgroups. Orientation constitutes again the secondary building characteristic. In more detail, buildings with 80% glazing shift 0.23% of their peak loads more than buildings with 30% glazing while their electricity net cost is 0.28 £/m^2 cheaper, on average. On the other hand, as 80% glazed building cases consume more electricity, they are capable of shifting higher amounts of energy than the 30% glazed cases and more specifically, 0.53 kWh/m^2 more.

The respective results for E5 are presented below in Table 5.6. Concerning the shifted electricity (% of peak loads), the difference between the two main groups is insignificant as 80% glazed buildings are able of shifting 0.06% more. However, the average of the absolute differences is 0.25%, really close to the E7 value, indicating that there is a certain level of variation inside the secondary subgroups. Only the heavyweight buildings that are 80% glazed are able to shift more of their peak loads compared to the 30% glazed heavyweight cases. On the other hand, lightweight buildings with 80% glazing shift slightly less electricity than the respective 30% glazed cases in terms of their peak loads.

Consequently, thermal mass does play a minor role when examining the results inside the subgroups; however, in this particular case its overall influence is minimal. A similar trend can be observed when looking at the E7 shifted electricity (% of peak loads) results from a thermal mass perspective as the difference between 30% and 80% glazed buildings is higher when comparing the heavyweight cases. Furthermore, the mean difference in net cost is identical to the E7 value (0.28 £/m^2) while 30% glazed buildings shift 0.57 kWh/m^2 more electricity, slightly higher when compared to the respective E7 value (0.53).

Table 5.5 – Impact of Window-to-Wall ratio (glazing) on different building groups for Operational Strategy E7 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (30% glazed)	**2nd Building Group (80% glazed)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m²)**	**Average of Differences in Net Cost (£/m²)**	**Average of Differences in Electricity Shifted (kWh/m²)**
1s, 2s, 3s, 4s	5s, 6s, 7s, 8s	-0.18	-0.57	0.29	0.59
1r, 2r, 3r, 4r	5r, 6r, 7r, 8r	-0.32	-0.52	0.33	0.55
9r, 10r, 11r, 12r	13r, 14r, 15r, 16r	-0.19	-0.47	0.27	0.50
17r, 18r, 19r, 20r	21r, 22r, 23r, 24r	-0.31	-0.50	0.29	0.53
25r, 26r, 27r, 28r	29r, 30r, 31r, 32r	-0.15	-0.46	0.23	0.49
Mean value		-0.23	-0.50	0.28	0.53
Mean value of the absolute differences		0.25	0.50	0.28	0.53

Table 5.6 – Impact of Window-to-Wall ratio (glazing) on different building groups for Operational Strategy E5 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (30% glazed)	**2nd Building Group (80% glazed)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m²)**	**Average of Differences in Net Cost (£/m²)**	**Average of Differences in Electricity Shifted (kWh/m²)**
1s, 2s, 3s, 4s	5s, 6s, 7s, 8s	-0.01	-0.61	0.29	0.63
1r, 2r, 3r, 4r	5r, 6r, 7r, 8r	-0.16	-0.55	0.33	0.58
9r, 10r, 11r, 12r	13r, 14r, 15r, 16r	-0.04	-0.49	0.26	0.53
17r, 18r, 19r, 20r	21r, 22r, 23r, 24r	-0.10	-0.55	0.29	0.58
25r, 26r, 27r, 28r	29r, 30r, 31r, 32r	0.03	-0.52	0.23	0.55
Mean value		-0.06	-0.54	0.28	0.57
Mean value of the absolute differences		0.21	0.54	0.28	0.57

Finally, the E0 results are of fundamental importance towards demonstrating the impact of glazing on arbitrage performance (Table 5.7). 80% glazed buildings can shift 0.98% of their peak loads more compared to the respective 30% glazed building cases. As the least energy efficient building group, 30% glazed buildings are still able to shift more electricity (kWh/m^2); however, the difference has now been decreased to 0.29 kWh/m^2. In economic terms, there are no differences from the previous two operational strategies, as mentioned in the previous chapter, as 80% glazed buildings still require 0.32 £/m^2 lower net cost. Overall, there are no particular differences between the mean value and the mean value of the absolute differences.

Table 5.7 – Impact of Window-to-Wall ratio (glazing) on different building groups for Operational Strategy E0 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (30% glazed)	**2nd Building Group (80% glazed)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1s, 2s, 3s, 4s	5s, 6s, 7s, 8s	-1.09	N/A	0.33	0.29
1r, 2r, 3r, 4r	5r, 6r, 7r, 8r	-1.14	N/A	0.37	0.29
9r, 10r, 11r, 12r	13r, 14r, 15r, 16r	-0.89	N/A	0.30	0.28
17r, 18r, 19r, 20r	21r, 22r, 23r, 24r	-1.05	N/A	0.33	0.30
25r, 26r, 27r, 28r	29r, 30r, 31r, 32r	-0.75	N/A	0.26	0.31
Mean value		-0.98	N/A	0.32	0.29
Mean value of the absolute differences		0.98	N/A	0.32	0.29

5.2.3 Impact of Orientation

In Table 5.8, the arbitrage results can be seen regarding the impact of orientation on the building's arbitrage performance, for Operational Strategy E7. Firstly, considering the southern orientation as the default one, a comparison is made for mechanically ventilated buildings and secondly the same comparison follows for buildings adopting natural ventilation. More specifically, when mechanical ventilation is used, it is clear that buildings with the default southern orientation shift 0.32% more peak electricity compared to the south-western and south-eastern orientations while they are able of shifting 0.70% more in contrast to buildings with the eastern orientation; the mean difference when moving away from the default orientation reaches the value of 0.40% for all buildings of both ventilation strategies.

Additionally, it is shown that there are no major differences in terms of exports and the electricity net cost between the two main building groups; buildings with southern orientation still perform slightly better when mechanical ventilation is deployed but this is not always the case for naturally ventilated cases which can perform marginally better or worse when moving away from the default orientation (e.g. Buildings 1rN – 4rN versus 9rN – 12rN). This is due to a certain level of variations of no discernible pattern that are present when comparing the several subgroups of the two main building categories and natural ventilation is used. The overall difference is trivial for exports and electricity shifted (kWh/m^2) while it's relatively small for the electricity net cost (0.05 £/m^2), favouring the default orientation. Because of the previously discussed variations that exist when natural ventilation is used, the mean and the absolute mean values are unsurprisingly not equal; nevertheless, their difference is not substantial. As shown in Table 5.9, the results for E5 are very similar and in some cases identical to their respective E7 values.

Table 5.8 – Impact of orientation on different building groups for Operational Strategy E7 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (Southern Orientation)	**2nd Building Group (9-16: South-West 17-24: South-East 25-32: East)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m²)**	**Average of Differences in Net Cost (£/m²)**	**Average of Differences in Electricity Shifted (kWh/m²)**
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	9r, 10r, 11r, 12r, 13r, 14r, 15r, 16r	0.32	0.09	-0.11	-0.08
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	17r, 18r, 19r, 20r, 21r, 22r, 23r, 24r	0.32	0.05	-0.09	-0.04
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	25r, 26r, 27r, 28r, 29r, 30r, 31r, 32r	0.70	0.12	-0.20	-0.11
1rN, 2rN, 3rN, 4rN	9rN, 10rN, 11rN, 12rN	0.67	-0.01	-0.14	0.03
1rN, 2rN, 3rN, 4rN	17rN, 18rN, 19rN, 20rN	-0.09	-0.27	0.16	0.27
1rN, 2rN, 3rN, 4rN	25rN, 26rN, 27rN, 28rN	0.46	-0.12	0.07	0.12
Mean value		0.40	-0.02	-0.05	0.03
Mean value of the absolute differences		0.45	0.12	0.13	0.12

Table 5.9 – Impact of orientation on different building groups for Operational Strategy E5 and the 220 kWh BSS

Building Category		**Parameter (Unit)**			
1st Building Group (Southern Orientation)	**2nd Building Group (9-16: South-West 17-24: South-East 25-32: East)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m²)**	**Average of Differences in Net Cost (£/m²)**	**Average of Differences in Electricity Shifted (kWh/m²)**
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	9r, 10r, 11r, 12r, 13r, 14r, 15r, 16r	0.29	0.09	-0.11	-0.08
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	17r, 18r, 19r, 20r, 21r, 22r, 23r, 24r	0.32	0.03	-0.09	-0.02
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	25r, 26r, 27r, 28r, 29r, 30r, 31r, 32r	0.67	0.11	-0.20	0.11
1rN, 2rN, 3rN, 4rN	9rN, 10rN, 11rN, 12rN	0.63	0	-0.14	0.02
1rN, 2rN, 3rN, 4rN	17rN, 18rN, 19rN, 20rN	-0.06	-0.27	0.16	0.27
1rN, 2rN, 3rN, 4rN	25rN, 26rN, 27rN, 28rN	0.45	-0.13	0.07	0.13
Mean value		0.38	-0.03	-0.05	0.07
Mean value of the absolute differences		0.43	0.11	0.13	0.11

Table 5.10 – Impact of orientation on different building groups for Operational Strategy E0

Building Category		**Parameter (Unit)**			
1st Building Group (Southern Orientation)	**2nd Building Group (9-16: South-West 17-24: South-East 25-32: East)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	9r, 10r, 11r, 12r, 13r, 14r, 15r, 16r	0.65	N/A	-0.12	0.03
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	17r, 18r, 19r, 20r, 21r, 22r, 23r, 24r	0.56	N/A	-0.09	0.03
1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	25r, 26r, 27r, 28r, 29r, 30r, 31r, 32r	1.24	N/A	-0.21	0.06
1rN, 2rN, 3rN, 4rN	9rN, 10rN, 11rN, 12rN	0.86	N/A	-0.14	0.07
1rN, 2rN, 3rN, 4rN	17rN, 18rN, 19rN, 20rN	-0.67	N/A	0.17	0.03
1rN, 2rN, 3rN, 4rN	25rN, 26rN, 27rN, 28rN	0.33	N/A	0.08	0.04
Mean value		0.49	N/A	-0.05	0.04
Mean value of the absolute differences		0.76	N/A	0.14	0.04

When exporting back to the grid is not allowed under the E0 strategy (Table 5.10), arbitrage stills performs better in terms of the electricity shifted (% of peak loads) and cheaper when a southern orientation is adopted with only one exception observed as naturally ventilated buildings with a southern-eastern orientation shift more peak electricity (%). Buildings with southern orientation can shift 0.49% more peak electricity while their lower net cost and electricity shifted (kWh/m^2) have not changed from the E7 and E5 strategies. Naturally ventilated buildings still include certain variations that affect the mean value of the shifted electricity (%) and consequently the absolute mean which in this particular case is 0.76%; therefore, buildings with southern orientation shift more electricity both in terms of their peak loads and the total amount of electricity shifted (kWh/m^2), under all strategies. For the latter parameter, the range of that difference is low, between 0.03 – 0.07 kWh/m^2 but it does constitute a significant change as, for the first time, both metrics of the shifted electricity are positive which was not the case when discussing the impact of energy efficiency and glazing. The highest difference is observed, for all three strategies, for the eastern orientation which leads to lower peak loads shifted by 1.24% for E0, when mechanical ventilation is deployed.

5.2.4 Impact of Thermal Mass

Thermal mass constitutes the fourth building element whose impact is investigated. The first subgroup of both main building groups consists of square buildings while the secondary design element for the remaining square subgroups is once again orientation (Table 5.11). When mechanical ventilation is deployed, lightweight buildings are capable of shifting higher amounts of electricity, in terms of their peak loads as well as the total shifted electricity, by 0.62% and 0.14 kWh/m^2, respectively. They are also slightly cheaper than heavyweight buildings by 0.05 £/m^2; on the other hand, they export 0.14 kWh/m^2 less electricity back to the grid. This is the first time that a building category, in this case lightweight mechanically ventilated buildings, can shift more electricity but at the same time export less than the other main building category. It should be pointed out that when no battery is used, the difference in the total electricity consumption between lightweight and heavyweight buildings is not significant as lightweight cases require only 0.07 £/m^2 less, on average.

While the buildings' overall consumptions are similar, the temporal distribution of their respective loads might differ because of the mechanism thermal mass operates on and the relevant thermal lag; nevertheless, the difference in exports is overall small. Finally, while results are consistent for the majority of lightweight buildings that use mechanical ventilation and it is clear they perform better for all metrics but exports, this is not the case for 80% glazed Best Practice buildings as thermal mass does not seem to have any major impact on them regardless of the orientation used. It is interesting to notice that the lightweight cases of this particular exception constitute the buildings with the highest levels of thermal discomfort, as already indicated in Chapter 4.3.

Despite the fact that the results for buildings with natural ventilation are consistent with the mechanical ventilation cases and similar trends can be observed, it is important to present them separately due to certain vital differences. More specifically, lightweight buildings with natural ventilation shift 2.87% higher peak loads than their heavyweight respective buildings. For comparison purposes, this is translated to approximately 360% higher shifting of electricity in terms of the peak loads than the average value observed under mechanical ventilation. The shifting can reach even higher values in specific cases, for example lightweight Part L buildings can shift 3.30% more peak loads than their heavyweight counterparts.

Table 5.11 – Impact of thermal mass on different building groups for Operational Strategy E7

Building Category		**Parameter (Unit)**			
1st Building Group (Heavyweight)	**2nd Building Group (Lightweight)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1s, 2s, 5s, 6s	3s, 4s, 7s, 8s	-0.47	0.13	0.03	-0.13
1r, 2r, 5r, 6r	3r, 4r, 7r, 8r	-0.69	0.18	0.04	-0.18
9r, 10r, 13r, 14r	11r, 12r, 15r, 16r	-0.58	0.11	0.05	-0.11
17r, 18r, 21r, 22r	19r, 20r, 23r, 24r	-0.71	0.15	0.05	-0.16
25r, 26r, 29r, 30r	27r, 28r, 31r, 32r	-0.66	0.14	0.06	-0.13
1rN, 2rN, 9rN, 10rN, 17rN, 18rN, 25rN, 26N	3rN, 4rN, 11rN, 12rN, 19rN, 20rN, 27rN, 287N	-2.87	0.09	0.32	-0.09
Mean value		-1.00	0.13	0.09	-0.13
Mean value of the absolute differences		1.03	0.14	0.11	0.14

Furthermore, lightweight naturally ventilated buildings are also less expensive in terms of the electricity net cost by 0.32 £/m^2 and shift more electricity in absolute terms by 0.09 kWh/m^2. On the contrary, their exports are slightly lower by 0.09 kWh/m^2 when compared to the respective heavyweight buildings. Taking into account the overall mean values, it is clear that a light thermal mass results into higher amounts of electricity shifted by 1% of peak loads and 0.13 kWh/m^2 as well as a lower net cost by 0.09 £/m^2; however, at the same time exports are reduced by 0.13 kWh/m^2. Finally, it has been shown that the impact of thermal mass on arbitrage performance is much more severe when natural ventilation is adopted.

Concerning the E5 strategy results, its arbitrage performance is similar to E7 both in terms of consistency and values (Table 5.12). The differentiation between natural and mechanical ventilation buildings remains as the impact of thermal mass is still major when natural ventilation is adopted. For example, lightweight naturally-ventilated buildings are capable of shifting 2.49% of the peak loads higher than their heavyweight counterparts; this difference is reduced to 0.53% for mechanically ventilated cases. The major difference between E7 and E5 results concerns the 80% glazed Best Practice Buildings as for these particular design characteristics, heavy thermal mass leads to a better arbitrage performance than the respective lightweight cases. In more detail, heavyweight buildings (80% glazed, Best Practice) can now shift on average more electricity by 0.19% of their peak loads and 0.04 kWh/m^2 whilst being more economical by 0.06 £/m^2.

Table 5.12 – Impact of thermal mass on different building groups for Operational Strategy E5

Building Category		Parameter (Unit)			
1st Building Group (Heavyweight)	**2nd Building Group (Lightweight)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1s, 2s, 5s, 6s	3s, 4s, 7s, 8s	-0.40	0.11	0.03	-0.11
1r, 2r, 5r, 6r	3r, 4r, 7r, 8r	-0.61	0.15	0.04	-0.15
9r, 10r, 13r, 14r	11r, 12r, 15r, 16r	-0.50	0.08	0.05	-0.08
17r, 18r, 21r, 22r	19r, 20r, 23r, 24r	-0.61	0.11	0.05	-0.12
25r, 26r, 29r, 30r	27r, 28r, 31r, 32r	-0.55	0.10	0.06	-0.09
1rN, 2rN, 9rN, 10rN, 17rN, 18rN, 25rN, 26N	3rN, 4rN, 11rN, 12rN, 19rN, 20rN, 27rN, 287N	-2.49	-0.04	0.30	0.04
Mean value		-0.86	0.08	0.09	-0.09
Mean value of the absolute differences		0.94	0.13	0.11	0.13

Table 5.13 - Impact of thermal mass on different building groups for Operational Strategy E0

Building Category		Parameter (Unit)			
1st Building Group (Heavyweight)	**2nd Building Group (Lightweight)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1s, 2s, 5s, 6s	3s, 4s, 7s, 8s	-0.29	N/A	0.02	-0.03
1r, 2r, 5r, 6r	3r, 4r, 7r, 8r	-0.46	N/A	0.03	-0.05
9r, 10r, 13r, 14r	11r, 12r, 15r, 16r	-0.50	N/A	0.04	-0.05
17r, 18r, 21r, 22r	19r, 20r, 23r, 24r	-0.53	N/A	0.04	-0.04
25r, 26r, 29r, 30r	27r, 28r, 31r, 32r	-0.55	N/A	0.06	-0.05
1rN, 2rN, 9rN, 10rN, 17rN, 18rN, 25rN, 26N	3rN, 4rN, 11rN, 12rN, 19rN, 20rN, 27rN, 287N	-3.16	N/A	0.31	0.01
Mean value		-0.92	N/A	0.08	-0.03
Mean value of the absolute differences		0.95	N/A	0.11	0.05

Considering all the scenarios under E5, lightweight buildings are more economical by 0.09 £/m^2 (same value as in E7) and they are able to shift higher amounts of electricity by 0.86% of their peak loads as well as 0.09 kWh/m^2. Variations do take place for the exports, as indicated by the comparison between the mean value and the mean of the absolute differences, 0.8 and 0.13 kWh/m^2, respectively.

The results for the final E0 operational strategy are shown in Table 5.13. When mechanical ventilation is deployed, lightweight buildings shift 0.47% more peak loads and 0.04 kWh/m^2 more electricity. The former value is slightly reduced when compared to the respective E7 and E5 results (0.62 and 0.53%); however, light thermal mass still leads to a small reduction of net costs by 0.04 £/m^2. The reduction of the mean shifted electricity value is the result of variations observed within the main building groups. For example, 80% glazed Best Practice Buildings now shift 0.07% more peak loads when having heavy thermal mass while thermal mass seems to have only a very minor impact for the 30% glazed Best Practice rectangular buildings. On the other hand, under E0, the difference has increased for the naturally ventilated cases as lightweight buildings shift 3.16% more of peak loads. It should be reminded that the respective percentage was 2.87 and 2.49% for strategies E4 and E5, respectively. With some minor exceptions, there are no major differences between the mean value and the mean value of the absolute differences, for all strategies. However, as discussed, this does not necessarily translate to a lack of variations within the main building groups.

Finally, it is worth pointing out that for all operational strategies and all subgroups, for both mechanical and natural ventilation settings, the impact of thermal mass is relatively higher for Part L buildings compared to Best Practice. For example, comparing Best Practice Buildings 1r and 3r under E0, heavy thermal mass leads to a difference in shifted peak loads by just 0.06% while the difference in net costs is close to zero. The same percentage regarding the difference between Part L buildings 2r and 4r is -1.11% for the shifted loads and a significant 0.16 £/m^2 for the net cost; however, this gap varies from subgroup to subgroup as other building elements affect the arbitrage performance results synergistically and it might not be as extreme as in the example mentioned above. Consequently, a less efficient energy efficiency intensifies the differences in arbitrage performance when comparing heavyweight and lightweight buildings.

5.2.5 Impact of Ventilation Method

The last major building element investigated is the ventilation strategy adopted for the needs of the buildings. The secondary building characteristic is again orientation. Looking at the overall average values for E7 (Table 5.14), mechanically ventilated buildings shift 0.43% higher peak loads, export slightly more electricity by 0.07 kWh/m^2 and are marginally more affordable by 0.07 £/m^2 than their naturally ventilated counterparts. In more detail, these values vary based on the selected orientation as when comparing building cases with a south-western orientation, the difference in shifted peak loads is 0.88% while a south-eastern orientation results into a minimal 0.06% difference between mechanical and natural ventilation. However, it can be seen that the mean value of the absolute differences for the shifted peak loads stands higher at 1.04%, indicating variations within the subgroups.

As shown previously while discussing the impact of thermal mass, the buildings' arbitrage performance has been dependent on the ventilation method used. This synergy between the two building elements in question is repeated as results are dissimilar between heavyweight and lightweight cases. More specifically, mechanically ventilated buildings do perform better overall, as mentioned in the previous paragraph, and this is the case as well for heavyweight buildings with mechanical ventilation. On the other hand, all lightweight buildings achieve a higher percentage of shifted peak loads when natural ventilation is used. For example, for the default orientation (Buildings 1r – 4r and 1rN – 4rN), heavyweight mechanically ventilated buildings can shift on average 1.65% higher peak loads while lightweight naturally ventilated cases can shift 0.72% higher compared to their mechanical ventilation counterparts; this trend is consistent within all building subgroups and demonstrates again the close relationship between ventilation method and thermal mass.

Table 5.14 – Impact of ventilation method on different building groups for Operational Strategy E7

Building Category		**Parameter (Unit)**			
1st Building Group (Mechanical Ventilation)	**2nd Building Group (Natural Ventilation)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1r, 2r, 3r, 4r	1rN, 2rN, 3rN, 4rN	0.47	0.22	-0.17	-0.21
9r, 10r, 11r, 12r	9rN, 10rN, 11rN, 12rN	0.88	0.14	-0.23	-0.13
17r, 18r, 19r, 20r	17rN, 18rN, 19rN, 20rN	0.06	-0.09	0.06	0.08
25, 26r, 27r, 28r	25rN, 26rN, 27rN, 28rN	0.31	0.00	0.05	-0.01
Mean value		0.43	0.07	-0.07	-0.07
Mean value of the absolute differences		1.04	0.13	0.15	0.12

Table 5.15 – Impact of ventilation method on different building groups for Operational Strategy E5

Building Category		**Parameter (Unit)**			
1st Building Group (Mechanical Ventilation)	**2nd Building Group (Natural Ventilation)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1r, 2r, 3r, 4r	1rN, 2rN, 3rN, 4rN	-0.22	0.53	-0.14	-0.53
9r, 10r, 11r, 12r	9rN, 10rN, 11rN, 12rN	0.18	0.47	-0.20	-0.45
17r, 18r, 19r, 20r	17rN, 18rN, 19rN, 20rN	-0.57	0.23	0.09	-0.24
25, 26r, 27r, 28r	25rN, 26rN, 27rN, 28rN	-0.34	0.32	0.09	-0.33
Mean value		-0.24	0.39	-0.04	-0.39
Mean value of the absolute differences		0.87	0.39	0.14	0.39

Regarding the E5 results (Table 5.15), mechanically-ventilated buildings are able to shift a slightly higher amount of peak loads by 0.24% while the mean value of the absolute differences is higher at 0.87%, indicating internal variations within the subgroup, similarly to the E7 results. Furthermore, their overall exports are higher by 0.39 kWh/m^2 compared to the respective building cases with natural ventilation. Finally, as seen in Table 5.16, under the E0 strategy mechanically-ventilated buildings shift on average more peak loads by 0.29% with the respective mean of the absolute differences reaching 1.32%. It should be highlighted that the difference in net cost is similar for all strategies. The impact of the ventilation method should be considered along with thermal mass, as mentioned in the previous paragraph.

Table 5.16 – Impact of ventilation method on different building groups for Operational Strategy E0

Building Category		**Parameter (Unit)**			
1st Building Group (Mechanical Ventilation)	**2nd Building Group (Natural Ventilation)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
1r, 2r, 3r, 4r	1rN, 2rN, 3rN, 4rN	0.68	N/A	-0.18	-0.19
9r, 10r, 11r, 12r	9rN, 10rN, 11rN, 12rN	1.02	N/A	-0.23	-0.16
17r, 18r, 19r, 20r	17rN, 18rN, 19rN, 20rN	-0.51	N/A	0.07	-0.19
25, 26r, 27r, 28r	25rN, 26rN, 27rN, 28rN	-0.03	N/A	0.07	-0.21
Mean value		0.29	N/A	-0.07	-0.19
Mean value of the absolute differences		1.32	N/A	0.15	0.19

5.2.6 Impact of Shape

The last building element whose comparison includes only a small amount of buildings is the shape, as shown in Table 5.17. Rectangular buildings perform better for all the presented parameters; however, the extent of that difference can be argued to be insignificant for strategies E7 and E5. This is because the average financial benefit is close to zero while the difference in shifted peak loads is around 0.20%. That difference increases to 0.38% for E0 with no major variations being present. Therefore, it can be concluded that the building shape has an insignificant impact on the arbitrage performance, when exports take place, and a small impact for operational strategy E0.

Table 5.17 – Impact of shape on different building groups for all Operational Strategies and the 220 kWh BSS. The mean of the absolute differences for each parameter is provided in brackets.

Operational Strategy	**Building Category**		**Parameter**			
	1st Building Group (Square shape)	**2nd Building Group (Rectangular Shape)**	**Average of Differences in Electricity shifted (% of peak loads)**	**Average of Differences in Exports (kWh/m^2)**	**Average of Differences in Net Cost (£/m^2)**	**Average of Differences in Electricity Shifted (kWh/m^2)**
E7	1s, 2s, 3s, 4s, 5s, 6s, 7s, 8s	1r, 2r, 3r, 4r, 5r, 6r, 7r, 8r	-0.21 (0.21)	-0.03 (0.09)	0.01 (0.05)	0.01 (0.08)
E5			-0.19 (0.19)	-0.02 (0.09)	0.01 (0.05)	-0.02 (0.09)
E0			-0.38 (0.40)	N/A	0.01 (0.05)	-0.04 (0.05)

5.3 Summary of 2017 Arbitrage Results

The results from the entire Chapter 5.2 are summarised in Tables F1 – F2 of the Appendix in terms of the mean values of the differences and absolute differences, respectively, for Operational Strategy E0. Therefore, it is possible to conclude this chapter with the more suitable Building categories for arbitrage:

i. Best Practice over Part L
ii. 80% glazing over 30% glazing
iii. Southern orientation over SW/SE/E orientation
iv. Lightweight over heavyweight
v. Mechanically-ventilated over naturally-ventilated
vi. Rectangular over Square

It is also critical to point out that while there is obviously a connection between differences in electricity shifted (% of peak loads) and the electricity consumption with no storage, the order of the former does not necessarily follow the order of the latter. For example, ventilation strategy comes third in terms of the differences in total electricity consumption by 0.60 kWh/m^2 but finishes sixth regarding the mean differences in electricity shifted (0.29%).

A similar case can be made for the shape as well while results for the highest differences in peak loads shifted (energy efficiency and glazing) are consistent for both parameters; however, it could be argued that the ranges of the values for orientation, thermal mass, ventilation and shape is relatively short (Table F1). In order to quantify the impact of each building element and classify them in order of descending importance, it is essential to consider the mean of the absolute differences (Table F2).

i. Energy Efficiency
ii. Ventilation Strategy
iii. Window-to-wall-ratio (Glazing)
iv. Thermal mass
v. Orientation
vi. Shape

Undoubtedly, the fabric's thermal efficiency constitutes the most significant building element of the current research and has the highest impact on a building's arbitrage performance. The comparison of the two main building categories gives a mean absolute value of almost 4% in terms of their peak loads shifted and 1.11 £/m^2 regarding the electricity net cost. Furthermore, ventilation strategy comes second with 1.32% difference, followed by glazing (0.98%) and marginally by thermal mass (0.95%). Orientation comes fifth (0.76%) while shape proves to be the least influential building element (0.21%).

The impact of all building elements can be seen in descending order of impact on arbitrage performance, in Figure 5.4. The second highest net cost difference is observed for glazing (0.32 £/m^2) while the range for the rest of the elements is between 0.05 and 0.15 £/m^2. By comparing the two tables, it is clear that considering the mean of the absolute differences and the respective variations adds more gravity to the ventilation strategy. Nevertheless, no other major changes take place but it should be noted that due to the variations taken into account, the differences in net cost do not always follow the same order as the shifted peak loads (Table F2). Finally, two building scenarios need to be mentioned:

- The building with all the recommended building design elements proves to have one of the best performing building in terms of arbitrage. Assuming a fabric efficiency of Best Practice, glazing of 80%, mechanical ventilation, rectangular shape, heavy thermal mass and a southern-northern orientation, Building HwBP80 (5r) is able to shift 31.76% of its peak loads (3rd of out of 56 buildings) and export 18.08 kWh/m^2 (1st out of 56) with an annual net cost of 7.19 £/m^2 (1st out of 56), under Strategy E7. With exports not allowed (E0), 39.68% of its peak loads are shifted (3rd out of 56) with an annual net cost of 6.20 £/m^2 (1st out of 56).

- On the other hand, assuming a Part L compliant thermal efficiency, 30% natural ventilation, rectangular shape and southern-western orientation, Building HwPL30-SW* (10rN) has comparatively much poorer arbitrage performance. Under Strategy E7, 27.14% of its peak loads are shifted (56th out of 56), 16.18 kWh/m^2 are exported back to the grid (53rd out of 56) with an annual net cost of 9.14 £/m^2 (56th out of 56). For Strategy E0, 31.12% of its peak loads are shifted (56th out of 56) with a net cost of 8.28 £/m^2 (56th out of 56).

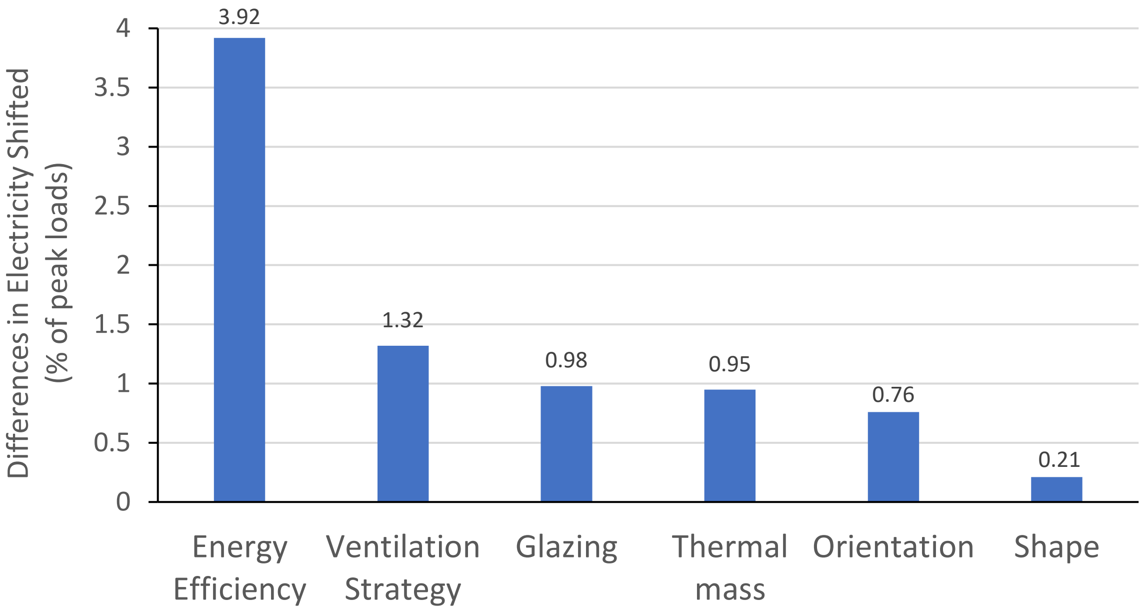

Figure 5.4 – Impact of Building Design Elements on Arbitrage Performance for Operational Strategy E0 (220 kWh BSS). Values refer to the mean of the absolute differences (Table F2)

5.4 Selection of Buildings for further analysis

Due to the large number of building scenarios and simulations required, the Birmingham IWEC Results (2017 RTP Data) discussed in Chapter 5.2 are used to narrow down their number and get rid of unnecessary comparisons in cases where the differences in arbitrage performance are trivial. The revised amount of buildings will then be used for further simulations, in Chapter 6. The process is simple and includes revising the presented results, focused exclusively on the E0 Operational Strategy values and the differences in electricity shifted (% of peak loads).

Comparison between secondary subgroups of the main categories can also identify building cases that warrant further investigation as well as eliminate building subgroups that present no interest. The building elements and their average arbitrage impact based on the mean value of the absolute differences for the shifted peak loads, mentioned in Figure 5.4, will be assessed in reverse order to identify potential candidate groups that could be eliminated. The values mentioned below refer to the mean or absolute mean of the differences in electricity shifted (% of peak loads).

- Shape constitutes the design element with the lowest impact on arbitrage with an absolute average of 0.21%. While the arithmetic mean is slightly higher at -0.38%, it is still considered low and therefore all 8 square buildings (1s – 8s) are eliminated from future simulations, leaving the rectangular geometry as the only option (Table 5.17).

- Regarding orientation, the absolute mean stands at 0.76%, higher than the mean (0.49%). It is essential to check the E0 results per building subgroup to see how the default orientation compares with the rest of the configurations and not rely exclusively in the overall mean value. More specifically, for mechanically ventilated buildings, when comparing the default southern orientation to the eastern orientation, the mean reaches its peak value (1.24%). Consequently, the eastern orientation is deemed to have a particular impact and is considered for further simulations (building cases 25r – 32r). When natural ventilation is adopted, SW orientation follows second overall in the entire category with a 0.86% mean difference, resulting in building cases 1rN – 4rN and 9rN – 12rN to be included in the next chapter as well. As there are no variations within each subgroup, the absolute means have identical values for both cases. Any other buildings with an orientation different than the default/eastern (mech. vent.) or SW (nat. vent.) are excluded: 9r – 24r, 17rN – 20rN and 25rN – 28rN (Table 5.10).

- As thermal mass has proved to be highly influential in naturally ventilated buildings, it is essential to conduct further simulations for all buildings with natural ventilation that have not been excluded in the previous two paragraphs; these buildings are 1rN – 4rN and 9rN – 12rN. When mechanical ventilation is used, thermal mass affects the results particularly for the least energy efficient buildings while their effect on Best Practice buildings is comparatively less significant. Therefore, half of the Best Practice buildings with mechanical ventilation can be eliminated; these include building cases 3r, 7r, 27r, 31r.

- Ventilation Strategy constitutes the building element with the second highest impact on arbitrage after energy efficiency with an absolute mean difference of 1.32% in terms of the shifted peak loads. Therefore, all naturally ventilated buildings that have not already been excluded are considered for further simulations:1rN – 4rN and 9rN – 12rN.

- Finally, the fabric's energy efficiency is undoubtedly the most important element of the comparison; therefore, similarly to ventilation strategy, all Best Practice and Part L buildings that have not already been excluded so far are considered for further simulations.

In conclusion, a total of 20 building cases are considered for the simulations that follow, a 35% proportion of the 56 original scenarios presented in Chapter 4; therefore, this reduction narrows down the required analysis significantly. Table 5.18 below presents the list of the 20 buildings in question.

Table 5.18 – Selected Building Cases for further simulations

Building ID	Description	Characteristics
1r	HwBP30	Heavyweight, Best Practice, 30% Glazed
2r	HwPL30	Heavyweight, Part L, 30% Glazed
4r	LwPL30	Lightweight, Part L, 30% Glazed
5r	HwBP80	Heavyweight, Best Practice, 80% Glazed
6r	HwPL80	Heavyweight, Part L, 80% Glazed
8r	LwPL80	Lightweight, Part L, 80% Glazed
25r	HwBP30-E	Heavyweight, Best Practice, 30% Glazed, Eastern Orientation
26r	HwPL30-E	Heavyweight, Part L, 30% Glazed, Eastern Orientation
28r	LwPL30-E	Lightweight, Part L, 30% Glazed, Eastern Orientation
29r	HwBP80-E	Heavyweight, Best Practice, 80% Glazed, Eastern Orientation
30r	HwPL80-E	Heavyweight, Part L, 80% Glazed, Eastern Orientation
32r	LwPL80-E	Lightweight, Part L, 80% Glazed, Eastern Orientation
1rN	HwBP30*	Heavyweight, Best Practice, 30% Glazed, Natural Ventilation
2rN	HwPL30*	Heavyweight, Part L, 30% Glazed, Natural Ventilation
3rN	LwBP30*	Lightweight, Best Practice, 30% Glazed, Natural Ventilation
4rN	LwPL30*	Lightweight, Part L, 30% Glazed, Natural Ventilation
9rN	HwBP30-SW*	Heavyweight, Best Practice, 30% Glazed, SW Orientation, Nat. Vent.
10rN	HwPL30-SW*	Heavyweight, Part L, 30% Glazed, SW Orientation, Nat. Ventilation
11rN	LwBP30-SW*	Lightweight, Best Practice, 30% Glazed, SW Orientation, Nat. Vent.
12rN	LwPL30-SW*	Lightweight, Part L, 30% Glazed, SW Orientation, Nat. Ventilation

6. Sensitivity Analysis

The current chapter investigates the impact that a key parameter change has on the electricity consumption and consequently the arbitrage performance of the buildings. These parameters include, among others, the utilisation of additional RTP electricity data, different battery capacity sizes and weather data, as described in Chapter 3.7.

6.1 Birmingham IWEC Results (2018 RTP Data)

New building simulations for the selected buildings have been performed for the 2018 calendar year to ensure that the buildings' electricity profiles match the exact dates and times of the electricity prices, with their output being fed into the MATLAB Arbitrage model, using the 2018 RTP NordPool data. In this chapter, the impact on arbitrage is again presented per building element, similarly to the previous chapter's structure. Additionally, the 2017 and 2018 results are compared in terms of the differences in electricity shifted (% of peak loads, kWh/m^2), exports (kWh/m^2) and net cost (£/m^2) to evaluate the performance of the arbitrage model under different annual price series. It should be noted that given the significantly smaller number of buildings, the mean values shown in the current chapter are not directly comparable to the 2017 respective values and the relevant discussion is not as detailed.

6.1.1 Impact of Energy Efficiency

The comparison includes 8 buildings from each category, Best Practice and Part L; therefore, a total of 16 buildings. For the year 2018, regarding the Operational Strategy E7, Best Practice buildings are able to shift 1.54% more peak loads, export higher amounts of electricity by 1.19 kWh/m^2 and have a lower net cost by 1.28 £/m^2 than their Part L counterparts. There is a high degree of consistency among the different building scenarios; it can be noticed that the smallest differences take place between the naturally ventilated lightweight buildings: 3rN and 4rN, 11rN and 12rN. This is in accordance to the observations made in Chapter 5.2 as results are subject to higher degrees of variation when natural ventilation is adopted.

Table 6.1 – Impact of Energy Efficiency on selected buildings for Operational Strategy E7

Building ID		**Parameter (Unit)**							
Building A (Best Practice)	**Building B (Part L)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Electricity Exports (kWh/m^2)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
1r	2r	1.77	1.70	1.27	1.29	-1.08	-1.28	-1.28	-1.29
5r	6r	2.04	1.84	1.09	1.09	-1.17	-1.34	-1.16	-1.23
25r	26r	1.83	1.68	1.08	1.16	-1.06	-1.25	-1.11	-1.16
29r	30r	2.28	2.04	1.06	1.05	-1.20	-1.38	-1.10	-1.18
1rN	2rN	1.86	1.72	1.13	1.29	-1.09	-1.39	-1.15	-1.29
3rN	4rN	0.87	0.75	1.14	1.19	-0.87	-1.08	-1.13	-1.19
9rN	10rN	1.95	1.76	1.08	1.18	-1.10	-1.38	-1.06	-1.17
11rN	12rN	0.98	0.79	1.16	1.23	-0.90	-1.11	-1.11	-1.19
Mean value		1.70	1.54	1.13	1.19	-1.06	-1.28	-1.14	-1.21
Mean value of the absolute differences		1.70	1.54	1.13	1.19	1.06	1.28	1.14	1.21

The respective differences between the two building categories for the 2017 year are 1.70%, 1.13 kWh/m^2 and 1.06 £/m^2, indicating that results for both years are very consistent and any changes are trivial. Concerning the differences in net cost, it can be seen that, on average, Best Practice Buildings are cheaper to operate by 1.06 £/m^2 in 2017 and by 1.28 £/m^2 in 2018 when compared to the least efficient building cases. This difference takes place as for 2018, more exports take place and more electricity is shifted in total in terms of kWh/m^2 (Table 6.1).

While the electricity shifted and exports take place if allowed by the operational strategy, the calculation of the net cost is dependent on the daily distribution of the RTP data. For example, even if a building category is able to shift the same amount of peak loads with another building category for two consecutive years, the respective annual net costs can be very different due to the utilisation of unique hourly RTP data.

Moreover, as the distribution of days and weeks is different from year to year, the same day can lead to extremely opposite electricity profiles. For example, 5th of February 2018 is a Monday and therefore a working day with the consequent electricity consumption. However, for the year 2017, it is a Sunday and a non-working day, resulting in insignificant electricity loads that only include auxiliary energy. While it can be argued that the overall working hours and days of each year are always equal, their distribution is not and coupled with different RTP electricity data, it has the potential to lead to various results. The last two observations are not the case only for E7 but for any operational strategy of the current thesis.

Regarding E5 and the year 2018, Best Practice buildings can shift 1.41% higher peak loads and export 1.14 kWh/m^2 more electricity back to the grid compared to the Part L category (Table 6.2). Once again, no major differences are observed when comparing the results for both years. The net cost difference values are identical to the E7, as explained in Chapter 5.2. Finally, with exports disabled, Best Practice buildings are capable of shifting 3.96% higher peak loads than Part L whilst being more affordable by 1.39 £/m^2, for 2018 (Table 6.3). Overall, it is evident that 2018 RTP data has been slightly more beneficial for the arbitrage operation of Best Practice buildings against their Part L counterparts, leading to a higher net cost difference by 0.25 £/m^2 in relation to 2017. No difference has been observed between the mean values and the mean absolute values as there has been no variation within the compared buildings of Table 6.1 – 6.3.

Table 6.2 – Impact of Energy Efficiency on selected buildings for Operational Strategy E5

Building ID		Parameter (Unit)							
Building A (Best Practice)	Building B (Part L)	Differences in Electricity shifted (% of peak loads)		Differences in Electricity Exports (kWh/m^2)		Differences in Net Cost (£/m^2)		Differences in Electricity shifted (kWh/m^2)	
		2017	2018	2017	2018	2017	2018	2017	2018
1r	2r	1.51	1.45	1.26	1.28	-1.07	-1.28	-1.27	-1.28
5r	6r	1.74	1.55	1.08	1.09	-1.18	-1.33	-1.15	-1.22
25r	26r	1.59	1.45	1.07	1.15	-1.05	-1.24	-1.10	-1.15
29r	30r	1.97	1.73	1.06	1.06	-1.21	-1.38	-1.10	-1.19
1rN	2rN	1.77	1.63	1.09	1.26	-1.09	-1.40	-1.11	-1.26
3rN	4rN	1.04	0.88	0.99	1.05	-0.88	-1.09	-0.98	-1.05
9rN	10rN	1.88	1.68	1.04	1.14	-1.11	-1.39	-1.02	-1.13
11rN	12rN	1.15	0.94	1.00	1.09	-0.92	-1.13	-0.95	-1.05
Mean value		1.58	1.41	1.07	1.14	-1.06	-1.28	-1.08	-1.17
Mean value of the absolute differences		1.58	1.41	1.07	1.14	1.06	1.28	1.08	1.17

Table 6.3 – Impact of Energy Efficiency on selected buildings for Operational Strategy E0

Building ID		**Parameter (Unit)**					
Building A (Best Practice)	**Building B (Part L)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**
1r	2r	4.54	4.27	-1.17	-1.40	-0.31	-0.42
5r	6r	4.51	3.93	-1.26	-1.44	-0.44	-0.68
25r	26r	4.09	4.10	-1.14	-1.36	-0.33	-0.30
29r	30r	4.52	4.19	-1.29	-1.49	-0.44	-0.55
1rN	2rN	4.55	4.35	-1.17	-1.52	-0.09	-0.29
3rN	4rN	3.57	3.30	-0.96	-1.20	-0.11	-0.22
9rN	10rN	4.35	4.13	-1.18	-1.50	-0.14	-0.25
11rN	12rN	3.46	3.42	-0.99	-1.24	-0.16	-0.16
Mean value		4.20	3.96	-1.15	-1.39	-0.25	-0.36
Mean value of the absolute differences		4.20	3.96	1.15	1.39	0.25	0.36

6.1.2 Impact of Window-to-Wall ratio (glazing)

A total of 10 buildings are included in this section to be compared based on their window-to-wall ratio. As shown in Table 6.4 for Operational Strategy E7, 80% glazed buildings are more efficient than their 30% glazed counterparts, arbitrage-wise, shifting 0.30% and 0.27% higher peak loads shifted for the years 2017 and 018, respectively. They also export more electricity back to the grid by 0.47 and 0.41 kWh/m^2, leading to a lower operational cost by 0.28 and 0.34 £/m^2. Results are largely consistent across all buildings regardless of orientation as well as calendar years; therefore, with only one minor exception, all mean absolute values are equal to their respective means.

Table 6.4 – Impact of Glazing on selected buildings for Operational Strategy E7

Building ID		**Parameter (Unit)**							
Building A (30% glazed)	**Building B (80% glazed)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Electricity Exports (kWh/m^2)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
1r	5r	-0.53	-0.47	-0.46	-0.41	0.42	0.48	0.53	0.55
2r	6r	-0.26	-0.33	-0.65	-0.61	0.33	0.42	0.65	0.61
25r	29r	-0.55	-0.47	-0.40	-0.32	0.34	0.39	0.44	0.44
26r	30r	-0.10	-0.11	-0.42	-0.42	0.20	0.26	0.44	0.42
28r	32r	0.11	-0.12	-0.40	-0.30	0.10	0.14	0.44	0.30
Mean value		-0.27	-0.30	-0.47	-0.41	0.28	0.34	0.50	0.46
Mean value of the absolute differences		0.31	0.30	0.47	0.41	0.28	0.34	0.50	0.46

Concerning E5, the differences in peak loads shifted is slightly decreased to 0.14 and 0.15% for the two consecutive years while the net cost differences remained the same, as expected

(Table 6.5). Finally, when exports are not allowed, 80% glazed buildings shift on average 0.86% and 0.67% higher peak loads and they constitute the least expensive building category of the two by 0.28 and 0.33 £/m^2, for 2017 and 2018 respectively. Again, with some very minor exceptions, all 80% glazed buildings perform better for both E5 and E0 with the mean values being identical to the mean absolute values. It should be reminded that 80% glazed buildings consume on average 2.40 kWh/m^2 less electricity due to the increased amount of solar heat gains, allowing the BSS to shift higher percentages of peak loads and potentially export back any energy left back to the grid depending on the dispatch strategy followed (Table 6.6).

Table 6.5 – Impact of Glazing on selected buildings for Operational Strategy E5

Building ID		Parameter (Unit)							
Building A (30% glazed)	Building B (80% glazed)	Differences in Electricity shifted (% of peak loads)		Differences in Electricity Exports (kWh/m^2)		Differences in Net Cost (£/m^2)		Differences in Electricity shifted (kWh/m^2)	
		2017	2018	2017	2018	2017	2018	2017	2018
1r	5r	-0.39	-0.31	-0.47	-0.43	0.43	0.47	0.54	0.56
2r	6r	-0.16	-0.21	-0.65	-0.62	0.32	0.42	0.66	0.62
25r	29r	-0.39	-0.28	-0.43	-0.36	0.35	0.39	0.47	0.48
26r	30r	-0.01	0.00	-0.43	-0.45	0.19	0.25	0.46	0.45
28r	32r	0.27	0.07	-0.46	-0.38	0.10	0.12	0.50	0.38
Mean value		-0.14	-0.15	-0.49	-0.45	0.28	0.33	0.53	0.50
Mean value of the absolute differences		0.24	0.17	0.49	0.45	0.28	0.33	0.53	0.50

Table 6.6 – Impact of Glazing on selected buildings for Operational Strategy E0

Building ID		Parameter (Unit)					
Building A (30% glazed)	Building B (80% glazed)	Differences in Electricity shifted (% of peak loads)		Differences in Net Cost (£/m^2)		Differences in Electricity shifted (kWh/m^2)	
		2017	2018	2017	2018	2017	2018
1r	5r	-1.19	-0.85	0.45	0.52	0.36	0.55
2r	6r	-1.22	-1.19	0.37	0.48	0.32	0.29
25r	29r	-0.95	-0.58	0.37	0.42	0.40	0.53
26r	30r	-0.52	-0.49	0.22	0.29	0.30	0.29
28r	32r	-0.43	-0.25	0.13	0.16	0.22	0.29
Mean value		-0.86	-0.67	0.31	0.37	0.32	0.39
Mean value of the absolute differences		0.86	0.67	0.31	0.37	0.32	0.39

6.1.3 Impact of Orientation

20 buildings are included in this comparison chapter, 8 of which are naturally ventilated. The results for both years, for Operational Strategy E7, can be seen in Table 6.7 with mean values being provided for each ventilation strategy along with the overall average values. To begin with, mechanically-ventilated buildings with the default southern orientation manage to shift higher percentage of their peak loads by 0.73% and 0.71%, export higher amounts of

electricity by 0.10 kWh/m^2, being therefore more affordable by 0.21 and 0.24 £/m^2, for the years 2017 and 2018, respectively. The results demonstrate high levels of consistence and, as shown in the previous chapter for the 2017 results, the highest differences take place when comparing the Part L cases with the highest glazing percentage (i.e. 6r and 8r vs 30r and 32r for the buildings of the current chapter) as the combination of these design elements maximises the numerical differences in this category.

Table 6.7 – Impact of Orientation on selected buildings for Operational Strategy E7

Building ID		**Parameter (Unit)**							
Building A (South)	**Building B (Eastern or SW)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Electricity Exports (kWh/m^2)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
1r	25r	0.62	0.66	0.17	0.11	-0.17	-0.20	-0.14	-0.11
2r	26r	0.68	0.64	-0.03	-0.02	-0.15	-0.17	0.03	0.03
4r	28r	0.63	0.61	0.06	0.06	-0.13	-0.16	-0.06	-0.06
5r	29r	0.60	0.66	0.23	0.21	-0.25	-0.29	-0.23	-0.22
6r	30r	0.84	0.86	0.20	0.17	-0.28	-0.33	-0.18	-0.17
8r	32r	0.98	0.82	0.05	0.09	-0.24	-0.27	-0.02	-0.10
Mean value (Mech. Ventilation)		0.73	0.71	0.11	0.10	-0.21	-0.24	-0.10	-0.10
Mean absolute value (Mech. Ventilation)		0.73	0.71	0.12	0.11	0.21	0.24	0.11	0.11
1rN	9rN	0.54	0.39	0.01	0.06	-0.14	-0.18	-0.01	-0.12
2rN	10rN	0.63	0.43	-0.05	-0.05	-0.15	-0.17	0.07	0.00
3rN	11rN	0.70	0.55	-0.01	-0.01	-0.12	-0.15	0.02	-0.06
4rN	12rN	0.81	0.59	0.01	0.04	-0.15	-0.18	0.04	-0.07
Mean value (Nat. Ventilation)		0.67	0.49	-0.01	0.01	-0.14	-0.17	0.03	-0.06
Mean absolute value (Nat. Ventilation)		0.67	0.49	0.02	0.04	0.14	0.17	0.04	0.06
Overall Mean value		0.70	0.62	0.07	0.06	-0.18	-0.21	-0.05	-0.09
Overall Mean absolute value		0.70	0.62	0.08	0.08	0.18	0.21	0.08	0.09

Moreover, naturally ventilated buildings with the default orientation are the most efficient building category arbitrage-wise as they can shift higher percentage of their peak loads by 0.67% and 0.49%, for the two consecutive years, respectively. This constitutes the only battery activity that differences are observed as both building categories manage to export the same amount of electricity, approximately, for both years. Finally, as a southern orientation results into a cheaper net cost by 0.14 and 0.17 £/m^2, results are once again consistent for the two time periods in question.

Overall, in technical terms, the arbitrage results appear to be more beneficial for buildings with the default orientation, for 2017 as the differences reach 0.70% for the peak with the respective 2018 value being slightly lower at 0.62%. There is no difference between the years in regards to the electricity exports difference which stays between 0.06 – 0.07 kWh/m^2. However, as mentioned previously, these technical advantages do not necessarily translate into a cheaper annual net cost because the electricity hourly prices are unique for each year. Consequently, the highest differences in net cost take place for 2018 as buildings with southern orientation are cheaper by 0.21 £/m^2, slightly higher than the 2017 net cost difference of 0.18 £/m^2.

For Operational Strategy E5, similar conclusions can be made regarding both mechanically and naturally ventilated buildings by observing Table 6.8. Overall, buildings with southern orientation still perform better as they are able to shift higher percentages of their peak loads by 0.67% and 0.60%, they export slightly more electricity by 0.06 and 0.05 kWh/m^2, for the two consecutive years, respectively. Similarly to E7, these technical benefits do not translate to economic benefits when comparing the results per year as the building category leads to cheaper net cot by 0.18£/m^2 for 2017 and slightly higher by 0.21£/m^2 for 2018. The nest cost results observed are identical to the E7 values, for both years.

Table 6.8 – Impact of Orientation on selected buildings for Operational Strategy E5

Building ID		**Parameter (Unit)**							
Building A (South)	**Building B (Eastern or SW)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Electricity Exports (kWh/m^2)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
1r	25r	0.56	0.61	0.16	0.11	-0.17	-0.21	0.16	-0.11
2r	26r	0.64	0.61	-0.03	-0.02	-0.15	-0.17	-0.03	0.03
4r	28r	0.60	0.59	0.05	0.05	-0.14	-0.15	0.05	-0.05
5r	29r	0.56	0.64	0.21	0.18	-0.25	-0.29	0.21	-0.19
6r	30r	0.79	0.82	0.19	0.15	-0.28	-0.34	0.19	-0.15
8r	32r	0.99	0.87	0.01	0.04	-0.24	-0.28	0.01	-0.05
Mean value (Mech. Ventilation)		0.69	0.69	0.10	0.08	-0.21	-0.24	0.10	-0.09
Mean absolute value (Mech. Ventilation)		0.69	0.69	0.11	0.09	0.21	0.24	0.11	0.09
1rN	9rN	0.50	0.36	0.02	0.07	-0.13	-0.18	-0.02	-0.13
2rN	10rN	0.61	0.41	-0.04	-0.05	-0.15	-0.17	0.07	0.00
3rN	11rN	0.65	0.52	0.01	-0.01	-0.11	-0.14	0.01	-0.06
4rN	12rN	0.76	0.58	0.01	0.02	-0.15	-0.18	0.03	-0.05
Mean value (Nat. Ventilation)		0.63	0.47	0.00	0.01	-0.14	-0.17	0.02	-0.06
Mean absolute value (Nat. Ventilation)		0.63	0.47	0.02	0.04	0.14	0.17	0.03	0.06
Overall Mean value		0.67	0.60	0.06	0.05	-0.18	-0.21	0.07	-0.08
Overall Mean absolute value		0.67	0.60	0.07	0.07	0.18	0.21	0.08	0.08

Finally, for Operational Strategy E0 (Table 6.9), it can be seen that buildings with the default orientation can shift on average higher percentage of their peak loads by 1.08% and 0.95% resulting in being cheaper by 0.19 and 0.22 £/m^2, for 2017 and 2018, respectively, when compared with buildings of other orientations. All the previously observations for E7 and E5 also apply here and orientation results are consistent for both years examined. It should be noted that there are very minor differences between the mean and absolute mean vales due to the lack of variations within the results.

Table 6.9 – Impact of Orientation on selected buildings for Operational Strategy E0

Building ID		**Parameter (Unit)**					
Building A (South)	**Building B (Eastern or SW)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**
1r	25r	1.27	0.94	-0.19	-0.21	0.07	-0.07
2r	26r	0.82	0.77	-0.15	-0.16	0.05	0.05
4r	28r	0.90	0.84	-0.14	-0.16	0.03	0.01
5r	29r	1.51	1.21	-0.27	-0.31	0.06	-0.09
6r	30r	1.52	1.47	-0.30	-0.35	0.06	0.04
8r	32r	1.36	1.32	-0.24	-0.28	0.09	0.07
Mean value (Mech. Ventilation)		1.23	1.09	-0.22	-0.25	0.06	0.00
Mean absolute value (Mech. Ventilation)		1.23	1.09	0.22	0.25	0.06	0.06
1rN	9rN	0.82	0.71	-0.15	-0.19	0.07	-0.03
2rN	10rN	0.62	0.49	-0.15	-0.17	0.02	0.00
3rN	11rN	1.06	0.82	-0.12	-0.15	0.11	0.00
4rN	12rN	0.95	0.94	-0.15	-0.19	0.06	0.07
Mean value (Nat. Ventilation)		0.86	0.74	-0.14	-0.17	0.07	0.01
Mean absolute value (Nat. Ventilation)		0.86	0.74	0.14	0.17	0.07	0.03
Overall Mean value		1.08	0.95	-0.19	-0.22	0.06	0.00
Overall Mean absolute value		1.08	0.95	0.19	0.22	0.06	0.04

6.1.4 Impact of Thermal Mass

A total of 12 buildings are compared in this chapter, 4 out of which are naturally ventilated. The comparison is not as extensive as in Chapter 5.2 due to the lack of several buildings, such as the 80% glazed Best Practice cases and any Best Practice buildings, in general. Overall, it is clear that for both years, lightweight buildings perform better in terms of arbitrage. More specifically, they are able to shift higher peak loads by 1.78% and 1.92%, they export more electricity back to the grid by 0.13 and 0.24 kW/m^2, resulting in a cheaper net cost by 0.20 and 0.23 £/m^2, for the two consecutive years, respectively. As previously discussed, while a specific building category, in this case buildings with lighter thermal mass, achieve an overall better arbitrage performance in terms of exports and electricity shifts for the 2017 calendar year, there are tangible financial benefits as the net cost differences for both years are almost identical; hence reflecting once again the importance of the RTP data.

Regarding the breakdown of the results, ventilation strategy proves to be the key secondary design characteristic when comparing buildings according to their thermal mass. For 2018, when mechanical ventilation is adopted and Operational Strategy E7 is followed (Table 6.10), lightweight buildings are able to shift on average 1.22% higher peak loads, 0.25 kWh/m^2 more electricity exports and are cheaper by 0.13 £/m^2. For naturally ventilated buildings, the benefits of lightweight buildings increase with their respective results reaching 3.34%, 0.23 kWh/m^2 and 0.40 £/m^2, for the same year. Results are consistent for both years; however, it must be noted that the sample of naturally ventilated buildings used for this comparison is relatively

Table 6.10 – Impact of Thermal mass on selected buildings for Operational Strategy E7

Building ID		Parameter (Unit)							
Building A (Heavyweight)	Building B (Lightweight)	Differences in Electricity shifted (% of peak loads)		Differences in Electricity Exports (kWh/m²)		Differences in Net Cost (£/m²)		Differences in Electricity shifted (kWh/m²)	
		2017	2018	2017	2018	2017	2018	2017	2018
2r	4r	-1.14	-1.20	0.07	0.11	0.17	0.20	-0.07	-0.11
6r	8r	-1.12	-1.20	0.32	0.38	0.05	0.03	-0.32	-0.37
26r	28r	-1.19	-1.23	0.15	0.19	0.19	0.21	-0.15	-0.19
30r	32r	-0.98	-1.24	0.17	0.31	0.09	0.09	-0.16	-0.31
1rN	3rN	-2.63	-2.85	0.03	0.27	0.23	0.27	-0.04	-0.26
2rN	4rN	-3.62	-3.82	0.04	0.17	0.45	0.58	-0.03	-0.15
Mean value		-1.78	-1.92	0.13	0.24	0.20	0.23	-0.13	-0.23
Mean absolute value		1.78	1.92	0.13	0.24	0.20	0.23	0.13	0.23

Table 6.11 – Impact of Thermal mass on selected buildings for Operational Strategy E5

Building ID		Parameter (Unit)							
Building A (Heavyweight)	Building B (Lightweight)	Differences in Electricity shifted (% of peak loads)		Differences in Electricity Exports (kWh/m²)		Differences in Net Cost (£/m²)		Differences in Electricity shifted (kWh/m²)	
		2017	2018	2017	2018	2017	2018	2017	2018
2r	4r	-1.05	-1.11	0.06	0.10	0.17	0.19	-0.05	-0.10
6r	8r	-1.01	-1.11	0.29	0.35	0.05	0.02	-0.28	-0.34
26r	28r	-1.09	-1.13	0.13	0.16	0.18	0.21	-0.13	-0.17
30r	32r	-0.81	-1.06	0.10	0.23	0.09	0.08	-0.09	-0.24
1rN	3rN	-2.36	-2.58	-0.05	0.19	0.22	0.25	0.04	-0.17
2rN	4rN	-3.09	-3.33	-0.16	-0.02	0.43	0.56	0.17	0.03
Mean value		-1.57	-1.72	0.06	0.17	0.19	0.22	-0.06	-0.14
Mean absolute value		1.57	1.72	0.13	0.17	0.19	0.22	0.13	0.16

Table 6.12 – Impact of Thermal mass on selected buildings for Operational Strategy E0

Building ID		Parameter					
Building A (Heavyweight)	Building B (Lightweight)	Differences in Electricity shifted (% of peak loads)		Differences in Net Cost (£/m²)		Differences in Electricity shifted (kWh/m²)	
		2017	2018	2017	2018	2017	2018
2r	4r	-1.11	-1.20	0.16	0.19	0.03	-0.03
6r	8r	-0.78	-0.74	0.03	-0.01	-0.11	-0.10
26r	28r	-1.03	-1.13	0.17	0.19	0.00	-0.07
30r	32r	-0.94	-0.89	0.09	0.06	-0.08	-0.07
1rN	3rN	-3.09	-3.11	0.23	0.24	0.01	-0.14
2rN	4rN	-4.07	-4.16	0.44	0.56	0.00	-0.07
Mean value		-1.84	-1.87	0.19	0.21	-0.03	-0.08
Mean absolute value		1.84	1.87	0.19	0.21	0.04	0.08

small and therefore the mean value might not be representative of the respective building category's population.

Moreover, the E5 results are presented below in Table 6.11. On average, for both years, lightweight buildings shift 1.57% and 1.72% more electricity in terms of their peak loads, they export higher amounts of electricity by 0.06 and 0.17 kWh/m^2 while their annual net costs have similar values with the previous strategy. As discussed in the 2017 results, the differences observed for both the shifted electricity and exports are lower for E5 when compared to the respective E7 values. The highest difference values take place again when comparing naturally ventilate cases. Regarding Operational Strategy E0, lightweight buildings are capable of shifting 1.84% and 1.87% higher peak loads for the two years, respectively (Table 6.12). Net cost differences are almost identical to the previous two strategies and results are consistent across both years. No major differences can be seen between the mean and mean absolute values for all three strategies, indicating the lack of any significant variations.

6.1.5 Impact of Ventilation Method

The final results consist of just 6 buildings and constitute the shortest comparison of Chapter 6.1 and are presented below in Tables 6.13 – 6.15. It is clear that the synergy of ventilation strategy and thermal mass is present, affecting the suitability of buildings to perform arbitrage. Under all operational strategies, mechanically ventilated buildings with a heavy thermal mass (1r, 2r) are able to perform better overall than their naturally ventilated counterpart (1rN, 2rN).

On the other hand, the lightweight naturally ventilated building 4rN can be seen to have a better performance than its mechanically ventilated counterpart, 4r, in terms of the electricity shifted. However, as its exports are lower, its overall net cost is slightly higher for both years; its net cost difference is still a fraction when compared to the rest of the buildings. Comparing the mean and mean absolute value, it is clear that significant variations take place due to the values introduced by the 4r – 4rN building couple. Given the very small size of the sample, the mean values should only be used for comparison purposes between the two years and operational strategies; no reliable conclusions can be made regarding differences in performance comparison of mechanical versus natural ventilation. In this direction, it is evident that the parameters' differences for the years 2017 and 2018 are once again consistent.

Table 6.13 – Impact of Ventilation Strategy on selected buildings for Operational Strategy E7

Building ID		**Parameter (Unit)**							
Building A (Mechanical Ventilation)	**Building B (Natural Ventilation)**	**Differences in Electricity shifted (% of peak loads)**		**Differences in Electricity Exports (kWh/m^2)**		**Differences in Net Cost (£/m^2)**		**Differences in Electricity shifted (kWh/m^2)**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
1r	1rN	1.60	1.53	0.34	0.29	-0.29	-0.29	-0.33	-0.23
2r	2rN	1.69	1.55	0.20	0.29	-0.30	-0.40	-0.20	-0.23
4r	4rN	-0.79	-1.07	0.17	0.35	-0.02	-0.02	-0.16	-0.27
Mean value		0.83	0.67	0.24	0.31	-0.20	-0.24	-0.23	-0.24
Mean absolute value		1.36	1.38	0.24	0.31	0.20	0.24	0.23	0.24

Table 6.14 – Impact of Ventilation Strategy on selected buildings for Operational Strategy E5

Building ID		Parameter (Unit)							
Building A (Mechanical Ventilation)	Building B (Natural Ventilation)	Differences in Electricity shifted (% of peak loads)		Differences in Electricity Exports (kWh/m²)		Differences in Net Cost (£/m²)		Differences in Electricity shifted (kWh/m²)	
		2017	2018	2017	2018	2017	2018	2017	2018
1r	1rN	0.65	0.63	0.74	0.67	-0.25	-0.24	-0.73	-0.61
2r	2rN	0.91	0.81	0.57	0.65	-0.27	-0.36	-0.57	-0.59
4r	4rN	-1.13	-1.41	0.36	0.53	-0.01	0.01	-0.35	-0.46
Mean value		0.14	0.01	0.56	0.62	-0.18	-0.20	-0.55	-0.55
Mean absolute value		0.90	0.95	0.56	0.62	0.18	0.20	0.55	0.55

Table 6.15 – Impact of Ventilation Strategy on selected buildings for Operational Strategy E0

Building ID		Parameter (Unit)					
Building A (Mechanical Ventilation)	Building B (Natural Ventilation)	Differences in Electricity shifted (% of peak loads)		Differences in Net Cost (£/m²)		Differences in Electricity shifted (kWh/m²)	
		2017	2018	2017	2018	2017	2018
1r	1rN	2.20	2.02	-0.30	-0.30	-0.30	-0.21
2r	2rN	2.21	2.10	-0.31	-0.42	-0.08	-0.08
4r	4rN	-0.75	-0.86	-0.03	-0.05	-0.11	-0.12
Mean value		1.22	1.09	-0.21	-0.26	-0.16	-0.14
Mean absolute value		1.72	1.66	0.21	0.26	0.16	0.14

6.1.6 Summary and further selection of Building Cases

The arbitrage results, presented in section 6.1, are summarised in Table G1 of the Appendix, for Operational Strategy E0 and both years 2017 and 2018. As discussed, the impact of the building design elements appear to be highly consistent for both calendar years, demonstrating the reliability of the Arbitrage MATLAB model. It is evident that all but one of the respective values are identical, indicating no variations or changes in patterns when comparing the individual buildings. The ventilation strategy used constitutes once more the exception, regarding the shifted electricity; while on average mechanically ventilated buildings are able of shifting 1.22% and 1.09% more electricity in terms of their peak loads for the two consecutive years, the respective mean absolute values are relatively higher at 1.72% and 1.66%. This is not surprising as the original 2017 results did demonstrate the high variation levels that are present while investigating the impact of the ventilation strategy on arbitrage performance as a design element. This has also been the primary reason that all the naturally ventilated building cases belonging to the same orientation (1rN – 4rN, 9rN – 12rN) have not been eliminated but chosen to be further assessed in the current section, using the 2018 RTP data.

The next sections of the Sensitivity Analysis focus on the building scenarios observed to have the best and the worst performances. Regarding building cases with natural ventilation, it is essential to include at least four naturally ventilated buildings that share the same orientation for the reasons stated above. As the differences between the default (1rN – 4rN) and the south-western (9rN – 12rN) orientation are not significant (Tables 6.7 – 6.9), Buildings 1rN –

4rN are the only cases with natural ventilation which are considered in the sensitivity analysis; however, the number of mechanically ventilated building cases still needs to be narrowed down from 12 to 4 to include two building cases with good performance and two more cases with bad performance.

As both the energy consumption of the buildings and their arbitrage performance must be taken into account, it is essential to take a look a their total electricity consumption without storage and the shifted electricity (% of peak loads) for Operational Strategy E0 (Figure G1). In summary:

- Buildings 29r (HwBP80-E) and 5r (HwBP80) require the least amount of electricity and therefore have the best overall energy performance. The buildings share the same design elements with the exception of orientation; both of them are best Practice in terms of their thermal efficiency, heavyweight and 80% glazed.

- Buildings 26r (HwPL30-E) and 2r (HwPL30) need the highest electricity grid purchases and constitute the least energy efficient cases. Similarly to above, the two cases are identical with different orientation; both are Part L compliant, heavyweight and 30% glazed.

Having these four building cases in mind and considering, in ascending order, the electricity shifted (% of peak loads) when exports are not allowed (Figure G2), it is evident that the previously mentioned buildings 26r and 5r constitute the cases with the lowest and highest values, respectively. While the other two buildings, 2r and 29r, do not constitute the second highest and lowest values, they do come third with a very small difference between them and the previous contenders, 30r and 1r. Therefore, these four mechanically ventilated buildings are indeed a representative mix of the worst and the best case scenarios. Together with the four naturally ventilated buildings 1rN – 4rN, they form the final eight cases that are considered for the rest of the Sensitivity Analysis.

The results in the rest of the chapter are presented as a comparison to the Base Case (Birmingham 2017) in terms of the dimensionless changes as percentages. For example, when considering the electricity shifted for the Base Case vs Southampton, the dimensionless value given is calculated as :

$$\text{Change (\%)} = \frac{\text{Electricity Shifted (Base Case)} - \text{Electricity Shifted (Southampton)}}{\text{Electricity Shifted (Base Case)}} \, x\ 100$$

6.2 Location

The main results of Chapter 4 use the location of Birmingham Airport and its associated IWEC weather data while the 2017 NordPool historical prices are used for the electricity tariffs; this model configuration should be referred to from now as the Base model. Two more UK locations have been strategically selected for the needs of this sensitivity analysis in order to include both a generally warmer and a colder climate. They have a distance of approximately 470 miles while the city of Birmingham is in the middle of England:

a) Bournemouth Airport (England), located in the south part of the country. Due to its proximity to the city of Southampton, the weather data are simply marked as 'Southampton TRY' by CIBSE.

b) Edinburgh Airport (Scotland), located in the northern part of the UK.

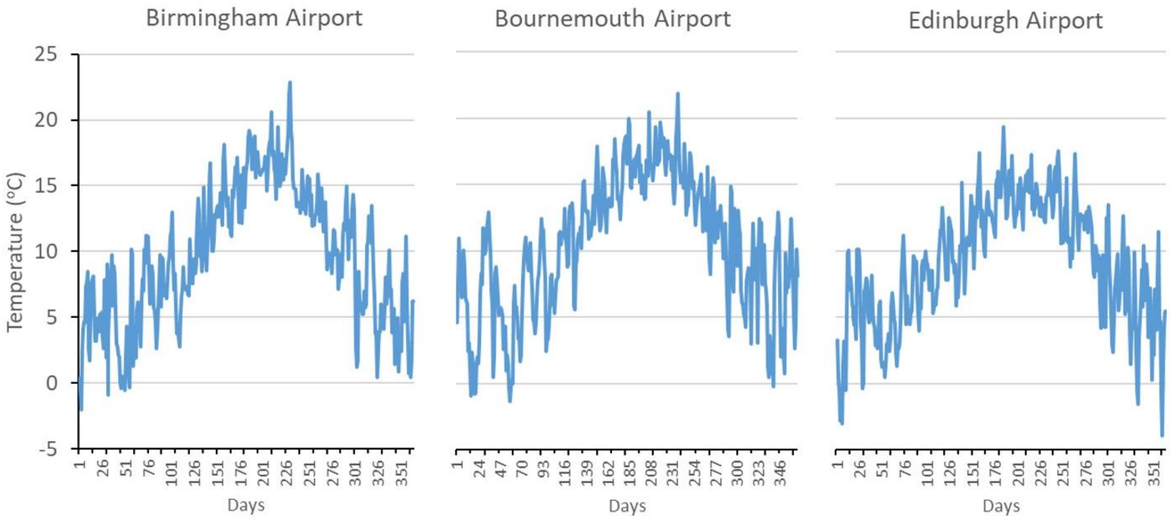

Figure 6.1 – Average daily outdoor dry-bulb temperature for the selected UK locations

While the average temperatures are 9.7^{0}C for Birmingham, 10.5^{o}C for Bournemouth and 9^{o}C for Edinburgh, there are significant seasonal variations throughout the year, as shown in Figure 6.1 regarding the average daily outdoor dry-bulb temperatures. Bournemouth observes higher temperatures than Birmingham for the majority of the year, including winter and especially January. On the other hand, Edinburgh is the coldest of the three locations and while marginally negative temperatures can be seen for Birmingham and Bournemouth, Edinburgh experiences even lower values, reaching -4^{o}C at the end of December. In summary, it can be said that the three location temperatures can be classified in accordance with their geographical latitude.

The total electricity consumption (kWh/m^2) for the two new locations can be seen in Figure 6.2 in comparison to the Base Case scenario. For the majority of the building scenarios, Southampton appears to be the location requiring the least amount of electricity with a range between 50.98 – 64.37 kWh/m^2, followed by Birmingham (52.57 – 67.36 kWh/m^2) while Edinburgh needs the highest amount of electricity for the same building functions (51.23 – 68.91 kWh/m^2).

It should be highlighted that Buildings 5r and 29r constitute marginally an exception to this general classification of electricity loads. For these specific cases, the Edinburgh location is now second in electrical demand with 51.23 and 54.08 kWh/m^2, respectively, as the Base

Case is the most energy intensive location for the two buildings in question with the respective values reaching 52.57 and 54.41 kWh/m^2. Regarding their design characteristics, they consist of the exact same configuration (heavyweight, best practice, 80% glazing), with the orientation being their only difference (south, eastern). Given the fact that they belong among the best-performing building scenarios in terms of their energy performance, this exception can be explained by looking at the electricity consumption for the major building sectors.

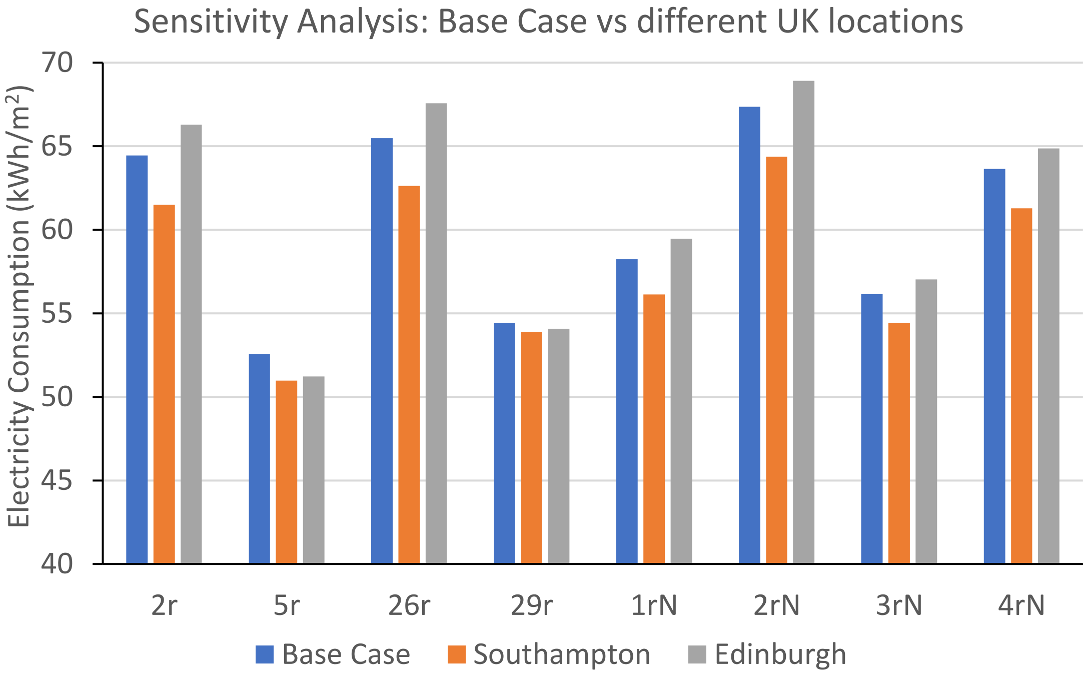

Figure 6.2 – Total Electricity Consumption in all locations and selected buildings

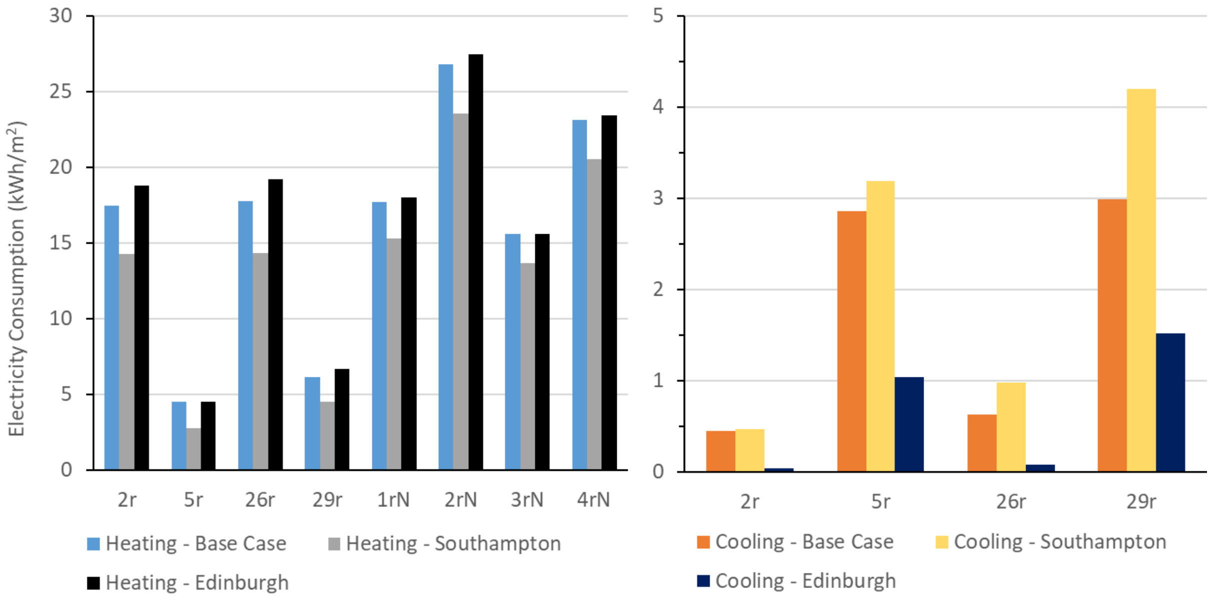

Figure 6.3 – Electricity Consumption for heating and cooling in all locations and buildings

As they belong to the Best Practice scenario and therefore have high energy efficiency and low thermal losses and U-values, the differences in their heating demand are trivial; on the other hand, due to the higher solar gains of the Base Case, especially in the summer period, the cooling loads are significantly higher in the warmer locations than in Edinburgh. Figure 6.3 compares the heating and cooling electricity consumption for all selected buildings. Geographically, as Birmingham is generally seen to be the middle scenario, between Southampton and Edinburgh, it is proven to be an appropriate location for the Base Case scenario.

Regarding the Arbitrage results, directly comparing the amounts of shifted electricity for the different locations would not be representative of the total electricity consumption differences, under Operational Strategies E7 and E5. As explained earlier in the chapter, arbitrage is the combination of shifting building electrical loads and exporting any excess electricity back to the grid; therefore, looking at the individual results might lead to misinterpretations and it is important for both parameters, shifted and exported electricity, to be taken into account. In this particular case, for example, the amount of shifted electricity decreases for the vast majority of the selected building scenarios when switching from Birmingham to Southampton and Edinburgh (Table 6.16). The highest changes take place when natural ventilation is used, for example in Southampton the best and worst performing buildings are able to shift 2.92% and 2.20% less compared to Birmingham while the respective values for the Edinburgh buildings are 1.44% and 0.56%.

Table 6.16 – Electricity Shifted for three UK Locations under E7

Building Groups	**Average Electricity Shifted (% of peak loads)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case**	**Southampton**	**Edinburgh**	**Base Case vs Southampton**	**Base Case vs Edinburgh**
Best (5r,29r)	31.46	31.30	31.41	+0.51	+0.17
Worst (2r,26r)	29.12	29.65	28.93	-1.80	+0.65
With Natural Ventilation					
Best (1rN, 3rN)	30.95	30.04	30.50	+2.92	+1.44
Worst (2rN,4rN)	29.58	28.93	29.42	+2.20	+0.56

Table 6.17 – Exports for three UK Locations under E7

Building Groups	**Exports (kWh/m^2)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case**	**Southampton**	**Edinburgh**	**Base Case vs Southampton**	**Base Case vs Edinburgh**
Best (5r,29r)	17.96	18.29	18.27	-1.83	-1.72
Worst (2r,26r)	16.35	16.76	15.95	-2.51	+2.44
With Natural Ventilation					
Best (1rN, 3rN)	17.26	17.90	17.17	-3.71	+0.50
Worst (2rN,4rN)	16.12	16.74	15.78	-3.86	+2.06

However, this is not the case when considering the export values of Table 6.17 for E7 as switching to Southampton results in higher exports with the difference being between 1.83 and 3.86%. On the other hand, buildings located in Edinburgh now perform worse than the Base Case, with one exception, exporting lower amounts of electricity with a difference range between 0.50 – 2.44%. It is clear that the results for the arbitrage parameters observed under E7 for the sensitivity analysis in question are mixed when analysed separately and do not confirm the electricity consumption trends seen in Figures 6.2 - 6.3.

This is not the case for the E0 results as exporting does not take place (Table 6.18). The impact of the location and the used weather data are directly comparable to the electricity used and shifted. According to Figure 6.4 which summarises the E0 arbitrage results, Southampton is the best performing location for the vast majority of the building scenarios with a range of 32.57 – 41.07 kWh/m^2. Birmingham, as the Base Case, follows with values between 31.74 – 39.68 kWh/m^2 while Edinburgh proves to be the worst performing location (30.98 – 38.25 kWh/m^2). There are still a couple of noticeable exceptions (5r, 29r) which again belong to the best performing buildings of the entire chapter both in terms of energy and arbitrage performance, as previously discussed.

Table 6.18 – Electricity Shifted for three UK Locations under E0

Building Groups	**Average Electricity Shifted (% of peak loads)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case**	**Southampton**	**Edinburgh**	**Base Case vs Southampton**	**Base Case vs Edinburgh**
Best (5r,29r)	38.93	39.99	39.98	-2.72	-2.70
Worst (2r,26r)	33.54	34.91	32.63	-4.07	+2.71
With Natural Ventilation					
Best (1rN, 3rN)	37.84	38.13	36.85	-0.78	+2.60
Worst (2rN,4rN)	33.78	33.96	32.77	-0.53	+2.98

Regarding the changes recorded for the best and worst performing building groups, switching to Southampton increases the peak loads shifted by a range of 0.53 – 4.07% while Edinburgh-located buildings are able of shifting less electricity by 2.60 – 2.98%. On average, taking into account any exceptions as well, for Operational Strategy E0, switching to Southampton leads to an increase in electricity shifted by an average percentage value of 2.03% while switching to Edinburgh reduces the total electricity shifted value by 1.40%.

Finally, the E0 net cost results are shown in Figure 6.5 and they are in accordance with the shifted electricity results. Southampton is clearly the most economical location for the arbitrage scheme as the annual net cost varies between 5.94 – 7.75 £/m^2. Birmingham is once again the middle scenario with a respective range of 6.20 – 8.13 £/m^2 while Edinburgh constitutes the most expensive location of the three with values between 6.03 – 8.30 £/m^2. The differences in certain locations, especially for Buildings 5r and 29r can be considered to be insignificant. Concerning the observed mean values, switching to Southampton decreases the net cost by 4.04% while it is on average 1.26% more expensive for Edinburgh-located buildings to perform the exact same functions as part of the arbitrage scheme.

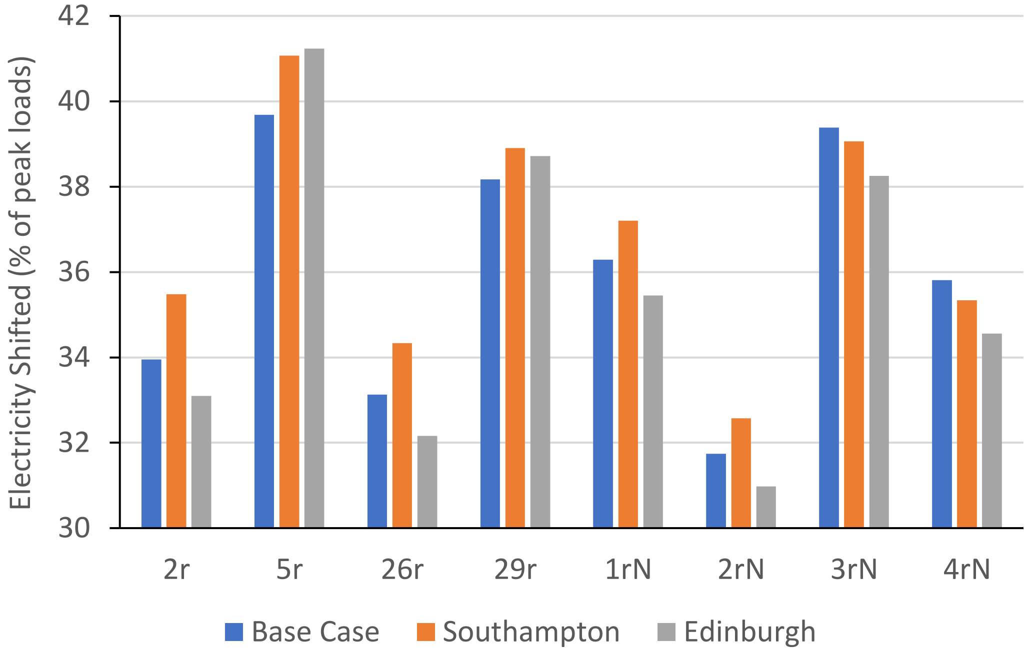

Figure 6.4 – Electricity Shifted under E0 for three UK locations

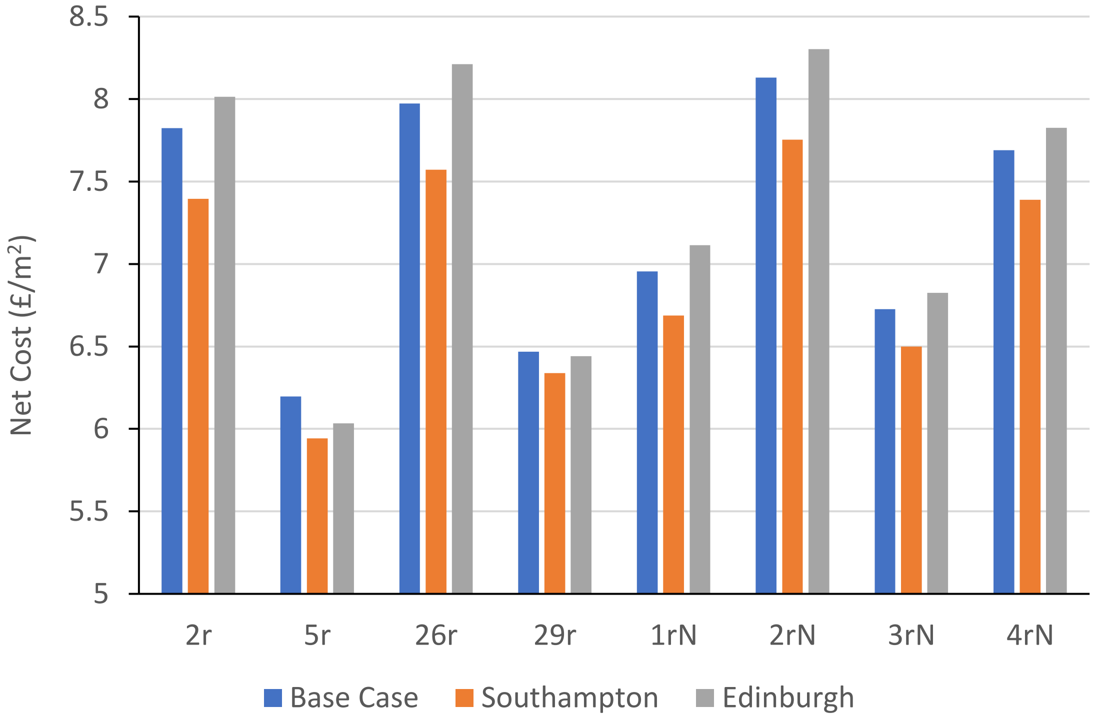

Figure 6.5 – Net Cost (£/m^2) under E0 for three UK locations

6.3 Historical Weather Data

Similarly to the previous section, different climate data are used to assess how real weather conditions affect the energy and arbitrage results. In this direction, historical hourly data from Manchester Airport and the calendar year 2017 (referred to from now on as MAN17) have been chosen and used in the simulations as the closest location with the available information. The outdoor dry-bulb temperature for the Base Case and MAN17 are shown in Figure 6.6 and, overall, the data follow the same seasonal patterns. In terms of the key values observed, the mean temperature for MAN17 is 10.5^{0}C, slightly higher than the Base Case value of 9.7^{o}C. Similarly, the respective minimum values for the two locations are -1.4^{o}C and -2^{o}C.

The maximum temperature that takes place in Birmingham (22.9^{o}C) is 1.5^{o}C higher than the respective value for MAN17. There are several fluctuations through the year and it can be seen that while the distribution of the temperatures is symmetric for the Base Case, it's slightly negatively skewed for the historical Manchester data, similarly to the other locations used for the previous subchapter. Key temperature statistics for the weather data used are summarised below, in Table 6.19.

Regarding the energy consumption results, buildings with mechanical ventilation require slightly more electricity when using the MAN17 historical weather data (Figure 6.7). In more detail, while Base Case buildings need between 52.57 – 65.47 kWh/m^2, the respective values increase to 54.36 – 67.08 kW/m^2. On the other hand, this is not the case for naturally-ventilated buildings which require lower amount of electricity between 54.25 – 64.55 kWh/m^2 in Manchester, higher than the respective Base Case range (56.15 – 67.36). Therefore, it is important to take a closer look at the building sectors, individually.

The electricity consumption towards cooling is significantly lower for the MAN17 building scenarios, ranging between 0.20 – 1.72 kWh/m^2 while the Base Case values are comparatively much higher, varying from 0.44 to 2.99 kWh/m^2. This difference indicates that the MAN17 weather data include lower solar gains values resulting into a smaller cooling electricity demand for the late spring and the summer periods.

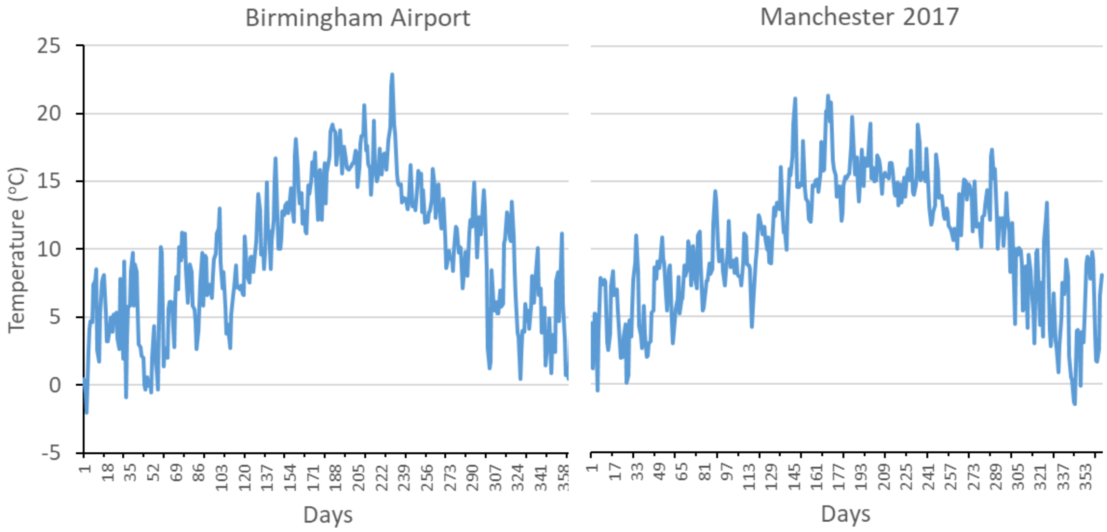

Figure 6.6 – Average daily outdoor dry-bulb temperature for Birmingham and Manchester 2017

Table 6.19 – Overview of the outdoor dry-bulb temperature for the weather data used

Location	Mean temperature	Minimum temperature	Maximum temperature	Standard Deviation	Skewness
Birmingham	9.69	-2.04	22.85	5.17	0
Southampton	10.46	-1.36	21.87	5.10	-0.28
Edinburgh	9.04	-3.95	19.38	4.55	-0.30
Manchester 2017	10.48	-1.44	21.36	4.75	-0.22

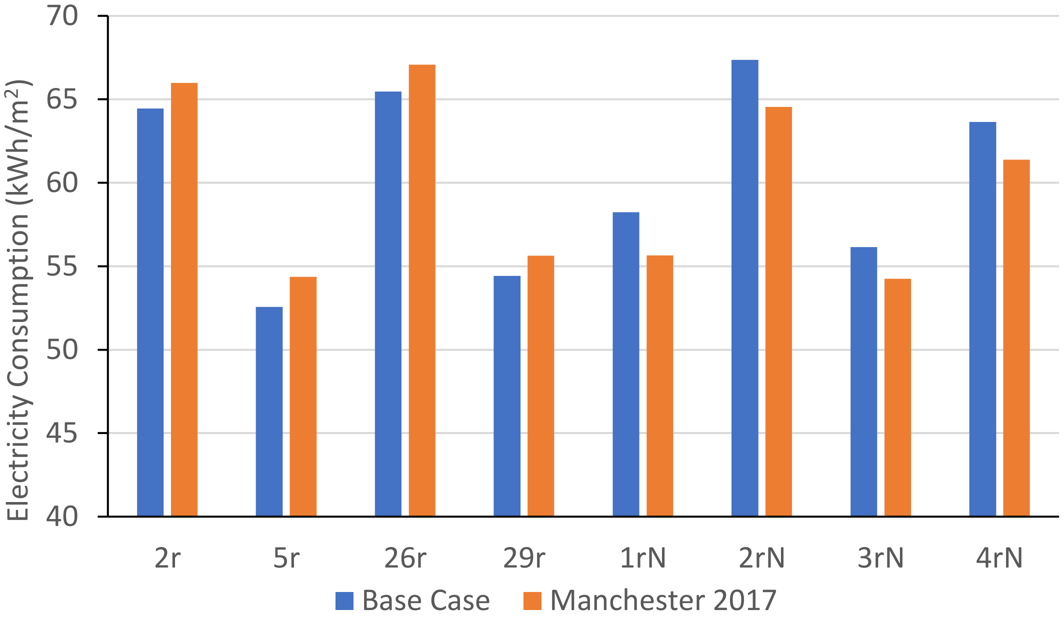

Figure 6.7 – Total Electricity Consumption in selected buildings for Base Case and the Manchester 2017 climate data

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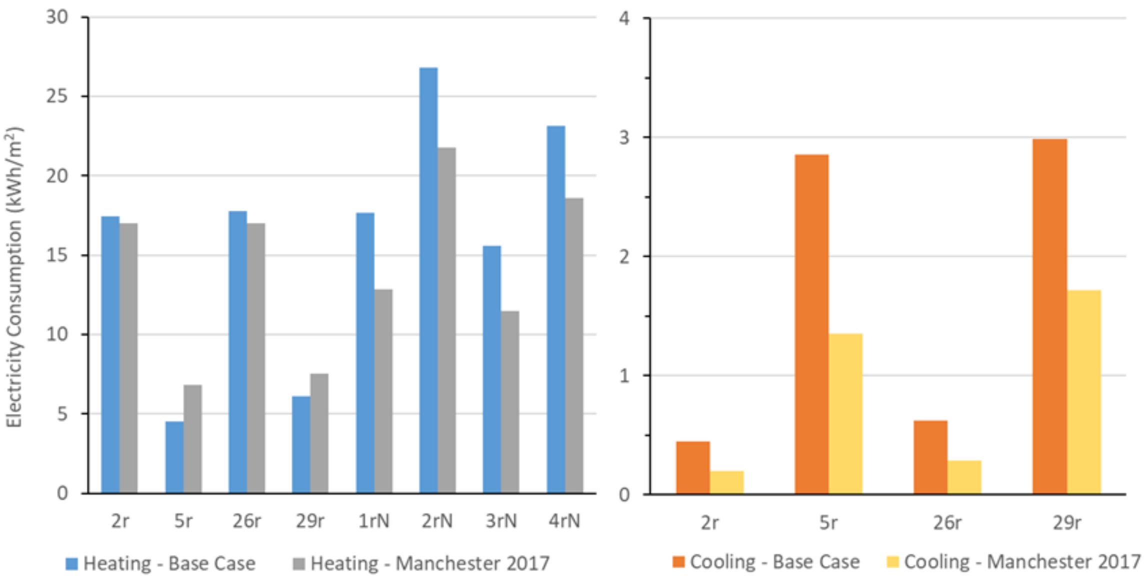

Figure 6.8 – Electricity Consumption for heating and cooling in selected buildings for Base Case and Manchester 2017 weather data

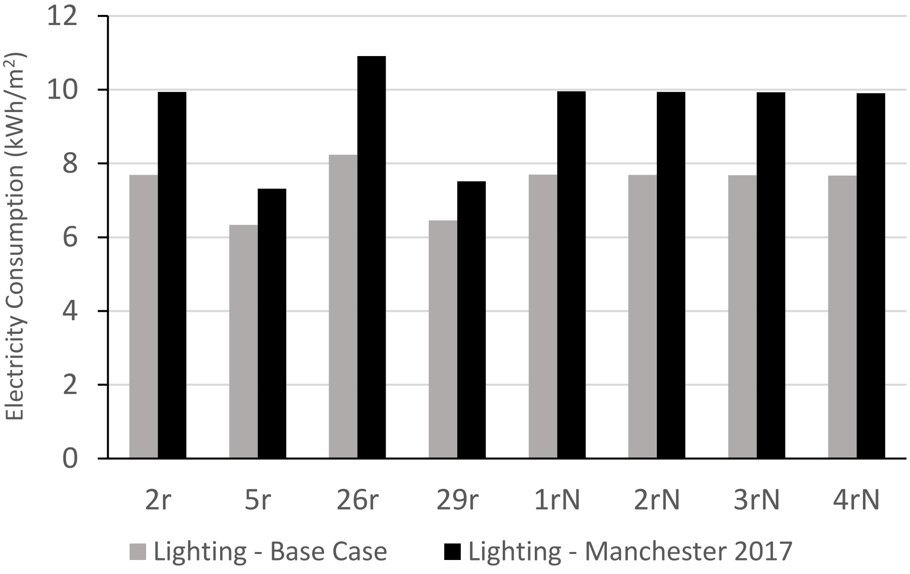

Figure 6.9 – Electricity Consumption for lighting in selected buildings for Base Case and Manchester 2017 weather data

Concerning heating demand, the differences can be considered to be insignificant for buildings with mechanical ventilation. However, when natural ventilation is adopted, the higher amounts of air infiltration lead to relatively higher electricity consumption towards heating, making the differences between the two locations much clearer. MAN17 naturally-ventilated buildings require between 11.46 – 21.76 kWh/m^2 with their Base Case counterparts consuming higher electrical loads between 15.60 – 26.80 kWh/m^2. Interpreting the cooling and heating demands, it can be concluded that for that particular year (2017), the summer period was warmer in Manchester when compared to the Birmingham IWEC Climate data while winter was observed to be colder in Birmingham. These results are also in accordance with the temperature statistics, as presented previously in Table 6.19. It should be highlighted that Buildings 5r and 29r continue to constitute exceptions to the heating demand trends due to their excellent thermal performance, as previously discussed in Chapter 6.2; nevertheless, their heating demand differences in MAN17 and Base Case are not significant. Heating and cooling electricity consumption for both locations can be seen in Figure 6.8.

Finally, in this sensitivity analysis, it is essential to also mention the third most important building load type, lighting, as it affects the total electricity consumption for the two locations (Figure 6.9). On average, MAN17 buildings need 2 kWh/m^2 more electricity than their Base Case counterparts to meet the set illuminance requirements in lux. Summing up, the performance of the buildings in the two different locations, using different types of climate data, has mixed results in terms of the building sectors, as demonstrated for heating, cooling and lighting. At the end, real weather data for MAN17 only resulted in a slight increase of the total electricity consumption for mechanically-ventilated buildings and a similar small reduction when natural ventilation was adopted.

In terms of the arbitrage performance, switching to MAN17 weather data leads all but one building group to an increase of the shifted electricity. However, it seems that ventilation strategy constitutes the most important parameter that classifies the results into two categories. For naturally ventilated buildings, the shifted electricity increases by 1.52% and 2.37% for the best and worst performing buildings, respectively. When mechanical ventilation is used, the difference observed is trivial for the Part L compliant buildings (+0.02%) while

Best Practice buildings is the only group that loses a part of its shifting capability by 1.64% (Table 6.20). In terms of exports, the impact of the MAN17 weather data is similar as for naturally-ventilated cases, an increase of 1.06% takes place for the best performing buildings while the worst performing subgroup is not affected. On the other hand, for mechanically-ventilated buildings, exports are reduced by 0.62% and 2.80%, respectively (Table 6.21). It should be highlighted that for this particular case the results refer to separate locations, Birmingham and Manchester, and therefore a direct comparison of the arbitrage performance should be done under careful consideration due to the differences of the buildings' energy demand in the two locations.

Table 6.20 – Electricity Shifted for Base Case and Manchester 2017 historical data under E7

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**Manchester 2017**	**Base Case vs MAN17**
Best (5r,29r)	31.46	30.95	+1.64
Worst (2r,26r)	29.12	29.13	-0.02
With Natural Ventilation			
Best (1rN, 3rN	30.95	31.42	-1.52
Worst (2rN,4rN)	29.58	30.28	-2.37

Table 6.21 – Exports for Base Case and Manchester 2017 historical data under E7

Building Groups	**Exports (kWh/m^2)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**Manchester 2017**	**Base Case vs MAN17**
Best (5r,29r)	17.96	17.85	+0.62
Worst (2r,26r)	16.35	15.89	+2.80
With Natural Ventilation			
Best (1rN, 3rN)	17.26	17.44	-1.06
Worst (2rN,4rN)	16.12	16.10	+0.09

Assessing the results for Operational Strategy E0 give a clearer picture of the impact of using historical weather data combining the two battery activities. As shown in Figure 6.10, the shifted electricity increases for all buildings that make use of natural ventilation as the Base Case range is between 31.74 – 39.38%, increasing to 33.04 – 39.79% for MAN17. On the contrary, the shifting capability of all mechanically-ventilated buildings is reduced with the MAN17 shifting range dropping to 32.34 – 38.97% of peak loads. The E0 results are further categorised based on performance and then presented in Table 6.22. In particular, when natural ventilation is used, a percentage increase of 2.44% and 2.24% are observed for the best and worst building groups, respectively. For mechanical ventilation, percentage reductions of 1.22% and 2.49% are observed for Best Practice and Part L compliant buildings, respectively.

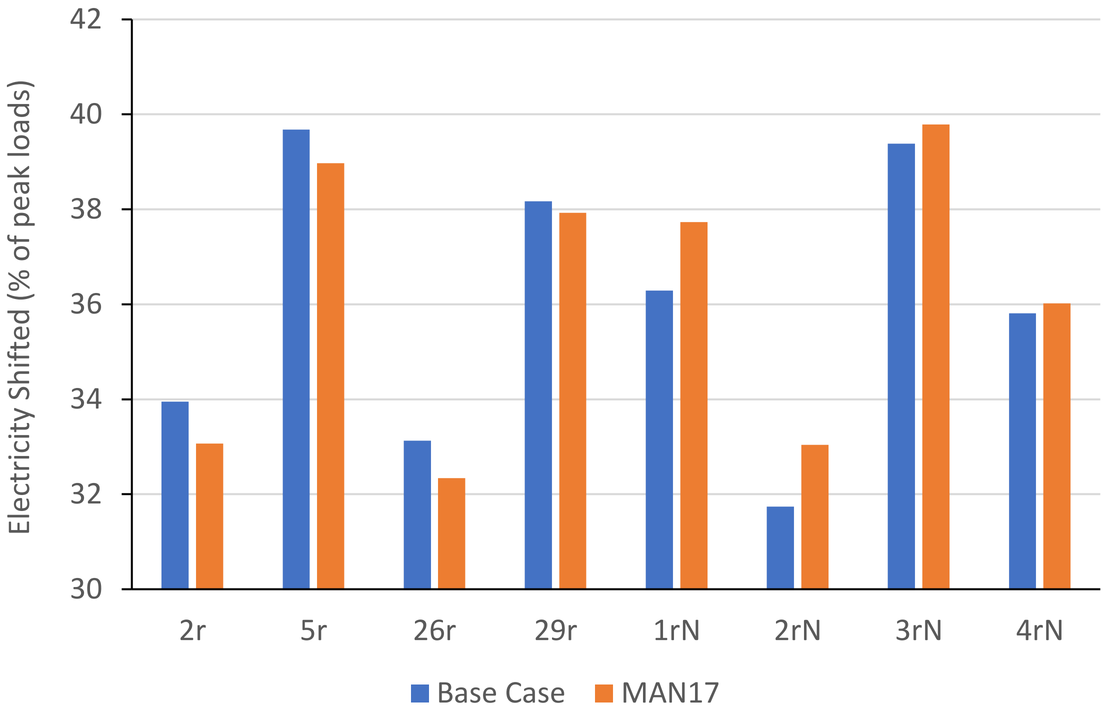

Figure 6.10 – Electricity Shifted under E0 for Base Case and Manchester 2017

Table 6.22 – Electricity Shifted for Base Case and Manchester 2017 historical data under E0

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**Manchester 2017**	**Base Case vs MAN17**
Best (5r,29r)	38.93	38.45	+1.22
Worst (2r,26r)	33.54	32.71	+2.49
With Natural Ventilation			
Best (1rN, 3rN)	37.84	38.76	-2.44
Worst (2rN,4rN)	33.78	34.53	-2.24

Finally, the net costs associated with the annual participation of the buildings in the arbitrage scheme are shown below, in Figure 6.11. It can be seen that using MAN17 weather data leads to more affordable buildings compared to the Base Case, only if natural ventilation is used. For the Base Case, the net costs are between 6.20 and 8.13 £/m^2 while MAN17 buildings require 6.47 – 8.17 £/m^2. For example, Building 29r require 6.64 £/m^2 in MAN17 instead of 6.47 £/m^2 in Birmingham while Building 2rN drops its net cost from 8.13 to 7.78 £/m^2.

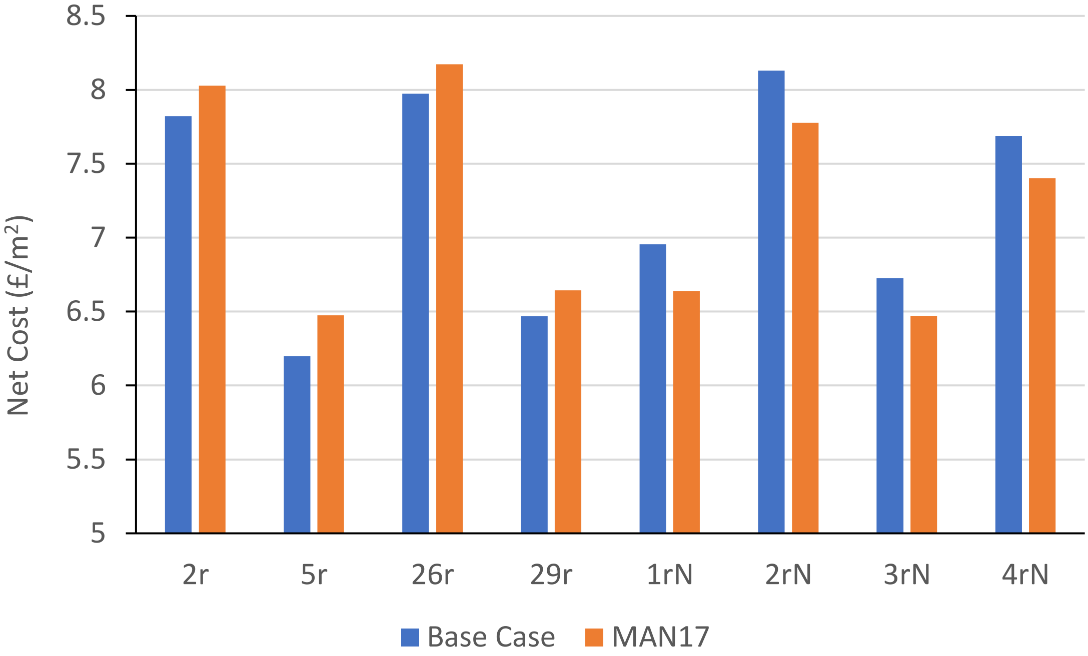

Figure 6.11 – Net Cost (£/m^2) under E0 for Base Case and Manchester 2017

6.4 Overheating

In this part of the chapter, extreme weather conditions are used in the model and in particular London DSY data from 1976 to assess the impact of extreme heat on the model results. The data in question include the historical climate parameters from London Heathrow Airport which are widely used for overheating analysis. Figure 6.12 presents a brief comparison between the Base Case and London DSY regarding the outdoor dry-bulb temperature and it is clear the DSY values are considerably higher between May and September. More specifically, the average monthly London temperatures for the summer months are 19.3, 20.8 and 19°C while the respective values for Birmingham are 14.2, 17.2 and 16.3°C. Similarly, regarding the maximum temperatures of the year for the same period, 34, 33.9 and 29.4°C are recorded for London with Birmingham observing lower values at 24.7, 28 and 30.4°C. The standard deviation of the DSY data stands at 6.58, higher than Birmingham (5.17) and any other weather data presented so far. It is also the only weather data that are positively skewed; although the skewness value is small (0.25).

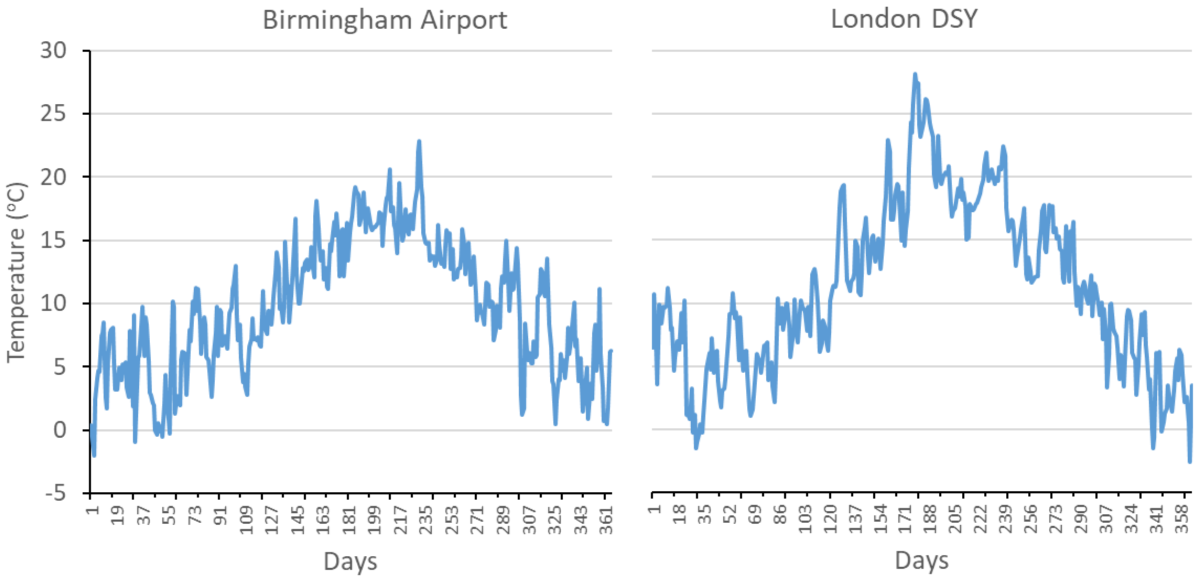

Figure 6.12 – Average daily outdoor dry-bulb temperature for Birmingham and London DSY

Regarding the electricity consumption comparison, the detailed values can be seen for all buildings in Figure 6.13. More specifically, for mechanically-ventilated buildings, the results are mixed as the electricity differences for the worst performing buildings (2r, 26r) appear to be trivial while building with the better performance (5r, 29r) require more electricity when using the London DSY data. On the other hand, when natural ventilation is used and therefore no electricity is consumed towards cooling , there is consistency among all building scenarios as switching to London actually reduces the total energy consumption.

It is fundamental to have a closer look at the building sectors individually, as shown in Figure 6.14. Concerning heating, as expected, the higher temperatures of London DSY result in lower electricity consumption for all the building scenarios from 3.74 to 19.83 kWh/m^2 while the respective Base case values vary between 4.52 – 26.80 kWh/m^2. This is also the reason that all naturally-ventilated buildings in London require overall less electricity than Birmingham, as shown in Figure 6.13.

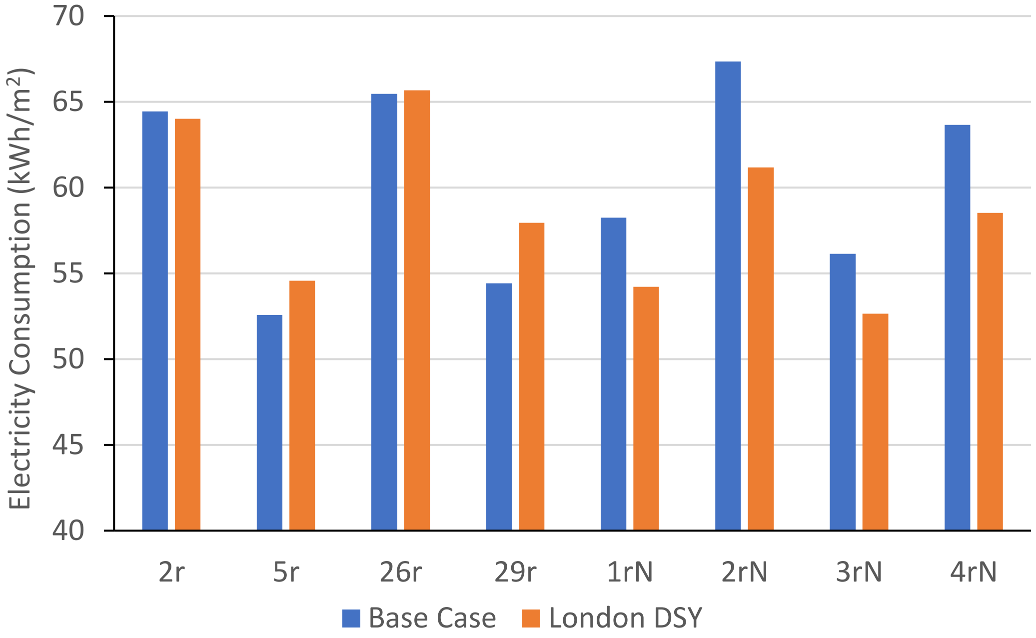

Figure 6.13 – Total Electricity Consumption in selected buildings for Base Case and the London DSY climate data

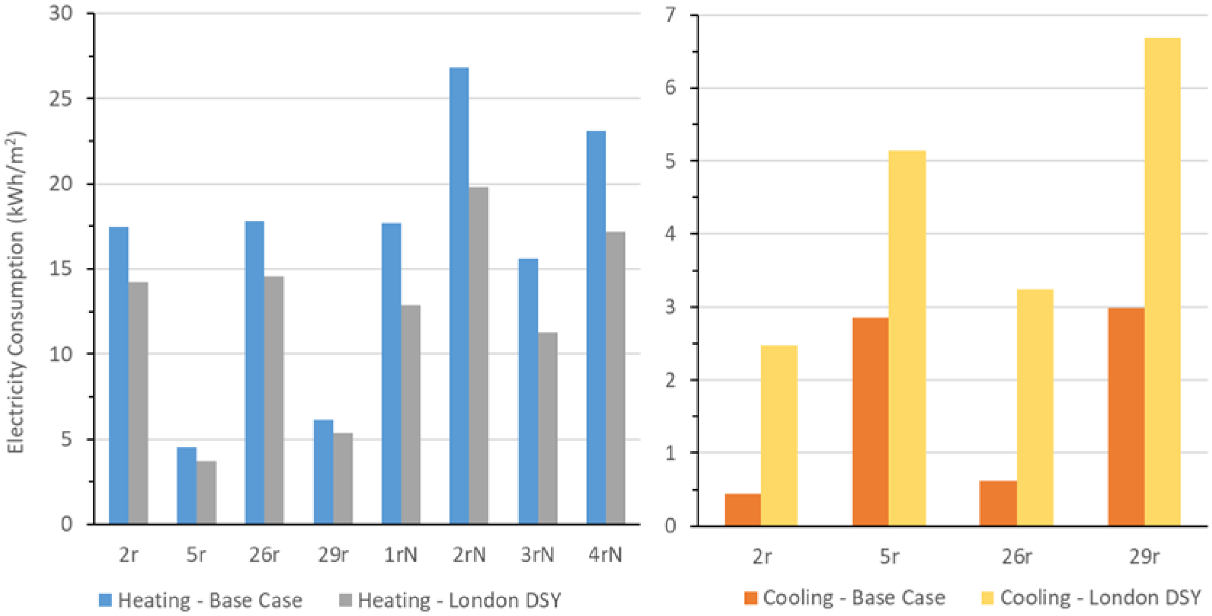

Figure 6.14 – Electricity Consumption for heating and cooling in selected buildings for Base Case and London DSY weather data

For the mechanically-ventilated cases, cooling consumption is higher for London DSY to mitigate the effect of the extreme summer temperatures, varying between 2.47 – 6.69 kWh/m^2. The respective range for the Base Case is between 0.44 – 2.99 kWh/m^2, it can be argued that the consequent differences introduced by the cooling consumption between the two locations is not significant in terms of the electricity purchases by the grid when taking into account the extreme nature of the temperatures involved in the DSY data. This is indeed correct but it should be reminded that the relatively high performance of the heat pumps are responsible for mitigating the difference in question. For example, when considering the buildings' cooling demand, or effectively assuming a CoP of 1, the respective ranges are 12.35 – 33.45 kWh/m^2 for London and 2.2 – 14.95 kWh/m^2 for Birmingham. The impact of the heat pumps' performance is investigated separately later in this chapter.

Finally, it is also essential to address the issue of thermal comfort as presented in Figure 6.15. For the majority of the mechanically-ventilated building scenarios, discomfort increases but remains below the 5% threshold of the occupancy hours. As discussed in Chapter 4.3, Building 29r is problematic and constitutes an outlier in terms of its thermal comfort, largely due to its orientation; hence a considerable value of 13.36% thermal discomfort hours is recorded. When natural ventilation is deployed, thermal discomfort still increases in London and varies between 6.65 – 8.03%. Suitable strategies need to be used to balance the overheating effect (e.g. shading) and for certain designs, reasonable thermal comfort will not be achievable. However, these are outside the scope of the current project and will not discussed any further.

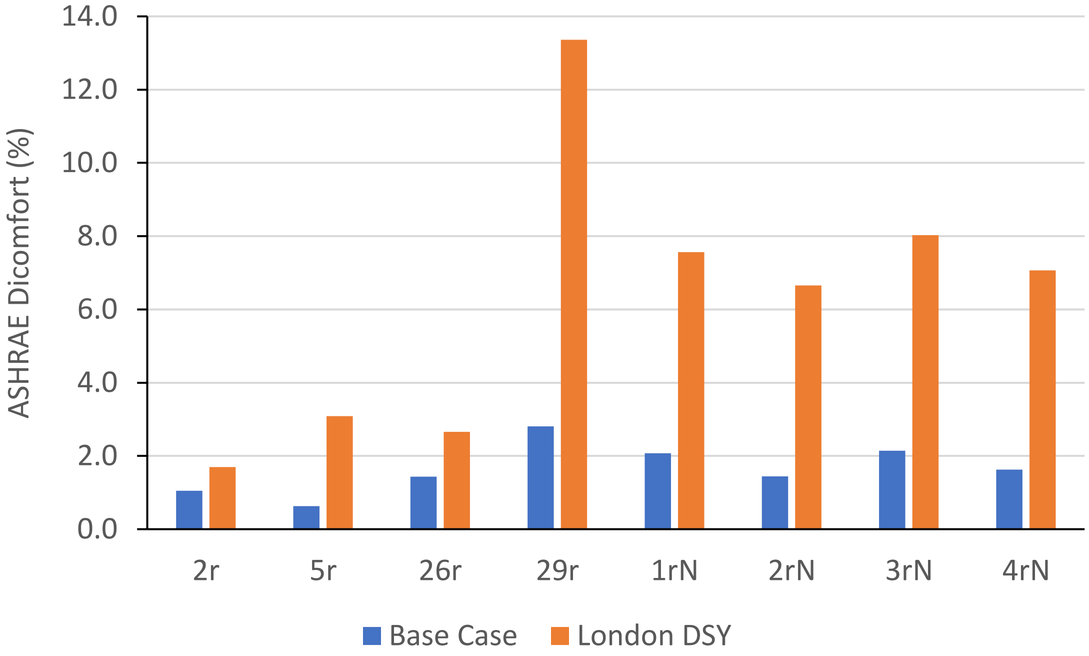

Figure 6.15 – Thermal Comfort (ASHRAE 55) for selected buildings in Birmingham and London DSY

In terms of the arbitrage performance and the differences observed between the Base Case and London DSY for Operational Strategy E7 (Table 6.23), the extreme overheating of the latter leads to an annual reduction of the shifted electricity for all the mechanically-ventilated buildings. The best performing building scenarios observe a percentage reduction of 3.78% while the worst performing group has a lower decrease of 1%.

On the other hand, buildings with natural ventilation are not particularly affected and only small differences take place. In fact, they perform marginally better, shifting 0.44% and 1.01% more, respectively, in terms of the dimensionless percentage changes; nevertheless, the actual percentages of the peak loads shifted are almost identical for the best performing buildings (30.95 and 31.08%) and only slightly higher for the worst performing group (29.58% and 29.88%).

Table 6.23 – Electricity Shifted for Base Case and London DSY under E7

Building Groups	Average Electricity Shifted (% of peak loads)		Dimensionless Changes (± %)
With Mechanical Ventilation	**Base Case**	**London DSY**	**Base Case vs London**
Best (5r,29r)	31.46	30.27	+3.78
Worst (2r,26r)	29.12	28.83	+1.00
With Natural Ventilation			
Best (1rN, 3rN	30.95	31.08	-0.44
Worst (2rN,4rN)	29.58	29.88	-1.01

Exports under E7 in London DSY follow the same patterns as they are also reduced, for mechanically-ventilated buildings, by 1.37% and 0.13% for the best and worst building groups, respectively. Naturally-ventilated buildings are capable of exporting more electricity in terms of their peak loads with percentage changes reaching 4.31% and 5.68%, respectively. This takes place because there is no increase in terms of any cooling loads as ventilation takes place through external infiltration and throughout the year heating electricity consumption is lower, especially after April (Table 6.24).

Table 6.24 – Exports for Base Case and London DSY under E7

Building Groups	Exports (kWh/m^2)		Dimensionless Changes (± %)
With Mechanical Ventilation	**Base Case**	**London DSY**	**Base Case vs London**
Best (5r,29r)	17.96	17.71	+1.37
Worst (2r,26r)	16.35	16.33	+0.13
With Natural Ventilation			
Best (1rN, 3rN)	17.26	18.00	-4.31
Worst (2rN,4rN)	16.12	17.03	-5.68

When exports are not allowed under E0 (Figure 6.16), all mechanically-ventilated buildings shift lower amounts of their peak loads in London DSY with a range of 32.56 – 38.43% of their peak loads. The respective range for the Base Case building scenarios is higher between 33.13 – 39.68%. However, considering the extreme overheating conditions of London DSY, the changes in arbitrage performance between the two locations is not that significant. This can be explained once again by the high performance of the heat pumps that keeps the cooling electricity consumption relatively low, minimising as much as possible the differences in shifted electricity in terms of the peak loads. On the other hand, the overheating conditions bring benefits to the naturally-ventilated buildings as they can now shift 34.27 – 39.89% of their peak loads instead of the lower Base Case figures of 31.74 – 39.38%. The difference in performance is maximised for the heavyweight buildings 1rN and 2rN.

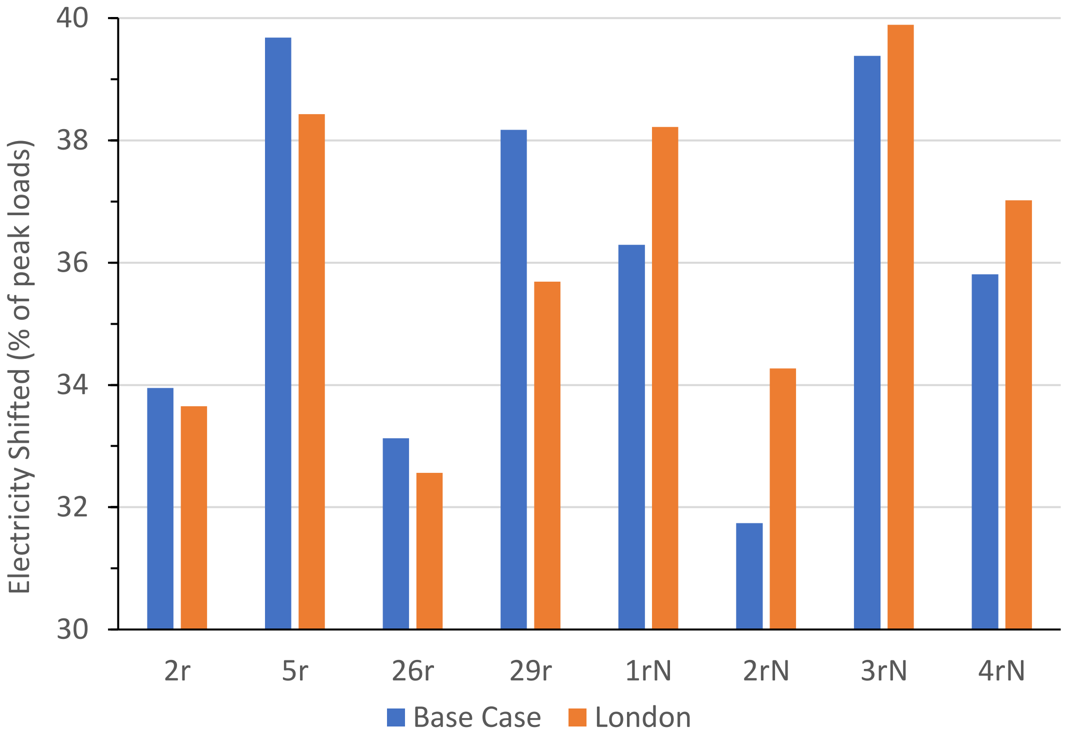

Figure 6.16 – Electricity Shifted under E0 for Base Case and London DSY

In terms of how overheating affects the best and worst performing groups under E0, these can be seen in detail In Table 6.25. When mechanical ventilation is adopted in London DSY, the best and worst performing buildings shift lower amounts of electricity in terms of their peak loads by 4.79% and 1.30%, respectively, compared to the Base Case. Naturally-ventilated buildings again take advantage of the overheating conditions and shift more percentage-wise by 3.22% and 5.54%, respectively. However, it should be reminded that their thermal comfort can be highly problematic, as previously shown and therefore should be taken into account. It should be concluded that due to the nature of this specific sensitivity analysis, the arbitrage performance is affected in the exact same way for both strategies E7 and E0 with the same trends being observed for all building groups and subgroups (e.g. ventilation, energy performance).

Table 6.25 – Electricity Shifted for Base Case and London DSY under E0

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**London DSY**	**Base Case vs London**
Best (5r,29r)	38.93	37.06	+4.79
Worst (2r,26r)	33.54	33.11	+1.30
With Natural Ventilation			
Best (1rN, 3rN	37.84	39.06	-3.22
Worst (2rN,4rN)	33.78	35.65	-5.54

Finally, the annual electricity net costs are presented below for Strategy E0, in Figure 6.17. From the mechanically-ventilated scenarios, the worst performing buildings 2r and 26r appear to have very similar net costs in both locations. On the other hand, the best performing group (5r, 29r) are proven to be more expensive to run in London DSY as they have respective net costs of 6.40 and 6.88 £/m^2, slightly higher than the Base Case values of 6.20 and 6.47 £/m^2. This is expected as building lower energy performance, belonging to the Part L compliant group, have higher air infilitration that has the beneficial side effect of cooling the building, especially during the summer months. As the overheating conditions in London DSY enable naturally-ventilated buildings to shift higher amounts of their peak loads, their consequent net costs are lower than their Base Case counterparts. More specifically, they have a net cost range between 6.29 – 7.38 £/m^2 in comparison to the higher Base Case range of 6.73 – 8.13 £/m^2.

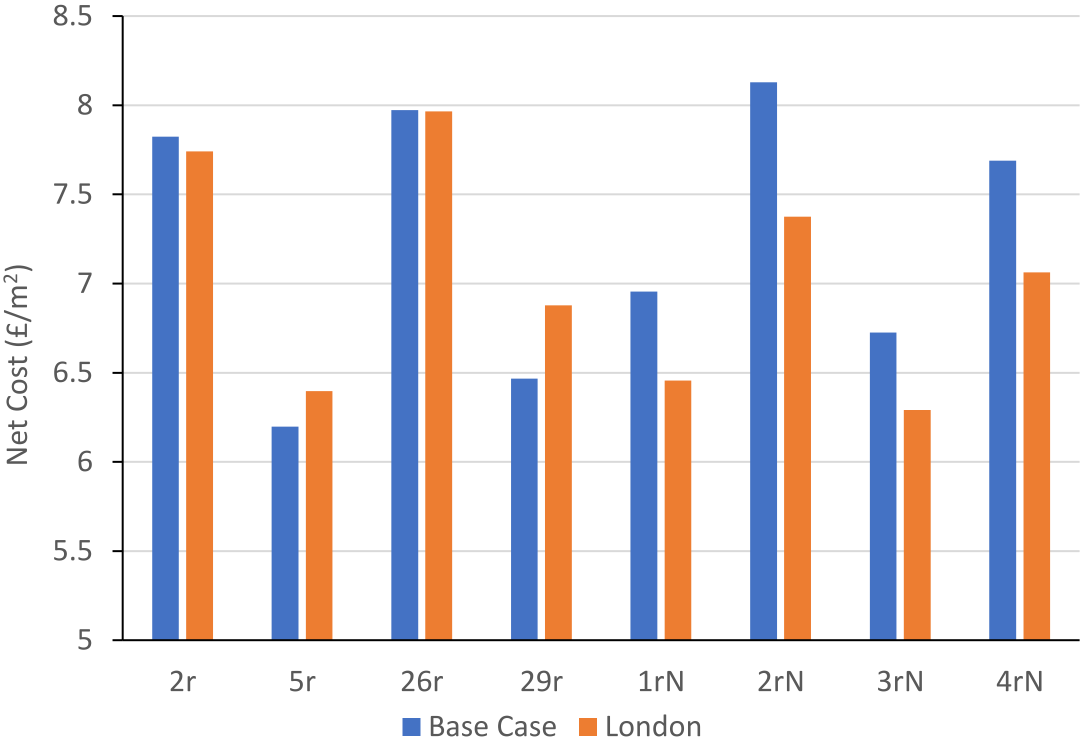

Figure 6.17 – Net Cost (£/m^2) under E0 for Base Case and London DSY

6.5 Heat pumps Coefficient of Performance (CoP)

It has been previously mentioned that the heat pumps performance plays an important role as it affects the electricity consumption towards heating and cooling and therefore it is crucial to investigate it in a quantitative way. In accordance with the methodology chapter, the original heat pumps CoP for heating and cooling are now reduced from 3.5 and 5 to 2.25 and 3, a reduction of approximately 35% and 40%, respectively. Consequently, an increase in electricity consumption of 35% is expected for heating and 40% towards cooling. The total electricity consumption for the standard and reduced heat pumps performance in London DSY is demonstrated in Figure 6.18. All buildings are affected by the change as naturally-ventilated buildings still require more electricity because of the heating electricity consumption.

It can be observed that the reduced heat pumps performance has a significant impact on the total electricity consumption of all building scenarios and undoubtedly the biggest impact than any other sensitivity analysis factor so far in the current chapter. More specifically, the original London DSY results have an electricity consumption range between 52.65 – 65.68 kWh/m^2 while the respective values vary from 61.78 to 78.79 kWh/m^2 under the reduced heat pumps performance.

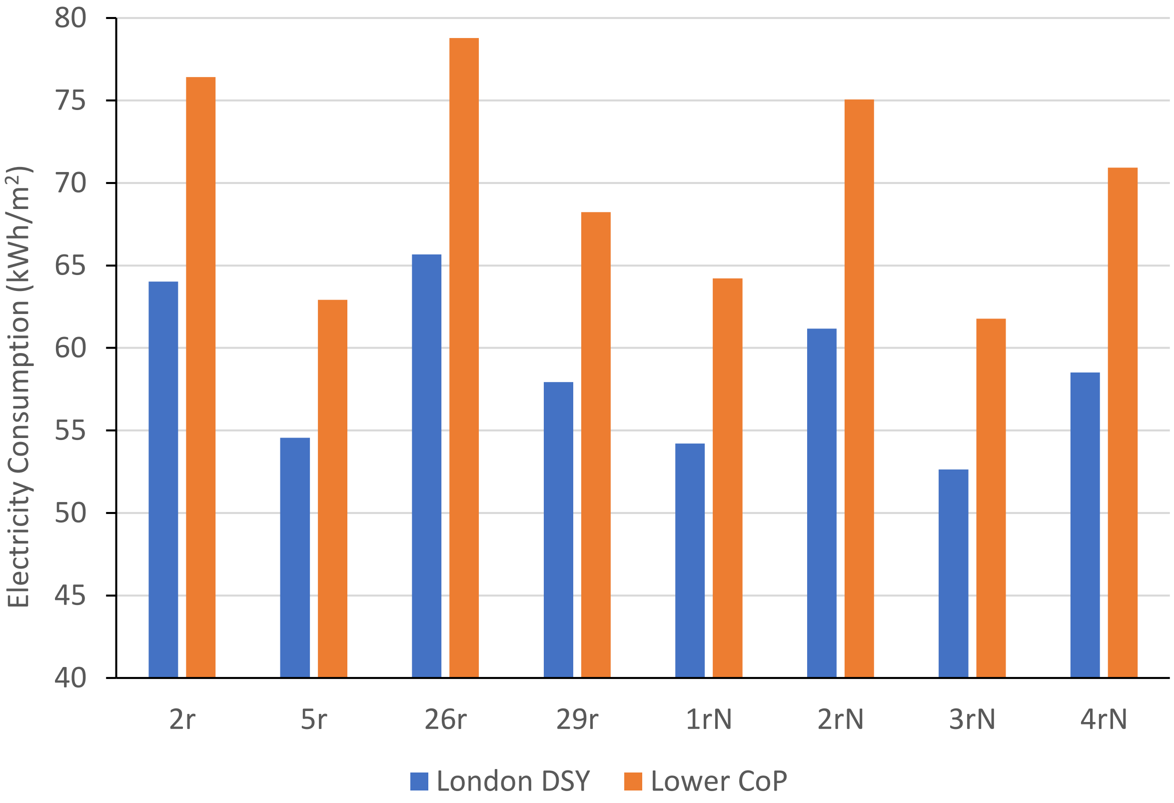

Figure 6.18 - Total Electricity Consumption for London DSY with original and reduced heat pumps performance

Looking at the breakdown of the individual building sectors in Figure 6.19, for the mechanically-ventilated building scenarios, reducing the CoP values has the least impact on Buildings 5r and 29r that belong to the best performing building group (Best Practice) as their excellent airtightness and the envelope's low U-values manage to keep the heating demand increase to a minimum. As all buildings are affected the same in terms of the percentage increase in heating electricity consumption, the scenarios the most affected in terms of the overall electricity consumption increase include the worst performing groups (Part L compliant) such as 2r and 26r. Due to the higher air infiltration taking place in naturally-ventilated buildings, the increase is most noticeable in Buildings 2rN and 4rN that also belong to the Part L compliant group. Regarding some characteristic examples, Buildings 5r and 2rN require 3.74 and 19.83 kWh/m^2 for heating under standard heat pump performance while reducing the CoPs brings these values up to 5.82 and 30.85 kWh/m^2, respectively.

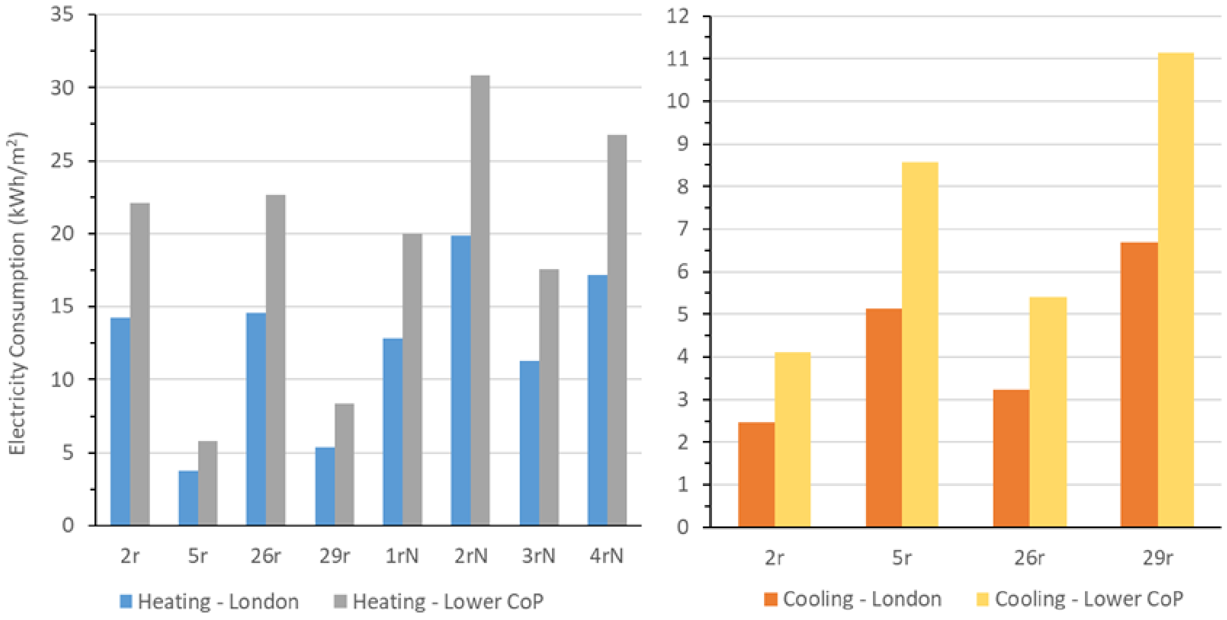

Figure 6.19 – Electricity Consumption for heating and cooling in London DSY with original and reduced heat pumps performance

Table 6.26 – Electricity Shifted under E7 in London DSY for standard and reduced heat pump performance

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**Lower CoPs**	**Standard vs Lower CoPs**
Best (5r,29r)	30.27	28.10	+7.19
Worst (2r,26r)	28.83	25.63	+11.12
With Natural Ventilation			
Best (1rN, 3rN	31.08	28.60	+7.98
Worst (2rN,4rN)	29.88	26.50	+11.33

Concerning the impact on cooling, the original electricity consumption for cooling is between 2.47 – 6.69 kWh/m^2, rising to a range of 4.11 – 11.15 kWh/m^2 for the reduced CoP values. Thermal comfort is exactly the same for both the original and the reduced CoP results.

Table 6.27 – Exports in London DSY under E7 for standard and reduced heat pump performance

Building Groups	**Exports (kWh/m^2)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**Lower CoPs**	**Standard vs Lower CoPs**
Best (5r,29r)	17.71	16.36	+7.63
Worst (2r,26r)	16.33	15.18	+7.04
With Natural Ventilation			
Best (1rN, 3rN)	18.00	16.95	+5.80
Worst (2rN,4rN)	17.03	16.05	+5.79

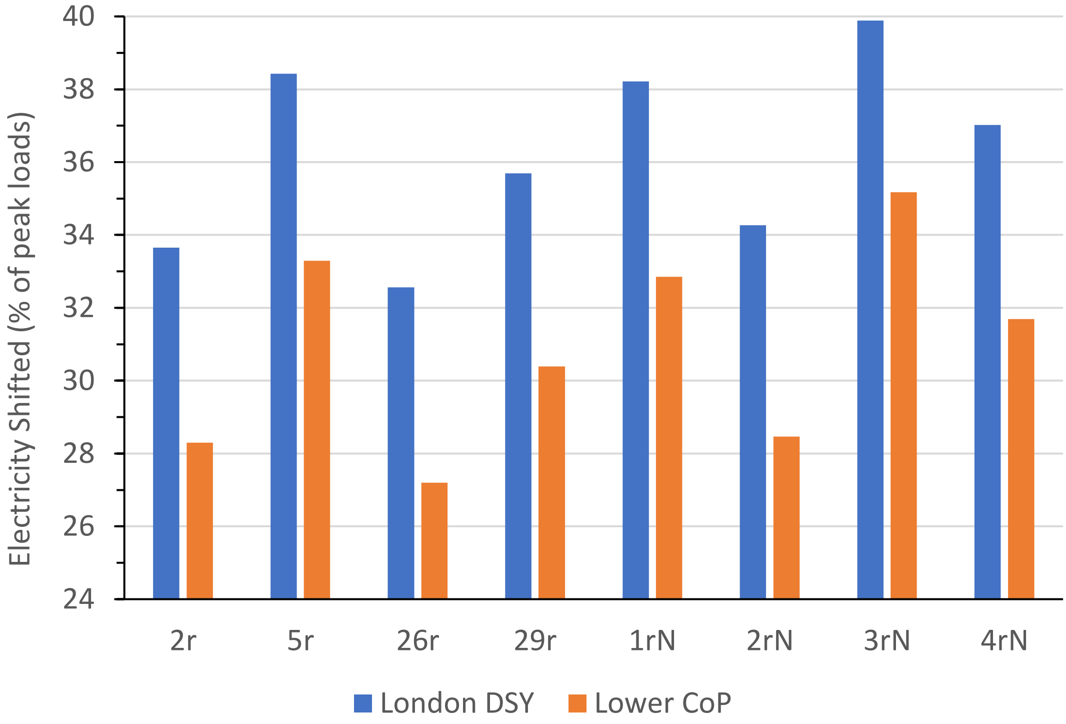

Figure 6.20 – Electricity Shifted under E0 in London DSY for standard and reduced heat pump performance

The arbitrage results for Operational Strategy E7 are presented in Table 6.26. Scenarios belonging to the Part L Compliant group are affected between three and four percentage points more when compared to the best performing buildings. In more detail, when mechanical ventilation is used, reducing the heat pumps CoPs leads to a reduction of the shifted electricity by 7.19% and 11.12%, in the best and worst performing building groups, respectively. Similarly, for naturally-ventilated buildings, the reductions reach 7.98% and 11.33% respectively. Moving on to the impact on the electricity exports (Table 6.27), the reduction of CoPs has the same effect for all building groups and no major difference can be seen this time between Best Practice and Part L Compliant buildings. For mechanically-ventilated buildings, exports are lower by 7.63% and 7.04% for the same building subgroups while a reduction of 5.80% is observed for naturally-ventilated building groups.

When exports are not allowed, the differences in electricity shifted are again maximised between the original and the revised CoP results, in London DSY. As shown in Figure 6.20, the original results have a range between 32.56 – 39.89% of the peak loads shifted while reducing the CoP values brings this range down to 27.20 – 35.17%. Looking at the grouped results in more detail in Table 6.28, the mechanically-ventilated buildings seem to be affected slightly more than their naturally-ventilated counterparts as their Best Practice and Part L groups observe a reduction of 14.09% and 16.18% respectively.

Additionally, when natural ventilation is used, the same percentages are slightly lower at 12.92% and 15.63%, potentially due to the absence of cooling loads. These dimensionless percentage changes constitute the highest values that have been observed in the sensitivity analysis so far, making the heat pumps performance a critical factor for both the electricity consumption and the arbitrage performance of all building scenarios. Finally, it is also worth taking a brief look at the economics, as shown in Figure 6.21. As expected, lowering the CoP values makes the electricity annual net cost significantly higher between 7.45 – 9.73 £/m^2 while when using the original CoP values, the respective range is between 6.29 – 7.97 £/m^2; hence a difference of 1.16 – 1.76 £/m^2.

Table 6.28 – Electricity Shifted under E0 in London DSY for standard and reduced heat performance

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**Lower CoPs**	**Standard vs Lower CoPs**
Best (5r,29r)	37.06	31.84	+14.09
Worst (2r,26r)	33.11	27.75	+16.18
With Natural Ventilation			
Best (1rN, 3rN	39.06	34.01	+12.92
Worst (2rN,4rN)	35.65	30.08	+15.63

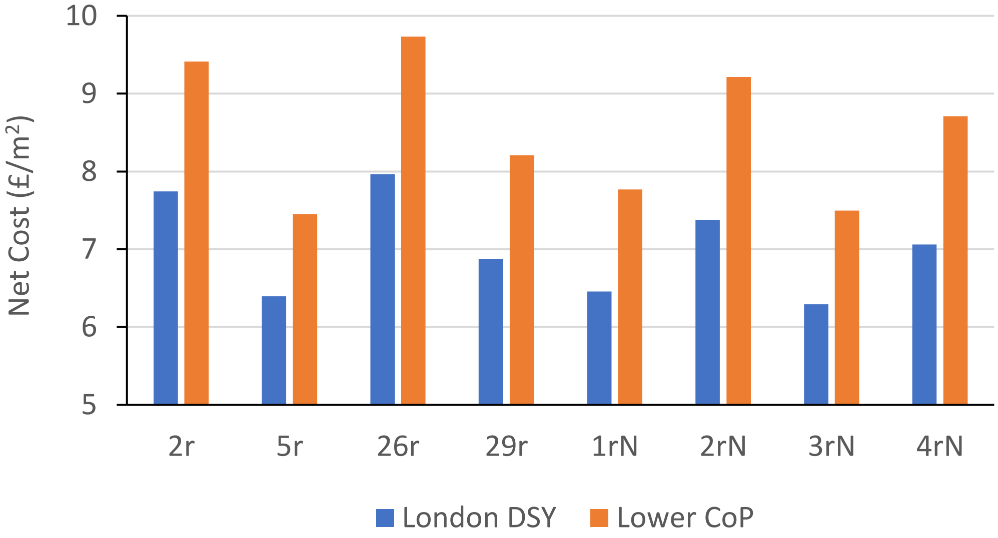

Figure 6.21 – Net Cost under E0 in London DSY for standard and reduced heat pump performance

6.6 No Free Cooling

The sixth sensitivity analysis factor is the free cooling strategy that has been used in all simulations so far; therefore, London DSY is also used as the base case, similarly to the previous subchapter, and is compared to the same location with free cooling turned off to evaluate the impact of this change to the cooling electricity consumption. Obviously, naturally-ventilated buildings are not affected by this change as demonstrated in Figure 6.22. Concerning buildings with mechanical ventilation, as expected, the total electricity consumption increases for all scenarios. In more detail, under the original London DSY results, the electricity consumption is between 54.56 – 65.68 kWh/m^2. The respective range with free cooling disabled is now increased to 58.31 – 66.52 kWh/m^2 while the highest increases take place for Best Practice buildings due to their excellent airtightness.

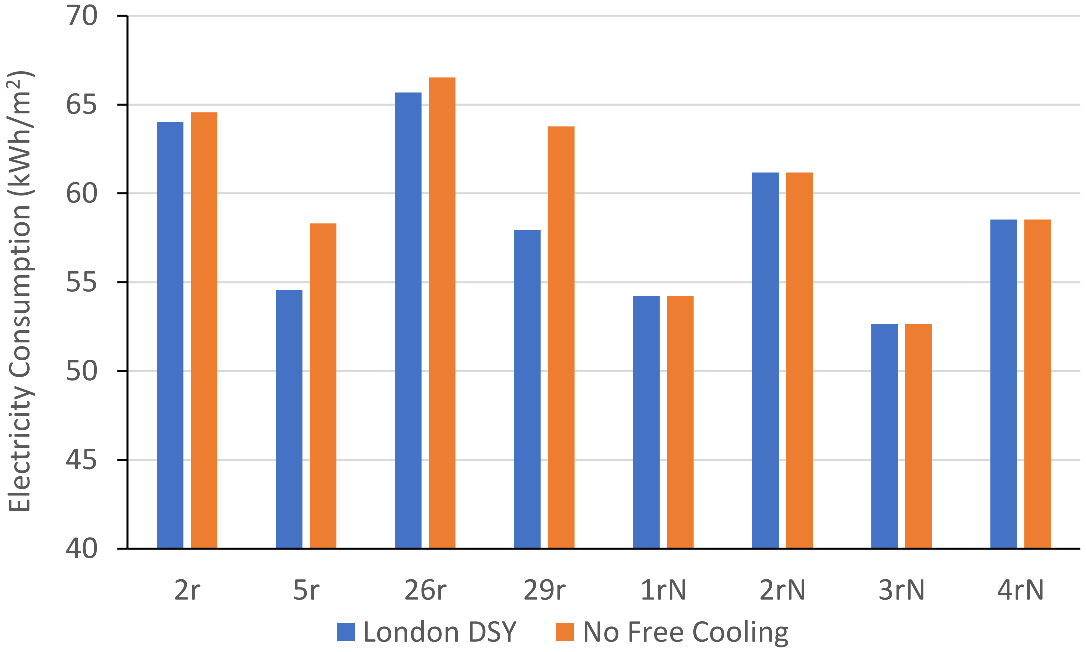

Figure 6.22 - Total Electricity Consumption for London DSY with and without free cooling enabled

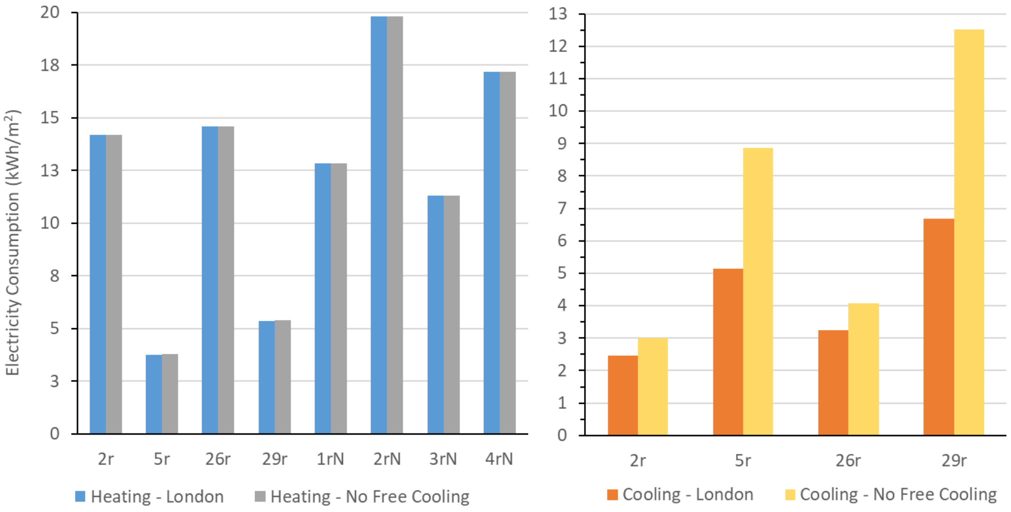

Figure 6.23 – Electricity Consumption for cooling in London DSY with and without free cooling

The electricity consumption for cooling is shown separately, in Figure 6.23, along with the heating breakdown which is also included in order to demonstrate that the operation of free cooling does not affect in any way the buildings' heating demand and consequent electricity needs for heating. The cooling part constitutes therefore the only building sector that contributes towards the electricity differences presented in Figure 6.22. The Part L Compliant Buildings 2r and 26r observe small increases from the original cooling values of 2.47 and 3.24 kWh/m^2 to 3.01 and 4.07 kWh/m^2, respectively, when disabling free cooling. The small change is likely due to the external infiltration that takes places in these Part L compliant buildings.

On the other hand, the cooling electricity consumption for the Best Practice buildings 5r and 29r raise from 5.15 and 6.69 kWh/m^2 to 8.86 and 12.52 kWh/m^2, respectively. While indeed requiring more electricity for cooling, it can be argued that the ramifications from disabling free cooling does not prove to be as serious as previously thought. This can be explained by the free cooling modelling limitations as an upper bound of 2 ac/h has been set originally. Therefore, the impact of disabling free cooling needs to be determined by the buildings' arbitrage results that follow. Despite the fact that naturally-ventilated scenarios are not affected, they are included for completion and also as validation of the results. Any ranges or values mentioned below refer to the mechanically-ventilated buildings exclusively.

Table 6.29 – Electricity Shifted under E7 in London DSY with and without free cooling

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**No Free Cooling**	**Free Cooling vs No Free Cooling**
Best (5r,29r)	30.27	30.22	+0.18
Worst (2r,26r)	28.83	28.85	-0.05
With Natural Ventilation			
Best (1rN, 3rN	31.08	31.08	0.00
Worst (2rN,4rN)	29.88	29.88	0.00

Table 6.30 – Exports in London DSY under E7 in London DSY with and without free cooling

Building Groups	**Exports (kWh/m^2)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**No Free Cooling**	**Free Cooling vs No Free Cooling**
Best (5r,29r)	17.71	16.42	+7.28
Worst (2r,26r)	16.33	16.12	+1.28
With Natural Ventilation			
Best (1rN, 3rN)	18.00	18.00	0.00
Worst (2rN,4rN)	17.03	17.03	0.00

By looking at Table 6.29 and the electricity shifted (% of peak loads), it is clear that the differences between the original London DSY results and those without free cooling are insignificant for both the best and worst performing groups. However, this is not the case for the battery exports which are reduced by 7.28% and 1.28% for the Best Practice and the Part L compliant buildings, respectively, when free cooling is not used. Consequently, while the battery is able to shift approximately the same peak load percentages without free cooling, there is no capacity left for the export function (Table 6.30).

Moving on to the E0 Operational Strategy, the arbitrage results are reflected in Figure 6.24. The original shifted electricity for London DSY have a range between 32.56 – 38.43% while disabling free cooling reduces the shifting capability of the buildings to 32.13 – 36.09% of the peak loads. The ranges in question do not present any significant differences and therefore it is important to look at the percentage changes per building group, as presented in Table 6.31. In more detail, the biggest impact of disabling free cooling takes place for the Best Practice building group as a percentage drop of 6.68% is observed on average for Buildings 5r and 29r. On the contrary, the impact is minimised for the Part L compliant group as the respective reduction is 1.10%.

Once again, the reason behind this contradiction between the buildings' arbitrage and energy performance is the absence of external air infiltration in the Best Practice buildings that would operate as an additional free cooling capacity; this extra capacity is present though in Part L compliant buildings due to their relatively poorer envelope airtightness. Nevertheless, disabling free cooling seems to constitute an important factor in the current chapter that could potentially have an important impact on the buildings' arbitrage capacity, after the heat pumps CoP reduction.

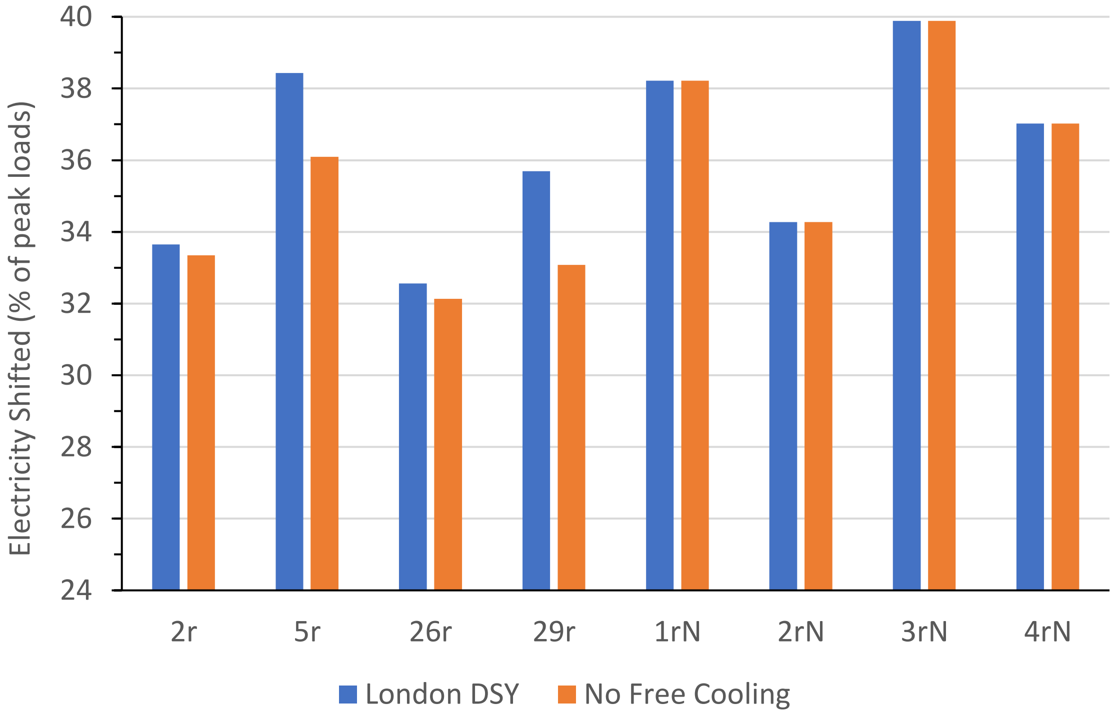

Figure 6.24 – Electricity Shifted under E0 in London DSY with and without free cooling

Table 6.31 – Electricity Shifted under E0 in London DSY with and without free cooling

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**No Free Cooling**	**Free Cooling vs No Free Cooling**
Best (5r,29r)	37.06	34.59	+6.68
Worst (2r,26r)	33.11	32.74	+1.10
With Natural Ventilation			
Best (1rN, 3rN	39.06	39.06	0.00
Worst (2rN,4rN)	35.65	35.65	0.00

Finally, the electricity net costs under E0 are presented in Figure 6.25. The original net cost values appear to be between 6.40 – 7.97 £/m^2 and disabling free cooling leads to a less cost-effective arbitrage scheme with a respective range of 6.82 – 8.07 £/m^2. As previously mentioned, because of their decreased arbitrage performance, the highest cost increase takes place for the Best Practice buildings 5r and 29 by 0.42 and 0.64 £/m^2, respectively.

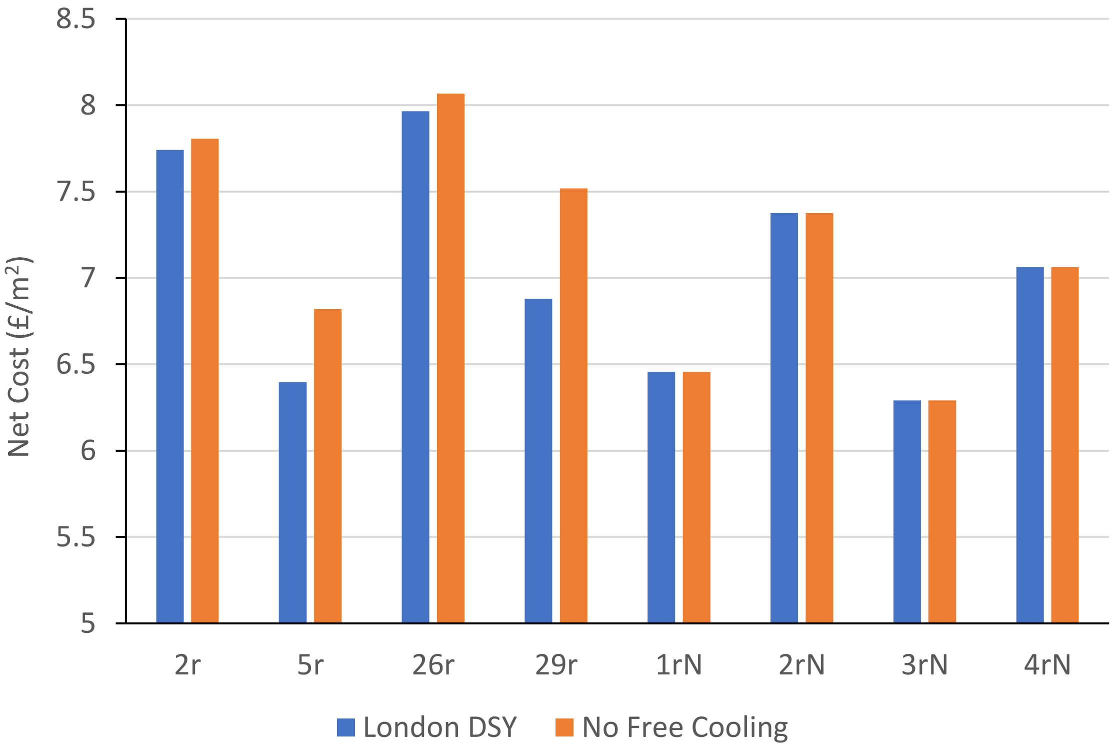

Figure 6.25 – Net Cost (£/m^2) under E0 in London DSY with and without free cooling

6.7 Equipment Loads

The sensitivity analysis factor in this subchapter are the equipment loads assumed to be running as part of the commercial character of the building model. As these loads are an important part of the total electricity consumption, they are now reduced by 1/3 to investigate their impact on the buildings' participation in the arbitrage scheme. Equipment loads are reduced from the original annual value of 24.71 to 16.48 kWh/m^2. All the other building sectors such as heating and cooling remain stable and are not affected by this change. The total electricity consumption for all building is illustrated in Figure 6.26 and in more detail, using the original equipment loads (Base Case) result to a range of 52.57 – 67.36 kWh/m^2. On the other hand, reducing the equipment loads by 1/3, the consequent range is now between 44.33 – 59.12 kWh/m^2.

Regarding the impact on the arbitrage, it is not a surprise that decreasing the equipment leads to an increase in both the shifted electricity and exports for all building scenarios and groups. For both metrics, the percentage changes differ and more specifically, a high increase range of 2.84% – 7.12% can be seen when shifting electricity while the respective export range increases even more by 7.95 – 11.19% (Tables 6.32 & 6.33). These percentage changes are among the highest of all the sensitivity factors presented and even comparable to the heat pumps performance. However, a proper comparison should be made for the E0 strategy using the shifted electricity values only. As shown in Figure 6.27, the Base Case results for the shifted electricity have a range between 31.74 – 39.68% while the respective values for reduced equipment loads are 35.78 – 45.80%, a significant average increase of 5% in terms of the peak loads shifted.

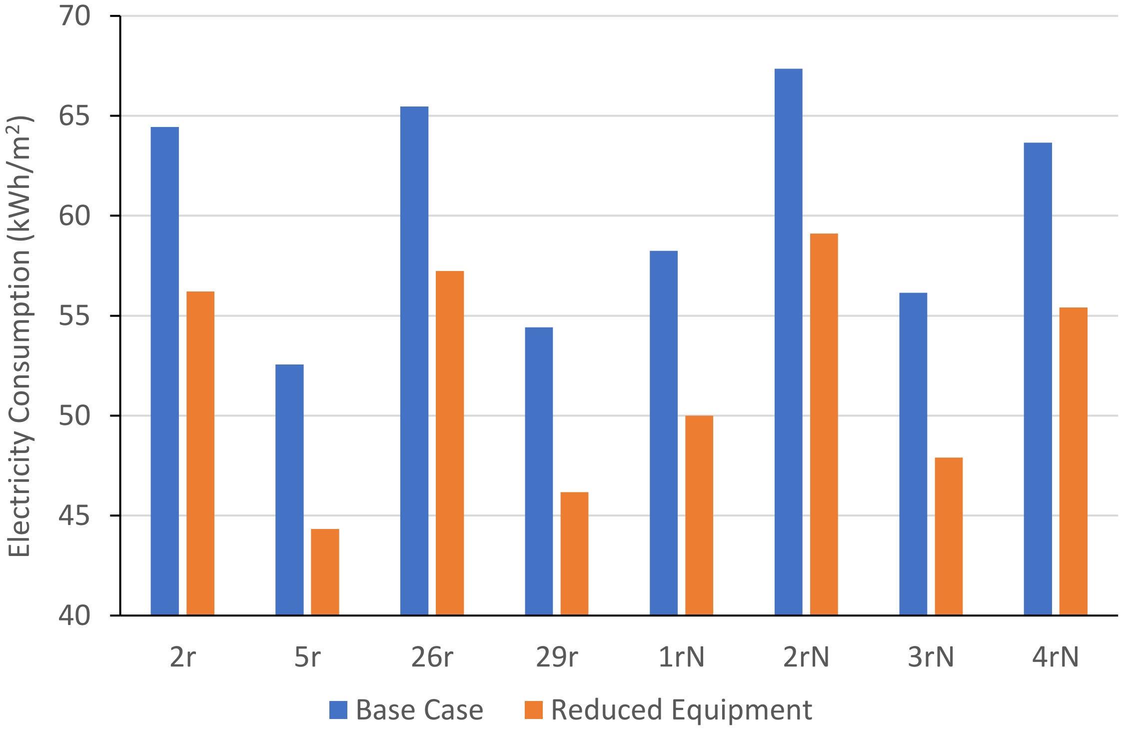

Figure 6.26 – Total Electricity Consumption for Base Case with original and reduced equipment loads

Table 6.32 – Electricity Shifted under E7 in Birmingham with original and reduced equipment loads

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**Reduced Equipment**	**Original vs Reduced Equipment**
Best (5r,29r)	31.46	32.36	-2.84
Worst (2r,26r)	29.12	30.67	-5.31
With Natural Ventilation			
Best (1rN, 3rN	30.95	32.24	-4.17
Worst (2rN,4rN)	29.58	31.69	-7.12

Table 6.33 – Exports under E7 in Birmingham with original and reduced equipment loads

Building Groups	**Exports (kWh/m^2)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**London DSY**	**No Free Cooling**	**Free Cooling vs No Free Cooling**
Best (5r,29r)	17.96	19.97	-11.19
Worst (2r,26r)	16.35	17.80	-8.86
With Natural Ventilation			
Best (1rN, 3rN)	17.26	19.04	-10.34
Worst (2rN,4rN)	16.12	17.40	-7.95

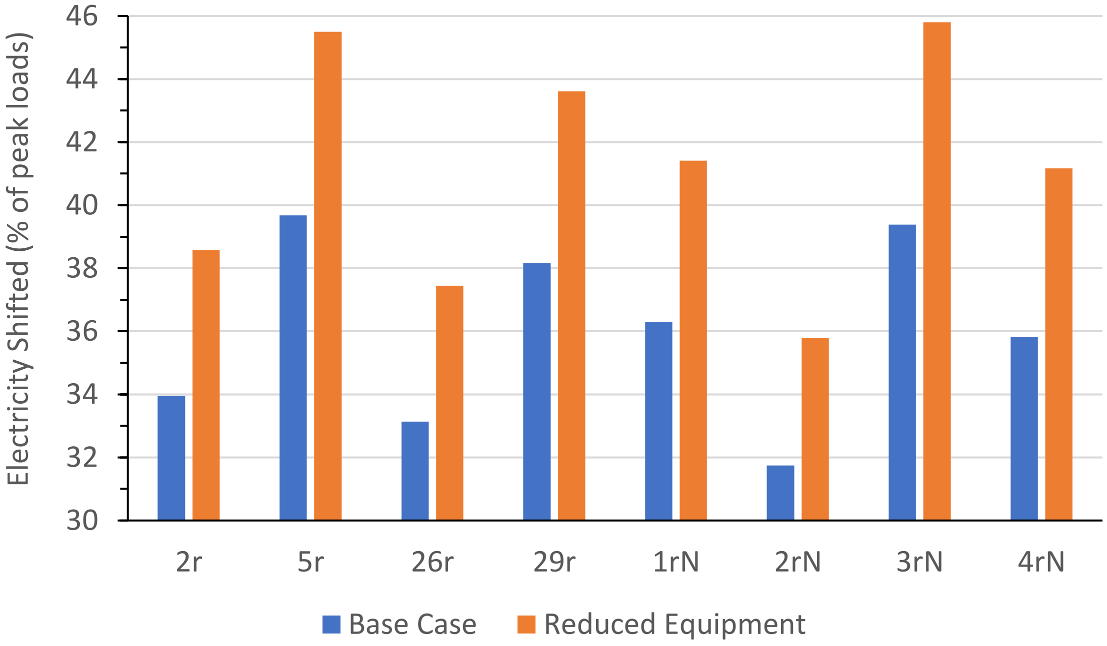

Figure 6.27 – Electricity Shifted under E0 in Birmingham with original and reduced equipment loads

Grouping the results per building group, the percentage changes are very similar for both types of ventilation as well as the energy efficiency category, Part L Compliant and Best Practice, as clearly shown in Table 6.34. Overall, the percentage increase is observed to have a considerable range between 13.33 – 15.25% and is comparable to the respective range for the heat pumps performance, as previously shown in Table 6.28; therefore, both of them constitute the most impactful sensitivity analysis factors in the current chapter so far.

Finally, concerning the economics of the arbitrage scheme, the net costs for the original and reduced equipment loas are demonstrated in Figure 6.28 and it is clear that they are drastically decreased when reducing the equipment loads. In detail, the Base case values range is between 6.20 – 8.13 £/m^2 while the revised values are from to 5.18 – 7.09 £/m^2. It should be noted that this reduction is not due to the increased arbitrage activity per se as even without using storage, the electricity costs would have been smaller for reduced equipment loads by 1/3.

Table 6.34 – Electricity Shifted (E0) in Birmingham with original & reduced equipment loads

Building Groups	**Average Electricity Shifted (% of peak loads)**		**Dimensionless Changes (± %)**
With Mechanical Ventilation	**Base Case**	**Reduced Equipment**	**Original vs Reduced Equipment**
Best (5r,29r)	38.93	44.56	-14.46
Worst (2r,26r)	33.54	38.01	-13.33
With Natural Ventilation			
Best (1rN, 3rN	37.84	43.61	-15.25
Worst (2rN,4rN)	33.78	38.48	-13.92

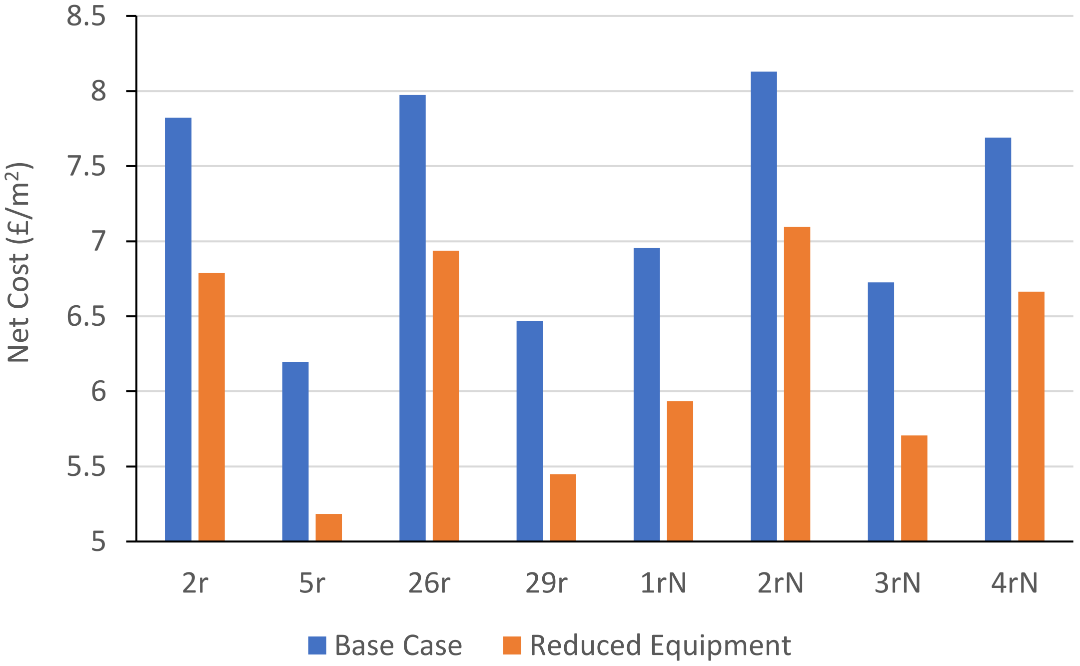

Figure 6.28 – Net Cost under E0 in Birmingham with original and reduced equipment loads

6.8 Inverter Rated Capacity

As an inverter capacity of 65 kW has been used for the main results and the sensitivity analysis factors so far, it is useful to investigate its impact on the arbitrage performance. Therefore, a smaller and a bigger rated capacity of 45 kW and 85 kW are chosen. There are no changes for the electricity consumption results as only the arbitrage model output is now different. For the E7 Operational Strategy and according to Table 6.35, increasing or decreasing the operational capacity threshold of the inverter has a critical affect on the shifted electricity of the best and worst performing building groups. For the smaller capacity of 45 kW, a significant percentage increase between 11.56 – 22.89% is observed while when using the higher 85 kW capacity, the shifted electricity is reduced considerably by 10.47 – 13.52%. The exact opposite trends can be seen in Table 6.36 as exports are dropped dramatically by 21.86 – 28.21% for the 45 kW capacity while an increase of 13.46 – 16.14% takes place for the 85 kW size.

Table 6.35 – Electricity Shifted under E7 for different inverter capacities (45-85 kW)

Building Groups	**Average Electricity Shifted (% of peak loads)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case (65 kW)**	**45 kW**	**85 kW**	**Base Case vs 45 kW**	**Base Case vs 85 kW**
Best (5r,29r)	31.46	38.66	27.38	-22.89	+12.98
Worst (2r,26r)	29.12	33.57	26.07	-15.26	+10.47
With Natural Ventilation					
Best (1rN, 3rN)	30.95	36.04	26.76	-16.46	+13.52
Worst (2rN,4rN)	29.58	33.00	25.77	-11.56	+12.90

Table 6.36 – Exports under E7 for different inverter capacities (45-85 kW)

Building Groups	**Exports (kWh/m^2)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case (65 kW)**	**45 kW**	**85 kW**	**Base Case vs 45 kW**	**Base Case vs 85 kW**
Best (5r,29r)	17.96	12.89	20.38	+28.21	-13.46
Worst (2r,26r)	16.35	12.27	18.55	+24.98	-13.46
With Natural Ventilation					
Best (1rN, 3rN)	17.26	13.12	19.82	+23.97	-14.84
Worst (2rN,4rN)	16.12	12.59	18.72	+21.86	-16.14

These results are consistent as when the battery is able to shift higher amounts of electricity in terms of the building's peak loads, lower amounts of electricity are left for potential exports and vice versa. Consequently, using a smaller inverter capacity changes the battery activity, effectively prioritising shifting as a higher amount of hours is now needed to utilise the full battery capacity with any leftover electricity being dedicated to exports. On the other hand, increasing the inverter size is automatically translated into more electricity being discharged per hour of battery activity and therefore it is more likely for any building loads to be covered regardless of their size; it should be reminded that the discharge operation is dependent on the electricity price of the hour in question provided that a small load thresholds is met. Consequently, when the discharge takes place, there is the potential for higher amounts of electricity exports when using a higher inverter capacity.

The E7 results for the electricity shifted are shown in Figure 6.29. For the Base Case, a range of 27.77 – 32.26% of peak loads takes place. Reducing the inverter size from 65 to 45 kW leads to an increase with the respective range being between 30.77 – 39.23% while increasing the inverter capacity to 85 kW results into a reduction of the range to 24.57 – 27.75% of peak loads. However, it should be noted that these ranges should only be considered in combination with the export ranges due to the nature of the E7 strategy. In this direction, an export range of 16.10 – 18.08 kWh/m^2 takes place for the Base Case. The respective ranges for the smaller and bigger inverter capacities are 12.25 – 13.21 and 18.54 – 20.49 kWh/m^2.

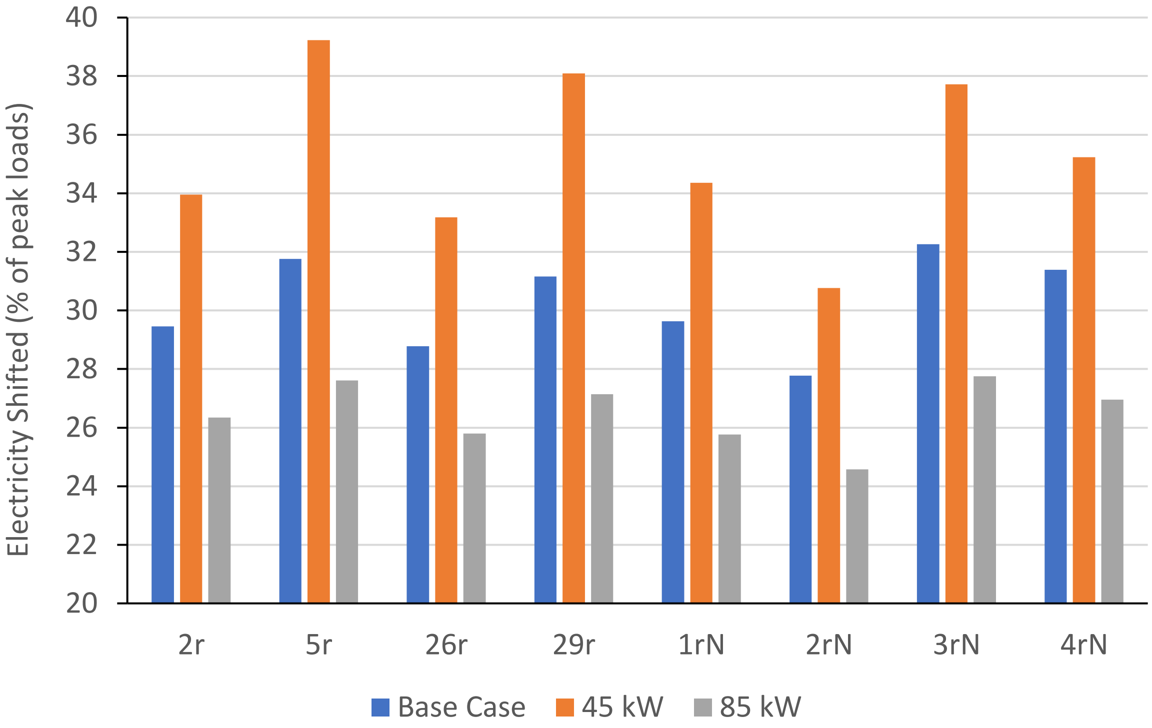

Figure 6.29 – Electricity shifted under E7 for different inverter capacities (45-85 kW)

Finally, with exports now disabled, the battery activity cannot change structurally. Indeed, as demonstrated in Figure 6.30, the differences between the three different inverter sizes are insignificant. For the Base Case, electricity shifted is between 31.74 – 39.68% of peak loads while a smaller inverter size of 45 KW leads to a respective range of 31.21 – 39.39% and the bigger 65 KW size between 31.81 – 39.70%. Regarding the results for the best and worst performing building groups, these are consistent as presented in Table 6.37. A smaller 45 kW inverter leads to an average 1.26% percentage reduction while the bigger 85 kW results to a 0.17% increase. Given the negligible nature of these values, the respective net costs are also similar, as presented in Figure 6.31.

In conclusion, changing the inverter size to be slightly smaller or bigger does not translate into any economic benefits. However, for Operational Strategy E7, if priority for a certain battery function is a requirement or desired for a specific arbitrage scheme, choosing an appropriate inverter capacity can critically influence the mixture of the battery activity towards shifting or exporting.

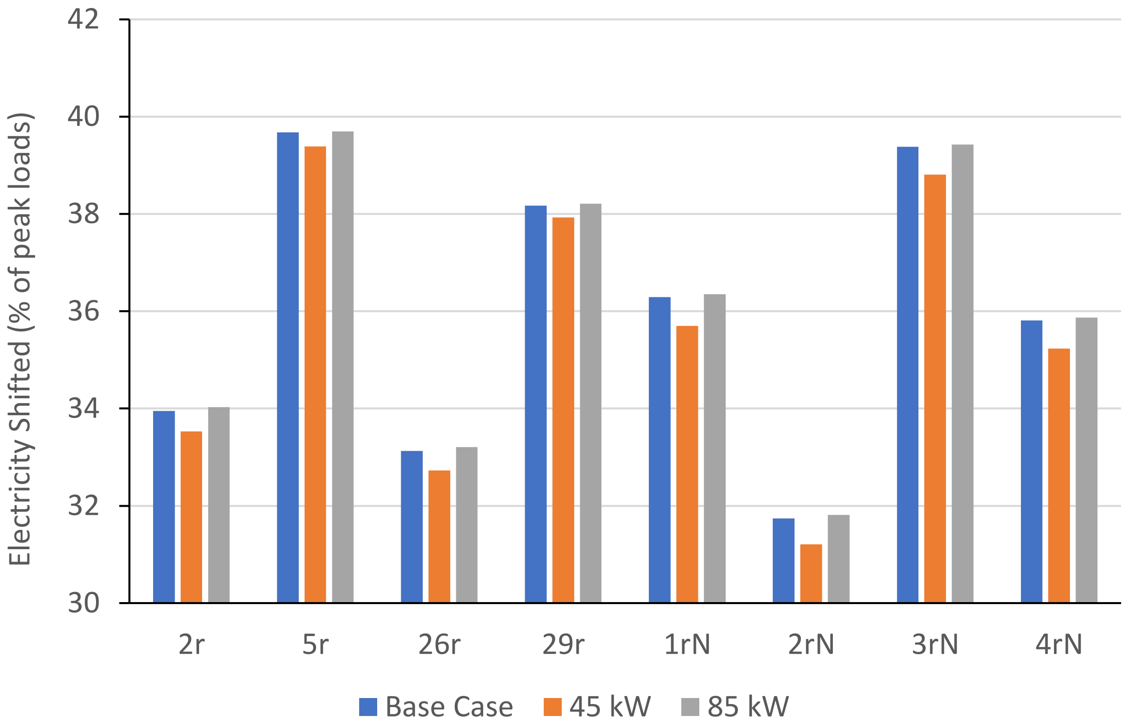

Figure 6.30 – Electricity shifted under E0 for different inverter capacities (45-85 kW)

Table 6.37 – Electricity Shifted under E0 for different inverter capacities (45-85 kW)

Building Groups	**Average Electricity Shifted (% of peak loads)**			**Dimensionless Changes (± %)**	
With Mechanical Ventilation	**Base Case (65 kW)**	**45 kW**	**85 kW**	**Base Case vs 45 kW**	**Base Case vs 85 kW**
Best (5r,29r)	38.93	38.66	38.96	+0.68	-0.08
Worst (2r,26r)	33.54	33.13	33.62	+1.22	-0.24
With Natural Ventilation					
Best (1rN, 3rN)	37.84	37.26	37.89	+1.53	-0.15
Worst (2rN,4rN)	33.78	33.22	33.84	+1.64	-0.19

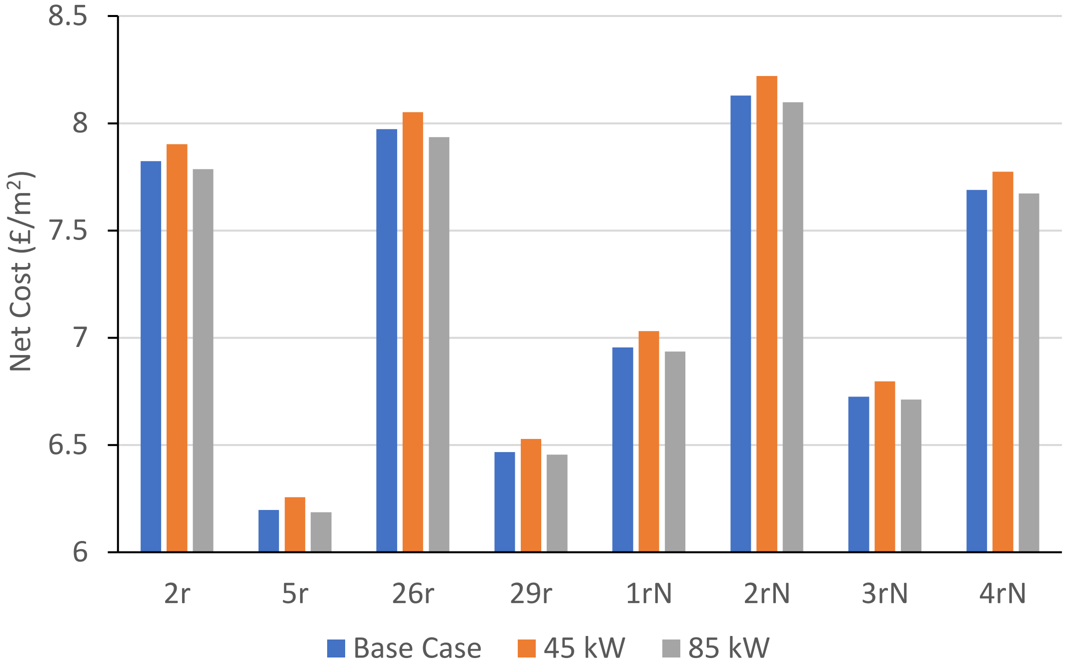

Figure 6.31 – Net Cost under E0 for different inverter capacities (45-85 kW)

6.9 Battery Capacity sizes

Regarding Operational Strategy E7 and the smallest battery size of 40 kWh is capable of shifting between 6.56 – 9.37% of the electrical loads whereas the range for the biggest BSS of 220 kWh is 27.14 – 32.26%. For the E5 strategy, the ranges are 5.85 – 7.79% and 26.09 – 30.83% for the smallest and the biggest batteries, respectively; therefore, a slight reduction of the electricity shifted can be noticed due to the auxiliary loads shifting that takes place during weekends under E7. For E0, while the electricity shifted is approximately the same as in E5 for the 40 kWh battery (5.82 – 7.79%), the values are significantly higher and vary between 31.12 – 39.95%. It is important to point out that these particular figures clearly reflect the fact that presenting all battery sizes is not particularly useful towards the aims and the objectives of this research. It is evident that a similar trend can be seen for all battery sizes and therefore the results can focus instead on the largest battery size of 220 kWh in order to make proper and direct comparisons regarding the different building design characteristics. In Figure 6.32, electricity shifted is shown as a percentage of the building peak loads for all cases and BSS sizes, for the Operational Strategy E0.

Under E7, as only excess electricity is exported back to the grid and meeting the local loads is prioritised, exports take minimal values for the smallest BSS; for example, for the 40 kWh battery, exports are between 2.17 – 2.53 kWh/m^2 while the values for the 220 kWh BSS are 16.09 – 18.08 kWh/m^2. At the same time, for battery sizes 40, 60 and 80 kWh exports retain the same or approximately the same values for all buildings while even for some bigger BSS (100, 120 kWh) the differences in exports are insignificant from building to building. Under the E5 strategy that allows for a significantly smaller amount of exports, the electricity sent back to the grid is negligible for batteries up to 80 kWh while 3.22 – 5.53 kWh/m^2 are exported back when the 220 kWh battery is deployed, significantly smaller when compared with the respective E7 figures.

Figure 6.33 introduces the electricity net costs for Operational Strategy E0. When a BSS is not deployed, the range of the electricity net cost is between 7.01 – 9.14 £/m^2. On the other hand, for the 40 kWh battery, the respective net costs are marginally lower around 6.79 – 8.92 while a significant reduction is noticed for the 220 kWh battery, between 6.20 – 8.28 £/m^2. It can be observed that increasing the battery size after reaching a specific threshold, in this case 140 kWh, does not necessarily translate to a proportional reduction of the net costs as the inverter's rated capacity remains the same at 65 kW, for all BSS with a battery capacity higher than 140 kWh. Nevertheless, there are still distinct differences between the buildings. In addition, the net cost range remains identical for Operational Strategy E5 for the 40 kWh battery while an increase takes place for the biggest battery size of 220 kWh with the net cost varying 6.59 – 8.51 £/m^2. When exports take place every day of the week under E7, the net cost reaches its highest range between 7.19 – 9.14 £/m^2.

Regarding the total electricity purchased from the grid under E7, the amount varies between 55.77 – 71.86 and 75.56 – 89.49 kWh/m^2 for the smallest and the biggest battery sizes, respectively. While the electricity used to cover the local needs always remain the same per building scenario, additional amounts are needed to charge the battery on a daily basis, including electricity to cover for the charging and discharging losses, with excess energy exported back to the grid. The electricity purchases from the grid are further augmented by the battery operation during the weekend when the local loads are trivial.

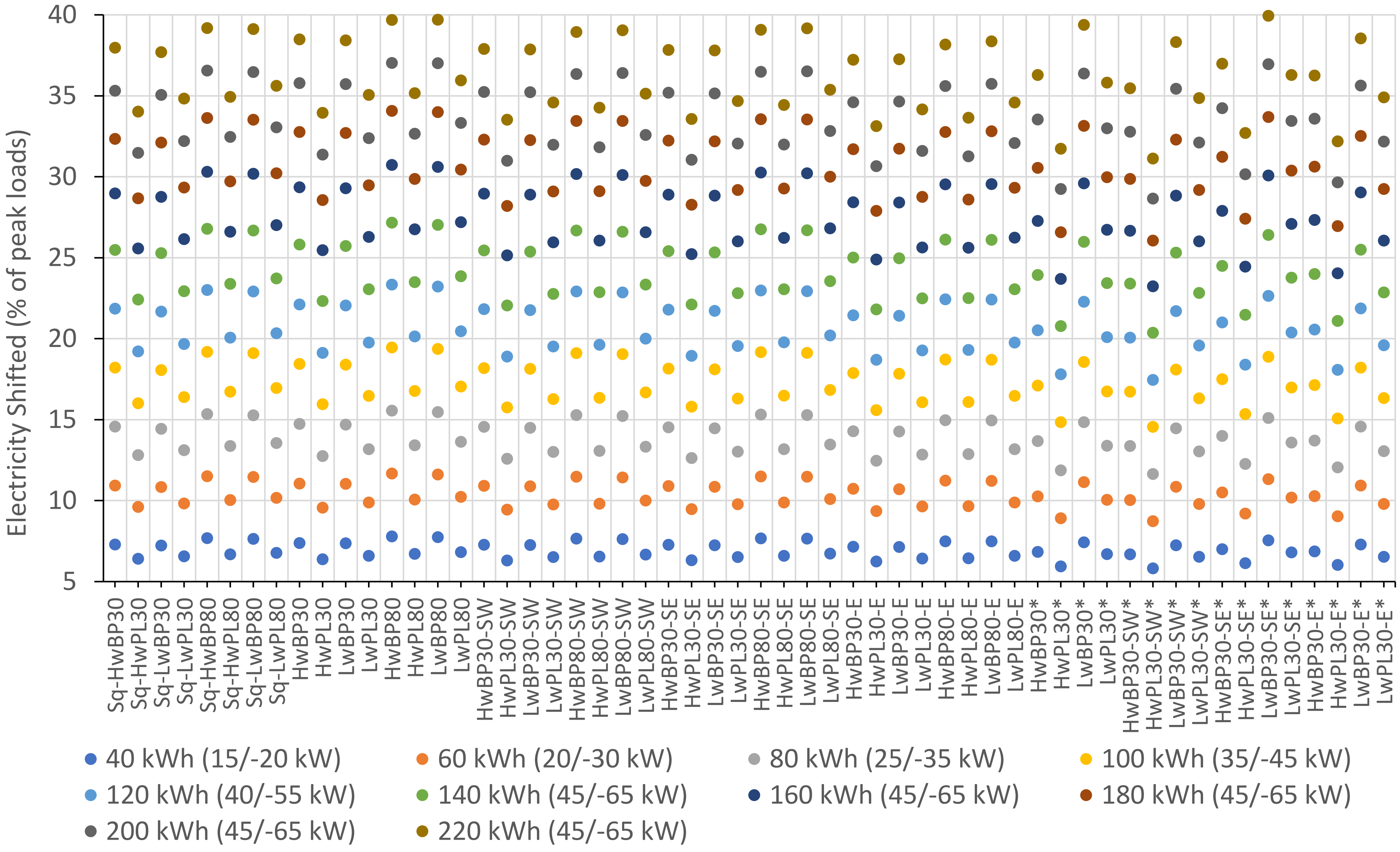

Figure 6.32 – Electricity shifted (% of peak loads) for all building cases under Operational Strategy E0

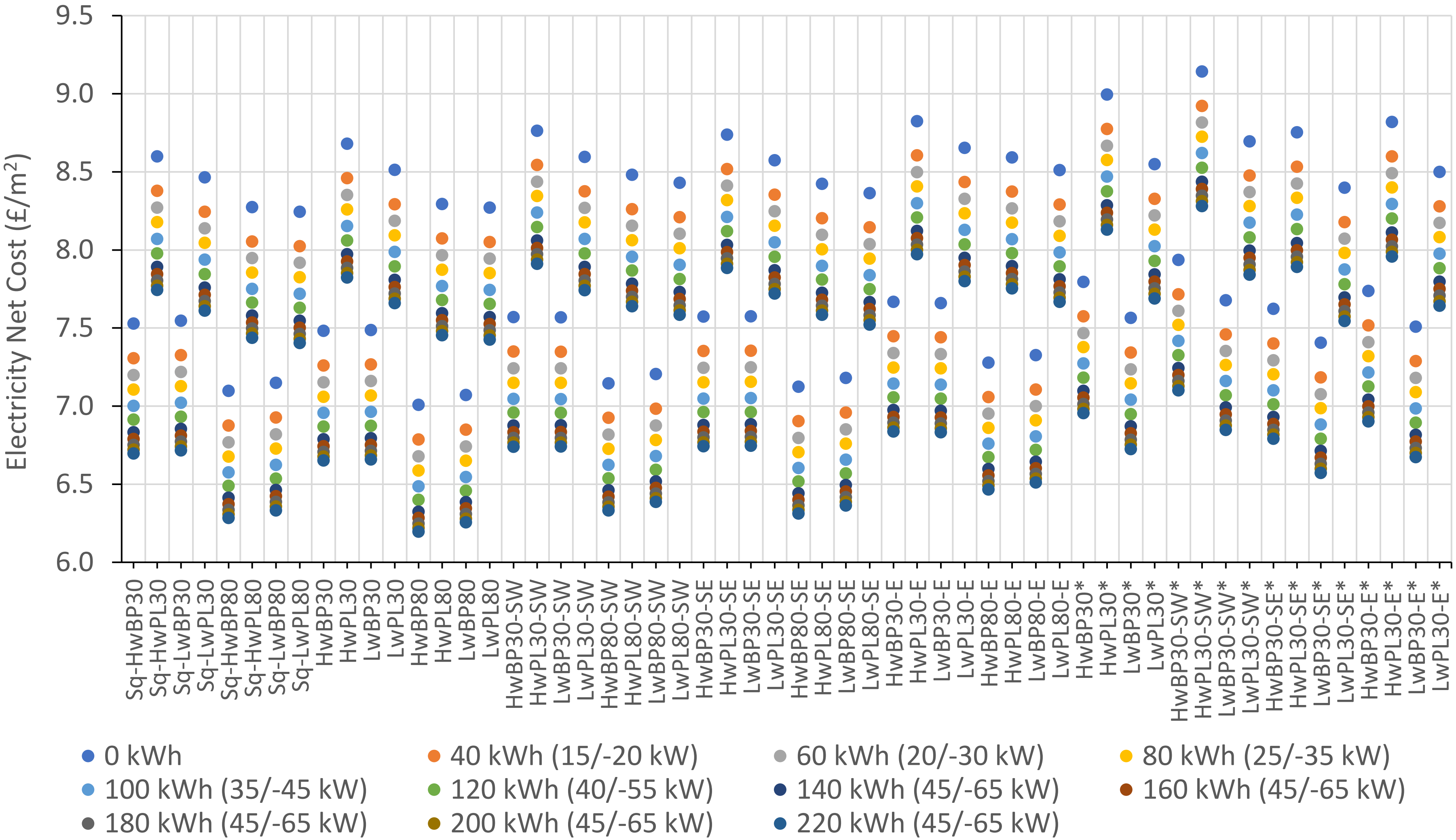

Figure 6.33 – Net Cost (£/m^2) for all building cases under Operational Strategy E0

Additionally, the ranges for operational strategy E5 are 53.09 – 68.91 and 60.94 – 74.50 kWh/m^2 with the reduction being significant for the largest battery size due to the lack of exports during weekends. For E0, the respective ranges are further reduced to 53.22 – 68.39 and 55.24 – 71.19 kWh/m^2 because of the complete lack of exports. For comparative purposes, the total electricity consumption varies between 52.57 – 68.39 kWh/m^2 when no storage is operational. Additional figures, including Operational Strategies E7 and E5, are shown at the end of Appendix G.

6.10 Summary and Conclusions

Summarising the finds of the sensitivity analysis chapter, it should be highlighted the fact that the different factors influence the results differently for each Operational Strategy. In Table 6.38, the absolute mean percentage changes are included for both the electricity shifted (% of peak loads) and exports for E7. The sensitivity analysis factors are then ranked in terms of their impact (higher to lower) based on the exports and shifted electricity values. The two rankings are consistent with only one exception, London DSY vs No Free Cooling that constitutes a special case as only buildings with mechanical ventilation are affected. The sensitivity analysis factors for Operational Strategy E7 are listed below in descending order based on their impact on the electricity shifted (% of peak loads). It should be noted that the signs above indicate if the shifted loads increase (+) or decrease (-) when switching from the Base Case/London DSY to the additional scenario.

1) Base Case vs 45 kW Inverter Capacity (+16.54%)
2) Base Case vs 85 kW Inverter Capacity (-12.47%)
3) London DSY vs Lower CoP (-9.40%)
4) Base Case vs Reduced Equipment Loads (+4.86%)
5) Base Case vs Southampton (-0.96%)
6) Base Case vs London DSY (-0.83%)
7) Base Case vs Edinburgh (-0.71%)
8) Base Case vs Manchester 2017 (+0.57%)
9) London DSY vs No Free Cooling (-0.06%)

The factors above have a wide range of impacts on the arbitrage performance and the peak loads shifted (%). For example, switching from the Base Case inverter capacity of 65 kW to 45 KW inverter leads to an average increase of 16.54% while disabling free cooling has a trivial reduction of 0.06%. Therefore, the inverter rated capacity undoubtedly constitutes the most significant sensitivity analysis factor for Strategy E7. As previously mentioned, the key difference observed between the E7 shifted electricity rankings and exports rankings is the fact that London DSY vs No Free Cooling is moved from the 9th to the 5th place without any further particular differences.

Moving on to the E0 Strategy, disabling exports and using the battery only to meet local building loads leads to a different classification of the sensitivity analysis factors. In London DSY vs Lower CoP, the arbitrage capability is reduced on average by 14.70% while reducing the equipment loads brings the shifted electricity down by 14.24%; these two factors are the most impactful for the E0 Strategy. In contrast with the E7 classification, the inverter rated capacity proves to be much less important for the E0 sensitivity analysis.

This has been previously explained as modifying its capacity under E7 leads to a different mix of the battery activity between shifting and exporting; this is obviously not the case under E0 and therefore its overall impact is reduced significantly. Finally, it should be noted that there are some minor differences when classifying the impact of sensitivity analysis factors based on shifted electricity and net cost, under E0; nevertheless, their rankings are generally consistent across the two parameters (Table 6.39).

Table 6.38 – Ranking of Sensitivity Analysis factors under Operational Strategy E7

Sensitivity Analysis Scenario	Absolute Mean Electricity Shifted Percentage Change (%)	Absolute Mean Export Change (%)	Scenario Rank based on Electricity Shifted	Scenario Rank based on Exports
Base Case vs Southampton	0.96	2.98	5	6
Base Case vs Edinburgh	0.71	0.82	7	8
Base Case vs Manchester 2017	0.57	0.61	8	9
Base Case vs London DSY	0.83	2.12	6	7
Base Case vs Reduced Equipment	4.86	9.58	4	3
Base Case vs 45 kW inverter	16.54	24.76	1	1
Base Case vs 85 kW inverter	12.47	14.47	2	2
London DSY vs Lower CoP	9.40	6.57	3	4
London DSY vs No Free Cooling	0.06	4.28	9	5

Table 6.39 – Ranking of Sensitivity Analysis factors under Operational Strategy E0

Sensitivity Analysis Scenario	Absolute Mean Electricity Shifted Percentage Change (%)	Absolute Mean Net Cost Change (%)	Scenario Rank based on Electricity Shifted	Scenario Rank based on Net Cost
Base Case vs Southampton	2.03	4.04	4	4
Base Case vs Edinburgh	1.40	1.26	5	6
Base Case vs Manchester 2017	0.24	0.51	8	8
Base Case vs London DSY	0.67	2.82	7	5
Base Case vs Reduced Equipment	14.24	14.27	2	2
Base Case vs 45 kW inverter	1.27	1.03	6	7
Base Case vs 85 kW inverter	0.16	0.30	9	9
London DSY vs Lower CoP	14.70	20.94	1	1
London DSY vs No Free Cooling	3.89	4.54	3	3

Summing up, the sensitivity analysis factors for Operational Strategy E0 are listed below in descending order based on their impact on the electricity shifted (% of peak loads):

1) London DSY vs Lower CoP (-14.70%)
2) Base Case vs Reduced Equipment (+14.24%)
3) London DSY vs No Free Cooling (-3.89%)
4) Base Case vs Southampton (+2.03%)
5) Base Case vs Edinburgh (-1.40%)
6) Base Case vs 45 kW inverter (-1.27%)
7) Base Case vs London DSY (+0.67%)
8) Base Case vs Manchester 2017 (+0.24%)
9) Base Case vs 85 kW inverter (+0.16%)

Regarding the rest of the sensitivity analysis parameters that have been examined, using the 2018 RTP electricity led to consistent results and conclusions with those of Chapter 5.2 and the 2017 RTP data. Several battery capacity sizes have been presented, varying from 40 to 220 kWh. Small batteries between 40 – 100 kWh are able to shift only a small percentage of the buildings' peak loads with insignificant exports back to the grid, for Strategy E7; therefore, they are not recommended to be deployed in non-domestic buildings for arbitrage purposes.

7. Cost-Benefit-Analysis (CBA)

7.1 10-year period

In this section, the cost effectiveness of the arbitrage scheme is investigated for a BSS of 240 kWh (80 kW/-60 kW) for a 10-year period, for Operational Strategies E7 and E0, considering the 2017 RTP data, with any exports being rewarded with the respective wholesale electricity prices. As mentioned in the Methodology Chapter, the lifetime of the BSS is expected to be 10.5 and 19.5 years for E7 and E0, respectively, due to the battery lifecycle and the associated operational needs. Therefore, no replacements are required for the period in question. While the BSS is near the very end of its life after 10 years for E7, there is still a decade left when exports are disabled and subsequently only 50% of the BSS life is utilised. It should be remarked that any remaining battery life at the end of the 10-year period is not deducted when calculating the scheme's NPC and while this does not affect Strategy E7, it does apply to E0.

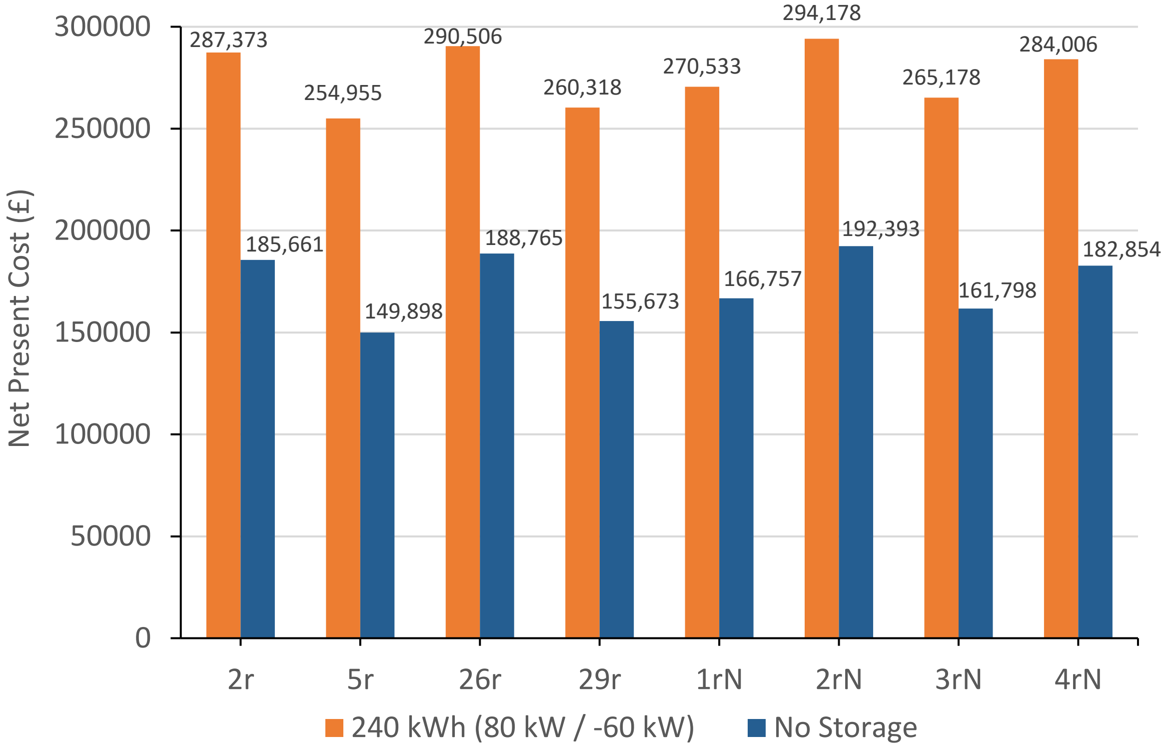

Figure 7.1 – NPC (£) with and without storage for a 10-year period under E7

The NPC results are demonstrated in Figure 7.1 for both the BSS and the No Storage scenarios. Their respective ranges are approximately £255k – 294k for the former and £150k – 192k for the latter with their difference being £103k, on average, due to the added BSS capital cost. When using the BSS, it is clear that the results are divided in two groups based on the buildings' energy performance. Best Practice Buildings (5r, 29r, 1rN, 3rN) are more affordable costing approximately between £255k – 275k while Part L compliant Buildings (2r, 26r, 2rN, 4rN) constitute the expensive group with a cost range of £284k – 294k. Regarding the mechanically-ventilated buildings, NPC slightly increases when moving away from the default to the eastern orientation. Buildings 2r and 5r with a southern orientation have NPCs of £287k and £255k while their easter-orientation counterparts experience a small increase with respective NPC values of £291k and 260k. Furthermore, switching from mechanical to natural ventilation also appears to lead to cost increase. For example, for Buildings 2r and 2rN which are identical with the only exception of their ventilation strategy, the respective costs are £287k and £294k. In conclusion, Best Practice Buildings 5r and 29r are seen to have the lowest NPC values (£255k and £260k) for the 10-year period while Part L Compliant Buildings 2rN and 26r are the most expensive of the selection (£294k and 291k).

LCOE is also an interesting economic parameter of this chapter and is illustrated in Figure 7.2. Without storage, as expected, the range of the values is very small with a mean of 11.47p, essentially reflecting that all buildings have access to the same electricity prices. When using BSS, the mean value is higher at 14.13p; therefore, when conducting arbitrage with exports enabled, LCOE increases on average by 2.66p. The increase of the electricity cost should be considered along with the very definition of LCOE which takes into account the building's electricity demand along with the amount of exported electricity.

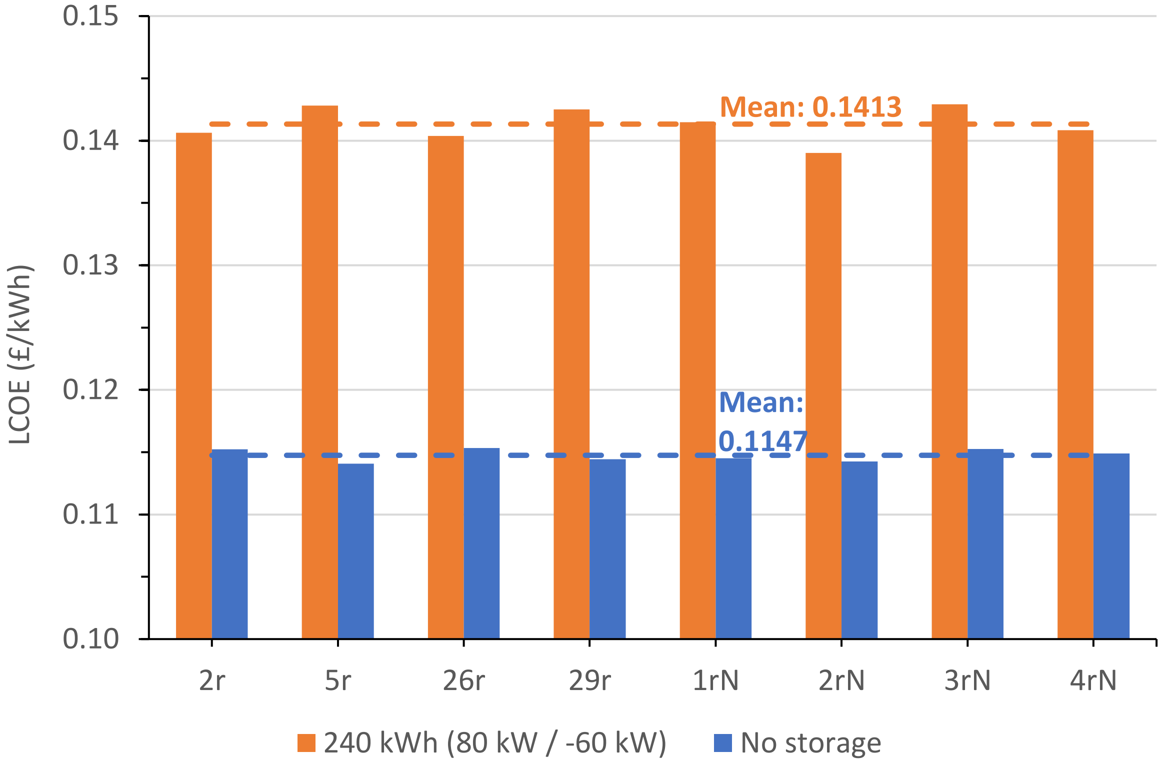

Figure 7.2 – LCOE (£/kWh) with and without storage for a 10-year period under E7

Given that the building provides a service to the grid by using storage, a financial motive is needed, especially since the NPC range is higher by an average of £103k, essentially compensating that difference and making the BSS arbitrage scheme at least as effective as the no storage scenario. In Figure 7.3, this required financial motive is shown based on the amount of electricity shifted along with the mean values for Best Practice and Part L Buildings. The financial motive varies between 21.40p – 24.70p for the selected buildings per kWh shifted. Similarly to the NPC results, there are two major groups formed with Best Practice buildings requiring a higher financial motive between 23.18p – 24.70p while Part L compliant buildings need a narrow respective range of 21.40p – 21.87p.

It is not a surprise that more energy efficient buildings require a higher financial motive as while the higher energy efficiency might result in higher percentages of the peak electricity shifted, this does not necessarily translate to higher amounts of electricity shifted in pure amounts of kWh. This has been previously discussed during the first arbitrage results and it has been pointed out that buildings that are less energy efficient have the potential to shift more electricity in terms of the total number of kWh as their electricity profile is generally more demanding than their Best Practice counterparts. Therefore, based on these ranges, the financial motive can be considered a financial reward as it rewards buildings for being more energy efficient and shifting higher amounts of their peak loads, in percentage terms. On average, Best Practice Buildings receive a higher financial reward of 23.93p per kWh shifted while Part L Buildings get a lower reward of 21.74p.

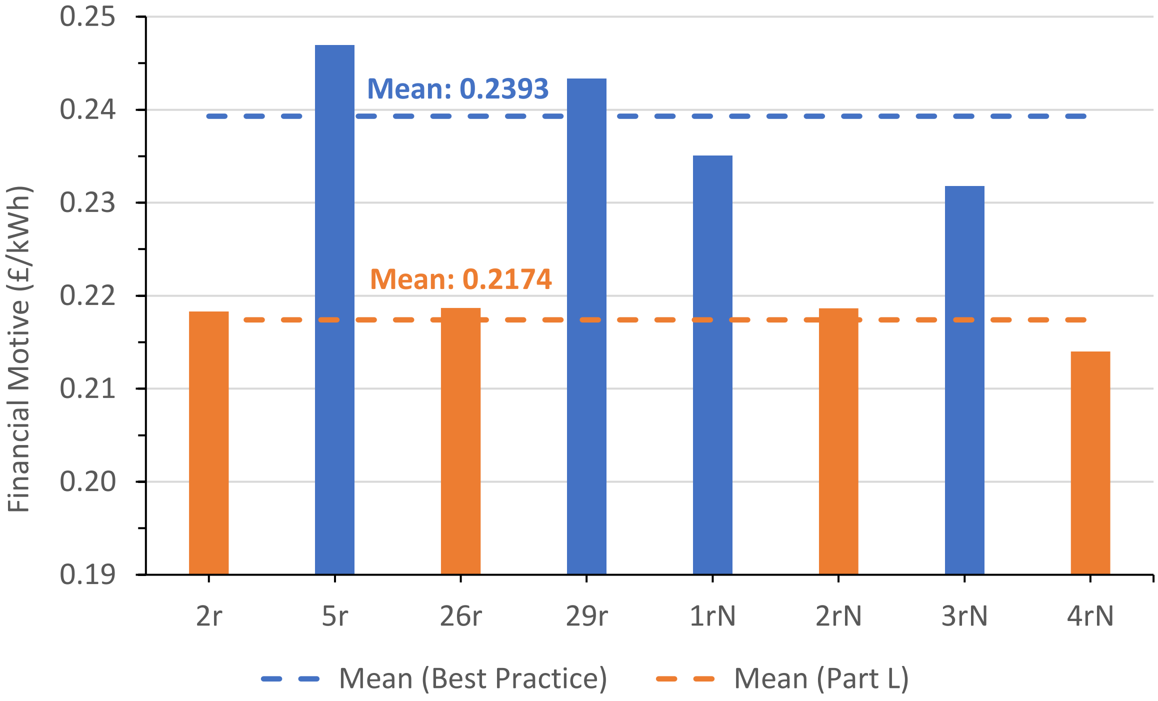

Figure 7.3 – Financial motive needed based on the electricity shifted (£/kWh) for a 10-year period under E7

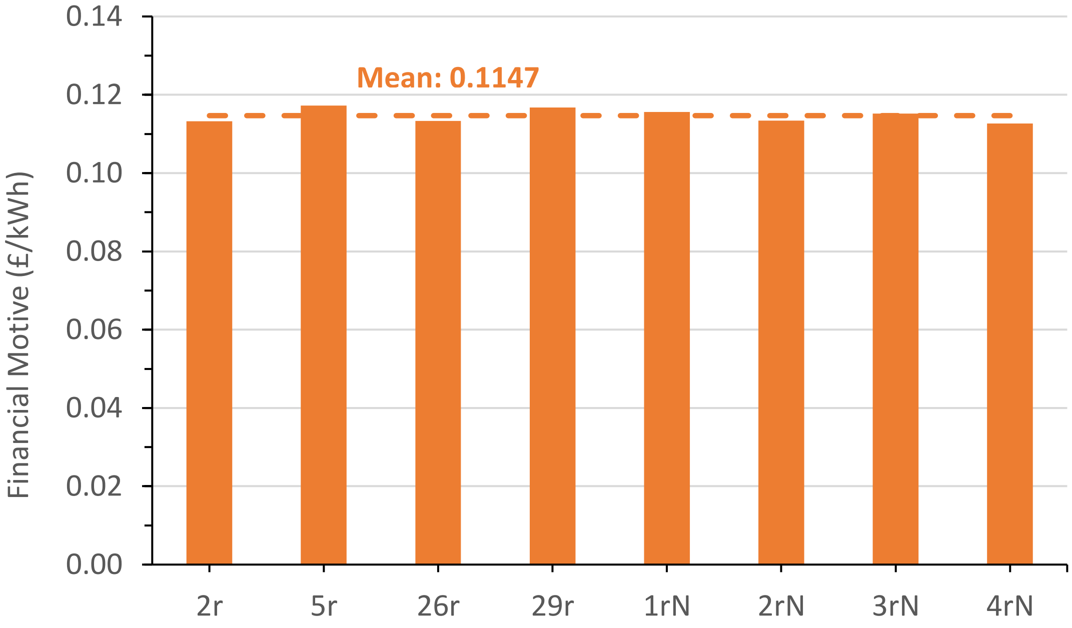

Figure 7.4 – Financial motive needed based on the electricity shifted and exports (£/kWh) for a 10-year period under E7

Figure 7.4 presents a different financial motive that takes into account both the amounts of the shifted electricity and exports back to the grid. The range of the values is very narrow, with a mean financial reward of 11.47p per kWh shifted or exported because of the particular financial motive definition bringing down the reward per kWh shifted or exported. Therefore, while as a reward it helps towards making the arbitrage scheme as cost-effective as possible as the no storage scenario, it does not constitute a useful or competitive metric when trying to evaluate, compare the arbitrage performance of different buildings and reward them accordingly. Furthermore, the exported electricity results in a separate revenue stream regardless of which financial motive is used and therefore it might not be appropriate policy-wise to reward exports with two different financial mechanisms.

Moving to the Operational Strategy E0 costs and Figure 7.5, using storage, the NPC values vary between £234k – 275k and when compared to the NPC range of £150k – 192k for the no storage scenario, this translates to an average £84k difference for all cases. NPCs for the buildings with the highest energy performance is between £234k – 250k while the respective range for the Part L compliant buildings is significantly higher and varies from £265k to 275k. Adopting natural ventilation also leads to an increase in the NPC, for example £269k and £275k are required for Buildings 2r and 2rN, respectively.

Moving on to the LCOE, a range of 16.36p – 17.82p is observed for the selected buildings, higher than the average LCOE value of 11.47p without storage (Figure 7.6). As exports are now disabled, it is not a surprise that electricity is cheaper for Part L compliant Buildings as they are able to shift higher amounts of electricity (kWh/m^2) than their more energy efficient counterparts and lower amounts of energy are included in the LCOE calculation; nevertheless, their LCOE difference is not significant.

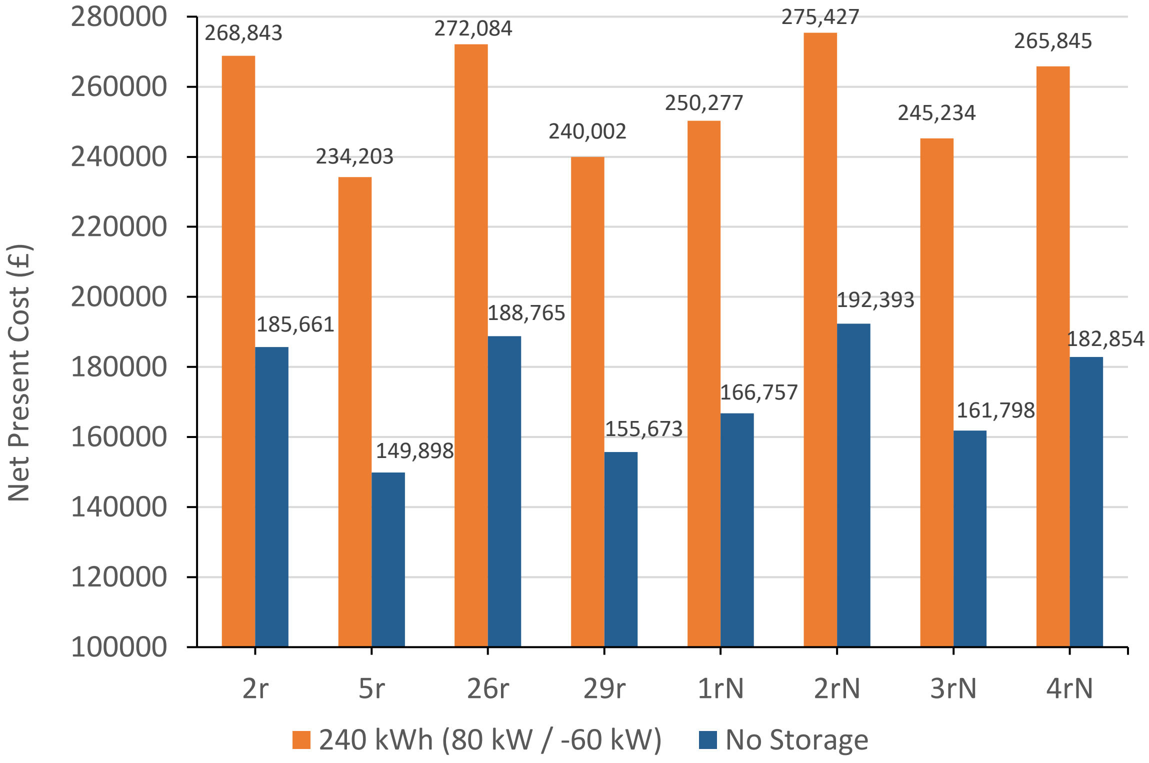

Figure 7.5 – NPC (£) with and without storage for a 10-year period under E0

The only financial motive presented for Operational Strategy E0 is based on the electricity shifted and is shown below, in Figure 7.7, with a range between 16.34p – 17.40p per kWh shifted. The highest financial rewards take place for the Best Practice Buildings with a mean value of 16.93p while the respective mean value for Part L Buildings is 16.40p; therefore, the mean values of the two building groups are very close and the results are consistent with E7.

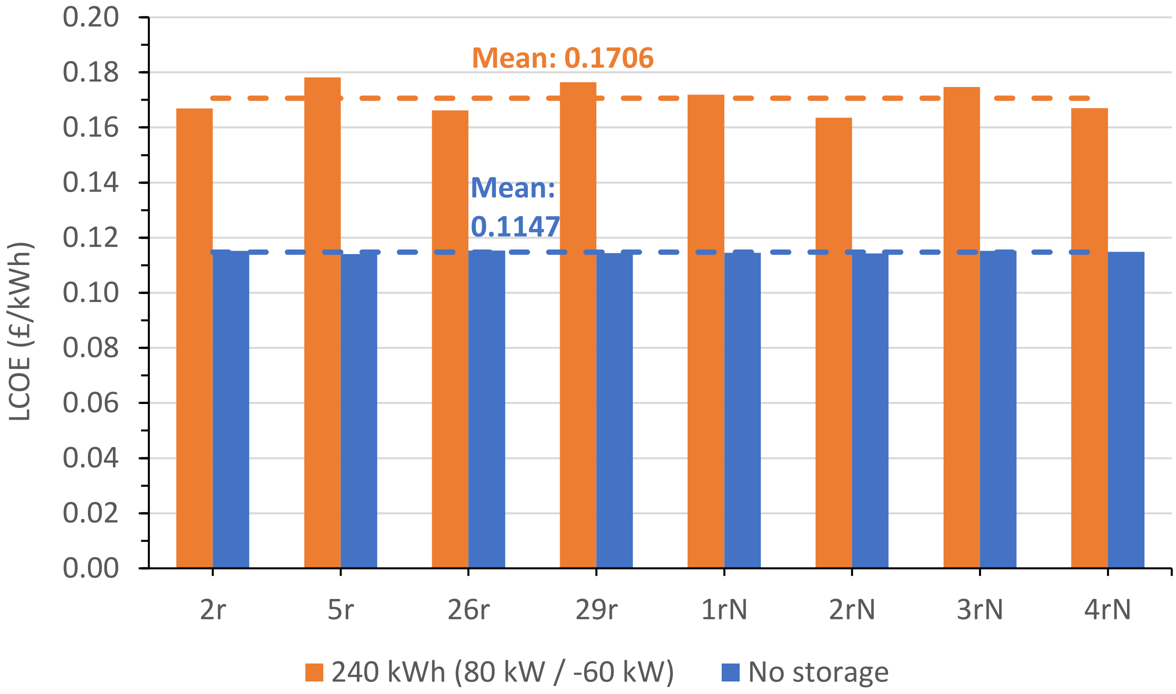

Figure 7.6 – LCOE (£/kWh) with and without storage for a 10-year period under E0

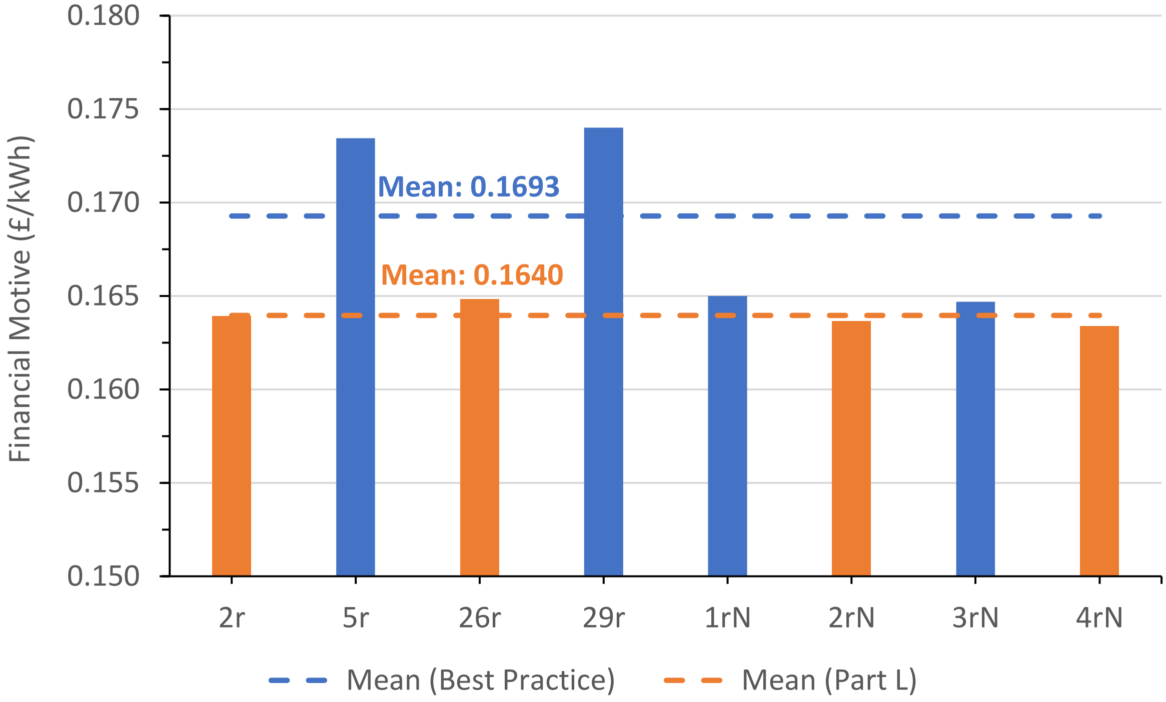

Figure 7.7 – Financial motive needed based on the electricity shifted (£/kWh) for a 10-year period under E0

Table 7.1 summarises the results for both operational strategies and without storage. In terms of the involved costs, it is clear that on average buildings have a lower NPC under the Operational Strategy E0 by £19k, indicating that the revenue streams from the exports taking place under E7 are not sufficient to reduce the overall NPC values. Consequently, the financial motive required per kWh shifted for E7 is considerably higher for all building scenarios (21.40p – 24.70p) when compared to the E0 range (16.34p – 17.40p); ergo, buildings opting to participate in the E7 strategy will need to receive a higher financial incentive for their exporting activity. Undoubtedly, when looking at the NPC and LCOE values for the E0 strategy, having the BSS dedicated to load-shifting incurs the lowest costs.

Table 7.1 – Economics summary for a 10-year period

Parameter	Strategy E7	Strategy E0	No Storage
NPC (£)	255k – 294k	234k – 275k	150k – 192k
LCOE (£/kWh)	13.90p – 14.29p	16.36p – 17.82p	11.47p
Financial Motive – Energy Shifted (£/kWh)	21.40p – 24.70p	16.34p – 17.40p	N/A
Financial Motive – Energy Shifted & Exports (£/kWh)	11.47p	N/A	N/A

Finally, a sensitivity analysis has also been conducted on the impact of the BSS capital cost on the arbitrage economics. In more detail, a 15%, 30% and 45% BSS reduction have been considered for Buildings 5r and 2rN that have the lowest and highest NPC values, respectively. Tables 7.2 and 7.3 present the range of these two buildings for the NPC, LCOE and the financial motive needed based on the energy shifted. It can be seen that gradually, going from a BSS cost of 100% to the final 55%, all values are reduced.

Table 7.2 – Economics summary considering a 15%, 30% and 45% reduction in the Battery capital costs for Operational Strategy E7 and Buildings 5r/2rN

Parameter	**NPC (£)**	**LCOE (£/kWh)**	**Financial Motive – Energy Shifted (£/kWh)**
100% BSS Cost	255k – 294k	13.90p – 14.28p	21.86p – 24.70p
85% BSS Cost	239k – 279k	13.17p – 13.41p	18.52p – 21.04p
70% BSS Cost	224k – 263k	12.43p – 12.54p	15.17p – 17.38p
55% BSS Cost	208k – 248k	11.67p – 11.70p	11.83p – 13.72p

Table 7.3 – Economics summary considering a 15%, 30% and 45% reduction in the Battery capital costs for Operational Strategy E0 and Buildings 5r/2rN

Parameter	**NPC (£)**	**LCOE (£/kWh)**	**Financial Motive – Energy Shifted (£/kWh)**
100% BSS Cost	234k – 275k	16.36p – 17.82p	16.37p – 17.34p
85% BSS Cost	219k – 260k	15.43p – 16.64p	13.30p – 14.14p
70% BSS Cost	203k – 244k	14.51p – 15.45p	10.23p – 10.94p
55% BSS Cost	188k – 229k	13.58p – 14.27p	7.16p – 7.73p

For example, under E7, the financial motive required is decreased from an original range of 21.86p – 24.70p to 11.83p – 13.72p when the battery cost is down by 45%. Considering E0, the respective 55% range is again lower than its E7 counterpart, between 7.16p – 7.73p.

LCOE does not drop significantly from its original E7&E0 range, observing a moderate average overall decrease of 2 – 3p. Figure 7.8 presents the financial motive required for the several BSS costs considered under Operational Strategy E0 and it is clear that for a battery reduction of 45%, the financial reward is dropped approximately by 10p per kWh shifted.

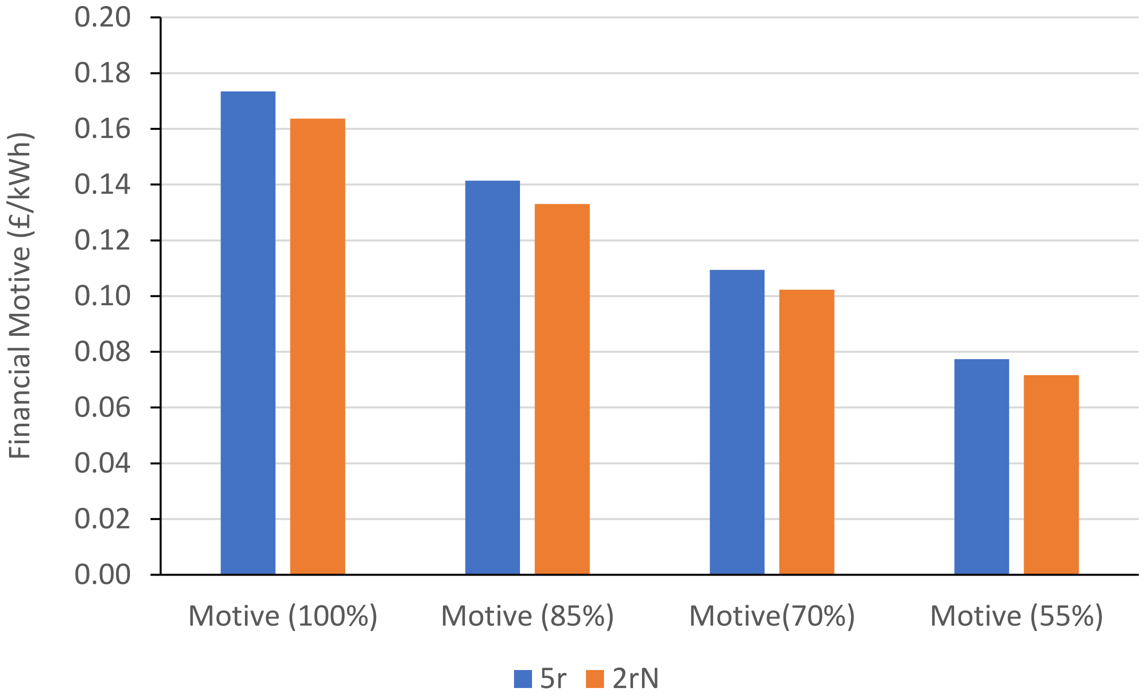

Figure 7.8 - Financial Motive based on Energy Shifted for Operational Strategy E0 for a 10-year period considering a 15%, 30% and 45% reduction in battery capital costs. Percentages refer to the total BSS cost in relation to the original (100%).

Table 7.4 – The impact of retail/wholesale electricity prices on export revenues and economics for Operational Strategy E7

Parameter	**Mean Value/Range**	
	Wholesale Revenues	**Retail Revenues**
NPC (£)	255k – 294k	216k – 258k
LCOE (£/kWh)	13.90p – 14.29p	12.10p – 12.33p
Financial Motive – Energy Shifted (£/kWh)	21.40p – 24.70p	13.93p – 15.55p
Financial Motive – Energy Shifted & Exports (£/kWh)	11.47p	7.35p

It is interesting to investigate how economics are affected when assuming that buildings are awarded with the retail prices, when exporting electricity back to the grid under E7, instead of the wholesale prices that have been considered so far in the current chapter. As shown in Table 7.4, considering retail prices for exports brings the NPC values down by £37k, on average, as buildings now earn higher amounts of revenues for the same amounts of exports. LCOE is reduced by 1.90p while the financial motive per kWh shifted is significantly down by 8.21p. In this particular scenario of retail prices being used and due to the increased amount of the respective revenue streams, Operational Strategy E7 proves to be more economical than E0 in terms of the NPC and LCOE values and therefore requiring lower financial motives for the shifted electricity. The detailed results of the retail revenues scenario can be seen in Figures F15 – F18 of the Appendix.

7.2 CBA Case Study

7.2.1 10-year period

The analysis that follows constitutes an extended part of the original CBA as, published in [9], and includes some limited methodology changes along with a comparison of the financial results when considering different time periods, albeit for only two selected buildings. The changes/additions are highlighted below:

- Two battery sizes are taken into account with the same rectifier/inverter configuration: 120 kWh (40/-60 kW) and 240 kWh (80/-60 kW).
- Operation and maintenance costs (O&M) of £100 per annum are now considered for the BSS.
- All Operational Strategies are included: E7, E5 and E0.
- Only two extreme building scenarios are investigated based on their energy performance: 2r (HwPL30) and 5r (HwBP80).
- No BSS component replacements are required for this time period.
- Any remaining life of the battery/converter at the end of the investigation period is deducted from the total NPC. The estimated lifetime of the battery and the converter differs per operational strategy due to the different number of daily cycles. E7 is not affected by this change as at the end of the period, the remaining lifetime of the BSS components is insignificant. However, this change has an impact on the NPC and financial motive calculations under E5 and E0 as the battery is expected to reach only 50% of its lifetime at the end of the 10-year period.
- When exports are allowed (E7 & E5), it is assumed that buildings are rewarded for the exported electricity with the retail RTP prices instead of the wholesale prices used previously in Chapter 7.1.

The NPCs are shown in Figure 7.9. For all scenarios considered, with and without storage, Building 5r appears to be cheaper than 2r by £35k due its relatively superior energy performance. Additionally, the differences between the E5 and E0 results seem to be insignificant indicating that the additional revenue stream that is present under E5 leads to a very limited reduction of the total NPC between £1k – 3k depending on the BSS size. Adding the smaller battery of 120 kWh or the bigger battery of 240 kWh increases the NPC by approximately £34k or £67k, respectively, for both buildings. Furthermore, despite the high amount of electricity exports taking place, the highest NPCs are observed under the E7 strategy. More specifically, the NPC values under E7 are £8k and £20k more expensive than the respective E5 costs for the 120 kWh and 240 kWh battery, respectively.

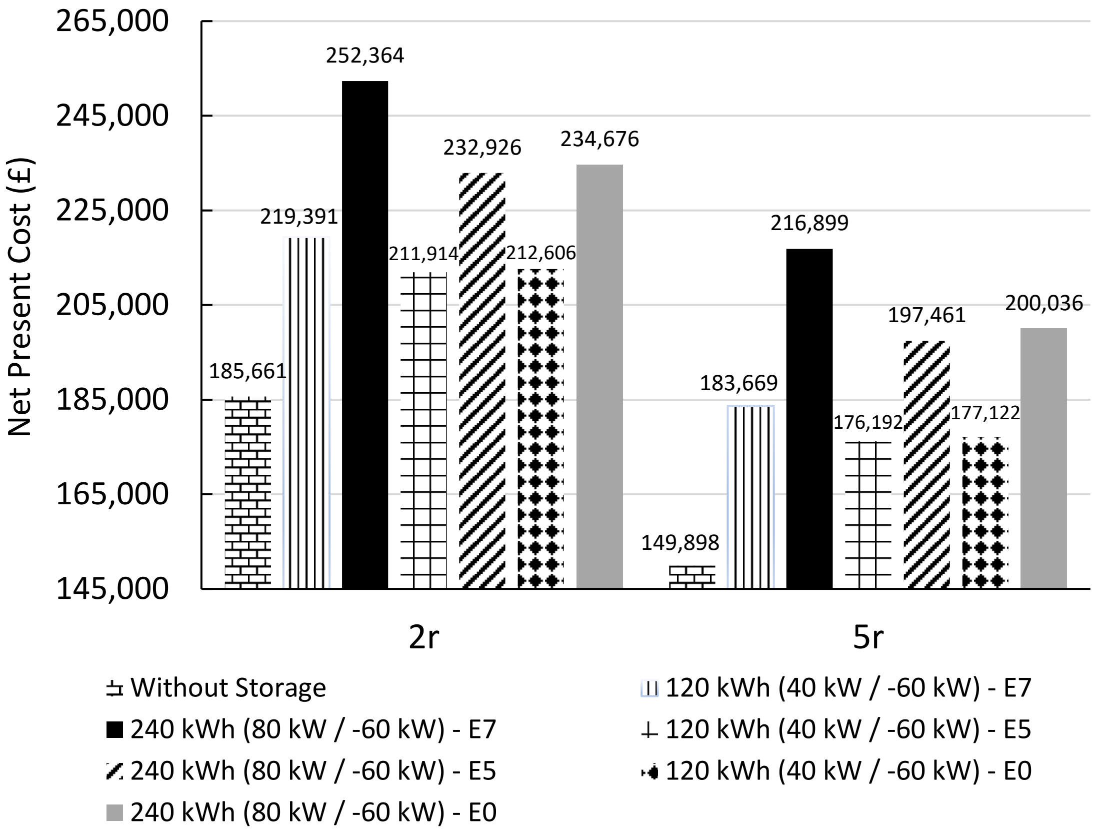

Figure 7.9 – NPC for 10-year period for all operational strategies [9]

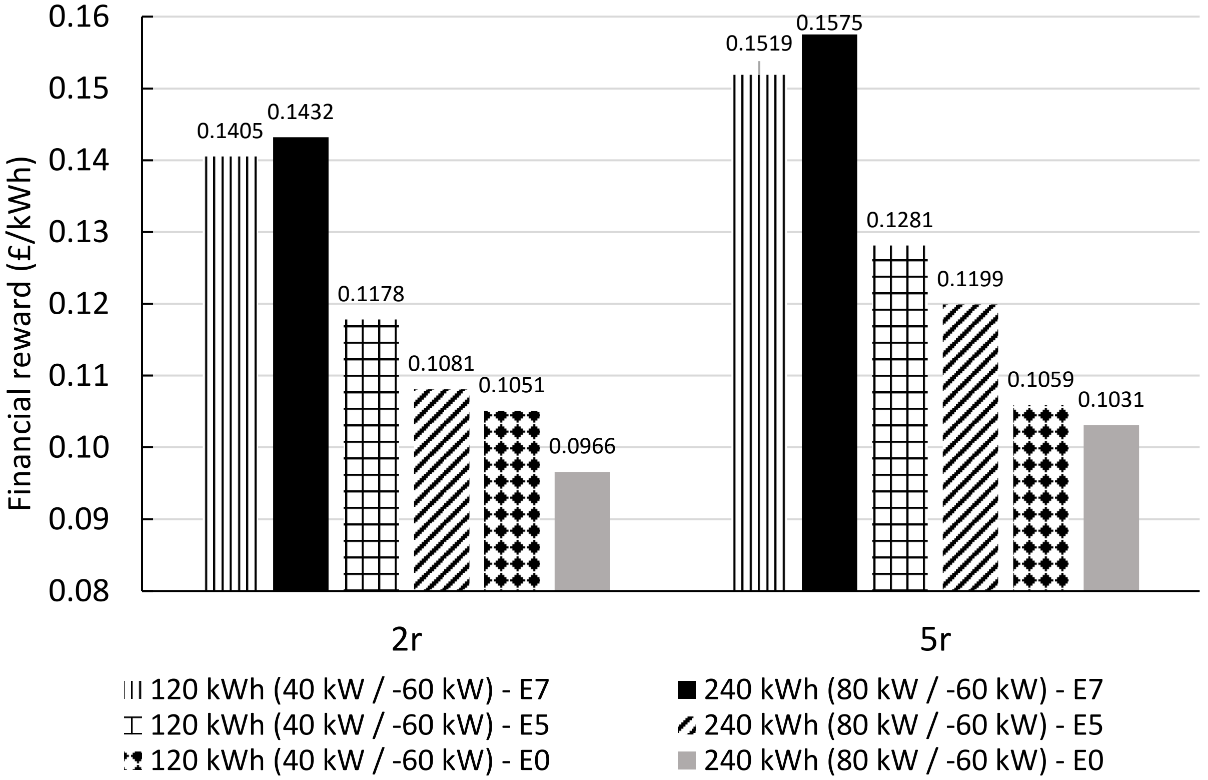

Figure 7.10 – Financial motive for 10-year period based on the energy shifted for all operational strategies [9]

It should be noted that at the end of the 10-year period, there is no remaining lifetime for the BSS components under E7 which affects significantly the NPC values. Comparing these NPC values with the results of Chapter 7.1, there are no differences under E7 due to the non-existent BSS lifetime at the end of the period. However, for the E0 strategy and the 240 kWh battery, when considering the remaining lifetime of the BSS, Building 2r has a NPC of £235k (Figure 7.9), significantly lower than the original NPC of £269k (Figure 7.5). Similarly, under E0, Building 5r has now a revised cost of £200k instead of the initial value of £234k and it is evident that this methodology change, regarding the remaining lifetime of the BSS components, has an impact of £34k for all buildings.

Regarding the financial reward needed, a range of 9.66p – 14.32p is observed for Building 2r and higher values between 10.31p – 15.75p for 5r (Figure 7.10), for both battery sizes. As the highest NPCs take place under E7, the respective financial rewards needed are higher for that strategy, followed by E5 and E0. In more detail and in descending order, there is a range of 14.05p – 15.75p required for E7, 10.81p – 12.81p for E5 and finally 9.66p – 10.59p for E0. Comparing the exact financial reward values for the two buildings as shown in Figure 7.10 with the original values of Figure 7.3 in Chapter 7.1, there are no major changes under E7, similarly to the NPC results comparison. However, under E0, the financial reward for the two buildings is now 9.66p and 10.31p for the 240 kWh battery while the original financial motives that did not take the remaining BSS lifetime into account were 16.39 and 17.34p (Figure 7.7), respectively, a substantial difference of approximately 7p for both buildings. This change is based on the very definition of the financial motive and the fact that while the amounts of the shifted electricity remain the same, there is an important NPC difference.

Finally, regarding the electricity costs when using the bigger battery of 240 kWh, LCOE is 12.35p and 12.15p for the two buildings under E7, respectively, approximately the same with the previous values reported in the previous chapter and Figure 7.2. Nevertheless, when considering the remaining BSS lifetime, the respective values under E0 are 14.56p and 15.22p, around 2p cheaper than the original values of 16.69p and 17.82p previously mentioned in the previous section (Figure 7.6). This is also related to the LCOE definition as the NPC values are divided by the sum of electricity demand and any exports that take place. While it can be argued that including the exports in the LCOE calculation might lead to an underestimation of the LCOE for E7 and E5, it should be reminded that this extra amount of electricity is only bought from the grid only to be exported back at a later time for a profit.

7.2.2 20-year period

When considering a 20-year period, one replacement battery and one replacement converter are needed for strategy E7. Under E5 and E0, only one replacement converter is needed. All costs are expected to increase, including the no-storage scenario, as higher amounts of electricity are purchased by the grid to meet the local building loads for the entire duration. Without storage, Building 2r has a total NPC of around £325k and is more expensive by £62k when compared to the respective values of Building 5r; this £62k difference between the two buildings is present for all strategies and BSS sizes. The additional capital costs of the replacement components have led to an increase of the NPC values for all storage scenarios. Generally, the 20-year results and trends are consistent with the 10-year period results.

At this point, it is important to focus on the comparison of the financial reward needed for the two periods, presented in Figure 7.11. It can be observed that for both study periods and buildings, the financial motives are approximately the same for the two battery sizes of 120 and 240 kWh; therefore, increasing the battery size by 100% does not appear to have a significant impact on the financial reward that needs to be paid to the building performing the arbitrage. In addition, it is clear that increasing the study period from 10 to 20 years results in an average reduction of the financial reward by 2p/kWh for all operational strategies despite the higher capital costs induced by the replacement components. The reduction of the buildings' financial reward when increasing the study period to 20 years is consistent for both battery sizes: 13% for E7 and 21% for E5 and E0.

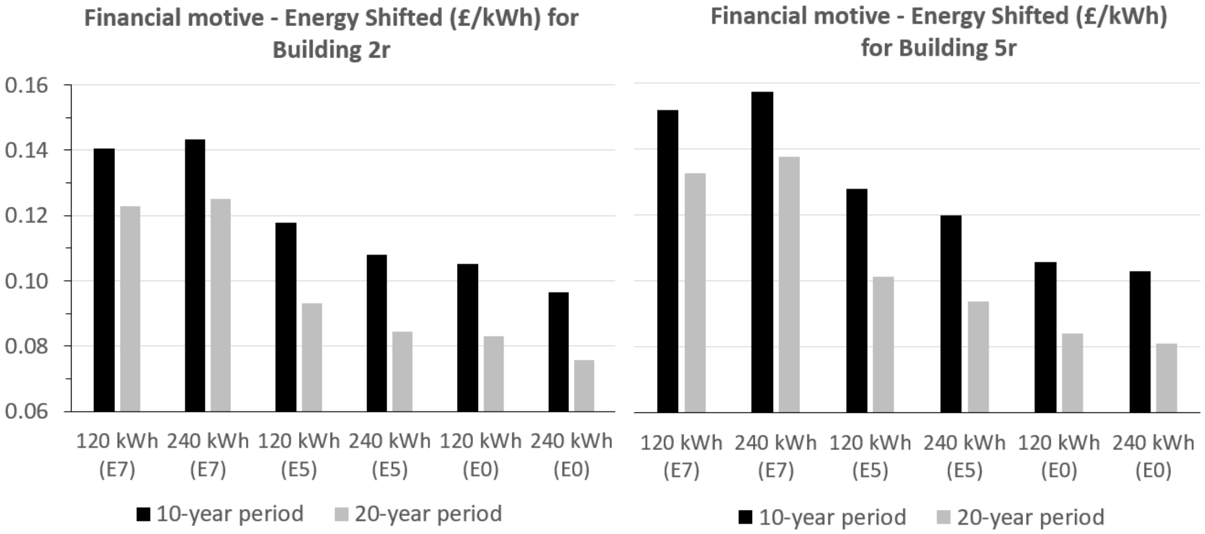

Figure 7.11 – Financial reward needed for a 10-year and 20-year period, based on the electricity shifted (GBP/kWh), for buildings 2r and 5r [9]

7.3 Summary & Conclusions

- For a 10-year period and using the 240 kWh battery, Operational Strategy E0 incurs the lowest NPC values with a range of £234k – 275k and an average LCOE of 17.06p with the mean required financial motive being 16.66p/kWh shifted. When exports take place and the exports revenue steam is present (E7), the NPC increases and varies between £255k – 294k with a respective average LCOE of 14.13p, resulting in a raised financial motive with a mean value of 22.84p/kWh shifted (Section 7.1).

- Despite the lower NPC values of Operational Strategy E0, it should be highlighted that its LCOE values are more expensive due to the LCOE definition and the significantly higher denominator under Strategy E7 that consists of both the building's electricity consumption without storage as well as electricity exports.

- For all strategies, including the no storage case, the best performing building (5r/HwBP80) is £38k – 42k cheaper than the worst performing building (2rN/HwPL30*).

- When the battery cost is reduced by 45% and for Operational Strategy E7, the financial motive (£/kWh shifted) decreases from its original range of 21.86p – 24.70p to 11.83p – 13.72p. For Strategy E0, the original range of 16.37p – 17.34p is also reduced significantly to 7.16p – 7.73p.

- For a conducted case study (Chapter 7.2) that took into account the remaining lifetime of the BSS components and retail revenues from exports, Strategy E7 incurs the highest costs as the lack of any remaining lifetime for the BSS components has a significant impact on the NPC calculation. For example, regarding Building 2r

(HwPL30) and using the 240 kWh BSS, the associated costs are £252,364, £232,926 and £234,676 for E7, E5 and E0, respectively. When increasing the investigated lifetime from 10 to 20 years, the required financial reward is reduced by 2p/kWh for all strategies.

8. Summary and Conclusions

8.1 Summary

This thesis aimed to investigate, evaluate and compare the impact of a grid-connected building's design characteristics on its ability to take part in energy arbitrage schemes by using battery storage, under RTP conditions. Buildings and especially the fully-electric SGOBs are expected to play a major role in the energy transition and decarbonisation of the electrical system, engaging in bidirectional power exchange with the electrical grid, making the best use of the available resources and emerging technologies, such as energy storage, and taking into account the dynamic nature of RTP electricity. The literature review demonstrated that there is a growing interest in battery storage and its applications in communities (CES) and buildings towards providing balancing services to the grid. However, using batteries to conduct energy arbitrage under RTP conditions in buildings of different design characteristics, has not been investigated before and therefore, the impact of building design on battery-enabled arbitrage performance is not known. Taking into account the large amounts of the building's sector energy consumption, utilising BSS in buildings of appropriate design to conduct arbitrage could result in avoiding or deferring the need for potential expensive infrastructure upgrades.

The research gap has been addressed by performing the appropriate building energy simulations, developing and implementing a techno-economic MATLAB arbitrage algorithm for building-integrated battery storage which included multiple dispatch operational strategies. The building design elements have been classified based on their impact on the arbitrage performance as well as the associated annual electricity costs. A detailed CBA was performed for both 10 and 20-year periods and a financial mechanism was suggested to motivate the participation of buildings in the arbitrage scheme. The lack of a current regulatory framework for utilising batteries in buildings as well as the uncertainty around the ownership and operation of energy storage were highlighted. The findings for each key research objective are summarised below.

8.2 Conclusions

A) *Develop a techno-economic battery storage arbitrage model for non-domestic buildings that will enable them to respond dynamically to real-time electricity prices, shift their loads and export electricity back to the grid.*

The model was developed in MATLAB and constitutes a modified and scaled-down version of a PHES arbitrage algorithm. Three operational strategies were devised and used in the model, an overview of which can be seen below, in Table 8.1. Regarding their key differences, under Strategy E7, exports are allowed to take place seven days a week while, under E5, exporting is restricted during working days only, under E5. On the other hand, under E0, the BSS operation is exclusively focused on meeting the local building loads; therefore, electricity exports are not permitted. For their participation in exporting electricity back to the grid, buildings are rewarded financially based on the wholesale electricity price during which the exports take place and the amount exported, similarly to the utilisation fee used in balancing services procured by the National Grid.

The battery specifications were based on a high-end commercial battery pack with a lifetime of 5,000 cycles at DOD 90% or 4,500 full equivalent cycles. Due to the associated number of cycles per day per operational strategy, the estimated battery lifetime was approximately 10 years for Strategy E7 and 20 years for Strategies E5 and E0. A 10-year lifetime was assumed for the bidirectional converter.

Table 8.1 – Overview of the Arbitrage Operational Dispatch Strategies [9]

Activity	**Operational Strategy**		
	E7	E5	E0
Battery is allowed to discharge to meet building loads on working-days	✓	✓	✓
Exports can take place on working-days	✓	✓	✗
Exports can take place on non-working days	✓	✗	✗
Revenues from exporting back to the grid	✓	✓	✗
Charging takes place when electricity prices are cheap and building loads insignificant.	✓	✓	✓
Discharging takes place when electricity prices are expensive and building loads significant	✓	✓	✓

Regarding the input used for the arbitrage model, hourly wholesale electricity pricing data from NordPool's day-ahead power exchange market were converted to retail prices, using the wholesale direct fuel cost percentage (36.63%), as reported by the six biggest UK electricity suppliers to account for the electricity transportation, network, social, environmental costs and VAT. Additionally, annual energy simulations of several non-domestic building scenarios with different design characteristics were performed in DesignBuilder/EnergyPlus and their hourly output were fed into the model; the building's total floor area was 2,500 m^2. The interaction of the research elements along with the different inputs and outputs are shown below, in Figure 8.1.

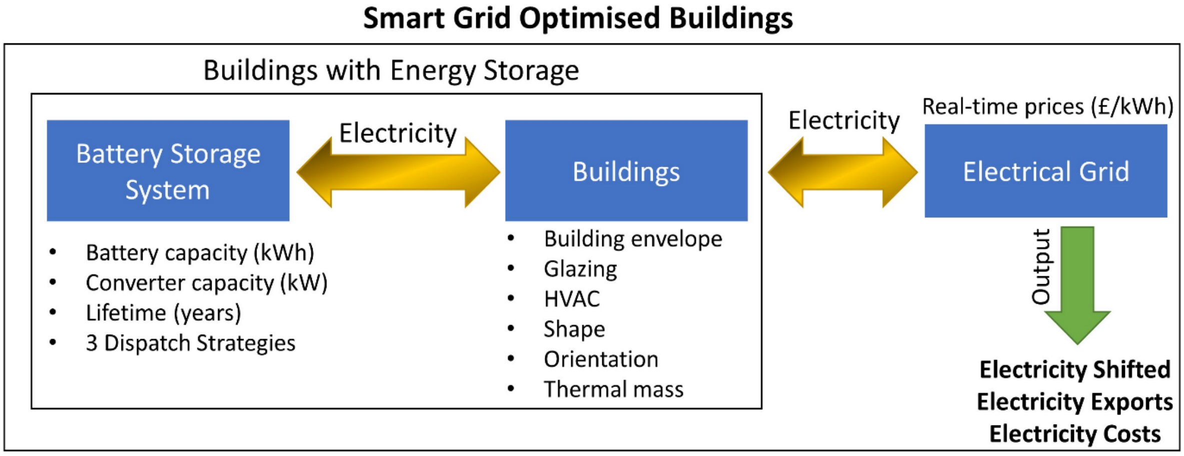

Figure 8.1 – Main research elements and their characteristics [9]

The original version of the arbitrage algorithm was used for the utilisation of large scale pumped-hydro as presented in detail in [246], [247], [248] and [249]. For the needs of the current research, significant changes and additions have been made to scale down the algorithm and adjust it at the building level and reality as the building's activity and consequent electricity loads are now considered to decide on the operation of the BSS. In this case, there are local loads that need to be met by the BSS. Furthermore, the battery is not allowed to discharge if the building loads that are present do not exceed a specific threshold. Similarly, charging the battery is not permitted if the building loads exceed the same threshold. The combined results generated by the MATLAB arbitrage model includes several variables the most important of which are the annual amounts of shifted electricity as a percentage of the building's peak loads, exported electricity (kWh/m^2) and electricity net cost (£/m^2) that takes into account both costs and revenues. Peak loads refer to loads that take place during the opening hours of the building (8 am – 6 pm).

B) *Investigate how the arbitrage operation of buildings is affected by their design parameters and define the most appropriate building design for BSS-enabled arbitrage.*

In total, six key building design characteristics have been investigated through 56 simulated building scenarios. As under Strategy E0, battery activity takes place to only meet the local building loads, it is appropriate to be used for a direct comparison of the building parameters and their subcategories. The design parameters are listed below, in descending order, based on their impact on the arbitrage performance, along with the more suitable building subcategories. Since there are no exports under E0, the arbitrage performance can be evaluated by the percentage of the peak loads shifted. The difference in terms of the electricity shifted (% of peak loads) that takes place when switching building subcategories for each design element can be seen in Figure 8.2.

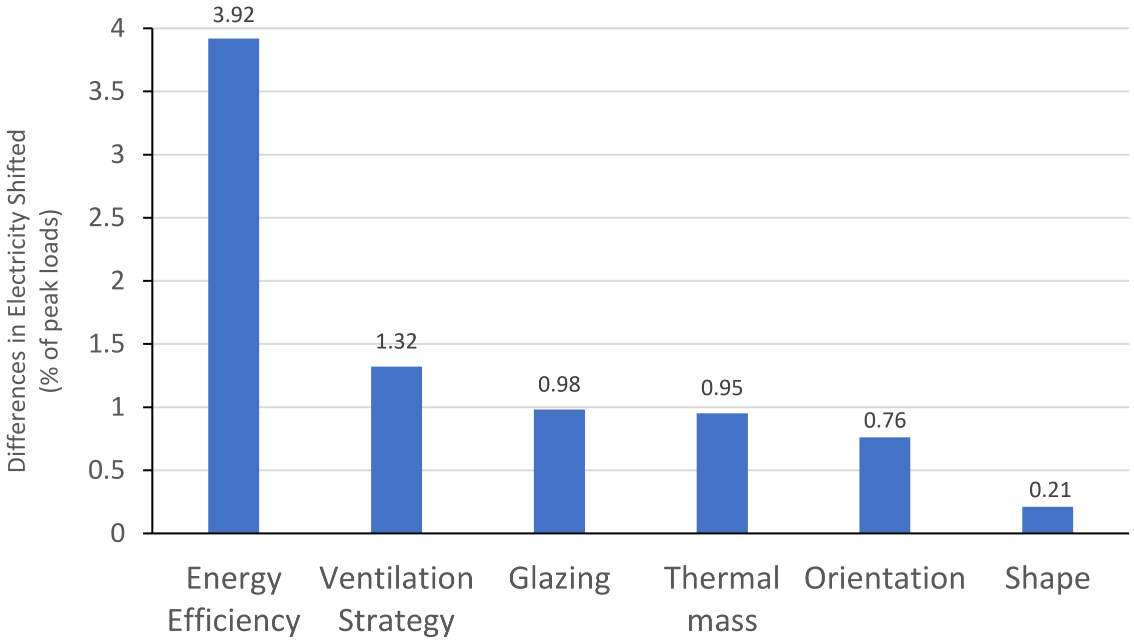

Figure 8.2 - Impact of Building Design Elements on Arbitrage Performance for Operational Strategy E0 (220 kWh BSS). Values refer to the mean of the absolute differences

For example, the fabric's energy efficiency constitutes the most important design characteristic as switching from Best Practice to Part L results into 3.92% less shifting of the peak loads, on average.

i. Best Practice over Part L compliant (Fabric's energy efficiency)
ii. Mechanically-ventilated over naturally-ventilated (Ventilation Strategy)
iii. 80% glazing over 30% glazing (Window-to-Wall ratio)
iv. Lightweight over heavyweight (Thermal mass)
v. Southern orientation over SW/SE/E orientation
vi. Rectangular over Square (Shape)

Building LwBP80 (7r) combines all the desired characteristics as it is a mechanically-ventilated, rectangular, lightweight, 80% glazed building with southern orientation. When exports are not allowed under E0, it is able to shift 39.70% of its peak loads (2nd best performance out of 56 buildings) with an annual electricity net cost of 6.26 £/m^2 (2nd out of 56). In contrast, under the no storage scenario, the respective electricity net cost value is 7.07£/m^2. It should be pointed out that for this particular building scenario, when switching the building's thermal mass to heavyweight, results are almost identical as Building HwBP80 (5r) can shift 39.68% of its peak loads (3rd out of 56) with an electricity annual net cost of 6.20 £/m^2 (1st out of 56); therefore, Building HwBP80 proves to be slightly more economical.

When exports are allowed to take place under Operational Strategy E7, Building HwBP80 (5r) can shift 31.76% of its peak loads and export 18.08 kWh/m^2 while the electricity net cost is now 7.19 £/m^2 (1st out of 56). Building LwBP80 (7r) follows second with a net cost of 7.25 £/m^2.

C) *Conduct a CBA to assess economically the cost-effectiveness of the suggested scheme, considering both current and future capital costs, and suggest a financial mechanism to reward buildings for their participation into the scheme.*

A CBA was conducted for a 240 kWh BSS (80 kW rectifier, 60 kW inverter) for a final selection of 8 buildings for both 10-year and 20-year periods. Due to the capital costs of the BSS, the NPC values of all scenarios are higher than their respective cases without storage. To eliminate the difference between the NPCs, a financial reward was suggested as a motive for a building to participate in an arbitrage scheme, as shown in Equation 8.1.

$$\text{Financial Reward (£/kWh shifted)} = \frac{\text{NPC\_with\_storage} - \text{NPC\_without\_storage}}{\text{Total Electricity Shifted}} \qquad (8.1)$$

For a 10-year period, Operational Strategy E0 incurs the lowest NPC with a range of £234k – 275k and an average LCOE of 17.06p with the required financial motive being 16.66p/kWh shifted. When exports take place, the NPC increases and varies between £255k – 294k with a respective average LCOE of 14.13p, resulting in a raised financial motive with a mean value of 22.84p per kWh shifted. As the NPC values increase under Strategy E7, the additional revenues earned from electricity exports are not deemed to be sufficient to make the strategy more cost-effective. However, buildings opting to participate in exports under E7 are rewarded with a higher financial motive for providing the service to the grid. this For a conducted case study published in [9], increasing the investigated lifetime from 10 to 20 years, the required financial reward is reduced by 2p/kWh shifted, for all operational strategies.

Furthermore, for all strategies, including the no storage case, the best performing building (5r/HwBP80) is £35 – 42k cheaper than the worst performing building (2rN/HwPL30*). Finally, when the battery cost is assumed to decrease by 45% and for Operational Strategy E7, the financial motive is reduced from its original range of 21.86p – 24.70p to 11.83p – 13.72p. For Strategy E0, the original range of 16.37p – 17.34p is also reduced significantly to 7.16p – 7.73p. These ranges are similar to the 2015 Ofgem FIT provided for photovoltaic installations which were later reduced and eventually phased out [257], [258].

The suggested financial reward is of fundamental importance to make the arbitrage scheme attractive to buildings. In terms of policy, it is recommended that only buildings that follow the recommended design parameters, shown above in Objective B, should receive this incentive. If this is not the case, they should be retrofitted before being allowed to participate in the arbitrage scheme and consequently have access to the financial reward and the additional revenue stream from exports. Exceptions should be made in certain scenarios where specific design elements do not result in significant arbitrage performance differences; these scenarios should be examined on a case-by-case basis.

The benefits of a single modelled building, with a total floor area of 2,500 m^2, participating in arbitrage by using its BSS is tiny. However, assuming that several non-domestic buildings of suitable design characteristics take part, the benefits could be significant for the grid. For example, taking into account the design and loads of Building HwBP80/5r and using the 220 kWh BSS (45 kW/-65 kW) for Operational Strategy E0, an average power reduction of 36.53 kW is observed when the battery is discharged. Assuming that approximately 71,000 identical buildings participate in the arbitrage scheme, their combined power reduction reaches 2.595 GW which constitutes the total power capacity of the Drax Power Station [259]. Considering the 2008 UK data for office buildings [260], 50% of the total floor area of office buildings in England and Wales are required to take part in the BSS arbitrage scheme in order for the Drax Power Station not to be needed to operate at all, during the hours of the battery operation. It should be noted that current data are expected to include a higher number of buildings and floor area while the figures do not include office buildings located in Scotland. Also, by 2050, the UK's non-domestic floor area is expected to grow by 28% with 60% of the existing building stock still being in use [261]; therefore, the actual percentage of the total floor area of office buildings required might be less than 50%.

Therefore, the aggregated effect of buildings taking part in the suggested arbitrage schemes can be considerable and depends on the number as well as the location of the participating buildings. This could potentially change the way that buildings are conceptualised and designed in the near future as, instead of the modern norms, energy performance and carbon targets, their interaction with the grid could be prioritised; buildings meeting certain combined design and arbitrage standards could be characterised as SGOB-ready or arbitrage-ready.

8.3 Limitations of the Study

Currently, there is no mechanism enabling a building to use a BSS in order to provide services to the grid such as arbitrage, peak-shaving, load-leveling and others. Taking into account the uncertainty around the ownership and operation of energy storage in the UK and Europe, the development of a proper regulatory framework is of fundamental importance. Undoubtedly, the associated capital costs of a BSS are high; however, battery prices have been declining. Therefore, there is considerable potential for buildings to use BSS to engage in bidirectional exchanges of power, responding to notifications issued by the grid operator, as suggested for SGOBs. This could eventually transform buildings from passive elements to protagonists of the grid.

Additionally, for the current research, RTP electricity data for the calendar years 2017 and 2018 were used as an input of the arbitrage model. Due to their dynamic nature and dependence on several factors, a huge increase was observed for both the wholesale and retail electricity markets due to the 2021 – 2023 global energy crisis. The mean values for the day-ahead wholesale monthly electricity prices for the NordPool UK market can be seen below, in Figure 8.3 for the period 2017 – 2023. While the overall average prices remained relatively low for the first four years of the time period in question, between 35 – 57 £/MWh, huge consecutive increases took place in the following years and the post-covid era with the prices reaching, on average, 117 and 204 £/MWh for 2021 and 2022, respectively.

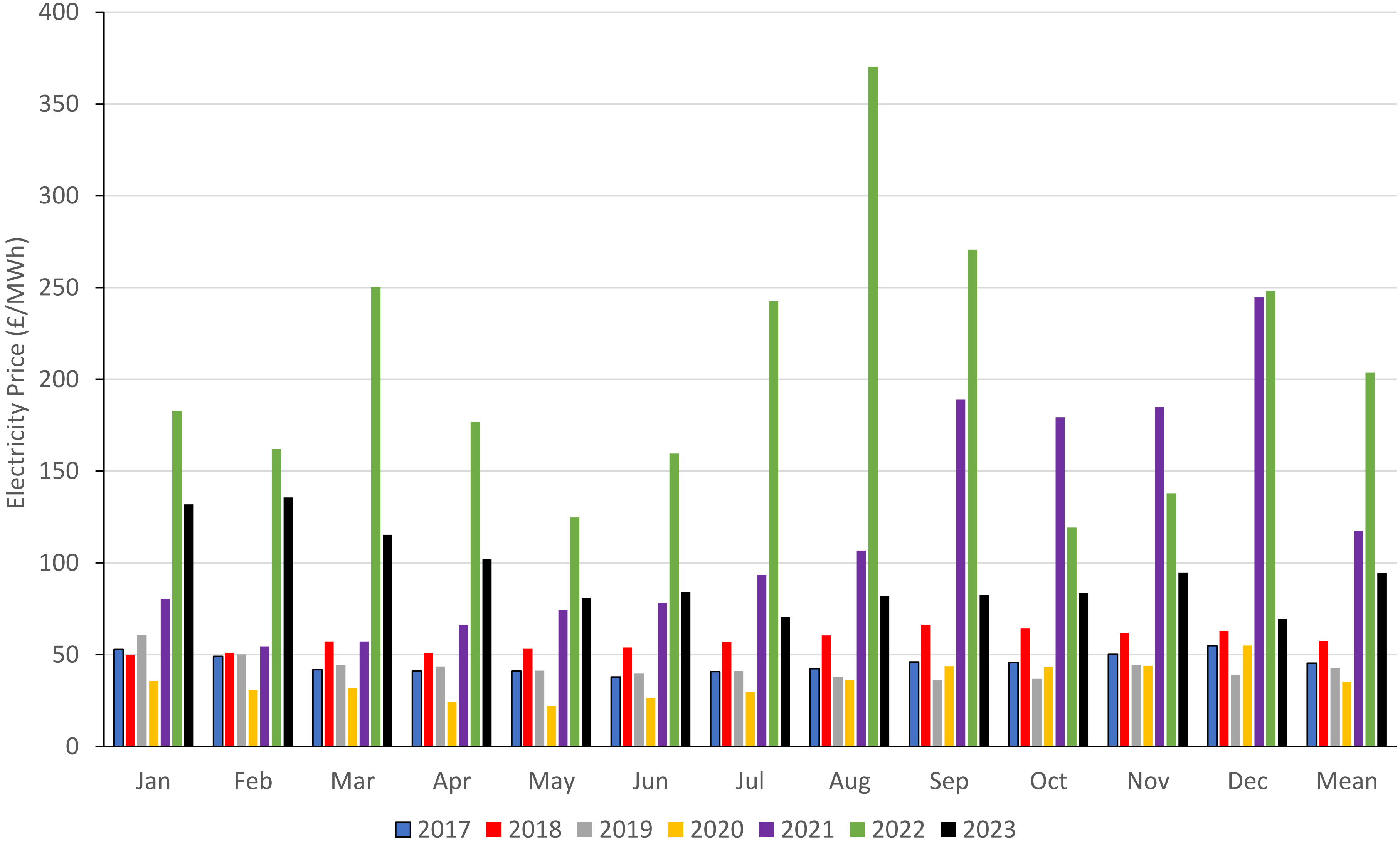

Figure 8.3 – Day-ahead wholesale electricity prices for the UK market between 2017 – 2023 [262]

While it is normal for seasonal and monthly variations to happen every year, the price range was 54 – 245 £/MWh for 2021 and further increased to 119 – 370 £/MWh for 2022, significantly broader than previous years. On the other hand, an important decrease took place in 2023 bringing the average price down to 95 £/MWh; nevertheless, the prices are still considered high when compared to the pre-2021 levels. As electricity prices constitute necessary and input data of critical importance for the arbitrage model, it is essential to consider the impact of the recent energy crisis on the key points made in the current thesis.

Compared to the 2017 – 2018 RTP data that have been used in this research, 2022 RTP data are more volatile and it is likely that the daily difference between the lowest and the highest prices are significantly higher, presenting considerable potential for more cost-effective arbitrage utilisation. Therefore, for the 2022 prices, there is no doubt that all NPC and LCOE values, with and without storage, would be significantly greater for all building scenarios.

Using the 2022 RTP data and regarding the financial reward for participating buildings, the amount of exports and shifted electricity are approximately the same and the arbitrage potential is higher than in 2017. Therefore, the difference between the two NPC values (with and without storage) is expected to be reduced and be smaller than the 2017 respective value, decreasing in this way the financial motive for all Operational Strategies. Due to the substantial amount of exports that take place during the weekends, it would be reasonable to assume that the NPC values for Operational Strategy E7 could approach the respective E0 values, up to a certain extent; however, it is not possible to quantify their difference with the current data.

In addition, the hierarchy of the building design elements on the buildings' arbitrage performance (Figure 8.2) is expected to remain the same but it is difficult to speculate how the individual percentage differences (% of peak loads shifted) would change. Undoubtedly, further modelling needs to be conducted using the hourly RTP data for the year(s) in question to reach safe and solid conclusions. Currently, it is no longer possible to publicly access hourly NordPool market data for an entire year as a new data portal is expected to be launched in the near future, requiring registration and a paid subscription [263]. Summing up, it is likely that energy crises and other events that lead to an increase of the volatility, unpredictability and variation of electricity prices could increase the potential of energy storage as a technology and make the utilisation of BSS in buildings for arbitrage more cost-effective.

Concerning other limitations of the study, the arbitrage model assumes that building loads are known in advance, assuming a perfect prediction of the required grid purchases. While this can be possible for certain types of non-domestic buildings where standard equipment is used during specific working hours and days, it does not always constitute a realistic assumption, especially during extreme weather conditions that can increase the electricity consumption for heating and cooling, significantly.

Finally, as there is a difference between the buildings' predicted energy consumption and their actual performance [264], the performance gap is a well-known phenomenon that needs to be taken into account due to the simulated nature of the buildings' electricity consumption, in the current research.

8.4 Recommendations for further work

As mentioned in Chapter 8.3, it is recommended that the arbitrage model is used with the newest RTP electricity data, specifically for 2021 – 2023, to investigate the impact of the ongoing global energy crisis to the model output and especially the CBA components, such as the financial motive and the NPC values. While the financial motive that was suggested is a step in the right direction, the NPC differences between storage and no storage scenario can be similar for several buildings; therefore, it is also recommended that additional financial rewards are proposed based on the percentage of the peak loads shifted which might constitute a more suitable financial mechanism, particularly for comparison purposes between different building cases.

Apart from the NordPool day-ahead UK power exchange market that was utilised, it would be beneficial to make use of the half-hourly intraday auction market to investigate which market type is more suitable and cost-effective for arbitrage in buildings. This would require running new building simulations and half-hourly electricity output to match the RTP data.

Four UK locations have been examined in detail in the current thesis. It would be recommended to investigate the viability of the proposed arbitrage scheme outside the UK, explore and compare its potential among other European countries with different climates (e.g., Norway, France). New building simulations with the respective weather data as well as NordPool's day-ahead RTP data for the locations in question will be required. This will allow to understand if certain countries are more appropriate to host such an initiative for buildings than others.

In addition, while an extensive number of building scenarios were included in this project, it is worth noting that further work can be done by considering more options for certain design categories. For example, the window-to-wall ratio could be extended to include additional values, other than 30% and 80%, thermal mass variations would be useful while different HVAC configurations would be advantageous: mechanical ventilation with heat recovery, mixed ventilation, air-source heat pumps for heating and cooling, electric radiators for heating, chillers for cooling.

Finally, conducting a field study would be beneficial in determining the benefits of an arbitrage scheme provided by batteries in buildings with the results being of fundamental importance towards devising an appropriate SGOB policy for buildings to be rewarded for their participation into the scheme.

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Appendix A – Building Models & Simulation Data

Table A1 – Geometry characteristics considered for the Building Simulations

Parameter	**Value**
Number of storeys	4 including the ground floor
Number of Zones	Zone 1: Open-plan office area Zone 2: Lift/lobby/stairwell area
Floor area	2,356 m^2 for Zone 1 144 m^2 for Zone 2
Zone 1 Dimensions	25 m x 25 m (Square) 52 m x 12.02 m (Rectangular)
Zone 2 Dimensions	6 m x 6 m (Square) 12.48 m x 2.89 m (Rectangular)
Storey height	3.5 m
Building Volume	8,750 m^3
Roof	Flat

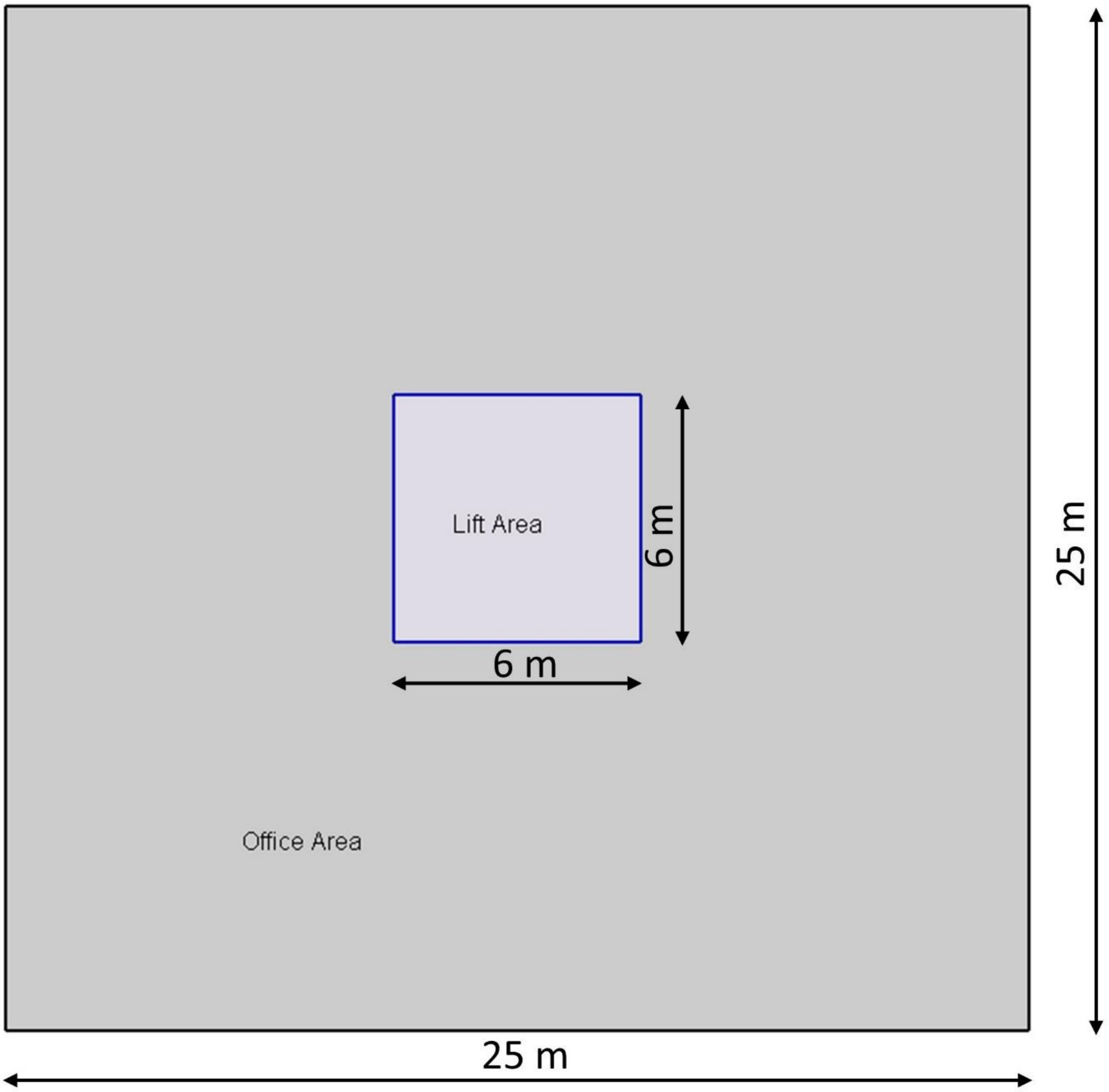


Figure A1 – Floor plan for the Square Building

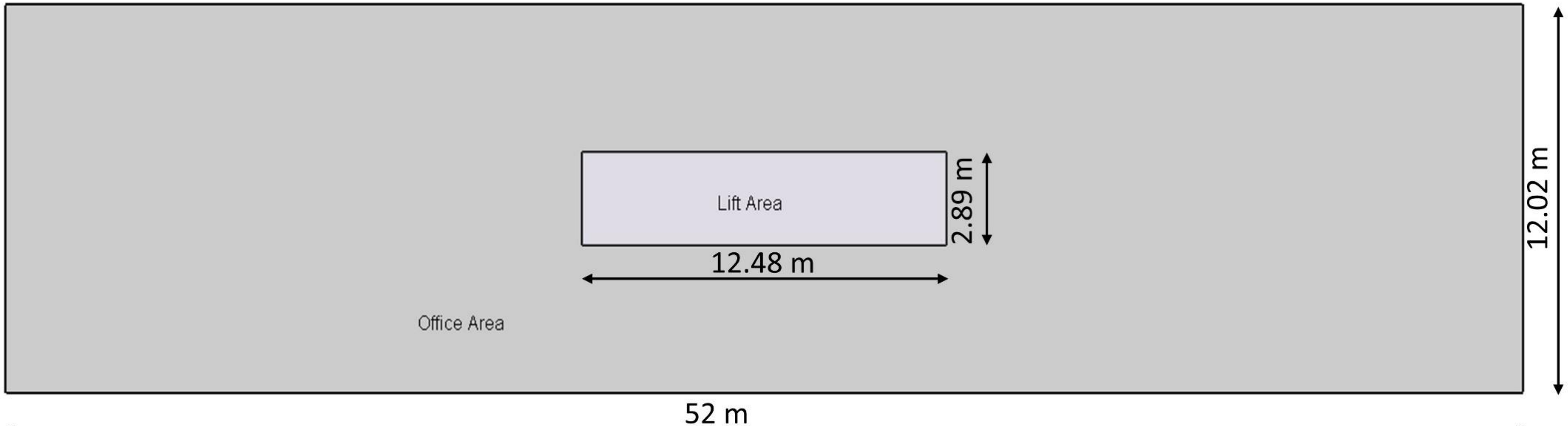


Figure A2 – Floor Plan for the Rectangular Building

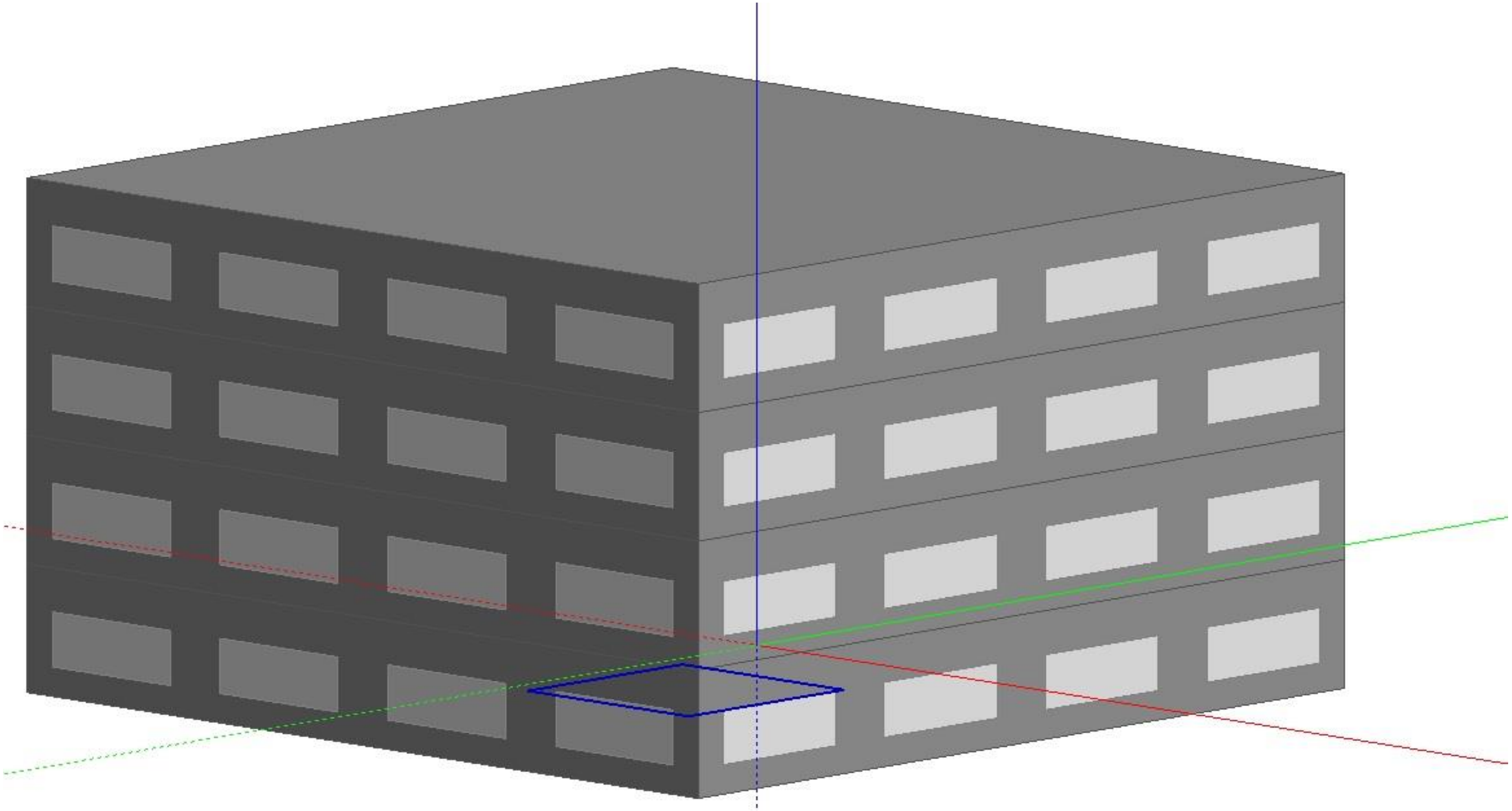


Figure A3 – Square Building model in DesignBuilder's Graphical User Interface (GUI)

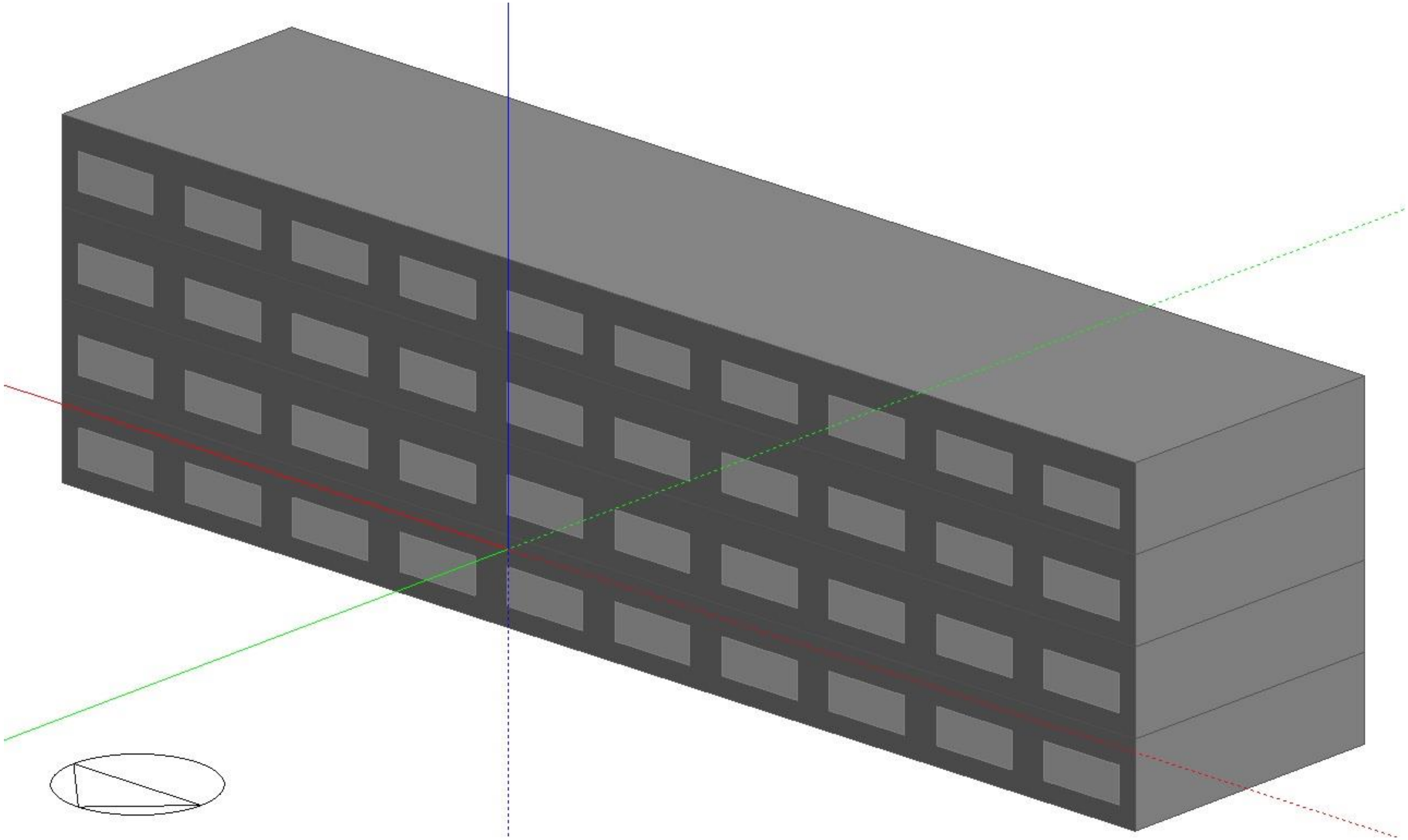


Figure A4 - Rectangular Building model in DesignBuilder's GUI

Table A2 - Summary of concurrent notional building specifications for buildings other than dwellings (L2A). Best Practice Buildings are based on their characteristics [1]

Element	Unit	Side lit or unlit (HVAC is heating only)	Side lit or unlit (HVAC includes cooling)	Top lit
Roof U-value	W/(m^{2}K)	0.18		
Wall U-value	W/(m^{2}K)	0.26		
Floor U-value	W/(m^{2}K)	0.22		
Window U-value	W/(m^{2}K)	1.6	1.6	N/A
Window G-value	%	40	40	N/A
Window light transmittance	%	71	71	N/A
Roof-light U-value	W/(m^{2}K)	N/A	N/A	1.8
Roof-light G-value	%	N/A	N/A	55
Roof-light light transmittance	%	N/A	N/A	60
Air permeability Gross internal area less than or equal to 250 m^2	m^3/(m^{2}h)	5	5	7
Air permeability Gross internal area greater than 250 m^2 and less than 3500 m^2	m^3/(m^{2}h)	3	3	7
Air permeability Gross internal area greater than 3,500 m^2 and less than 10,000 m^2	m^3/(m^{2}h)	3	3	5
Air permeability Gross internal area greater than or equal to 10,000 m^2	m^3/(m^{2}h)	3	3	3
Lighting luminaire	lm/circuit watt	60		
Occupancy Control	Yes or No	Yes		
Daylight control	Yes or No	Yes		
Maintenance factor	N/A	0.8		
Constant illuminance control	Yes or No	No		
Heating efficiency	%	91		
Central Ventilation SFP	W/(l· s)	1.8		
Terminal unit SFP	W/(l· s)	0.3		
Cooling - air conditioned (SEER/SSEER)	N/A	N/A	4.5 / 3.6	4.5 / 3.6
Cooling - mixed mode (SSEER)	N/A	N/A	2.7	2.7
Heat recovery efficiency	%	70		
Variable speed control of fans & pumps	Yes or No	Yes		
Demand control (mech. vent. only). Variable speed control of fans via CO_2 sensors.	Yes or No	Yes		

Table A3 – Fabric parameters for new buildings according to Part L Regulations. Part L Compliant Buildings are based on the L2A characteristics [1], [2], [3]

Fabric Element	**Value** (units in W/m^{2}K unless stated otherwise)			
	Limiting values for New Dwellings (L1A)	**Notional Dwelling Specifications (L1A)**	**Limiting values for new buildings other than dwellings (L2A)**	**Values for new thermal elements in existing buildings (L1B, L2B)**
Roof	0.20	0.13	0.25	0.16 or 0.18
Wall	0.30	0.18	0.35	0.28
Floor	0.25	0.13	0.25	0.22
Party wall	0.20	0	N/A	N/A
Swimming pool basin	0.25	N/A	0.25	0.25
Windows, roof windows, roof-lights, curtain walling and pedestrian doors	2	1.4 for windows and glazed elements g-value = 0.63	2.2	N/A
Opaque doors	N/A	1	N/A	
Semi-glazed doors	N/A	1.2	N/A	
Vehicle access and similar large doors	N/A	N/A	1.5	
High-usage entrance doors	N/A	N/A	3.5	
Roof ventilators	N/A	N/A	3.5	
Air permeability	10 m^3/(m^{2}hour)	5 m^3/(m^{2}hour)	10 m^3/(m^{2}hour)	

Table A4 – Construction elements for the Heavyweight Best Practice Building

Element(s)	**Layer No**	**Layer Material (outer to inner for walls & roofs, inner to outer for floors)**	**Layer Thickness (mm)**	**Element U-Value (W/ (m^2· K)**	**Element k-value (kJ/m^{2}K)**
External Wall	1	Brickwork outer	105	0.26	134.8
	2	XPS Extruded Polysterene	113		
	3	Concrete Block	100		
	4	Gypsum Plastering	13		
Flat Roof	1	Asphalt	190	0.18	4.9
	2	Fibreboard	130		
	3	XPS Extruded Polystyrene	101		
Internal floor	1	Cast concrete (dense)	300	2.065	176.4
Ground floor	1	Timber flooring	30	0.22	93.96
	2	Floor screed	70		
	3	Cast concrete	100		
	4	Urea Formaldehyde Foam	154.80		
Internal partition	1	Gypsum plastering	13	1.959	131.32
	2	Brickwork, inner leaf	115		
	3	Gypsum plastering	13		

Table A5 – Construction elements for the Heavyweight Part L Building

Element(s)	Layer No	Layer Material (outer to inner for walls & roofs, inner to outer for floors)	Layer Thickness (mm)	Element U-Value (W/ (m^2· K)	Element k-value (kJ/m^{2}K)
External Wall	1	Brickwork outer	100	0.35	134.8
	2	XPS Extruded Polystyrene	79.60		
	3	Concrete Block	100		
	4	Gypsum Plastering	13		
Flat Roof	1	Asphalt	190	0.25	N/A
	2	Fibreboard	130		
	3	XPS Extruded Polystyrene	48.50		
Internal floor	1	Cast concrete (dense)	300	2.065	176.4
Ground floor	1	Timber flooring	30	0.25	93.96
	2	Floor screed	70		
	3	Cast concrete	100		
	4	Urea Formaldehyde Foam	132.70		
Internal partition	1	Gypsum plastering	13	1.959	131.32
	2	Brickwork, inner leaf	115		
	3	Gypsum plastering	13		

Table A6 – Construction elements for the Lightweight Best Practice Building

Element(s)	Layer No	Layer Material (outer to inner for walls & roofs, inner to outer for floors)	Layer Thickness (mm)	Element U-Value (W/ (m^2· K)	Element k-value (kJ/m^{2}K)
External Wall	1	Lightweight metallic cladding	6	0.26	17.263
	2	XPS Extruded Polystyrene	123		
	3	Gypsum Plastering	13		
Flat Roof	1	Asphalt	10	0.18	32.6144
	2	Glass wool (rolls)	207		
	3	Air gap (cavity)	200		
	4	Plasterboard	13		
Internal floor	1	Cast concrete	100	2.929	88.20
Ground floor	1	Timber flooring	30	0.22	93.96
	2	Floor screed	70		
	3	Cast concrete	100		
	4	Urea Formaldehyde Foam	154.80		
Internal partition	1	Gypsum plastering	25	1.639	22.50
	2	Air gap (cavity)	100		
	3	Gypsum plastering	25		

Table A7 – Construction elements for the Lightweight Part L Building

Element(s)	**Layer No**	**Layer Material (outer to inner for walls & roofs, inner to outer for floors)**	**Layer Thickness (mm)**	**Element U-Value (W/ (m²· K)**	**Element k-value (kJ/m²K)**
External Wall	1	Lightweight metallic cladding	6	0.35	15.963
	2	XPS Extruded Polysterene	89		
	3	Gypsum Plastering	13		
Flat Roof	1	Asphalt	10	0.25	32.6144
	2	Glass wool (rolls)	144.50		
	3	Air gap (cavity)	200		
	4	Plasterboard	13		
Internal floor	1	Cast concrete	100	2.929	88.20
Ground floor	1	Timber flooring	30	0.25	93.96
	2	Floor screed	70		
	3	Cast concrete	100		
	4	Urea Formaldehyde Foam	132.70		
Internal partition	1	Gypsum plastering	25	1.639	22.50
	2	Air gap (cavity)	100		
	3	Gypsum plastering	25		

Figure A5 – External Wall construction and materials for (a) Heavyweight – Best Practice, (b) Heavyweight – Part L, (c) Lightweight – Best Practice and (d) Lightweight - Part L Building models. The layer thicknesses are not to scale.

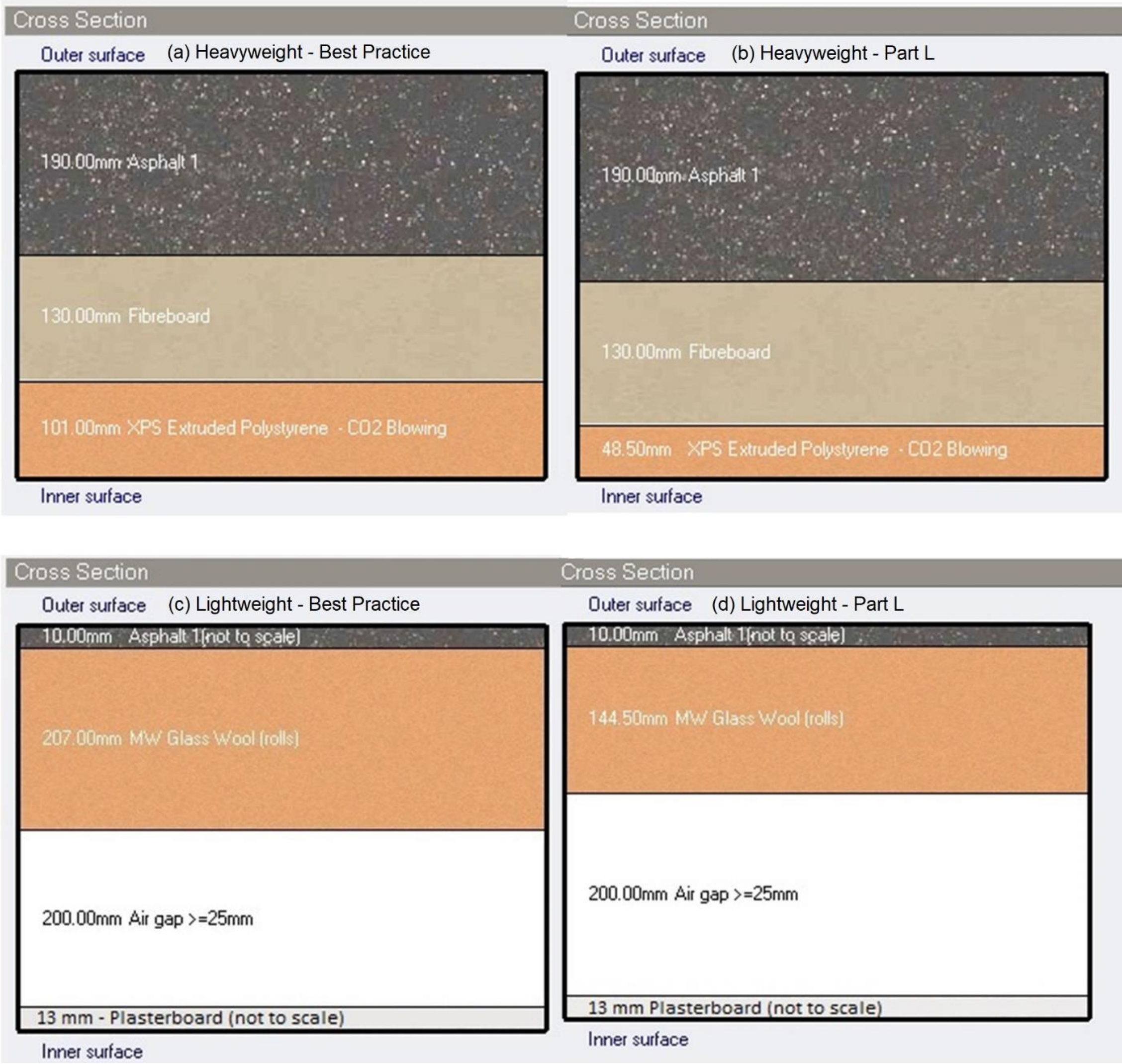


Figure A6 –Flat roof construction and materials for (a) Heavyweight – Best Practice, (b) Heavyweight – Part L, (c) Lightweight – Best Practice and (d) Lightweight - Part L Building models. The layer thicknesses are not to scale

.

Table A8 – Initial Glazing Construction parameters

Glazing Parameter	**Unit**	**Part L Compliant**		**Best Practice**	
Vertical Fenestration	%	**0 – 40%**	**60 – 80%**	**0 – 40%**	**60 – 80%**
Total solar transmission (SHGC or g-value)	%	58	28	40	23
Light transmission	%	61	49	71	39
U-value	$W/(m^2{\cdot}K)$	2.2	1.5	1.6	1.1
Shading	N/A	Blinds with high reflectivity slats. Activated when solar radiation exceeds 150 W/m^2 (solar setpoint)			
Frame and dividers	N/A	The divider elements project out from the outside and inside surfaces of the glazing and divide the glazing into individual lites. The window frame is painted wooden.			

Table A9 – Test Simulations to determine the infiltration rate of DesignBuilder's preset crack templates for mechanically-ventilated buildings

Template (All windows: SHGC=38% g= 40% Lighting 55%)	**Infiltration rate (ac/h)**		**Heating Energy Demand (kWh/m^2)**	
	Square Heavyweight Best Practice 30% Glazing (Window U-value = 1.6)	Square Lightweight Part L 80% Glazing (Window U-value = 1.5)	Square Heavyweight Best Practice 30% Glazing (Window U-value = 1.6)	Square Lightweight Part L 80% Glazing (Window U-value = 1.5)
Excellent	0 – 0.01	0 – 0.01	12.85	24.19
Good	0.01 – 0.07	0.01 – 0.06	14.14	25.30
Medium	0.07 – 0.18	0.06 – 0.16	20.79	29.89
Poor	0.25 – 0.63	0.29 – 0.67	39.41	48.48
Very Poor	0.52 – 1.31	0.41 – 1.44	72.59	84.04

Table A10 – Crack templates characteristics used for the calculation of external infiltration in mechanically-ventilated buildings

Construction Element	**Poor template**		**Medium template**		**Good template**		**Excellent template**	
	Flow coefficient	**Flow exponent**	**Flow coefficient**	**Flow exponent**	**Flow coefficient**	**Flow exponent**	**Flow coefficient**	**Flow exponent**
Window	0.001000	0.60	0.000140	0.65	0.000060	0.70	0.000010	0.70
Internal floor	0.002000	0.70	0.000900	0.70	0.000030	0.70	0.000010	0.70
Internal wall	0.005000	0.75	0.003000	0.75	0.002000	0.75	0.001000	0.75
External wall	0.000200	0.70	0.000100	0.70	0.000040	0.70	0.000010	0.70
Roof	0.000150	0.70	0.000100	0.70	0.000030	0.70	0.000010	0.70

Table A11 – Flow coefficients for external windows in Naturally Ventilated Buildings. Values may include natural ventilation for cooling purposes. The average infiltration rate refers to a test simulation conducted for Building 1rN and corresponds to Months 1-5 and 10-12 in order to avoid including additional air flows for cooling purposes that take place predominantly during the summer period. The average value is considerably close to the required 0.85 ac/h vale for fresh air supply, as shown in Equation 3.1. Other construction elements continue to have their existing values, presented in Table A2.

Cracks template	Revised Window flow coefficient	Revised Window flow exponent	Test Building's average infiltration (ac/h)
Medium (Best Practice)	0.006	0.50	0.98
Poor (Part L)	0.007	0.50	1.08

Table A12 – Building Activity and Occupancy

Parameter	Value/Characteristic
Metabolic Activity	Filing/Standing: 144 W/person
Sex Factor	Average value of 0.93 (1 for men and 0.85 for women by default)
Clothing insulation	1.0 clo for the summer period 0.5 clo for the winter period
Occupancy	12.01 m^2/person or 0.0833 people/m^2
Non-working days	Weekends 1 January, 25-26 December, 10 April. When the days above fall during weekends, the following day functions as a non-working substitute day.

All the schedules used in DesignBuilder are listed below:

```
Schedule:Compact,
1OCCUPANCY8amto6pm,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 09:00, 0.25,
Until: 10:00, 0.5,
Until: 12:00, 1,
Until: 14:00, 0.75,
Until: 15:00, 1,
Until: 17:00, 0.5,
```

```
Until: 18:00, 0.25,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Schedule:Compact,
HEATING8amto6pm,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0.5,
Until: 18:00, 1,
Until: 24:00, 0.5,
For: WinterDesignDay,
Until: 24:00, 1,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0.5;


Schedule:Compact,
1COOLING8amto6pm,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
```

```
Until: 07:00, 0.5,
Until: 18:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.5;
Schedule:Compact,
1VENTILATION8amto6pm_LIGHTWEIGHT,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 18:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Schedule:Compact,
1VENTILATION8amto6pm_HEAVY_NIGHT_COOLING_ALT,
Fraction,
Through: 31 May,
For: Weekdays,
Until: 08:00, 0,
Until: 18:00, 1,
Until: 24:00, 0,
```

```
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0,
Through: 30 Sep,
For: Weekdays,
Until: 24:00, 1,
For: Weekends,
Until: 24:00, 1,
For: Holidays SummerDesignDay,
Until: 24:00, 1,
For: AllOtherDays,
Until: 24:00, 0,
Through: 31 Dec,
For: Weekdays,
Until: 08:00, 0,
Until: 18:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Schedule:Compact,
DomesticHotWater,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
```

Until: 08:00, 0,
Until: 09:00, 0.25,
Until: 10:00, 0.5,
Until: 12:00, 1,
Until: 14:00, 0.75,
Until: 15:00, 1,
Until: 17:00, 0.5,
Until: 18:00, 0.25,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Schedule:Compact,
1LIGHTING8amto6pm,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 18:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Schedule:Compact,

EQUIPMENT8amto6pm,

Fraction,

Through: 31 Dec,

For: Weekdays SummerDesignDay,

Until: 08:00, 0.05394,

Until: 18:00, 1,

Until: 24:00, 0.05394,

For: Weekends,

Until: 24:00, 0.05394,

For: Holidays,

Until: 24:00, 0.05394,

For: WinterDesignDay AllOtherDays,

Until: 24:00, 0;

Table A13 – Location and Weather Data used for Building Energy Simulations

Parameter	**Value/Property**
Site	Birmingham Airport
Location	Solihull, West Midlands, England, United Kingdom
Latitude	52.45
Longitude	-1.73
Elevation above sea level	99 m
ASHRAE Climate Zone	5C
Exposure to wind	Normal
Time zone	Greenwich Mean Time (GMT)
Daylight Saving Time (DST)	Not observed
Weather Data File	IWEC (ASHRAE) – Birmingham Airport
Data Type	Typical Year (TRY)
Outside Design Temperature	-5.1°C
Wind Speed	12.4 m/s

Appendix A References

[1] HM Government, “The Building Regulations 2010. Conservation of fuel and power (L2A),” 2016. Accessed: May 12, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/540328/BR_PDF_AD_L2A_2013_with_2016_amendments.pdf

[2] HM Government, “The Building Regulations 2010. Conservation of fuel and power (L1A),” 2016. Accessed: May 12, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/540326/BR_PDF_AD__L1A__2013_with_2016_amendments.pdf

[3] HM Government, “The Building Regulations 2010. Conservation of fuel and power (L1B),” 2018. Accessed: May 10, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/697629/L1B_secure-1.pdf

Appendix B – Real Time Pricing Electricity Data

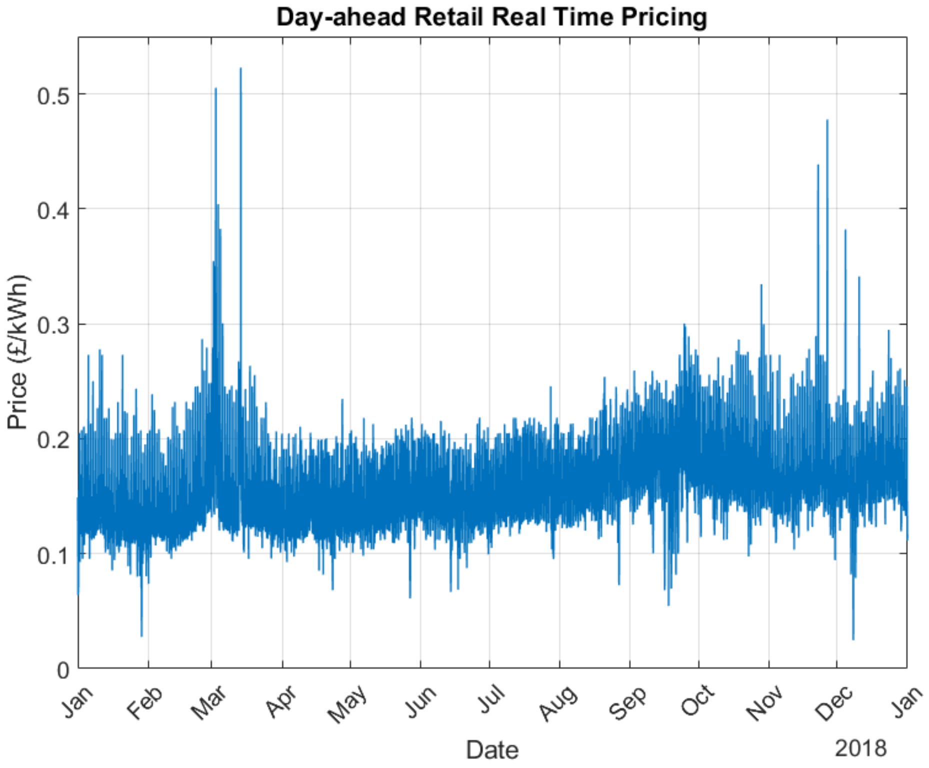


Figure B1 - Synthetic real-time retail electricity prices based on the NordPool 2018 day-ahead data. The wholesale percentage is assumed constant throughout the year at 36.63%.

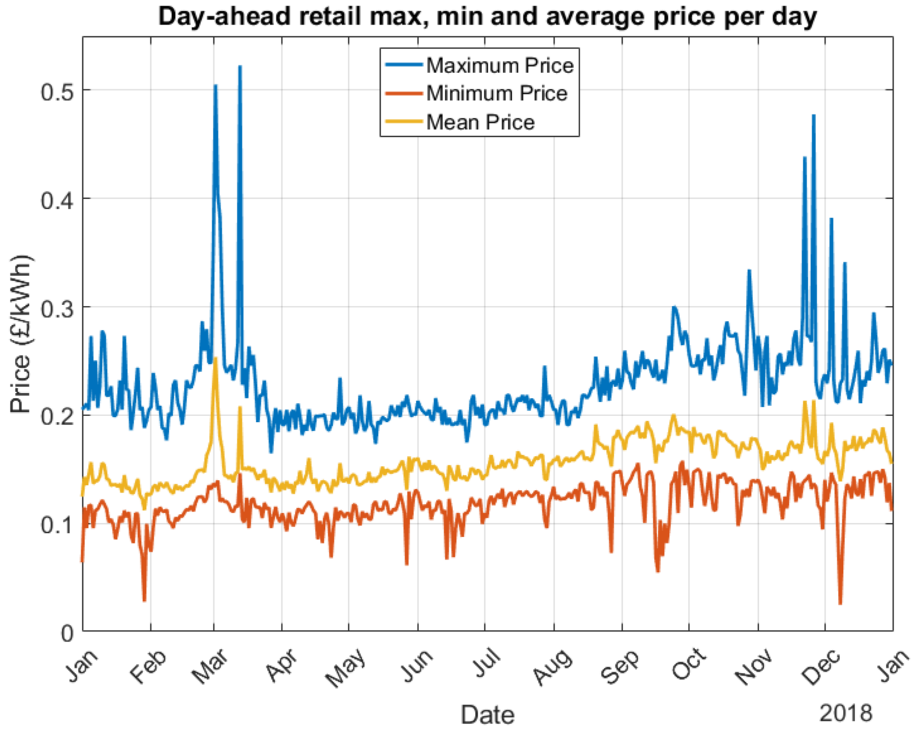


Figure B2 - Minimum, maximum and average daily values for the synthetic real-time retail electricity prices based on the NordPool 2018 day-ahead data

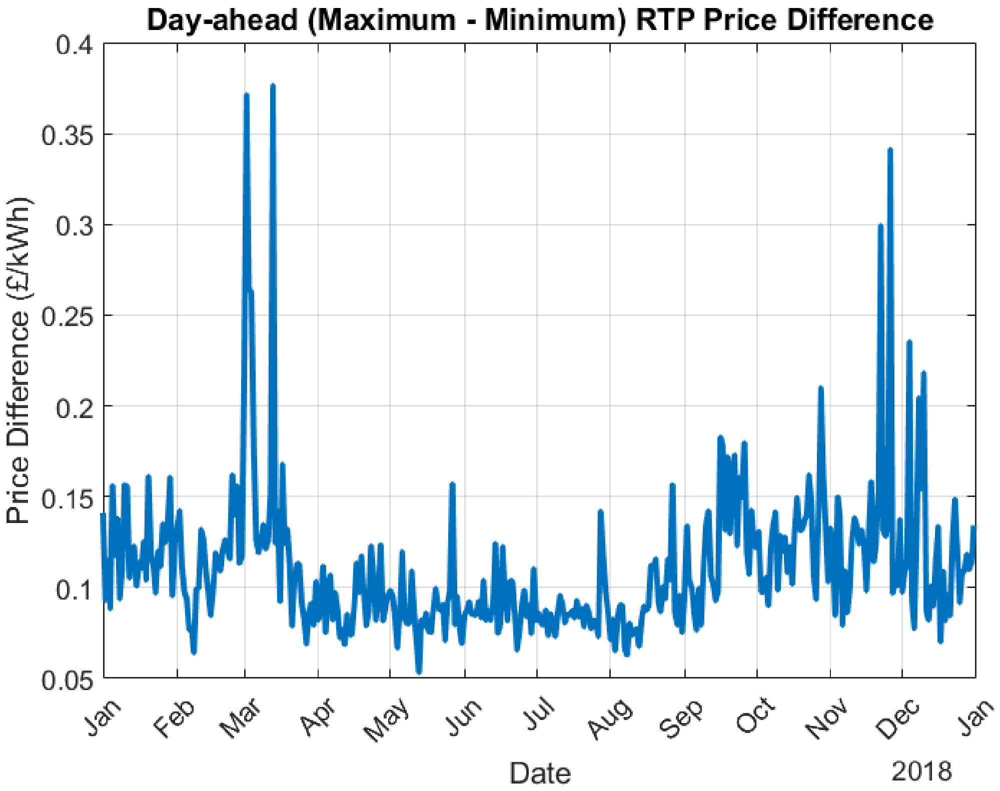


Figure B3 - Minimum, maximum and average daily values for the synthetic real-time retail electricity prices based on the NordPool 2018 day-ahead data

Appendix C – Investigated Building Scenarios

Table C1 – Scenarios for Square Buildings

Case	Scenario ID	Thermal Mass	Insulation	Orientation	Glazing	VAC
1s	Sq-HwBP30	Heavyweight	Best practice	South	30%	Mechanical Ventilation + Cooling (includes free cooling).
2s	Sq-HwPL30	Heavyweight	Part L	South	30%	
3s	Sq-LwBP30	Lightweight	Best practice	South	30%	
4s	Sq-LwPL30	Lightweight	Part L	South	30%	
5s	Sq-HwBP80	Heavyweight	Best practice	South	80%	
6s	Sq-HwPL80	Heavyweight	Part L	South	80%	
7s	Sq-LwBP80	Lightweight	Best practice	South	80%	
8s	Sq-LwPL80	Lightweight	Part L	South	80%	

Table C2 – Scenarios for Rectangular Buildings (Mechanically Ventilated)

Case	Scenario ID	Thermal Mass	Insulation	Orientation	Glazing	VAC
1r	HwBP30	Heavyweight	Best Practice	South	30%	Mechanical Ventilation + Cooling (includes free cooling).
2r	HwPL30	Heavyweight	Part L	South	30%	
3r	LwBP30	Lightweight	Best Practice	South	30%	
4r	LwPL30	Lightweight	Part L	South	30%	
5r	HwBP80	Heavyweight	Best Practice	South	80%	
6r	HwPL80	Heavyweight	Part L	South	80%	
7r	LwBP80	Lightweight	Best Practice	South	80%	
8r	LwPL80	Lightweight	Part L	South	80%	
9r	HwBP30-SW	Heavyweight	Best Practice	South-West	30%	
10r	HwPL30-SW	Heavyweight	Part L	South-West	30%	
11r	LwBP30-SW	Lightweight	Best Practice	South-West	30%	
12r	LwPL30-SW	Lightweight	Part L	South-West	30%	
13r	HwBP80-SW	Heavyweight	Best Practice	South-West	80%	
14r	HwPL80-SW	Heavyweight	Part L	South-West	80%	
15r	LwBP80-SW	Lightweight	Best Practice	South-West	80%	
16r	LwPL80-SW	Lightweight	Part L	South-West	80%	
17r	HwBP30-SE	Heavyweight	Best Practice	South-East	30%	
18r	HwPL30-SE	Heavyweight	Part L	South-East	30%	
19r	LwBP30-SE	Lightweight	Best Practice	South-East	30%	
20r	LwPL30-SE	Lightweight	Part L	South-East	30%	
21r	HwBP80-SE	Heavyweight	Best Practice	South-East	80%	
22r	HwPL80-SE	Heavyweight	Part L	South-East	80%	
23r	LwBP80-SE	Lightweight	Best Practice	South-East	80%	
24r	LwPL80-SE	Lightweight	Part L	South-East	80%	
25r	HwBP30-E	Heavyweight	Best Practice	East	30%	
26r	HwPL30-E	Heavyweight	Part L	East	30%	
27r	LwBP30-E	Lightweight	Best Practice	East	30%	
28r	LwPL30-E	Lightweight	Part L	East	30%	
29r	HwBP80-E	Heavyweight	Best Practice	East	80%	
30r	HwPL80-E	Heavyweight	Part L	East	80%	
31r	LwBP80-E	Lightweight	Best Practice	East	80%	
32r	LwPL80-E	Lightweight	Part L	East	80%	

Table C3 – Scenarios for Naturally Ventilated Buildings

Case	Scenario ID	Thermal Mass	Insulation	Orientation	Glazing	VAC
1rN	HwBP30*	Heavyweight	Best Practice	South	30%	Natural Ventilation
2rN	HwPL30*	Heavyweight	Part L	South		
3rN	LwBP30*	Lightweight	Best Practice	South		
4rN	LwPL30*	Lightweight	Part L	South		
9rN	HwBP30-SW*	Heavyweight	Best Practice	South-West		
10rN	HwPL30-SW*	Heavyweight	Part L	South-West		
11rN	LwBP30-SW*	Lightweight	Best Practice	South-West		
12rN	LwPL30-SW*	Lightweight	Part L	South-West		
17rN	HwBP30-SE*	Heavyweight	Best Practice	South-East		
18rN	HwPL30-SE*	Heavyweight	Part L	South-East		
19rN	LwBP30-SE*	Lightweight	Best Practice	South-East		
20rN	LwPL30-SE*	Lightweight	Part L	South-East		
25rN	HwBP30-E*	Heavyweight	Best Practice	East		
26rN	HwPL30-E*	Heavyweight	Part L	East		
27rN	LwBP30-E*	Lightweight	Best Practice	East		
28rN	LwPL30-E*	Lightweight	Part L	East		

The following rules apply to the Case ID and respective scenario ID of each building to identify its design characteristics:

- Odd numbers refer to a Best Practice energy efficiency regarding the building’s fabric.
- Even numbers refer to a Part L compliant energy efficiency regarding the building’s fabric.
- Orientation changes per 8 building cases. For example, Buildings 1r-8r have a southern-northern orientation while Buildings 9r-16r have a southern-western orientation.
- The first 4 buildings of each orientation are 30% glazed (e.g. 1r-4r) while the following four are 80% glazed (e.g. 5r-8r).
- The letter ‘s’ indicates a square shape
- The letter ‘r’ indicates a rectangular shape
- The letter ‘N’ at the end of the Case ID indicates a building with natural ventilation. If this is not the case, then no letter is present at the end of the Case ID and mechanical ventilation is used instead.

Table C4 – BSS Sizing scenarios for Initial Simulations

Battery Size (kWh)	Inverter & Rectifier Rated Power (kW/-kW)
40	15 / -20
60	20 / -30
80	30 / -40
100	35 / -45
120	40 / -55
140	45 / -65
160	45 / -65
180	45 / -65
200	45 / -65
220	45 / -65

Table C5 – BSS Sizing Scenarios for the CBA

Battery Size	Rectifier (kW)	Inverter (- kW)
120	40	- 40
120	40	- 60
120	40	- 80
240	80	- 40
240	80	- 60
240	80	- 80
240	80	- 100
240	80	- 120

Appendix D – Code and Validation of the MATLAB Arbitrage model

The MATLAB files and the RTP electricity data of this research are accessible on the cloud: bit.ly/arbitE7E5E0

The three MATLAB scripts are publicly accessible on https://github.com/andreasgrk/phdcode

Daylight Saving Time (DST) and building load issues

After a typical working profile was set in DesignBuilder for the commercial building (8am – 6pm), inconsistencies were observed regarding its energy profile throughout the day. More specifically, after a specific date, the last working hour of the building occur one hour earlier i.e. 5pm instead of 6pm. At first, for the reason of this deviation, the activity profiles set on DesignBuilder were considered. However, this explanation was later discarded as all the schedules (occupation, heating, cooling, lighting & equipment) were found to be consistent. In Figure D1, the building's energy profile can be seen for the dates 24 – 27 March 2017 and on the 27th of March, there is a change on the building's operation and its energy consumption, for the first time. The building loads reach their minimum value, equal to the constant parasitic (auxiliary) loads, one hour earlier than normal.

However, this phenomenon can be explained as the Daylight Saving time (DST) started on the 26th of March and clocks were turned forward one hour. It should be noted that the United Kingdom observes DST from March until October and during that period the time zone is called British Summer Time (BST). For the rest of the year, the UK is on Greenwich Mean Time (GMT). By checking the DesignBuilder Location Settings, it was discovered that DST is enabled by default (Figure D2) and that DesignBuilder takes into account DST but at the same time, the timestamps are not corrected. By disabling DST from the options, the energy profile remains constant and no loads are shifted one hour earlier, as illustrated in Figure D3. As 25 – 26 March 2017 is a weekend and the respective loads are insignificant, that portion of the graph was removed to make it more presentable.

In order to guarantee a consistent energy profile and building operation, DesignBuilder and the consequent MATLAB calculations make the assumption that the UK does not observe DST; on the contrary, it remains on GMT for the entire year. Regarding the validity of such an assumption and its consequences for the energy consumption, the literature was examined. Verdejo et al. [1] calculated an average electricity reduction of 3.18% thanks to the application of DST time in Chile, concerning residential loads only. However, the authors mention that international experience has demonstrated that the benefits of applying DST are at least questionable as several studies have supported that DST does not induce energy improvements.

Another case study that investigated the DST effects in both the residential and commercial sectors in Jordan concluded that during the period when DST is observed, the electricity consumption was reduced by 0.2% while it was increased by 0.2% at DST removal [2]. The authors of a study, investigating the impacts of DST in Turkey, another country that already observes DST, have concluded that the optimal scenario includes continuous 30 minutes forward with single DST from April to October, that could lead to residential lighting savings of 0.7% when compared to the status quo [3]. Hill et al. [4] investigated the DST potential to reduce the energy demand in Great Britain. They supported that advancing the click by an hour in October would lead to energy savings of at least 0.4%. However, the authors recognise the fact that effects of observing DST vary depending on the geographical location and the climate of the region in question. More specifically, countries with shorter and colder days in winter will see more benefits.

In conclusion, as the advantages of using DST are debatable and questionable and the energy savings minimal, the removal of DST from the modelling process in DB and MATLAB is deemed to have an insignificant impact to the respective results.

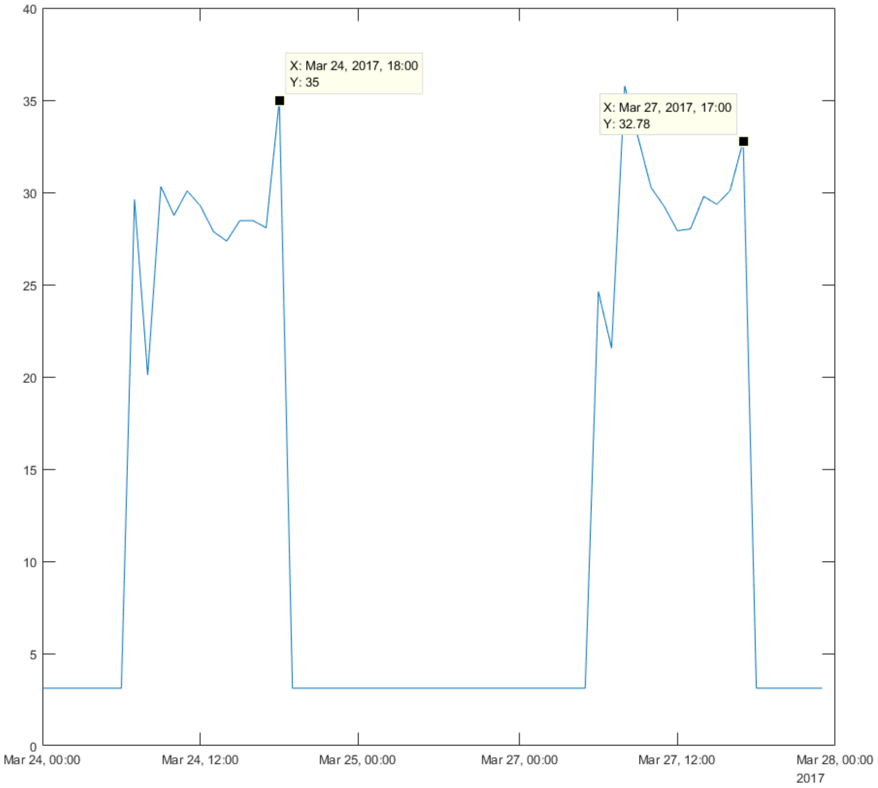
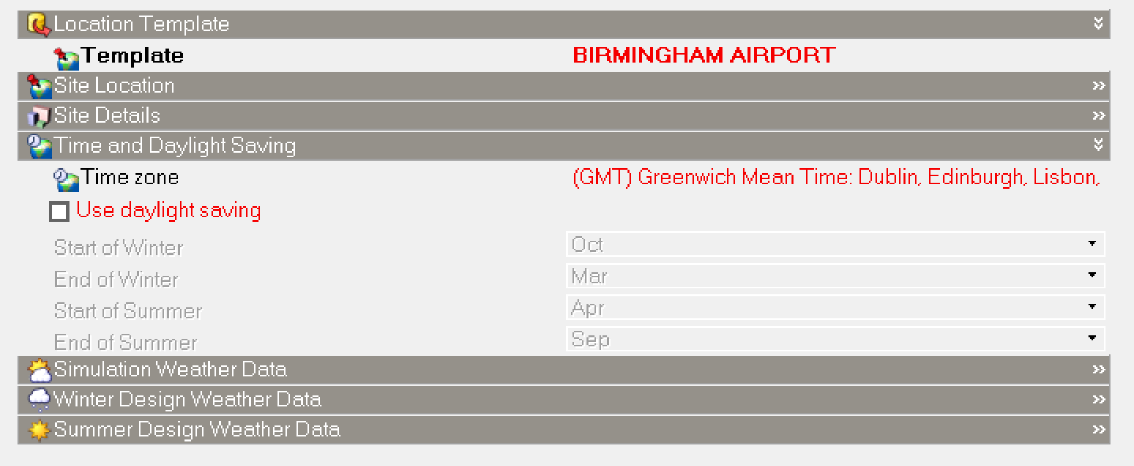


Figure D1 – Building's Energy Profile with DST enabled



Template BIRMINGHAM AIRPORT

Time zone (GMT) Greenwich Mean Time: Dublin, Edinburgh, Lisbon,

☐ Use daylight saving

Start of Winter Oct

End of Winter Mar

Start of Summer Apr

End of Summer Sep

Figure D2 – Disabling Daylight Saving Time in DesignBuilder

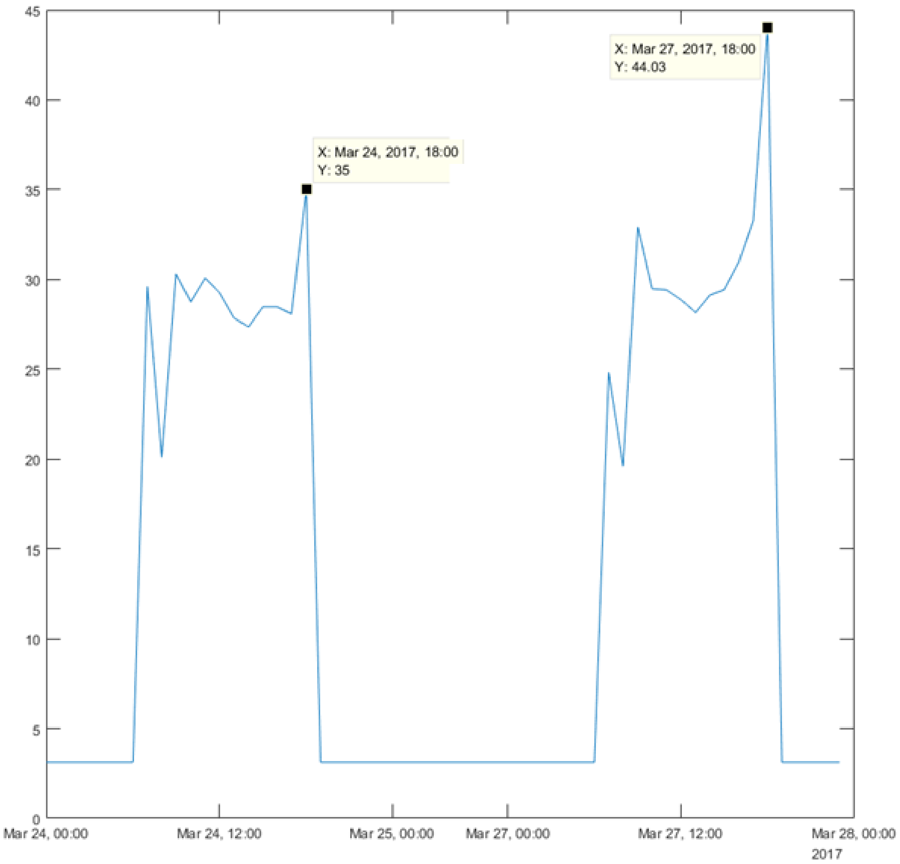


Figure D3 – Building's Energy Profile with DST disabled

Appendix D References

[1] H. Verdejo, C. Becker, D. Echiburu, W. Escudero, E. Fucks, and M. Jose Reveco, "Impact of daylight saving time on the Chilean residential consumption," *Energy Policy*, vol. 88, pp. 456–464, 2016, doi: 10.1016/j.enpol.2015.10.051.

[2] M. Awad Momani, B. Yatim, and M. A. M. Ali, "The impact of the daylight saving time on electricity consumption-A case study from Jordan," *Energy Policy*, vol. 37, no. 5, pp. 2042–2051, 2009, doi: 10.1016/j.enpol.2009.02.009.

[3] S. Karasu, "The effect of daylight saving time options on electricity consumption of Turkey," *Energy*, vol. 35, no. 9, pp. 3773–3782, 2010, doi: 10.1016/j.energy.2010.05.027.

[4] S. I. Hill, F. Desobry, E. W. Garnsey, and Y. F. Chong, "The impact on energy consumption of daylight saving clock changes," *Energy Policy*, vol. 38, no. 9, pp. 4955–4965, 2010, doi: 10.1016/j.enpol.2010.03.079.

Appendix E – Building Simulation Results

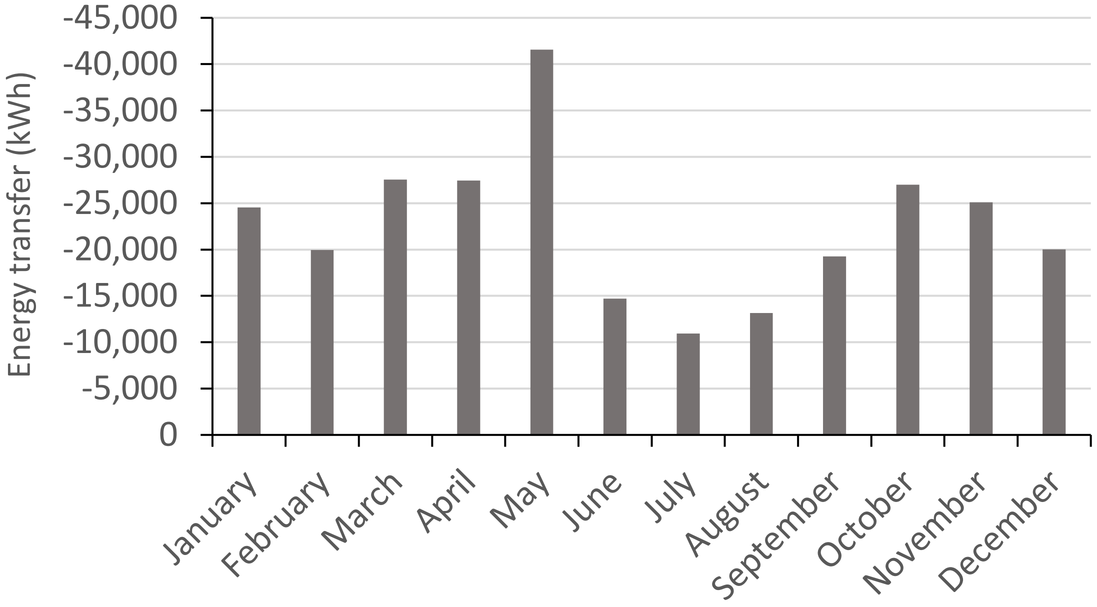


Figure E1 – Thermal losses due to external infiltration for Building HwPL30*

Table E1 – Building Simulation Energy Results for Mechanically-Ventilated Buildings

Building ID	Description	Lighting	Heating	Cooling	Room Electricity	DHW	Auxiliary	Total
1s	Sq-HwBP30	9.09	7.43	0.79	24.71	5.13	9.01	56.16
2s	Sq-HwPL30	9.07	15.39	0.55	24.71	5.13	9.01	63.87
3s	Sq-LwBP30	9.04	6.61	1.97	24.71	5.13	9.01	56.47
4s	Sq-LwPL30	9.02	13.73	1.37	24.71	5.13	9.01	62.97
5s	Sq-HwBP80	7.05	4.39	2.93	24.71	5.13	9.01	53.22
6s	Sq-HwPL80	7.05	12.94	2.39	24.71	5.13	9.01	61.24
7s	Sq-LwBP80	7.02	4.25	3.64	24.71	5.13	9.01	53.77
8s	Sq-LwPL80	7.02	12.33	3.06	24.71	5.13	9.01	61.26
1r	HwBP30	7.70	8.61	0.62	24.71	5.13	9.01	55.79
2r	HwPL30	7.69	17.46	0.44	24.71	5.13	9.01	64.45
3r	LwBP30	7.68	7.73	1.73	24.71	5.13	9.01	56.00
4r	LwPL30	7.67	15.59	1.18	24.71	5.13	9.01	63.30
5r	HwBP80	6.34	4.52	2.85	24.71	5.13	9.01	52.57
6r	HwPL80	6.34	14.00	2.16	24.71	5.13	9.01	61.35
7r	LwBP80	6.33	4.51	3.52	24.71	5.13	9.01	53.22
8r	LwPL80	6.33	13.39	2.89	24.71	5.13	9.01	61.45
9r	HwBP30-SW	7.77	8.99	0.78	24.71	5.13	9.01	56.39
10r	HwPL30-SW	7.75	17.84	0.55	24.71	5.13	9.01	64.99
11r	LwBP30-SW	7.74	8.06	1.89	24.71	5.13	9.01	56.55
12r	LwPL30-SW	7.73	15.96	1.31	24.71	5.13	9.01	63.86
13r	HwBP80-SW	6.34	5.37	2.94	24.71	5.13	9.01	53.51
14r	HwPL80-SW	6.34	15.07	2.39	24.71	5.13	9.01	62.65
15r	LwBP80-SW	6.33	5.27	3.68	24.71	5.13	9.01	54.13
16r	LwPL80-SW	6.33	14.32	3.05	24.71	5.13	9.01	62.56
17r	HwBP30-SE	8.05	8.80	0.76	24.71	5.13	9.01	56.46
18r	HwPL30-SE	8.03	17.45	0.54	24.71	5.13	9.01	64.88
19r	LwBP30-SE	8.02	7.86	1.90	24.71	5.13	9.01	56.64
20r	LwPL30-SE	8.00	15.57	1.33	24.71	5.13	9.01	63.76
21r	HwBP80-SE	6.41	5.20	2.90	24.71	5.13	9.01	53.37
22r	HwPL80-SE	6.41	14.67	2.38	24.71	5.13	9.01	62.31
23r	LwBP80-SE	6.40	5.06	3.64	24.71	5.13	9.01	53.96
24r	LwPL80-SE	6.40	13.83	3.03	24.71	5.13	9.01	62.11
25r	HwBP30-E	8.25	9.14	0.89	24.71	5.13	9.01	57.13
26r	HwPL30-E	8.23	17.76	0.62	24.71	5.13	9.01	65.47
27r	LwBP30-E	8.22	8.16	2.02	24.71	5.13	9.01	57.25
28r	LwPL30-E	8.20	15.86	1.43	24.71	5.13	9.01	64.34
29r	HwBP80-E	6.46	6.12	2.99	24.71	5.13	9.01	54.41
30r	HwPL80-E	6.46	15.67	2.50	24.71	5.13	9.01	63.48
31r	LwBP80-E	6.45	5.91	3.75	24.71	5.13	9.01	54.97
32r	LwPL80-E	6.45	14.70	3.15	24.71	5.13	9.01	63.15

Table E2 – Building Simulation Energy Results for Naturally-Ventilated Buildings

Building ID	Description	Lighting	Heating	Cooling	Room Electricity	DHW	Auxiliary	Total
1rN	HwBP30*	7.70	17.68	0.00	24.71	5.13	3.01	58.25
2rN	HwPL30*	7.69	26.80	0.00	24.71	5.13	3.01	67.36
3rN	LwBP30*	7.68	15.60	0.00	24.71	5.13	3.01	56.15
4rN	LwPL30*	7.67	23.12	0.00	24.71	5.13	3.01	63.65
9rN	HwBP30-SW*	7.77	18.53	0.00	24.71	5.13	3.01	59.15
10rN	HwPL30-SW*	7.75	27.77	0.00	24.71	5.13	3.01	68.39
11rN	LwBP30-SW*	7.74	16.38	0.00	24.71	5.13	3.01	56.99
12rN	LwPL30-SW*	7.73	24.17	0.00	24.71	5.13	3.01	64.77
17rN	HwBP30-SE*	8.05	15.94	0.00	24.71	5.13	3.01	56.85
18rN	HwPL30-SE*	8.03	24.51	0.00	24.71	5.13	3.01	65.41
19rN	LwBP30-SE*	8.02	14.09	0.00	24.71	5.13	3.01	54.97
20rN	LwPL30-SE*	8.00	21.68	0.00	24.71	5.13	3.01	62.55
25rN	HwBP30-E*	8.25	16.47	0.00	24.71	5.13	3.01	57.58
26rN	HwPL30-E*	8.23	24.68	0.00	24.71	5.13	3.01	65.77
27rN	LwBP30-E*	8.22	14.70	0.00	24.71	5.13	3.01	55.78
28rN	LwPL30-E*	8.20	22.24	0.00	24.71	5.13	3.01	63.30

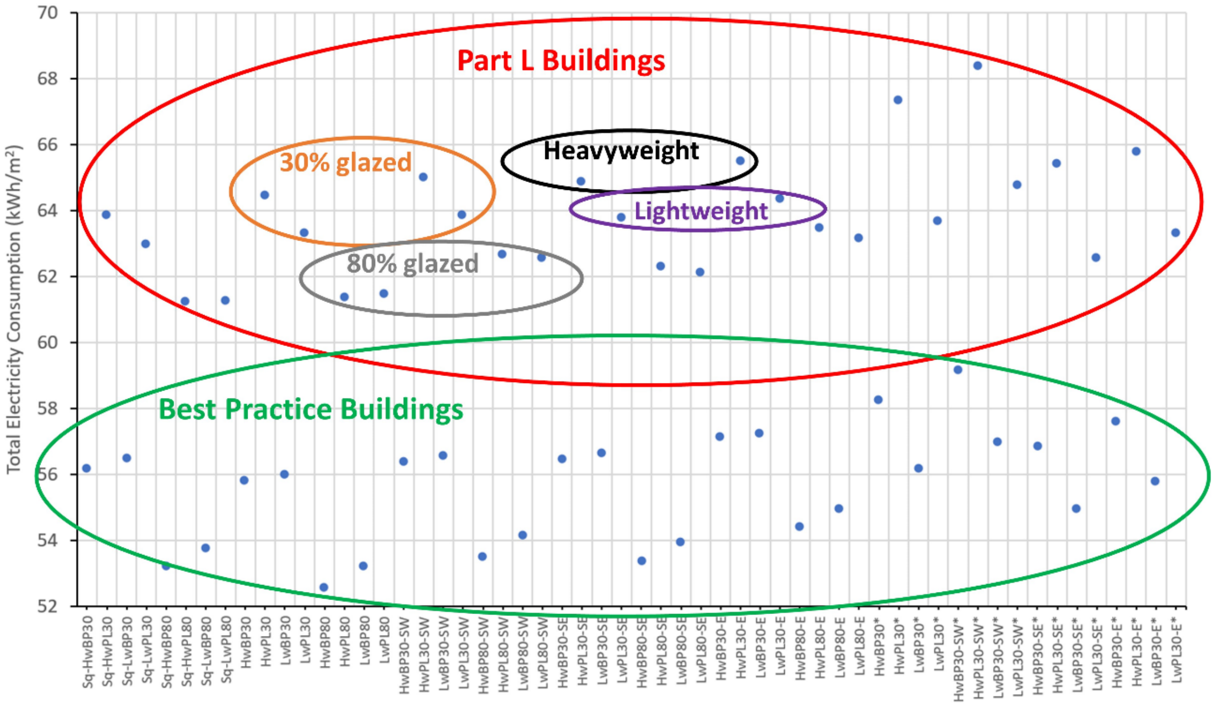


Figure E2 – Analysis of Figure 4.4 and classification of buildings in groups and subgroups based on their energy efficiency and glazing percentage. For visibility purposes, certain subgroups do not include all the relevant building cases while only one of the two thermal mass patterns is illustrated. The figure constitutes a simplified sketch and should not be interpreted as a Venn diagram.

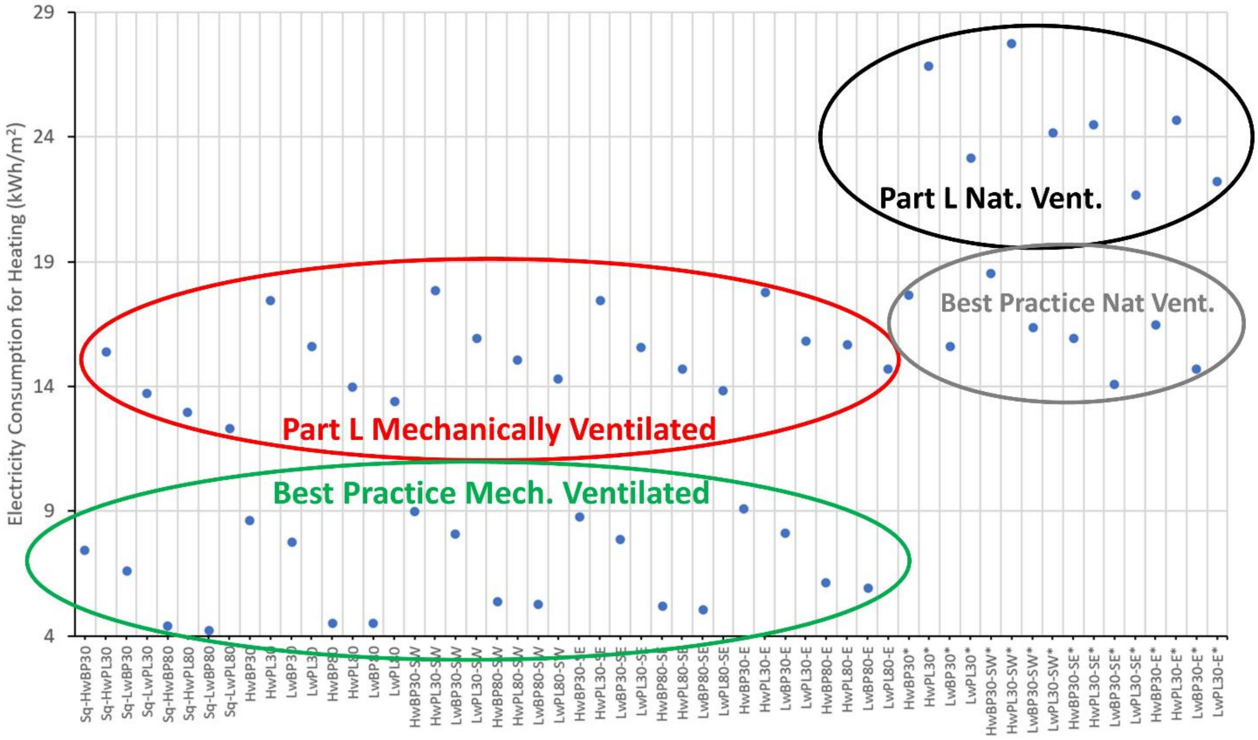


Figure E3 – Analysis of Figure 4.5 and classification of buildings in groups based on the impact of ventilation strategy and energy efficiency on heating electricity consumption

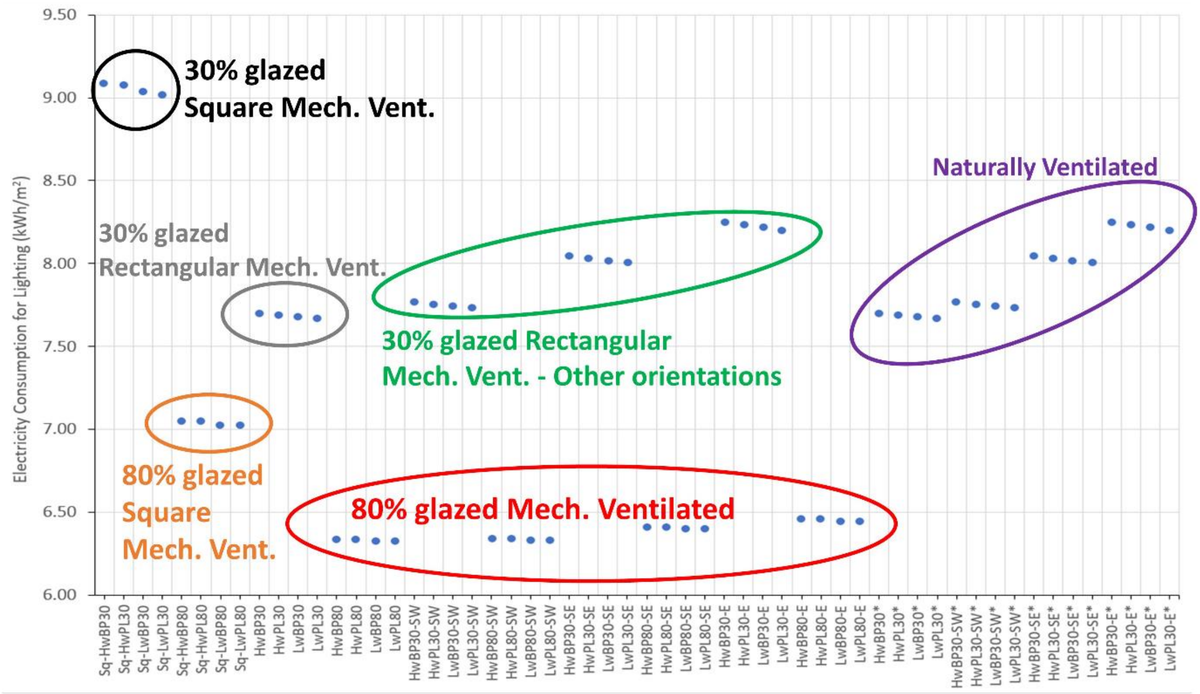


Figure E4 - Classification of buildings in groups based on the impact of Window-to-Wall-ratio and shape on lighting electricity consumption

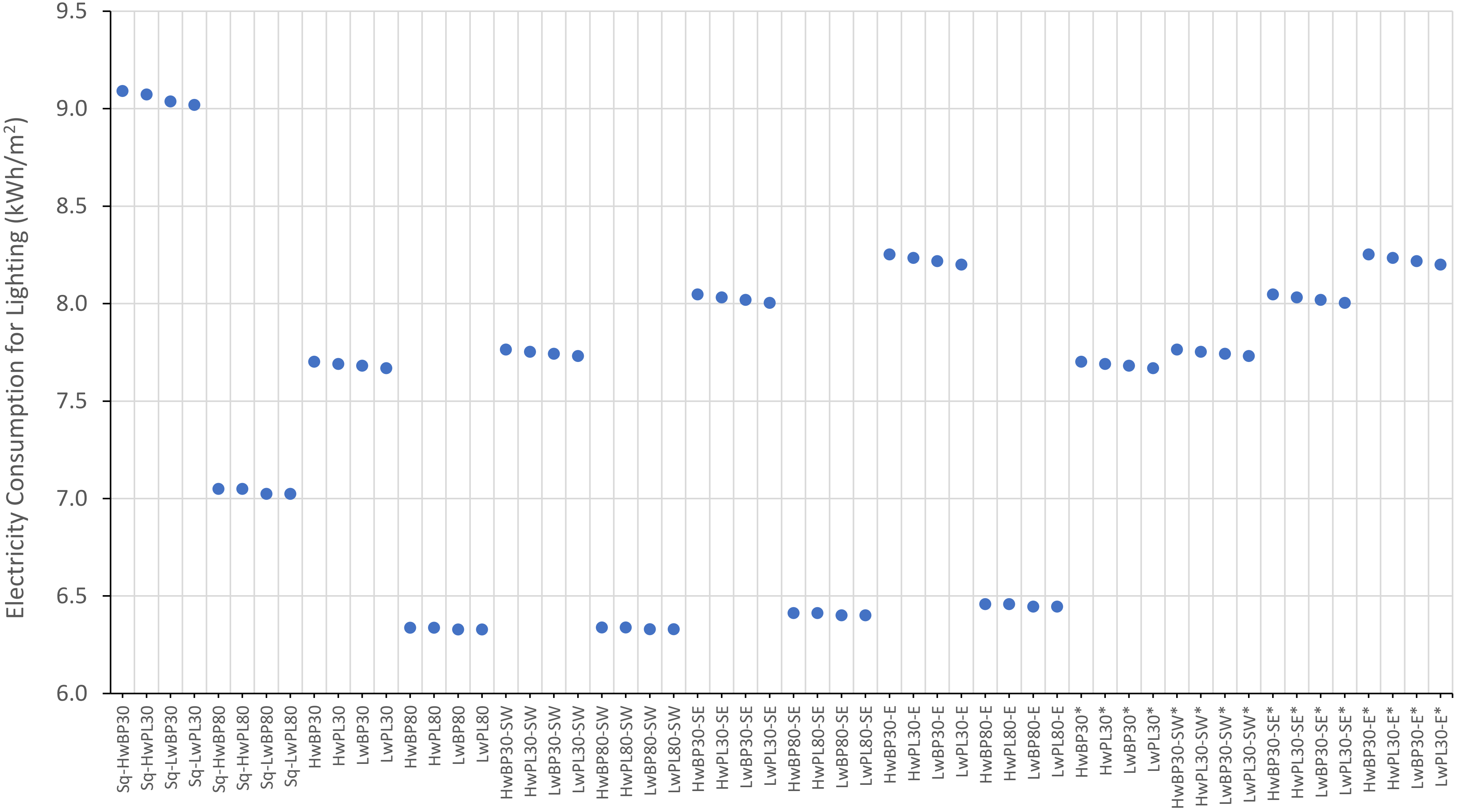


Figure E5 – Electricity Consumption for Lighting (kWh/m^2) for all building models

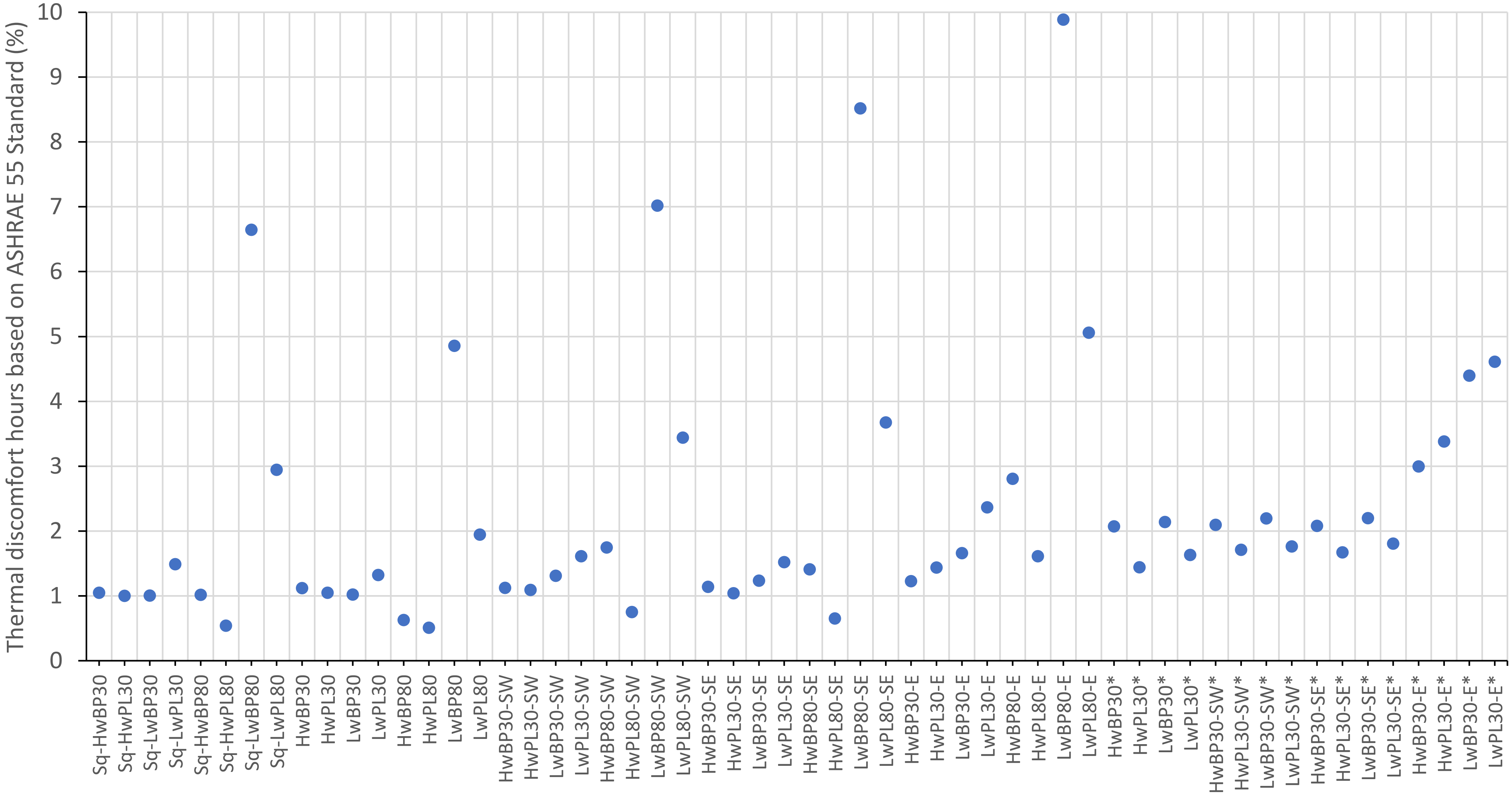


Figure E6 – Thermal comfort results based on the ASHRAE 55 Standard

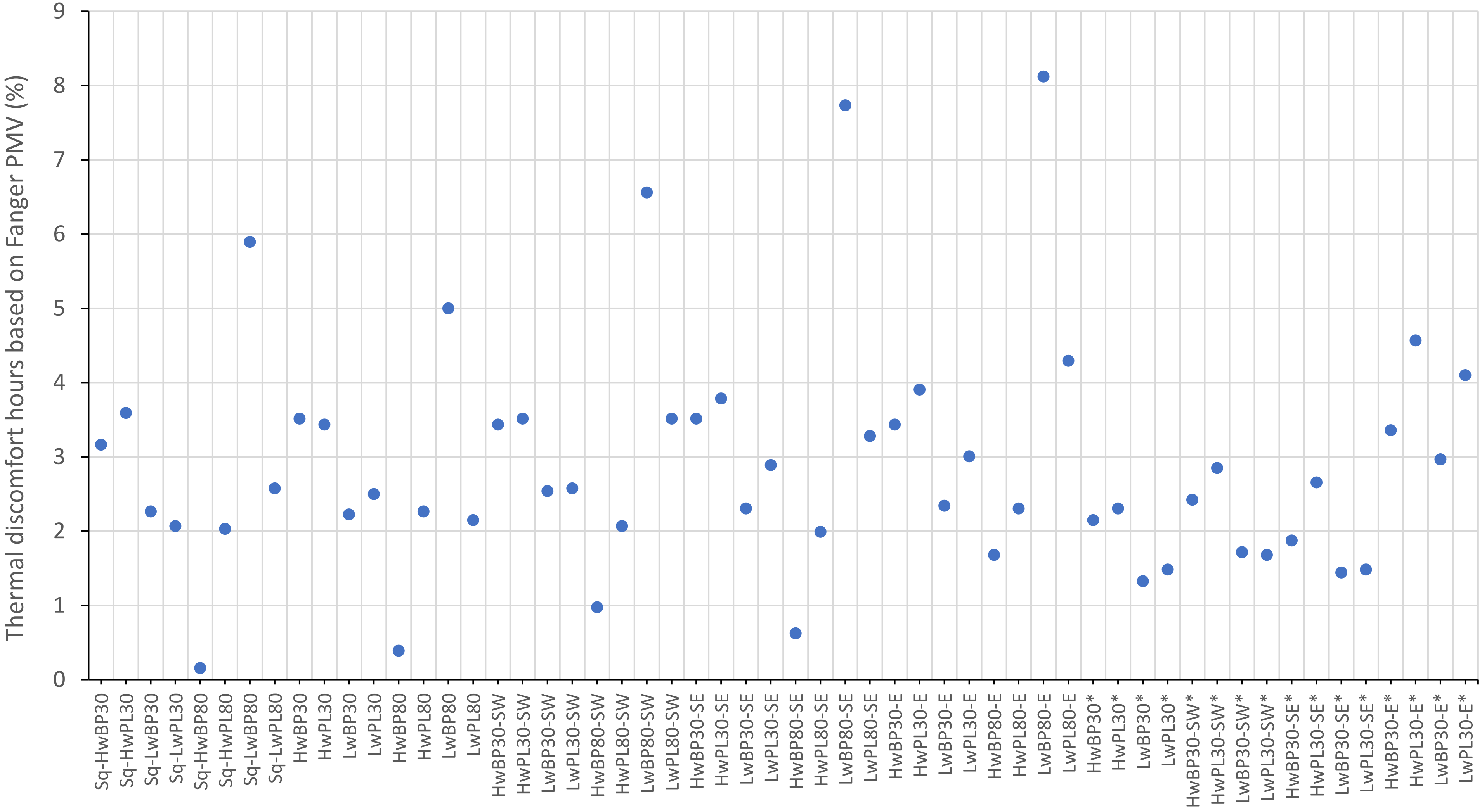


Figure E7 – Thermal comfort results based on Fanger PMV

Table E3 – Thermal comfort results for the mechanically-ventilated Buildings

Building ID	Description	ASHRAE Discomfort (h)	Fanger PMV (h)	ASHRAE (%)	Fanger (%)
1s	Sq-HwBP30	26.82	81.00	1.05	3.16
2s	Sq-HwPL30	25.54	92.00	1.00	3.59
3s	Sq-LwBP30	25.65	58.00	1.00	2.27
4s	Sq-LwPL30	38.05	53.00	1.49	2.07
5s	Sq-HwBP80	26.00	4.00	1.02	0.16
6s	Sq-HwPL80	13.78	52.00	0.54	2.03
7s	Sq-LwBP80	170.13	151.00	6.65	5.90
8s	Sq-LwPL80	75.32	66.00	2.94	2.58
1r	HwBP30	28.59	90.00	1.12	3.52
2r	HwPL30	26.86	88.00	1.05	3.44
3r	LwBP30	26.06	57.00	1.02	2.23
4r	LwPL30	33.80	64.00	1.32	2.50
5r	HwBP80	16.07	10.00	0.63	0.39
6r	HwPL80	12.95	58.00	0.51	2.27
7r	LwBP80	124.25	128.00	4.85	5.00
8r	LwPL80	49.80	55.00	1.95	2.15
9r	HwBP30-SW	28.78	88.00	1.12	3.44
10r	HwPL30-SW	27.97	90.00	1.09	3.52
11r	LwBP30-SW	33.50	65.00	1.31	2.54
12r	LwPL30-SW	41.25	66.00	1.61	2.58
13r	HwBP80-SW	44.68	25.00	1.75	0.98
14r	HwPL80-SW	19.17	53.00	0.75	2.07
15r	LwBP80-SW	179.64	168.00	7.02	6.56
16r	LwPL80-SW	88.09	90.00	3.44	3.52
17r	HwBP30-SE	29.19	90.00	1.14	3.52
18r	HwPL30-SE	26.57	97.00	1.04	3.79
19r	LwBP30-SE	31.57	59.00	1.23	2.30
20r	LwPL30-SE	38.91	74.00	1.52	2.89
21r	HwBP80-SE	36.10	16.00	1.41	0.63
22r	HwPL80-SE	16.62	51.00	0.65	1.99
23r	LwBP80-SE	218.02	198.00	8.52	7.73
24r	LwPL80-SE	94.04	84.00	3.67	3.28
25r	HwBP30-E	31.34	88.00	1.22	3.44
26r	HwPL30-E	36.75	100.00	1.44	3.91
27r	LwBP30-E	42.40	60.00	1.66	2.34
28r	LwPL30-E	60.49	77.00	2.36	3.01
29r	HwBP80-E	71.80	43.00	2.80	1.68
30r	HwPL80-E	41.20	59.00	1.61	2.30
31r	LwBP80-E	253.03	208.00	9.88	8.13
32r	LwPL80-E	129.47	110.00	5.06	4.30

Table E4 – Thermal comfort results for the naturally-ventilated Buildings

Building ID	**Description**	**ASHRAE Discomfort (h)**	**Fanger PMV (h)**	**ASHRAE (%)**	**Fanger (%)**
1rN	HwBP30*	52.98	55.00	2.07	2.15
2rN	HwPL30*	36.91	59.00	1.44	2.30
3rN	LwBP30*	54.78	34.00	2.14	1.33
4rN	LwPL30*	41.71	38.00	1.63	1.48
9rN	HwBP30-SW*	53.59	62.00	2.09	2.42
10rN	HwPL30-SW*	43.78	73.00	1.71	2.85
11rN	LwBP30-SW*	56.17	44.00	2.19	1.72
12rN	LwPL30-SW*	45.10	43.00	1.76	1.68
17rN	HwBP30-SE*	53.17	48.00	2.08	1.88
18rN	HwPL30-SE*	42.72	68.00	1.67	2.66
19rN	LwBP30-SE*	56.30	37.00	2.20	1.45
20rN	LwPL30-SE*	46.25	38.00	1.81	1.48
25rN	HwBP30-E*	76.68	86.00	3.00	3.36
26rN	HwPL30-E*	86.49	117.00	3.38	4.57
27rN	LwBP30-E*	112.52	76.00	4.40	2.97
28rN	LwPL30-E*	118.02	105.00	4.61	4.10

Appendix F – Arbitrage Results (2017 RTP Electricity Data)

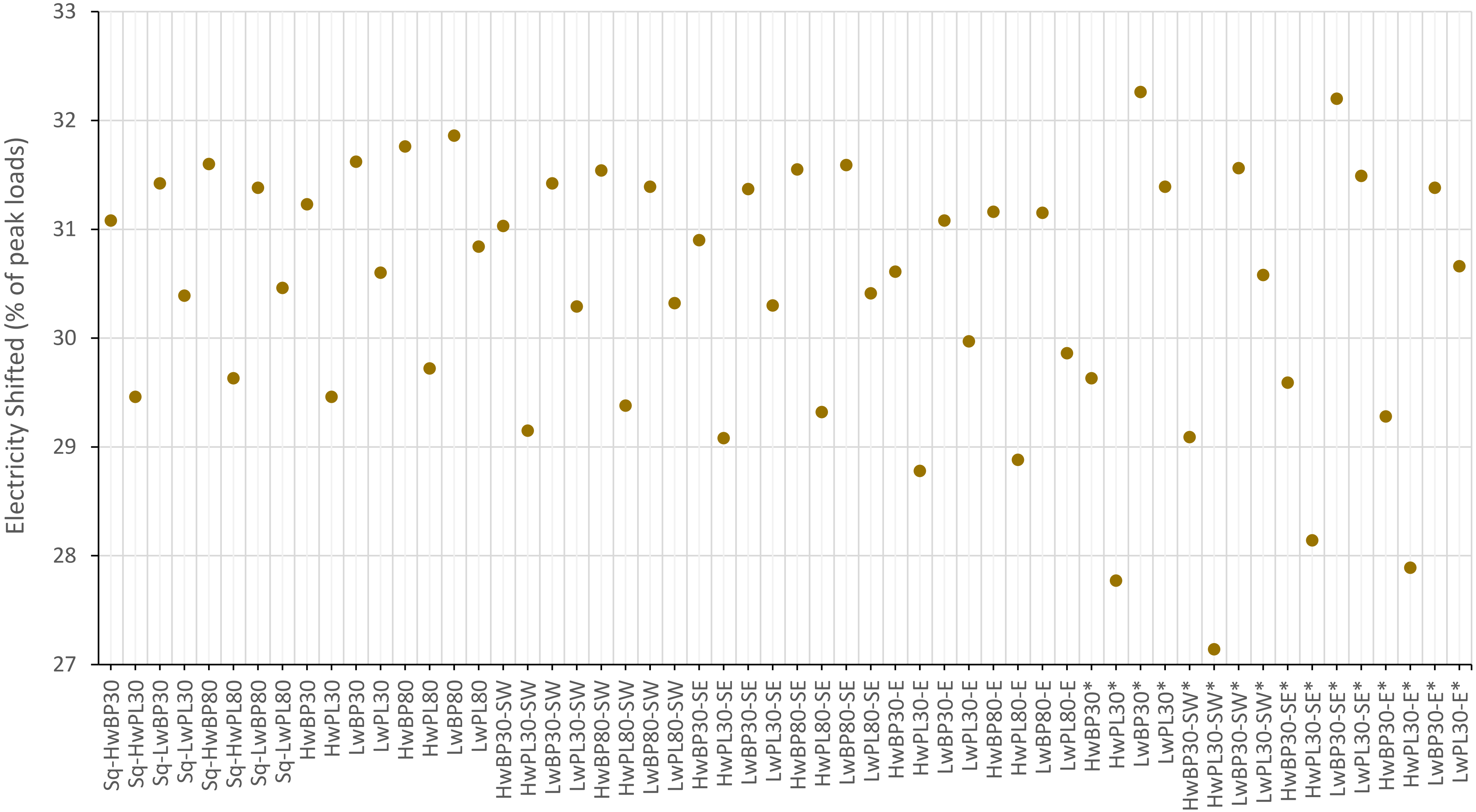


Figure F1 – Electricity Shifted (% of peak loads) for Operational Strategy E7 (220 kWh & 45/-65 kW)

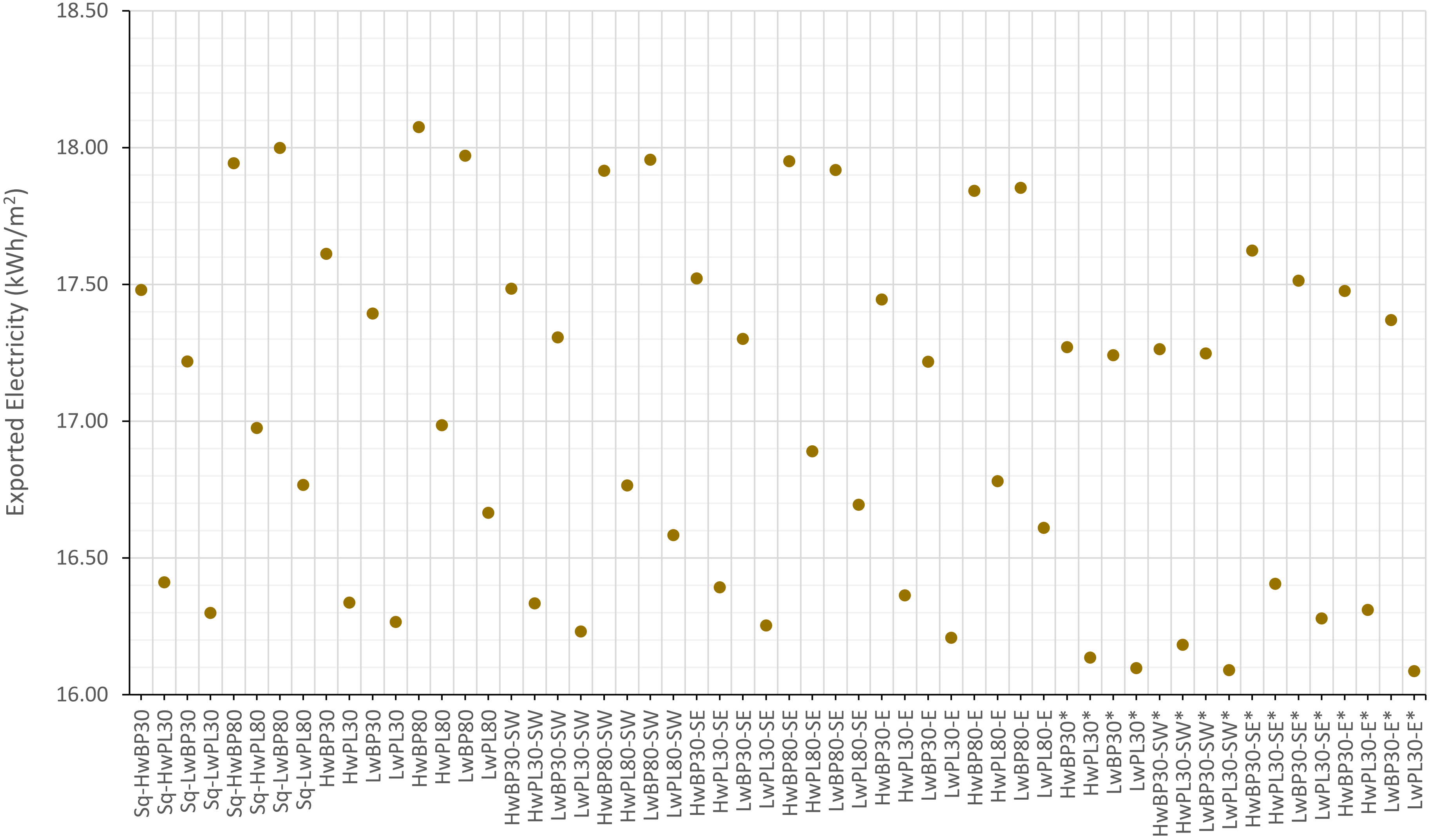


Figure F2 – Electricity Exports (kWh/m^2) for Operational Strategy E7 (220 kWh & 45/-65 kW)

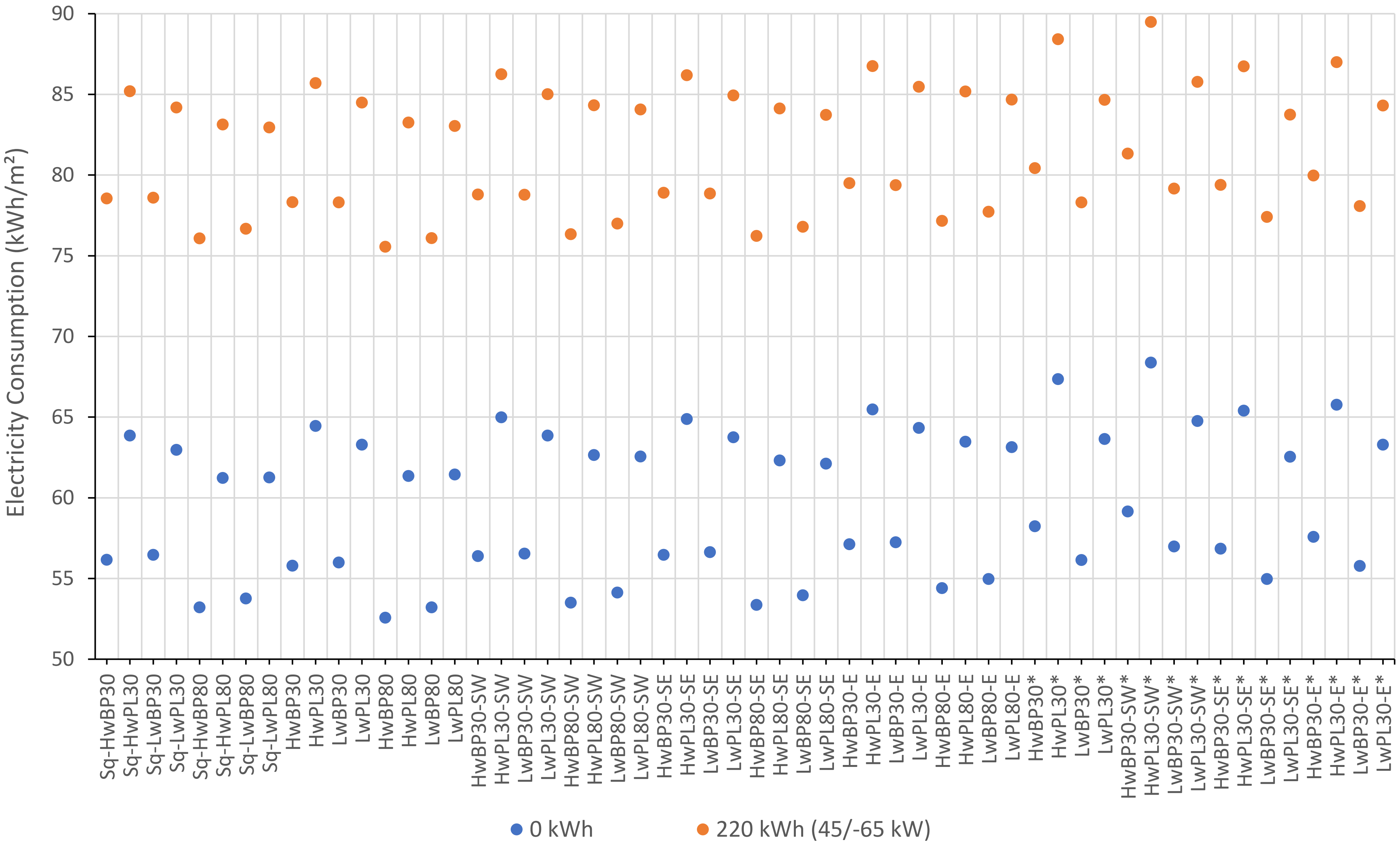


Figure F3 – Total Electricity Consumption (kWh/m^2) for Operational Strategy E7 with and without storage (220 kWh & 45/-65 kW)

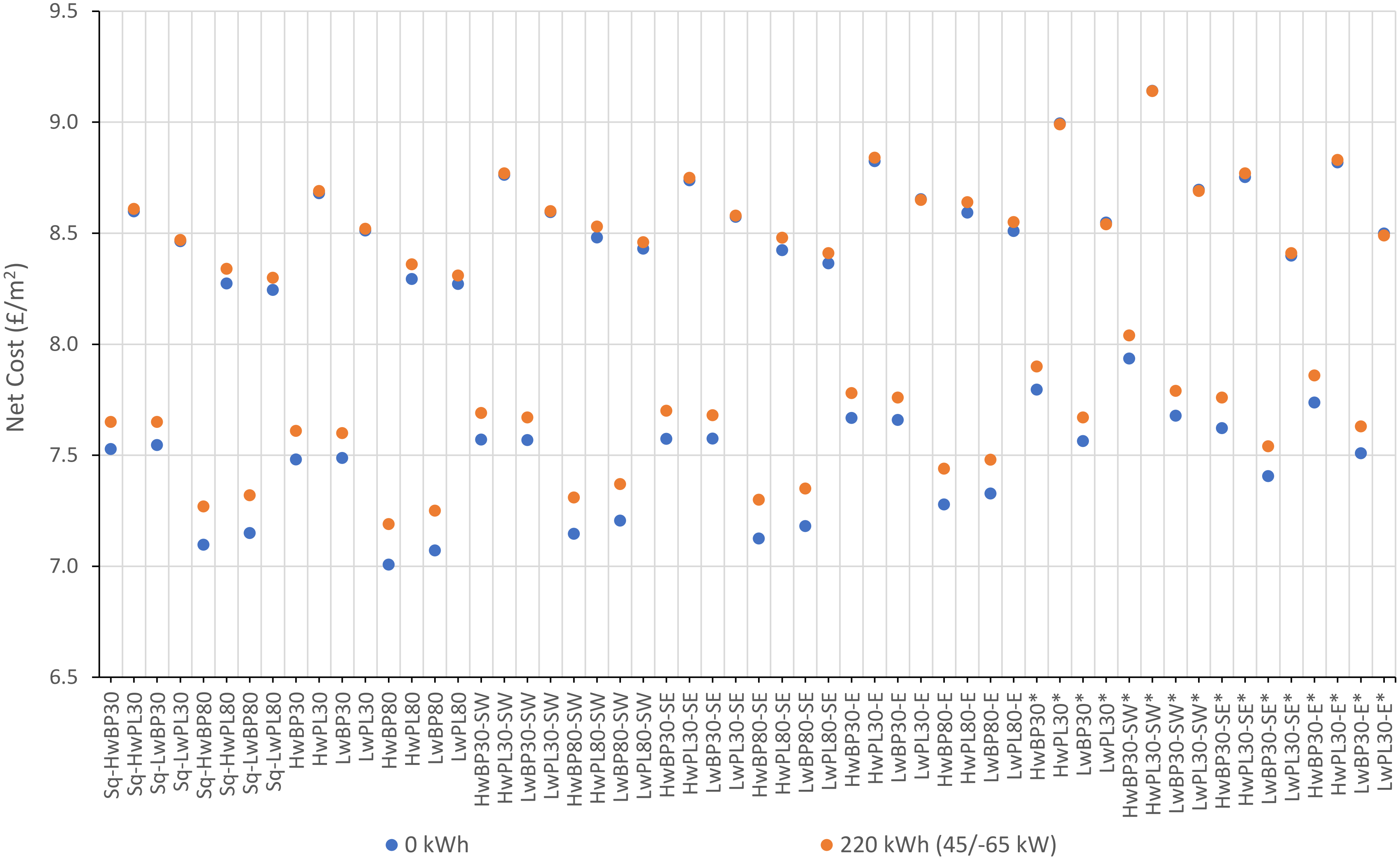


Figure F4 – Net Cost (£/m^2) for Operational Strategy E7 with and without storage (220 kWh & 45/-65 kW)

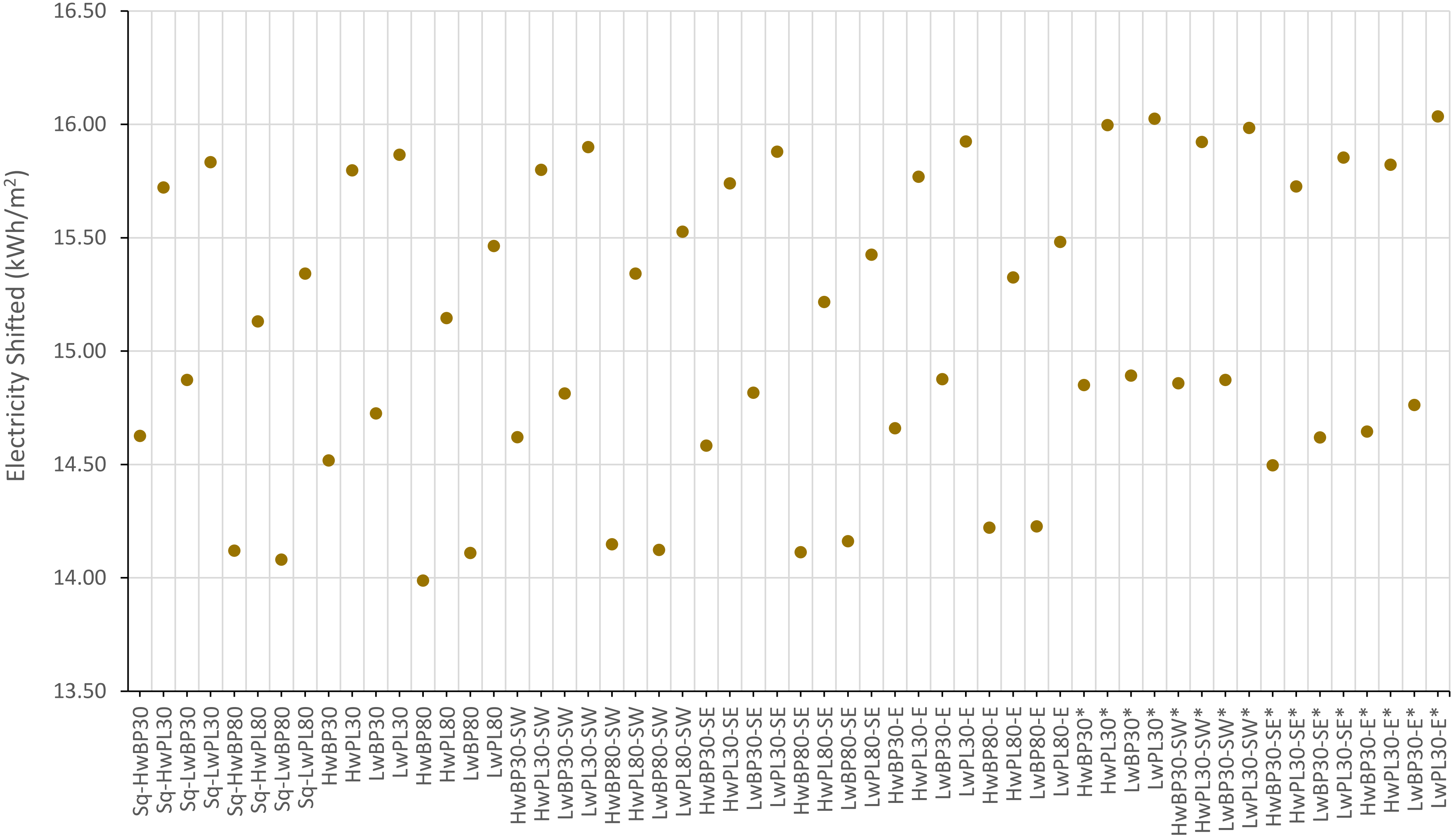


Figure F5 – Electricity Shifted (kWh/m^2) for Operational Strategy E7 (220 kWh & 45/-65 kW)

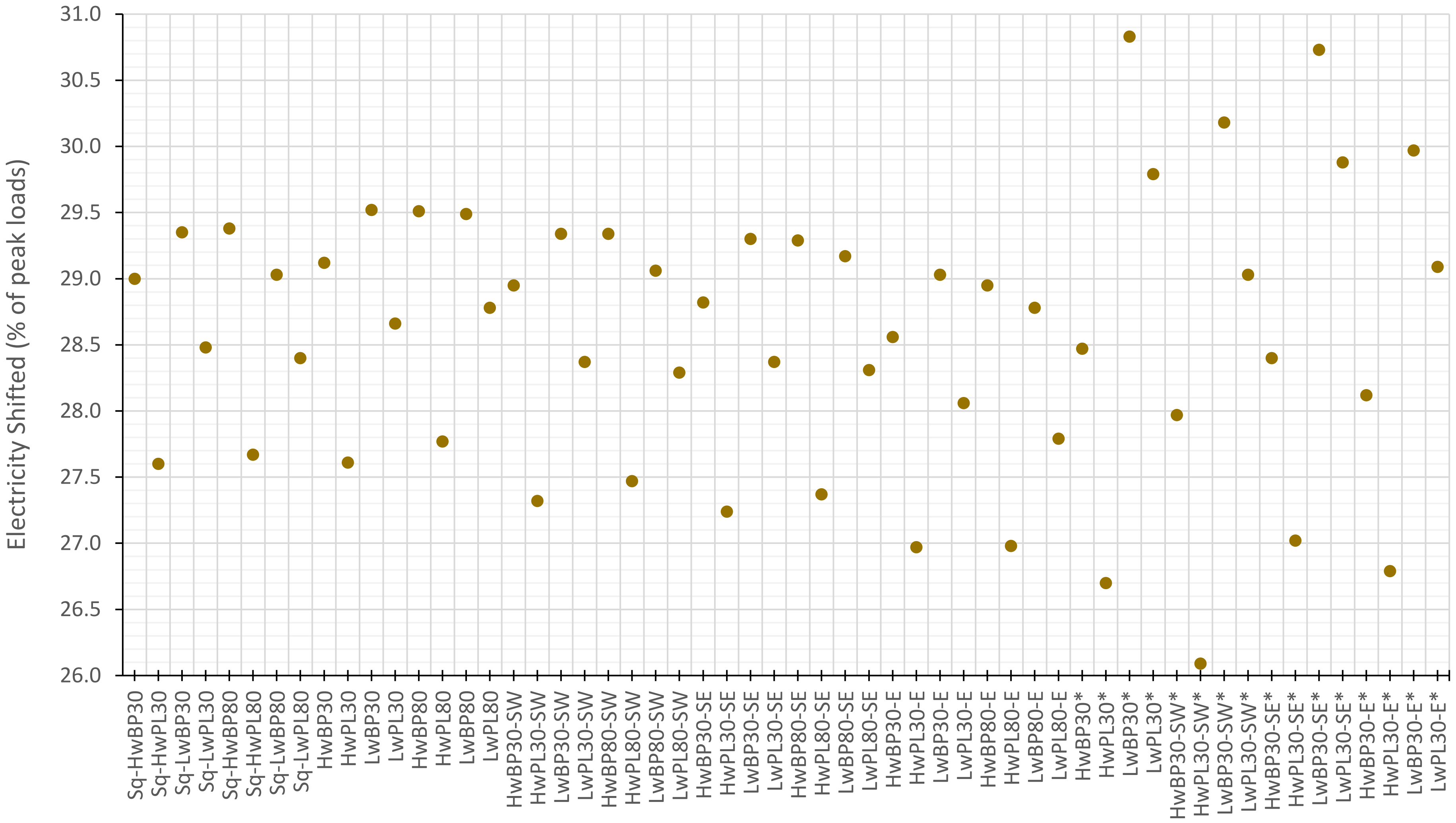


Figure F6 – Electricity Shifted (% of peak loads) for Operational Strategy E5 (220 kWh & 45/-65 kW)

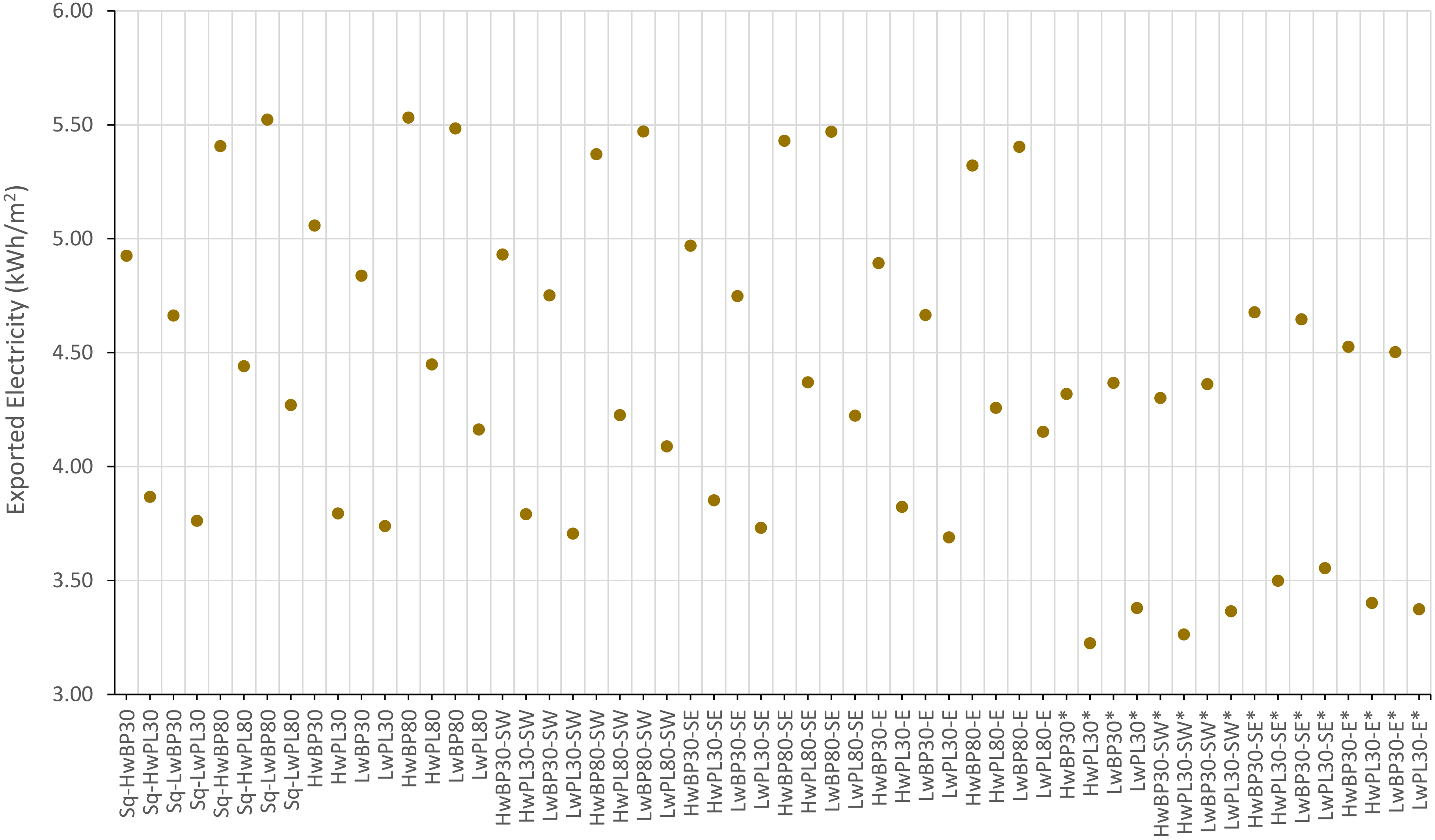


Figure F7 – Electricity Exports (kWh/m^2) for Operational Strategy E5 (220 kWh & 45/-65 kW)

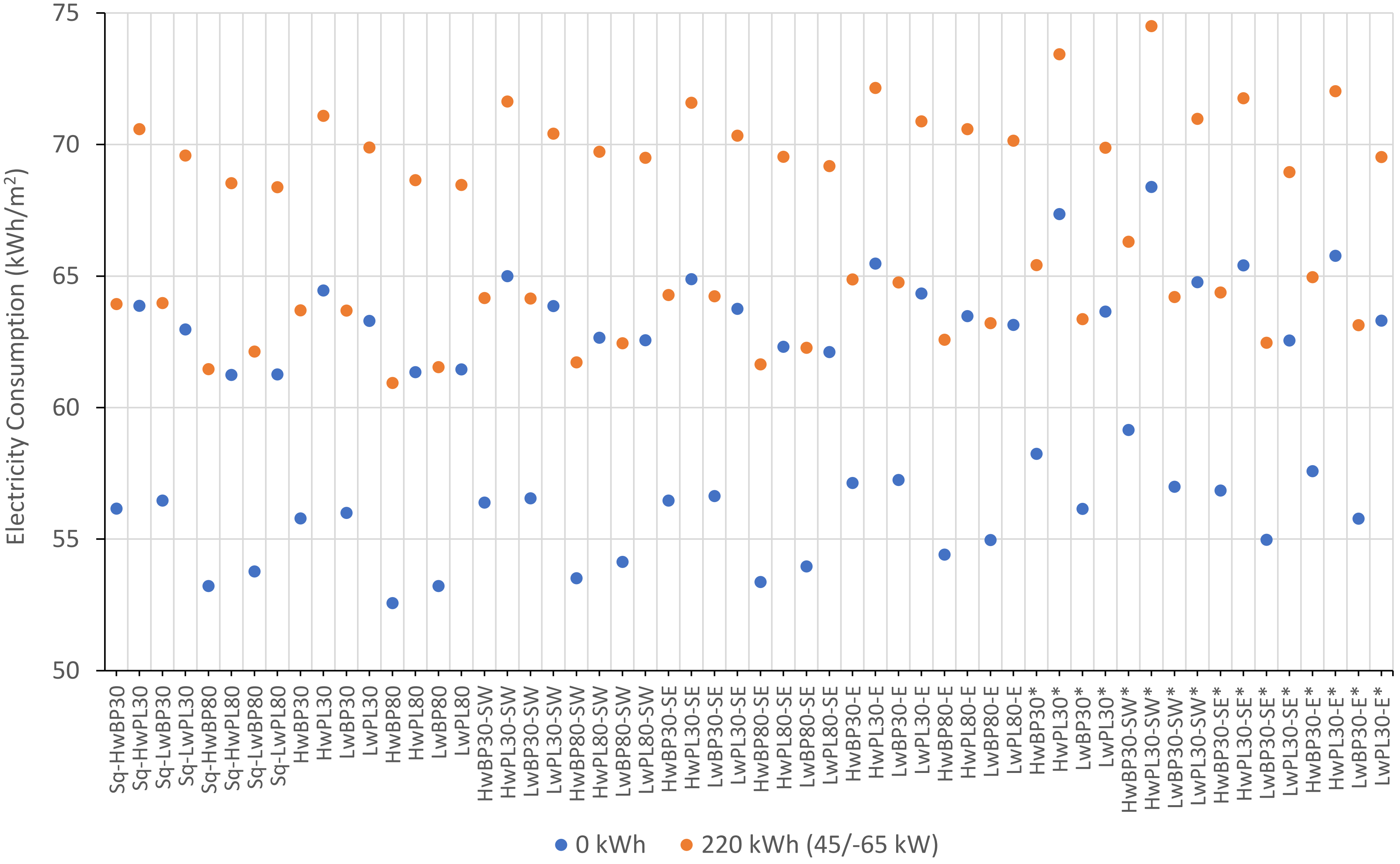


Figure F8 – Total Electricity Consumption (kWh/m^2) for Operational Strategy E5 with and without storage (220 kWh & 45/-65 kW)

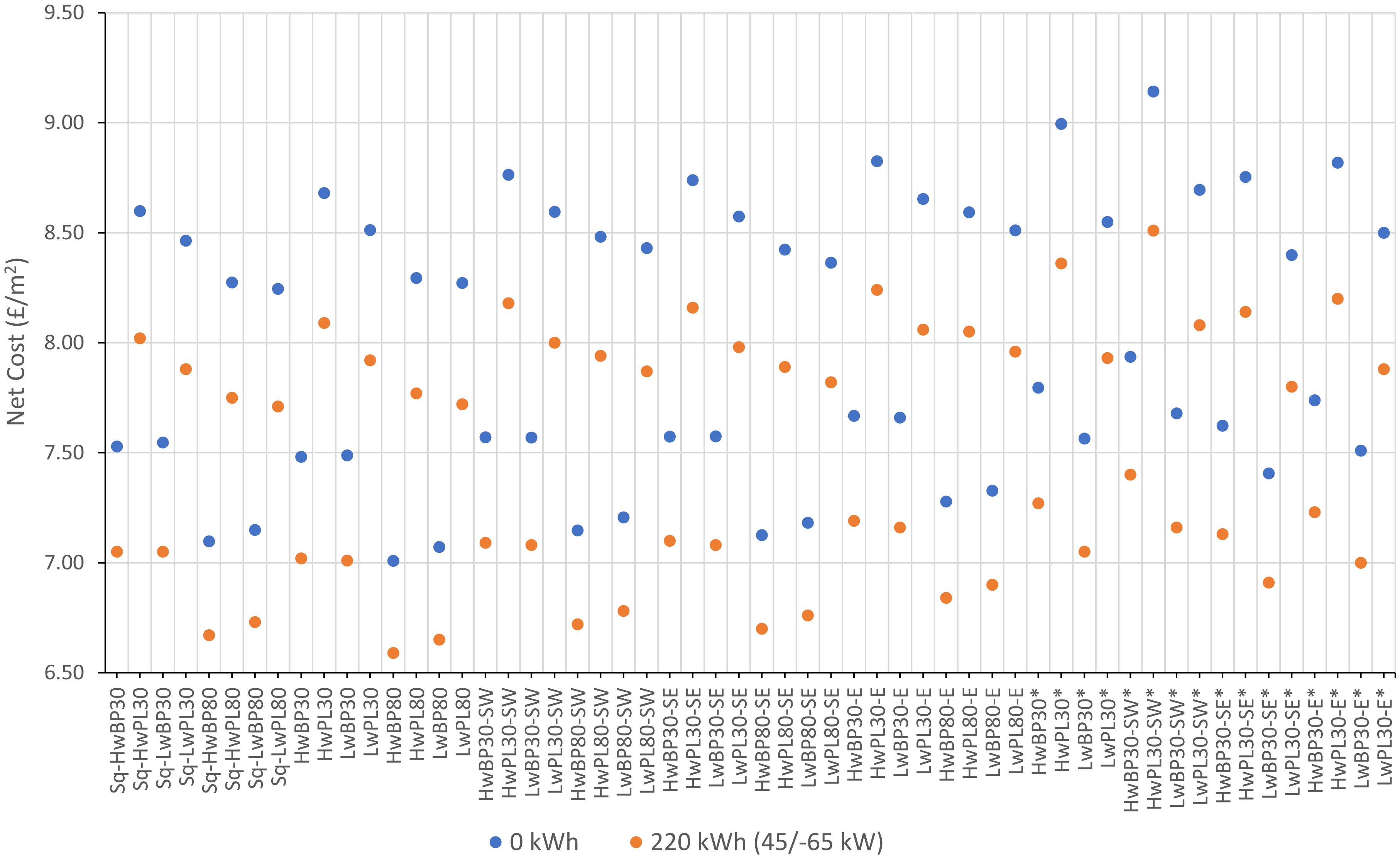


Figure F9 – Net Cost (£/m^2) for Operational Strategy E5 with and without storage (220 kWh & 45/-65 kW)

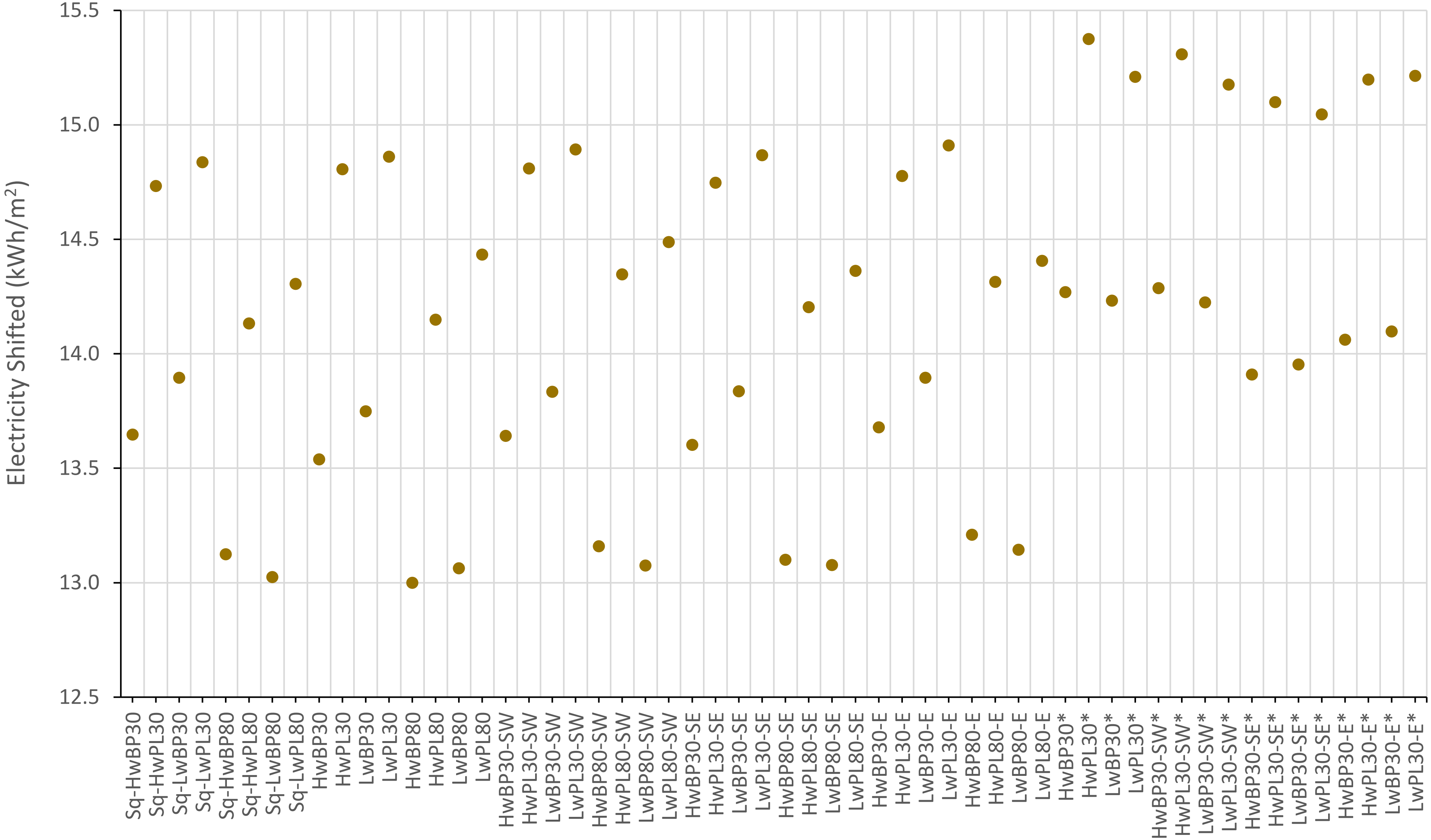


Figure F10 – Electricity Shifted (kWh/m^2) for Operational Strategy E5 (220 kWh & 45/-65 kW)

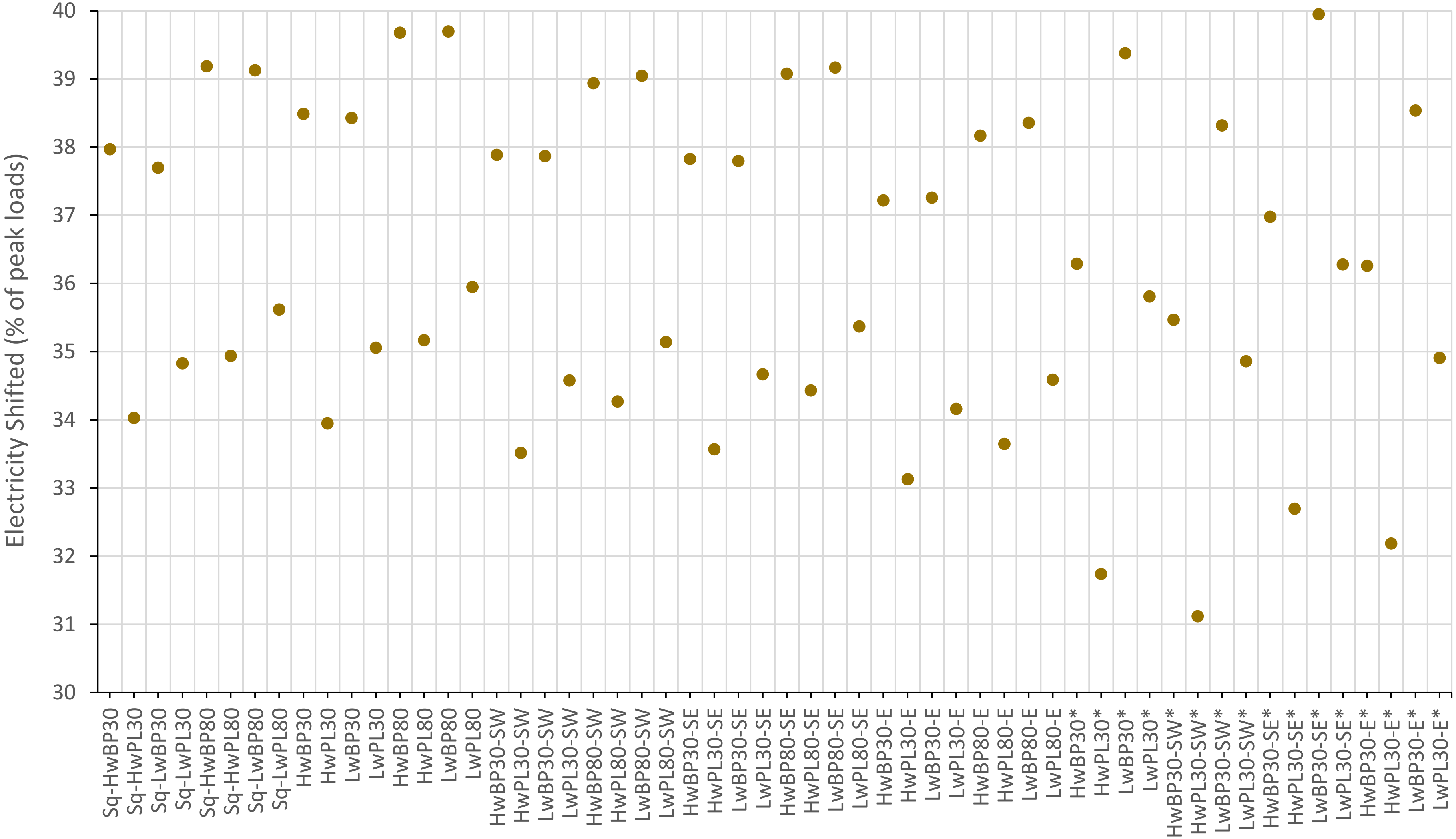


Figure F11 – Electricity Shifted (% of peak loads) for Operational Strategy E0 (220 kWh & 45/-65 kW)

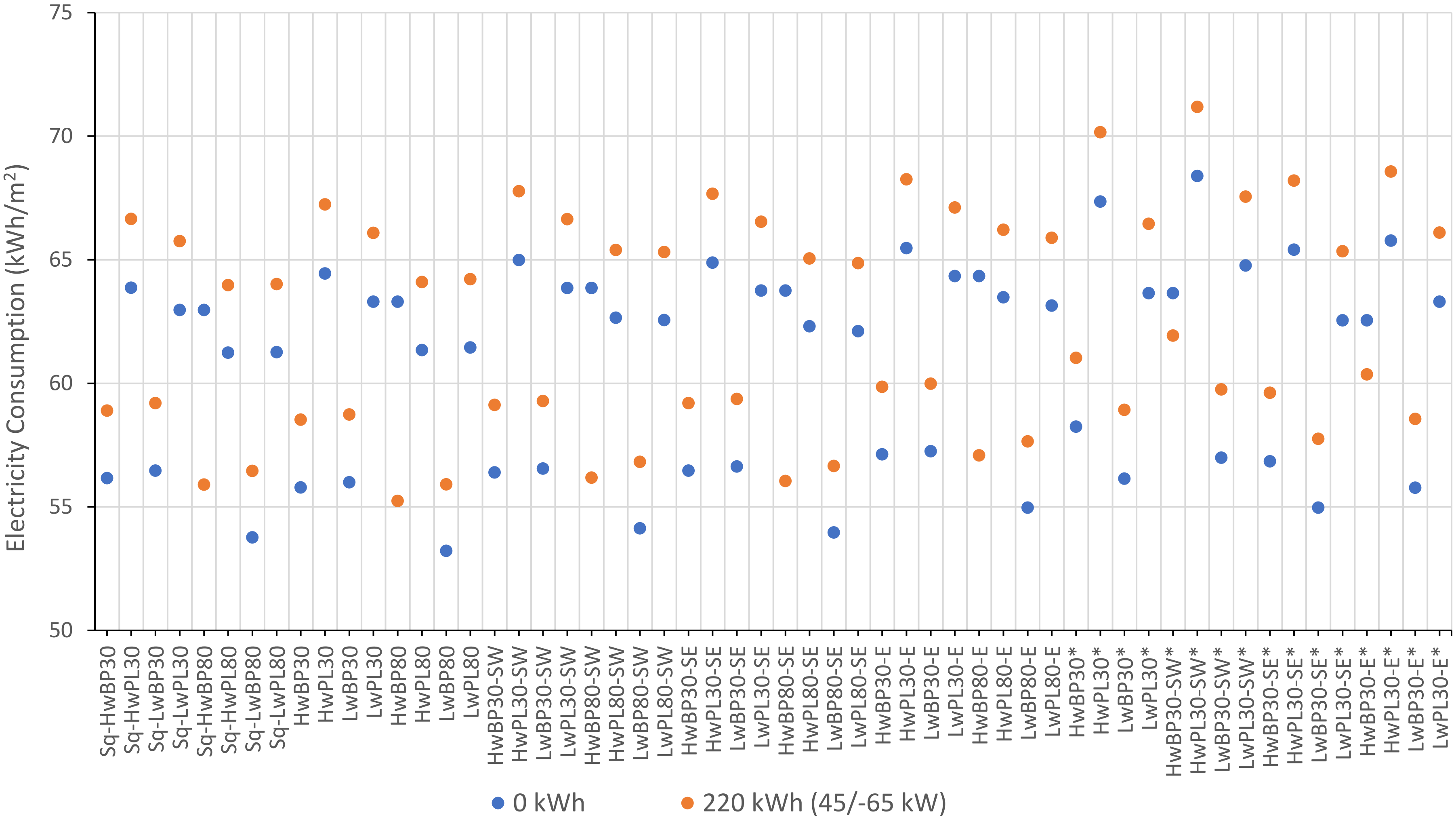


Figure F12 – Total Electricity Consumption for Operational Strategy E0 (220 kWh & 45/-65 kW)

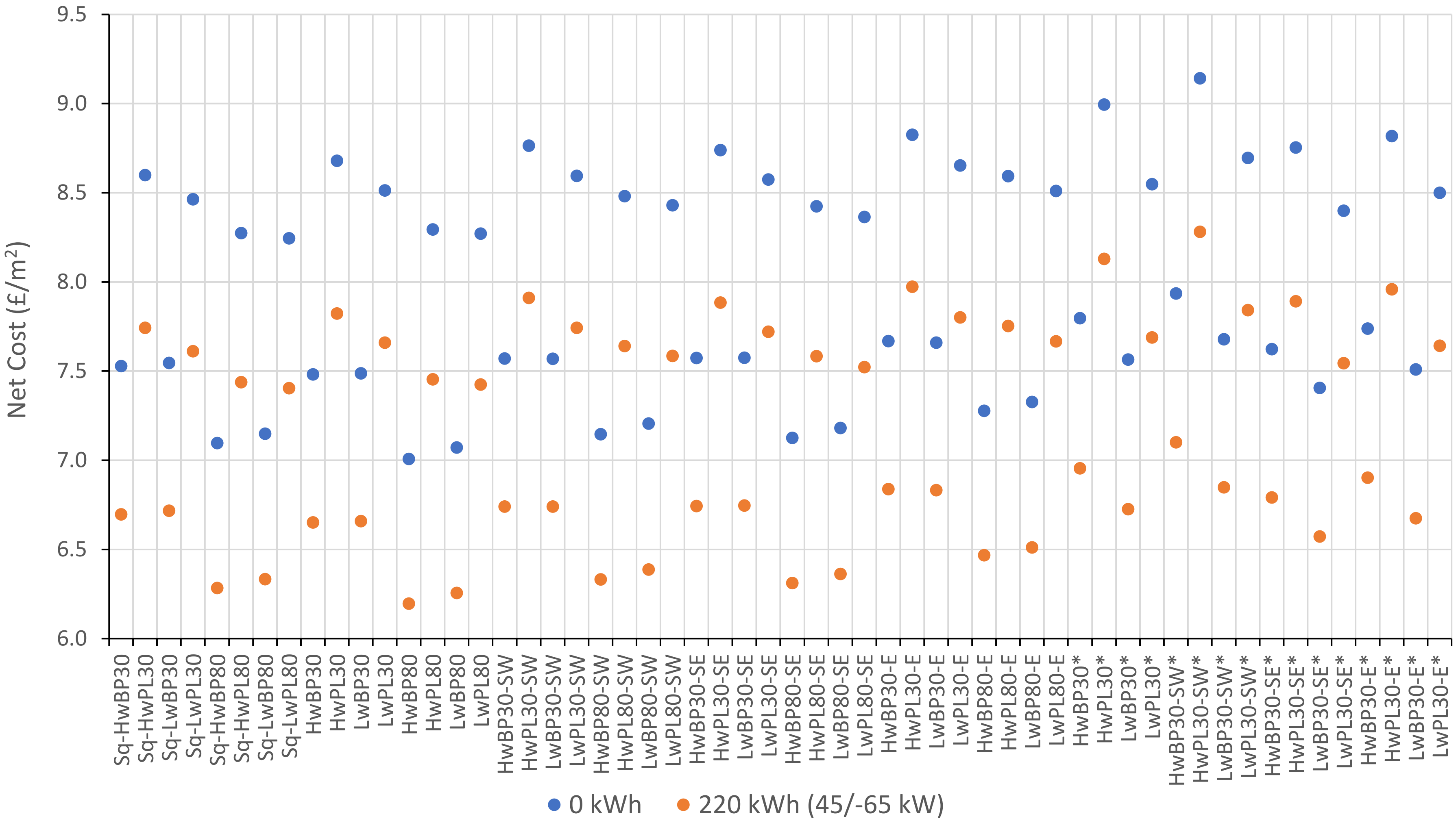


Figure F13 – Net Cost (£/m^2) for Operational Strategy E0 with and without storage (220 kWh & 45/-65 kW)

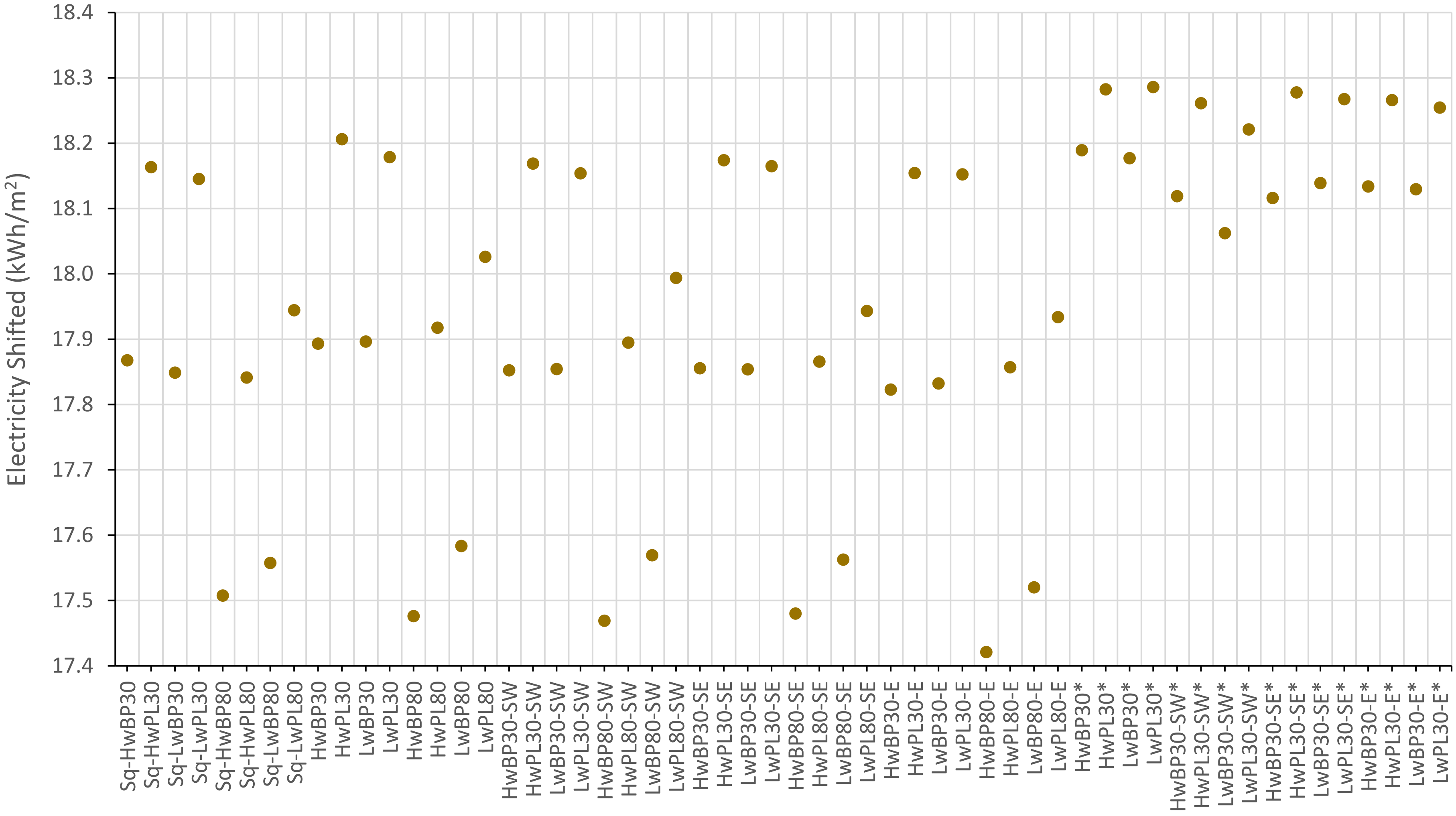


Figure F14 – Electricity Shifted (kWh/m^2) for Operational Strategy E0 (220 kWh & 45/-65 kW)

Table F1 – Impact of building design elements on arbitrage performance for the E0 Operational Strategy. Mean values of the differences are included (2017 RTP results)

Building Design Element	**Comparison Description**	**Parameter (Unit)**		
		Differences in Electricity shifted (% of peak loads)	**Differences in Net Cost (£/m^2)**	**Differences in Electricity Consumption – No BSS (kWh/m^2)**
Energy Efficiency	Best Practice vs Part L	3.92	-1.11	-8.09
Glazing	30% vs 80% glazed	-0.98	0.32	2.40
Orientation	Southern vs SW, SE, E	0.49	-0.05	-0.30
Thermal mass	Heavy vs Light	-0.92	0.08	0.49
Ventilation Strategy	Mechanical vs Natural	0.29	-0.07	-0.60
Shape	Square vs Rectangular	-0.38	0.01	0.10

Table F2 – Impact of building design elements on arbitrage performance for the E0 Operational Strategy. Mean values of the absolute differences are included (2017 RTP results)

Building Design Element	**Comparison Description**	**Parameter (Unit)**		
		Differences in Electricity shifted (% of peak loads)	**Differences in Net Cost (£/m^2)**	**Differences in Electricity Consumption – No BSS (kWh/m^2)**
Energy Efficiency	Best Practice vs Part L	3.92	1.11	-8.09
Glazing	30% vs 80% glazed	0.98	0.32	2.40
Orientation	Southern vs SW, SE, E	0.76	0.14	-0.30
Thermal mass	Heavy vs Light	0.95	0.11	0.49
Ventilation Strategy	Mechanical vs Natural	1.32	0.15	-0.60
Shape	Square vs Rectangular	0.21	0.05	0.10

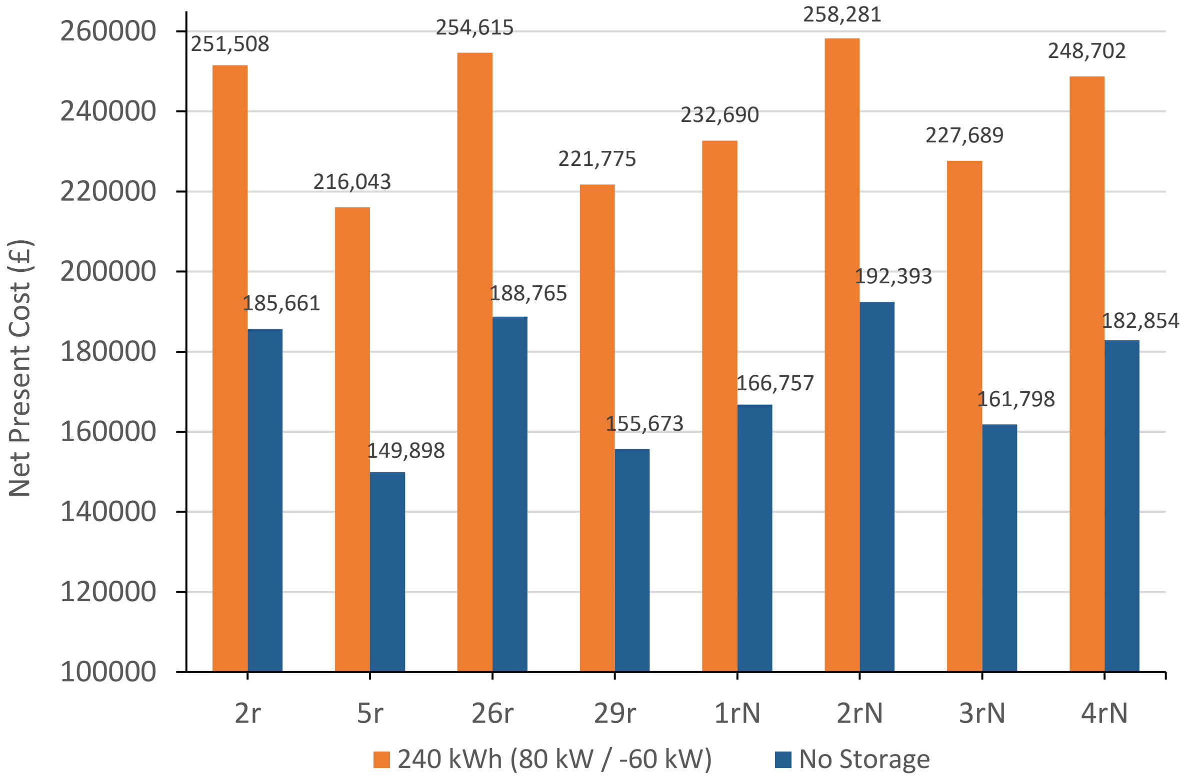


Figure F15 – NPC (£) with and without storage for a 10-year period under E7, with retail revenues considered

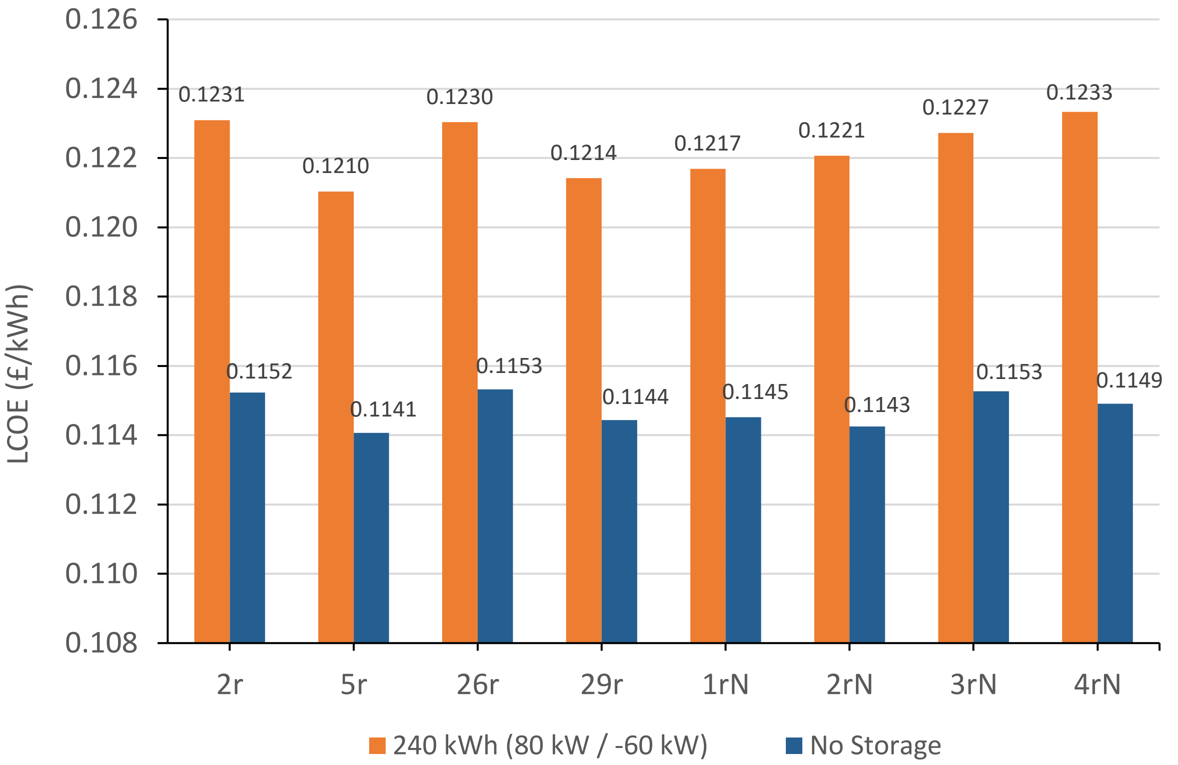


Figure F16 – LCOE (£/kWh) with and without storage for a 10-year period under E7, with retail revenues considered

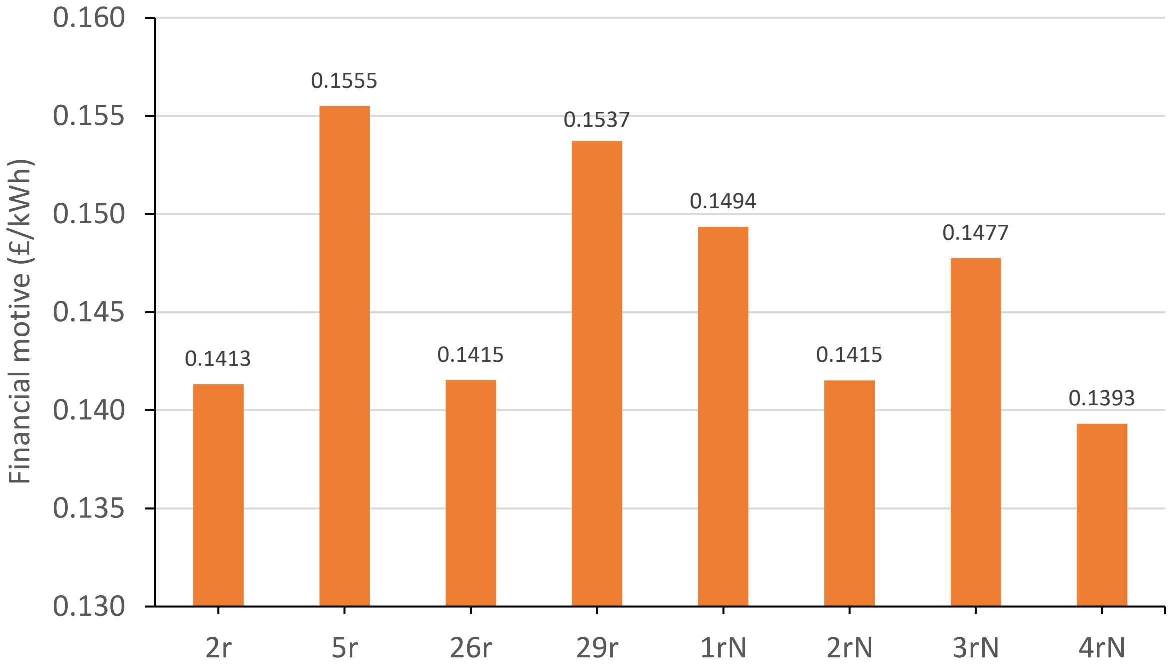


Figure F17 – Financial motive needed based on the electricity shifted (£/kWh) for a 10-year period under E7, with retail revenues considered

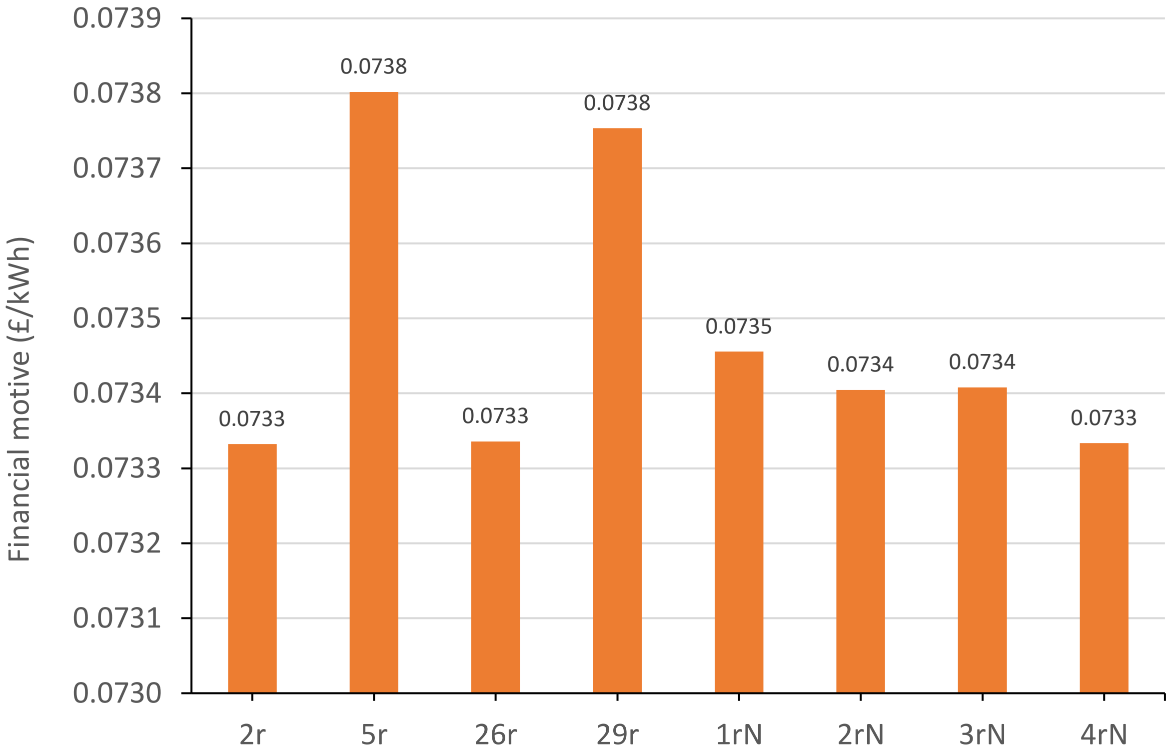


Figure F18 – Financial motive needed based on the electricity shifted and exports (£/kWh) for a 10-year period under E7, with retail revenues considered

Appendix G – Sensitivity Analysis Results

Table G1 – Impact of building design elements on arbitrage performance for the E0 Operational Strategy and the calendar years 2017 and 2018. The mean values of the absolute differences are included in brackets if different from the respective mean.

Building Design Element	**Parameter (Unit)**			
	Mean value of Differences in Electricity shifted (% of peak loads)		**Mean value of Differences in Net Cost (£/m^2)**	
	2017	**2018**	**2017**	**2018**
Energy Efficiency	4.20	3.96	-1.15	-1.39
Glazing	-0.86	-0.67	0.31	0.37
Orientation	1.08	0.95	-0.19	-0.22
Thermal mass	-1.84	-1.87	0.19	0.21
Ventilation Strategy	1.22 (1.72)	1.09 (1.66)	-0.21	-0.26

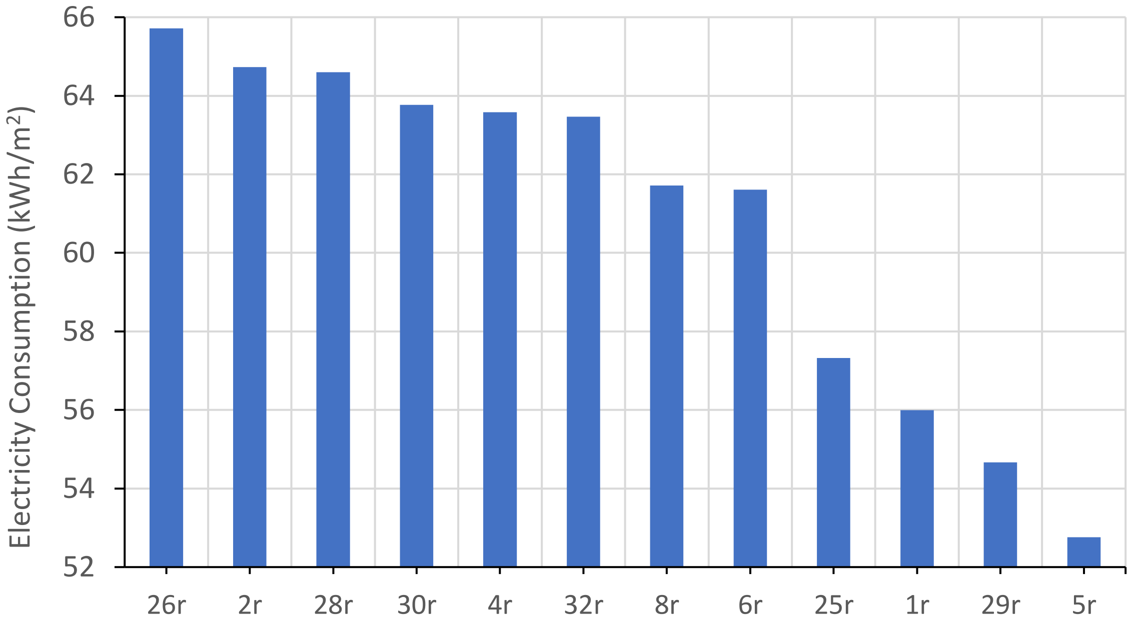


Figure G1 – Total Electricity Consumption without storage for the selected buildings of Chapter 5.3 (2018 RTP results)

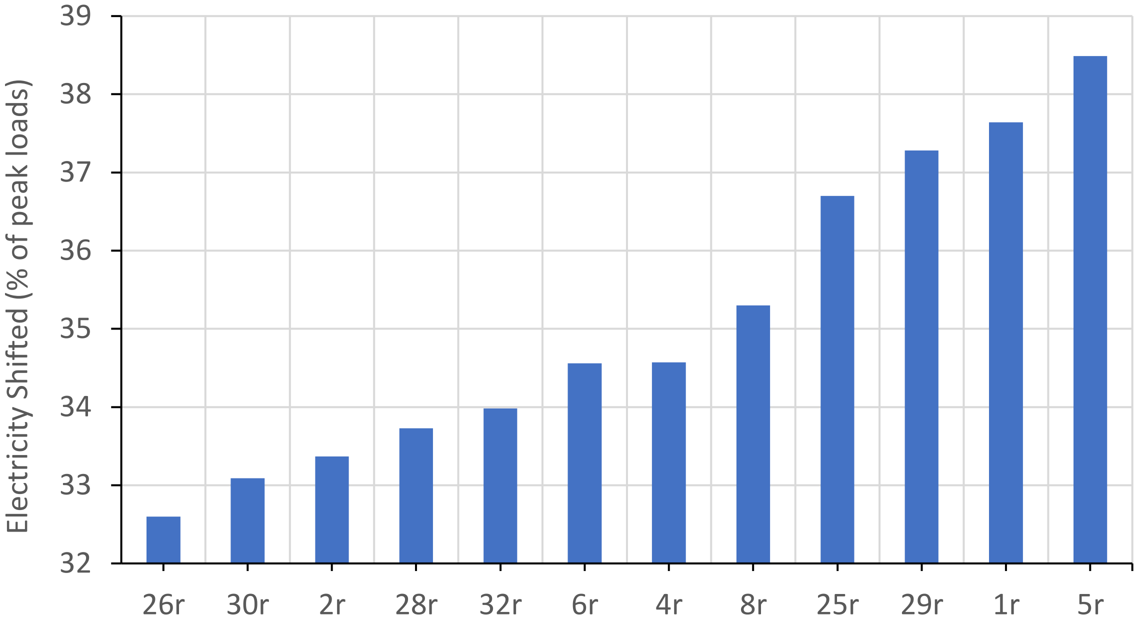


Figure G2 – Electricity Shifted (% peak loads) for Operational Strategy E0, for the selected buildings of Chapter 5.3 (2018 RTP results)

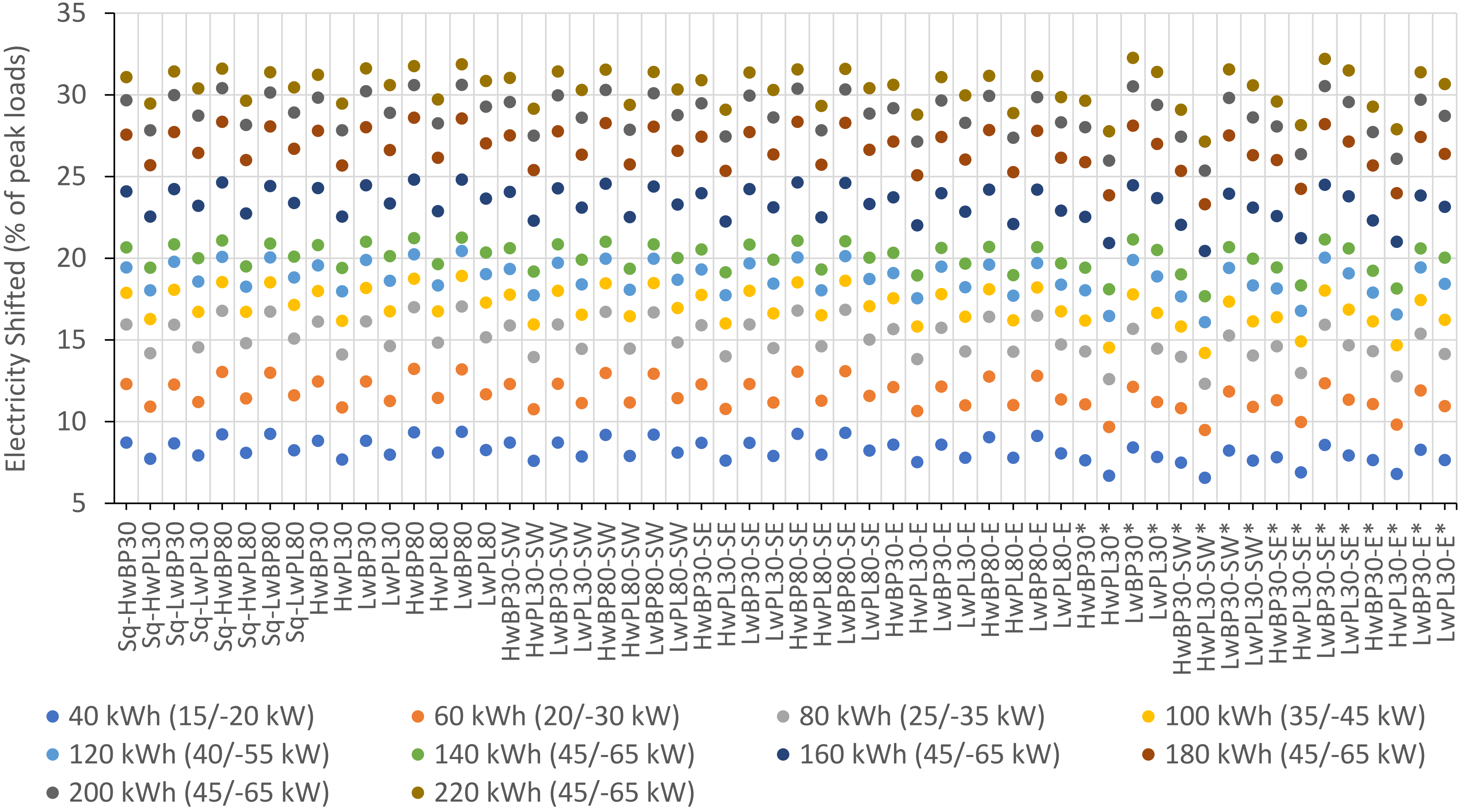


Figure G3 – Electricity shifted (% of peak loads) for all building cases under Operational Strategy E7

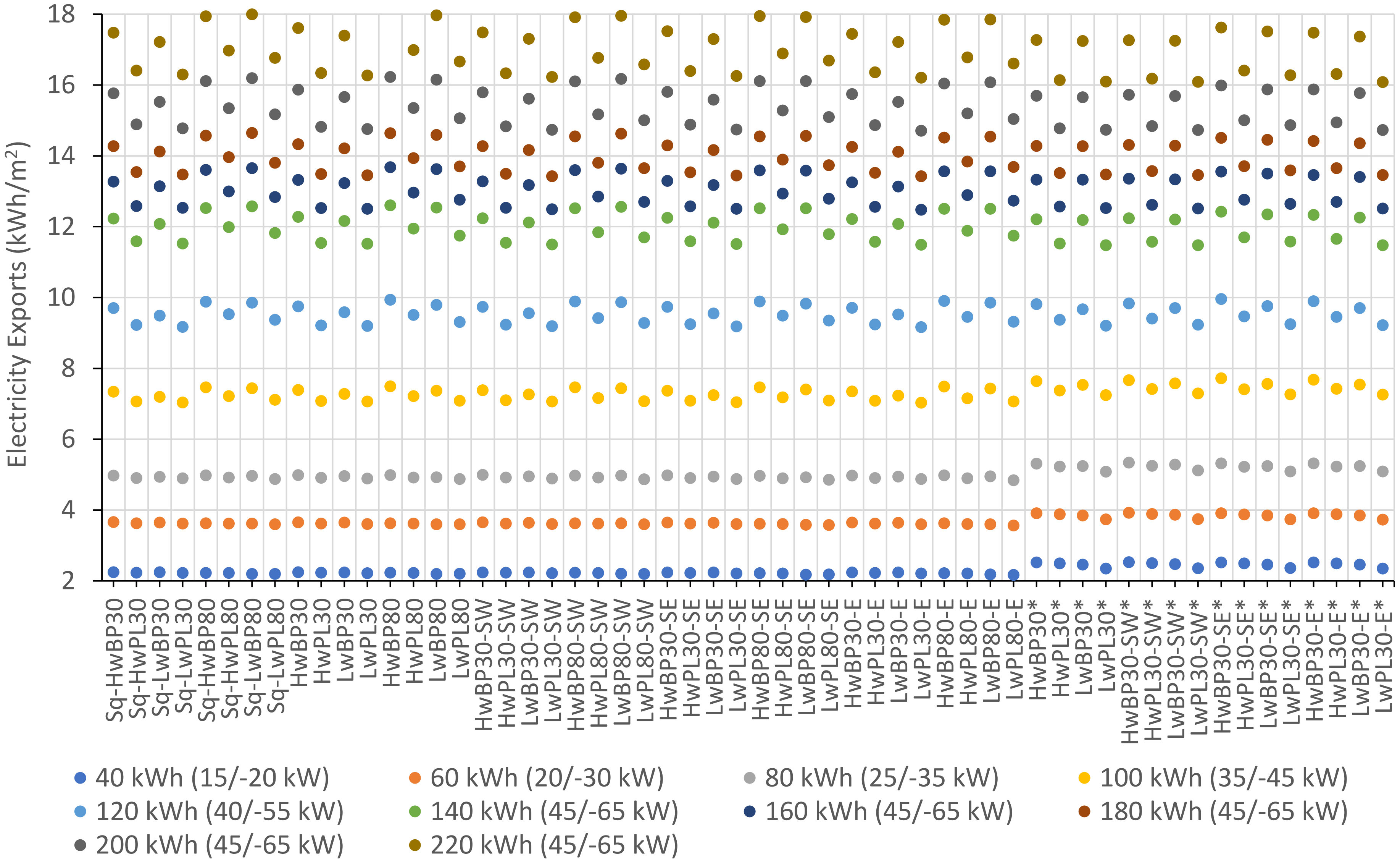


Figure G4 – Exported Electricity (kWh/m^2) for all building cases under Operational Strategy E7

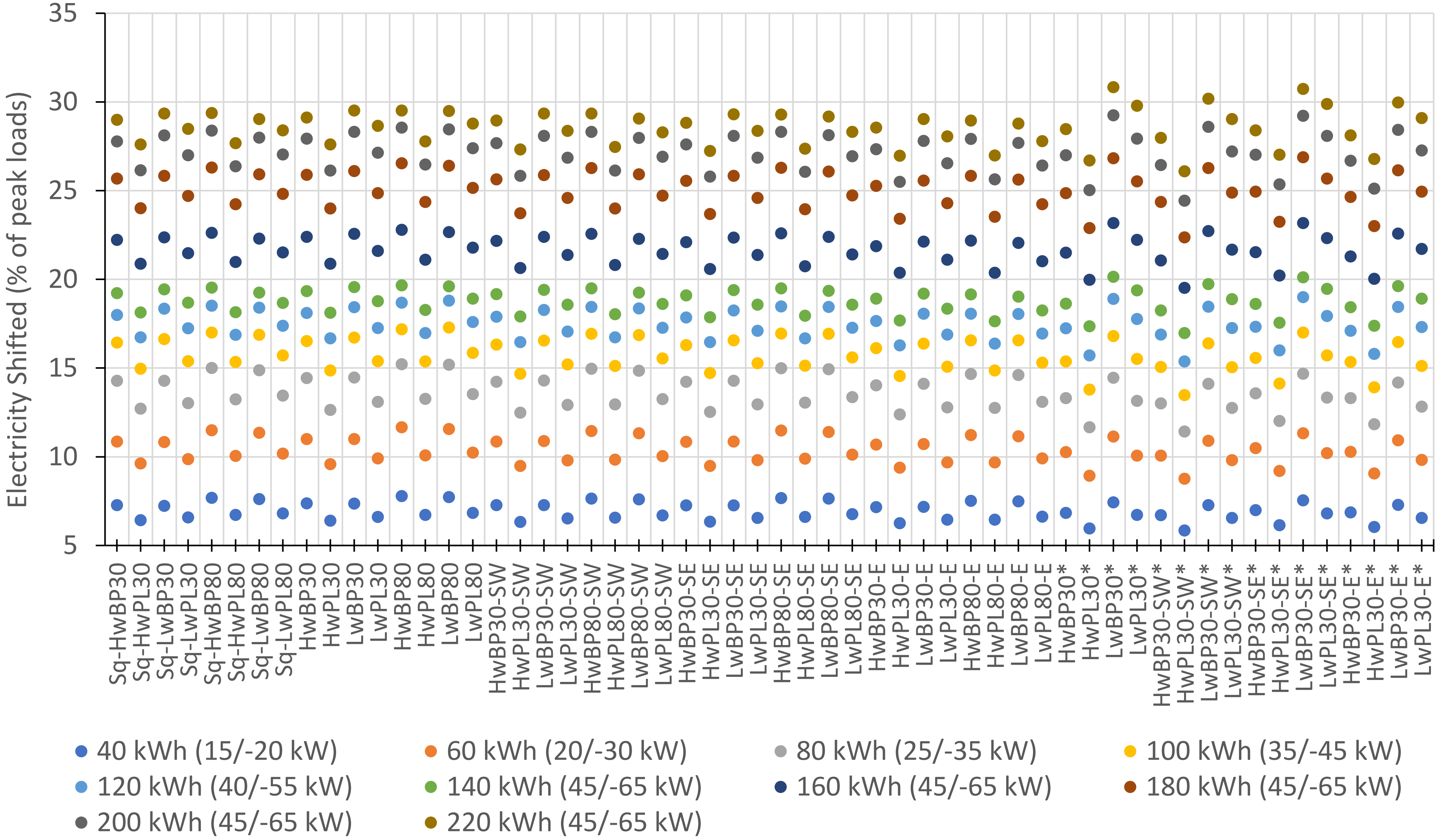


Figure G5 – Electricity Shifted (% of peak loads) for all building cases under Operational Strategy E5

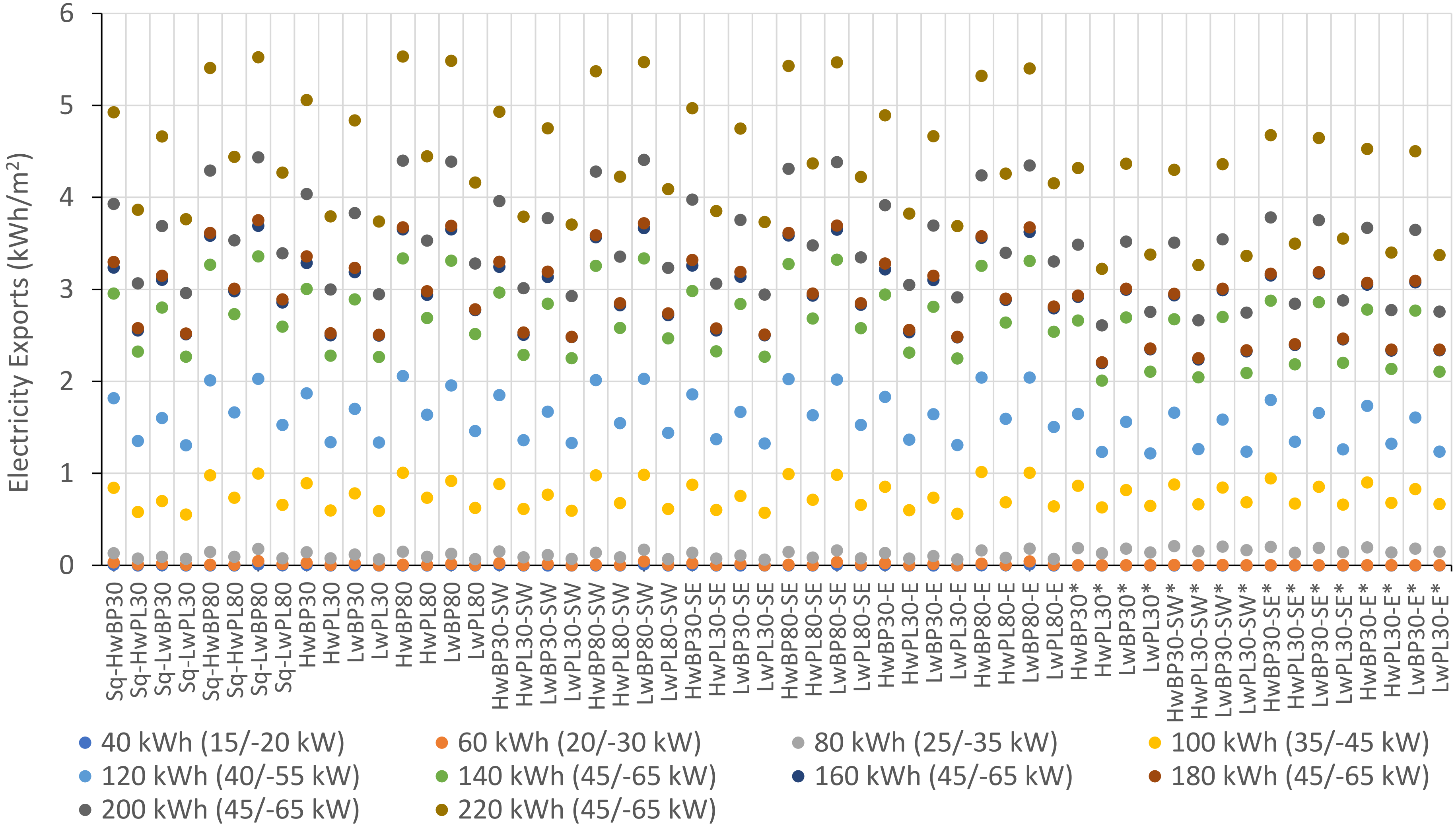


Figure G6 – Exported Electricity (kWh/m^2) for all building cases under Operational Strategy E5

Appendix H – Publications

Three publications are directly related to the current work:

- A. D. Georgakarakos, M. Mayfield, A. H. Buckman, S. A. Jubb, and C. Wootton, “What are Smart Grid Optimised Buildings?,” in *Living and Sustainability: An Environmental Critique of Design and Building Practices, Locally and Globally. London South Bank University, London, 08 – 09 February 2017*, 2018, pp. 21–36.

- A. D. Georgakarakos, M. Mayfield, and E. A. Hathway, “Battery Storage Systems in Smart Grid Optimised Buildings,” *Energy Procedia*, vol. 151, pp. 23–30, 2018, doi: 10.1016/j.egypro.2018.09.022.

- A. D. Georgakarakos, B. Vand, E. A. Hathway, and M. Mayfield, “Dispatch Strategies for the Utilisation of Battery Storage Systems in Smart Grid Optimised Buildings,” *Buildings*, vol. 11, no. 10, 2021, doi: 10.3390/buildings11100433.