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Simulation of a Smart Grid

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Abstract

As the current British electricity network shifts towards a more efficient and smarter grid, there is a strong desire amongst the new energy market participants to be able to quantify the return on investment of smart grid initiatives. Additionally, the electricity industry faces the major task of understanding how energy storages contained in smart grids perform at the different stages of their life cycle. The Simulink block diagram environment offers an attractive simulation method to provide solutions to these growing challenges. Indeed, it allows to generate robust, flexible and scalable models of complex electricity networks. The aim of this project is to lay the foundations for a future software capable of evaluating the return on investment of a range of smart grid assets. An unprecedented literature review of the current UK energy landscape is presented. A Simulink micro-grid model is developed to assess the efficiency of a typical local smart grid. The model is then employed to provide novel insights on the non-linearity of batteries in a smart micro-grid environment. Suggestions for future research to bring the model to maturity are additionally outlined.

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Acronyms

AC Alternating Current. 21, 26, 28–30

BEIS Department for Business, Energy and Industrial Strategy. 15

BM Balancing Mechanism. v, 5, 6, 9

BMU Balancing Mechanism Unit. 6

BOA Bid Offer Acceptance. 6, 7

BSC Balancing and Settlement Code. 5, 6, 9

CCS Controlled Current Source. 22, 24, 28, 30, 32

CDCM Common Distribution Charging Methodology. 39

CSG China Southern Power Grid. 2, 34

DC Direct Current. 26

DCC Data Communications Company. 10, 17

DER Distributed Energy Resource. 1, 9, 11, 12, 14, 15, 17, 22, 38, 40

DNO Distribution Network Operator. 3, 4, 7–10, 12–16, 39, G1

DPA Data Protection Act. 17

DSR Demand Side Response. ii, 11, 13, 14, 38, 40

DUoS Distribution Use of System. 16, 35, 38, 39

EFR Enhanced Frequency Response. 7

ENW Electricity North West Ltd. 7

ESC Energy Systems Catapult. 13, 17

EV Electric Vehicle. 1, 12–15, 34, 37

GDPR General Data Protection Regulation. 17

GEMA Gas and Electricity Markets Authority. 5

GUI Graphical User Interface. 19, 20

IEEE Institute of Electrical and Electronics Engineers. 1

MBD Model-Based Design. 19

MO Market Operator. 5, 6

NETA New Electricity Trading Arrangements. 5

NG National Grid Plc. 1–3, 6, 34

NGESO National Grid Electricity System Operator. 3, 6, 7, F2

NGET National Grid Electricity Transmission Plc. 7

NP Northern Powergrid. 7

NRPW Network Replicating Private Wire. 16, 39

Ofgem Office of Gas and Electricity Markets. 5, 7–9, 11–14, 40

PS Price Signal. 11

PV Solar Panel. 9–13, 18, 21, 22, 24, 30, 32–37, F2

RIIO Revenue Incentives Innovation Outputs. 7, 8

RMS Root Mean Square. 25–27, 29–32, 34

ROI Return On Investment. 2, 18, 38, 39

SG Smart Grid. 1, 2, 18, 19, 38

SHET Scottish Hydro-Electric Transmission Plc. 7

SM Smart Meter. 8–11, 16, 17, 38

SME Small and Medium Enterprise. 12

SMP Smart Metering Program. 9

SO System Operator. 3, 5–7, 9, 14

SOC State Of Charge. 12, 23, 25, 31, 32, 35–37

SP Settlement Period. 6, 9, 10

SPEN ScottishPower Energy Networks Ltd. v, 4, 7, 14

SPT Scottish Power Transmission Ltd. 7

SSE Scottish and Southern Energy Plc. 7

STOR Short Term Operating Reserve. 7

TNO Transmission Network Operator. 3, 6–8, G1

UKPN UK Power Networks. 7, 15

V2G Vehicle-to-Grid. ii, 13, 14, 34

VPW Virtual Private Wire. 16, 39

WPD Western Power Distribution. 7

1 Introduction

What is the potential return on investment for all stakeholders arising from a shift to a smart electrical grid?

This question has become increasingly relevant in recent years in the UK as its national electrical grid is in the midst of a transformation. Indeed, climate change, new technologies and continuous innovations disrupt the traditional models of the current electricity system, gradually transitioning to what is termed as a Smart Grid (SG).

Even-though there appears to be no unique definition for an SG, an interpretation by Dr. I. Colak from the Electrical and Electronics Engineering department of the Nişantaşi University (Istanbul, Turkey) adequately summarises the different perspectives from academia, industry and competent authorities regarding this subject. Indeed, he states that an SG "can be defined as [a set of] self-sufficient systems, which allow integration of any type and any scale of generation sources to the grid that reduce the workforce, [allowing to deliver] sustainable, reliable, safe and quality electricity to all consumers" [10]. This definition, supported by the renowned Institute of Electrical and Electronics Engineers (IEEE), therefore encompasses the three following trends which are currently converging to produce game-changing disruptions in the electrical field:

1. The rapid and growing Electrification of the majority of everyday life assets such as domestic appliances, heating, as well as Electric Vehicles (EVs). As a matter of fact, the UK is at the forefront of the EV revolution, with projections from the National Grid Plc (NG) suggesting a leap from 195,000 vehicles at the end of February 2019 [11], to EV stocks which could total as high as 10.6 million by 2030 [12];

2. The rise in Decentralisation of energy generation and storage, also referred to as Distributed Energy Resources (DERs). This term depicts the wide range of local energy production and storage technologies which do not rely directly on the high-voltage electricity grid and are present "within the distribution networks or on the customer side of the [eletricity] network" [13].

3. The ongoing process of Digitalisation, which according to Gartner's IT Glossary can be described as the "use of digital technologies to change a business model and provide new revenue and value-producing opportunities" [14].

These three trends act in a virtuous cycle, enabling, amplifying and reinforcing the development of an SG beyond their individual contributions. In addition, three factors fuel the potential for disruption by grid edge technologies. First is their exponentially decreasing costs and continuous technical enhancements. Second, is their enabling role for innovative business models built around empowered customers. Last, is the sizeable improvement potential of the electricity network's asset utilisation rate. Indeed, in the UK the ratio of maximum electricity load to total potential energy generation capacity was calculated to be only 67% in 2014 [15]. Furthermore, a comparative study between the China Southern Power Grid (CSG) and the NG showed that such value remained in a 65% to 71% interval between 2009 and 2014 [15], hence exposing the ample room for improvement possible in this sector.

The common goal for all stakeholders in implementing an SG is therefore to reduce infrastructure and operational costs while transitioning to a more sustainable energy network. The ultimate aim down the line being to deliver electricity to the end user at the lowest possible rate, solely using renewable energy sources.

Deeply rooted into this prevailing objective, this paper seeks to build a novel framework which will serve as the foundation for the development of a future software able to quantify the cost savings and Return On Investment (ROI) of SG initiatives for all stakeholders. Being the initial step of an ongoing effort, the aim of this research is to first model an SG on a micro-grid scale and assess the influence of stationary storage capacity on the power consumption of this micro-grid. This is achieved through the use of numerical simulations, which can be defined as the implementation and automation of mathematical models to represent a physical system [16]. For this research, the smart micro-grid was simulated using the Simscape™ modelling environment, itself a subset of the MATLAB® Simulink® block diagram environment specifically built for multi-domain simulation and model-based design [17].

This paper is structured as follows. An exhaustive literature review (Section 2) covers all the background information on the current grid problems and the numerous smart grid initiatives in Great Britain at all development stages. Some examples of research on battery modelling are also presented, exposing one of the main limitation of the current smart grid projects. Section 3 builds on the insights of the literature review, to depict the particular focus of this work. A detailed description of the simulation model's structure and entities is then provided in Section 4, coupled to an explanation of the validation process. The obtained results are presented and critically discussed in Section 5, before concluding the report (Section 6) and opening up on suggestions for future work (Section 7).

Please note that throughout this report, the use of terms such as "energy", "power" and "grid" amongst others, exclusively refer to electrical energy, electrical power and electrical grid. This research does not consider other power sources such as gas, fuels and biofuels which do not feed into the electrical grid before being consumed by the end-user.

2 Literature Review

2.1 UK's Electricity Grid

2.1.1 Structure

In the UK electricity grid, energy starts its journey from centralised generators such as gas or nuclear power-plants, delivering three-phase electricity at a voltage of 25kV and a nominal frequency of 50Hz. Shortly after the current leaves the power station, it is fed into a first substation containing a "step-up" transformer which raises the voltage to 275kV or 400kV [18]. This increase in voltage allows to transfer electricity through cables more efficiently than in its initial 25kV state. In fact, the power in a circuit corresponds to the rate at which energy is absorbed or produced within this circuit. Power is given by the following simple relationship [19]:

$$P = V \times I \tag{2.1}$$

where P is in Watts (W), the voltage V in Volts (V) and the current I in Amperes (A). Therefore, for a given power, an increase in voltage permits a reduction in current. Additionally, the energy losses in cables which are mainly due to resistive heating of the wires, are quantified using the following formula [20]:

$$E = a \times R \times I^2 \tag{2.2}$$

where energy E is calculated in W, a corresponds to the number of line coefficient such that $a = 1$ for a single phase cable and $a = 3$ for a three-phase circuit, and the resistance R given in Ohms (Ω) is that of one active line. Hence, it becomes clear that to transmit a certain amount of power, it is more advantageous to maximise the electricity's voltage, in order to minimise the necessary current and thus reduce the associated cable losses. Nevertheless, this voltage rise comes at the expense of additional cable insulation requirements. A detailed study of this optimisation problem can be found in Appendix E of the NG's *2014 Electricity Ten Year Statement* [21].

Once the 400kV electricity flows out of these "step-up" substations, it is then carried via three-phase overhead lines owned and maintained by the relevant regional Transmission Network Operator (TNO) [22]. The transmission system as a whole however is operated by a single System Operator (SO), the National Grid Electricity System Operator (NGESO), which is responsible for ensuring the stable and secure activity of the entire high voltage network [22]. This transmission system terminates at the "major grid supply points", which correspond to large "step-down" substations [23]. At these "step-down" transformers, the voltage is lowered to 132kV and the three-phase electric power is then carried through the distribution network. This system is segmented in regional distribution services areas, each of which are managed by a Distribution Network Operator

(DNO) [24]. DNOs are then responsible for further reducing the transported electricity's voltage via a serie of "step-down" substations, before delivering the power directly to the different end-users. Typically in GB, heavy industry customers receive electricity at 33kV, while town, villages and light industrial factories get distributed power at an 11kV rating. For domestic and commercial usage, the three-phase power is further de-rated via secondary substations, which transform the 11kV electricity down to either 415V for large buildings, but more commonly to 230V for households [23]. It is worth noting however, that the end-users do not buy directly electricity from the DNOs, but rather from energy suppliers who rent DNO lines and trade on the wholesale energy market.

Figure 2.1 below displays the different layers of the UK grid, from electricity generation to end-user consumption. An additional Table G.1 with the principal grid characteristics can be found in Appendix G.

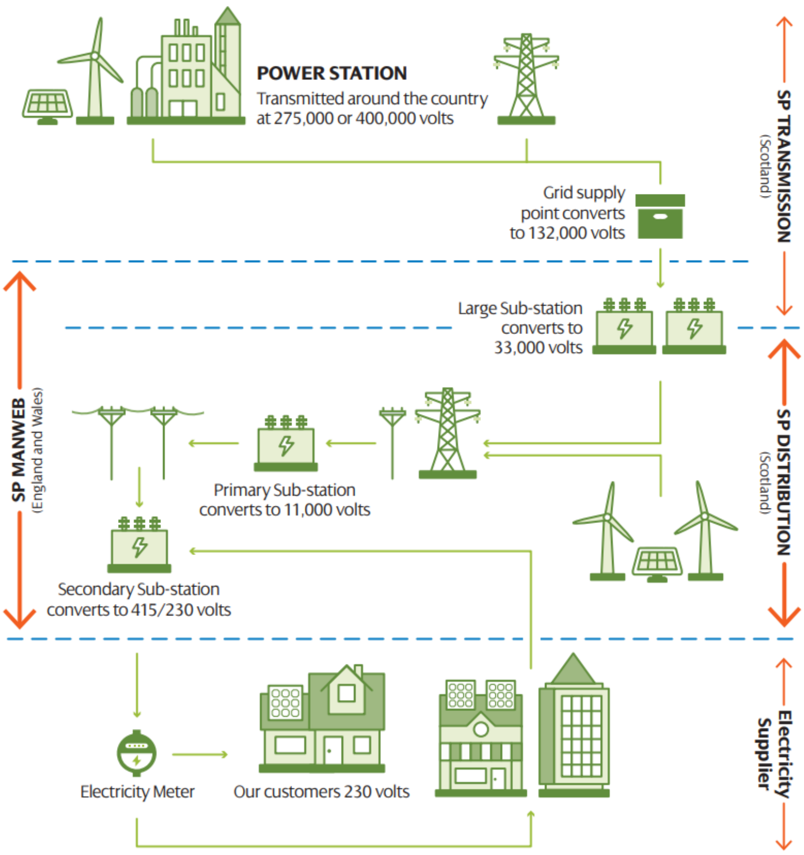


Figure 2.1: Diagram of the UK electricity system by ScottishPower Energy Networks Ltd [1].

2.1.2 Principal Stakeholders

As outlined in the previous Section 2.1.1, the generation, transmission, distribution and retail of electricity in the UK involves numerous stakeholders. The most significant ones are presented here.

Regulator

The Office of Gas and Electricity Markets (Ofgem) is the official regulatory body for the energy markets in GB. This entity is itself governed by the Gas and Electricity Markets Authority (GEMA) [25], and is funded by taxes on the energy companies it regulates. The main task for Ofgem is to ensure that the energy network operates as efficiently as possible while maintaining a fair competition between the market participants. The aim being to guaranty the protection of consumer interests by ensuring the lowest possible electricity prices for the end-users. This can be done through investigations into energy supplier behaviour, which can lead to fines for the suppliers which have breached their license conditions [26]. As stated by Ofgem, the regulator guarantees consumer protection by [26]:

- Promoting security of the UK's energy supply, and ensuring it is sustainable for future users;
- Promoting value for money regarding energy tariffs;
- Regulating government schemes as well as helping deliver them;
- Supervising and developing competition within the energy market, such as between suppliers [27].

The latter point is quantified by the Ofgem through the promotion of "liquidity" which, as explained in [28], is "a measure of the ability to buy or sell a product – such as electricity - without causing a major change in its price and without incurring significant transaction costs." Liquidity is a key performance indicator for the energy market, and it is typically monitored by looking at "churn". This corresponds to the number of times electricity present in the market is traded by the different players [28].

In its quest to protect consumer interests, the Ofgem has also been using the *Electricity System Operator Incentives Framework* [29] since April 2018. This relatively recent scheme is employed to assess the performance of the electricity SO. It involves the use of rewards or penalties applied to the SO, based on a holistic evaluation of its latest performance [29,30]. Moreover, the Ofgem also works in close cooperation with the energy Market Operator (MO), by supervising from a legal perspective the implementation of the Balancing and Settlement Code (BSC) [31].

Market Operator

As the UK electricity market is a competitive environment with numerous actors involved, it is necessary to have a governing body ensuring the proper functioning of this nation-wide trading place. This role is currently guaranteed by ELEXON, which is responsible for administering the Balancing and Settlement Code [31].

The BSC was instated in March 2001 as part of the New Electricity Trading Arrangements (NETA) [32], and it contains the governing arrangements for the electricity Balancing Mechanism (BM) in GB [31]. Indeed, the BM is the principal tool employed by the System Operator to balance electricity supply and demand close to real time [33]. Such mechanism is necessary due to the current absence of large-scale energy storage capacity, hence requiring the production of electricity at the time of demand. Where the SO predicts that there will be an imbalance between energy generation and consumption over a certain time period, the SO will accept a "bid" (generation reduction or demand increase) or "offer" (generation reduction or demand increase) from a market participant [33]. The players involved are typically suppliers, which, based on customer consumption forecasts, buy electricity either directly from generators, or through energy traders and power exchanges on the wholesale market [32]. The following diagram from ELEXON in Figure 2.2, displays the functioning of this Balancing Mechanism.

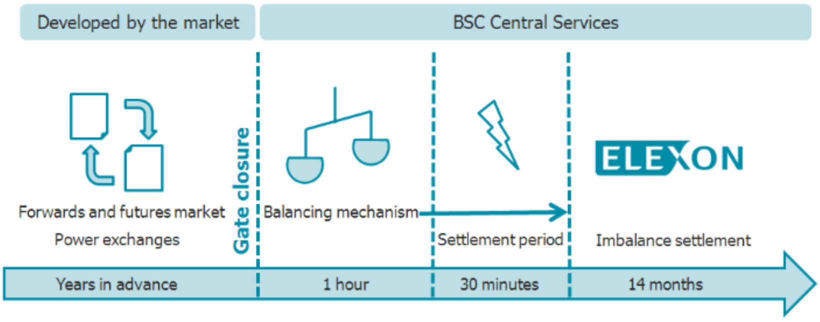


Figure 2.2: Diagram of the implementation of the Balancing Mechanism [2].

The operation of the BM relies on the real-time flow of data and information between the SO and the market participants which are organised into Balancing Mechanism Units (BMUs) [33]. As depicted in Figure 2.2, for each half hour trading period, known as a Settlement Period (SP), companies can trade months and even years in advance. This exchange can continue up to one hour before each SP, this milestone being called the gate closure [2, 31]. The trading activity up to this point must be notified to ELEXON. In parallel with this trading activity, generators are also required to disclose their intended level of production for each Settlement Period, providing the SO with an electricity output forecast [33].

Following gate closure, the System Operator accepts the “bids” and “offers” required to balance the electricity on the transmission network. This leads to the delivery of instructions to market participants, called Bid Offer Acceptances (BOAs). Upon accepting these instructions, the participants must then guarantee that their Balancing Mechanism Units produce the required eletricity output. A failure to do so results in an imbalance, which will be subsequently penalised by ELEXON up to 14 months after the SP [2, 33] .

In fact, the key function of the Market Operator is to undertake the settlement of activities carried out during the Balancing Mechanism [33]. To achieve this, ELEXON utilises data from a multitude of sources, including the SO's instructions based on BOAs, along with over 1.25 million daily meter readings [32]. Once this data is processed and reconciled, the MO applies the Balancing and Settlement Code to compare a market participant's contracted energy volume with the actual metered quantity of electricity used or generated during the Settlement Period. If a party is in imbalance of its contracted volume (both above or below the agreed quantity), then it will be subject to disparity charges [2, 32]. These imbalance penalties are designed to reflect the prices associated with the BOAs selected by the System Operator to balance the energy flows in the transmission network, as well as reserve scarcity [34, 35]. Through this process, ELEXON handles approximately £1.5 billion of the customer's funds every year [32].

System Operator (SO)

The National Grid Electricity System Operator, which became a legally separate entity within the NG group on the 1st of April 2019, is the SO for the UK electricity grid. Its main role, outlined in the previous Section 2.1.2, involves balancing the transmission system (TNO network), ensuring that the supply of electricity matches demand on a second-by-second basis through the Balancing

Mechanism [22, 32]. As detailed earlier, the wholesale energy market participants such as the generators and suppliers face financial incentives to ensure that they meet their contractual energy volumes. However, unexpected deviations in production or consumption mean that the market will not always be able to balance supply and demand [36]. This mismatch can lead to changes in network frequency which, if not dealt with, can cause system outages. Hence, the NGESO plays a critical role in ensuring that the system frequency remains stable, within its statutory limits of 49.5Hz and 50.5Hz [37].

To accomplish such a feat, the SO first needs to accurately predict the energy output and consumption for the future period of interest. This is typically done by considering historical data, combined with weather forecasts, and in some particular cases the planification of upcoming major events such as international sports competitions. Secondly, as mentioned earlier, the NGESO receives the exact output forecast from the generators at the time of gate closure. Finally, the SO employs a range of balancing methods to ensure the network's stability. By using its Enhanced Frequency Response (EFR), it is capable of dynamically altering the active power in the transmission network in response to changes in system frequency. This allows to maintain the frequency closer to 50Hz thus preventing any faults [38]. Additionally, to face unexpected power imbalances in the system, the NGESO possesses amongst others, two types of "reserves". The "fast reserve" provides rapid and reliable delivery of active power via the instructions and Bid Offer Acceptances imposed on the generators and suppliers [39]. The Short Term Operating Reserve (STOR) service on the other hand, allows any technology connected to either the transmission or distribution network, and with the ability to increase generation or reduce demand by at least 3MW, to participate in the energy trade as a complement to the regular participants [40].

Transmission Network Operators

A Transmission Network Operator is the company in charge of transmitting the electrical power produced by generation plants to regional or local Distribution Network Operators via a high voltage (transmission) system. In the UK, this transmission network is owned, developed and maintained by three regional TNOs. These are the National Grid Electricity Transmission Plc (NGET) for England and Wales, the Scottish Power Transmission Ltd (SPT) for southern Scotland, and the Scottish Hydro-Electric Transmission Plc (SHET) for northern Scotland and the Scottish islands groups [22]. The TNOs rely on charging electricity producers and suppliers for the usage of their cables. However, in order to protect the consumer's interests, the Ofgem sets the maximum amount of revenue which the TNOs can recover from their users [22, 32]. These price controls are based on the Revenue Incentives Innovation Outputs (RIIO)-T1 model for network regulation which were implemented on the 1st of April 2013 and will cover the period up to the 31st of March 2021 [41, 42].

Distribution Network Operators

Similar to a TNO, a Distribution Network Operator is a company licensed to distribute electricity in the UK. DNOs own and operate the system of towers, transformers, poles, cables and meters which distribute energy from the TNOs at the "grid supply points" [23], directly to the industrial, commercial and domestic users [24]. Great Britain counts 14 different DNO regions which are managed by the following 6 operators: Scottish and Southern Energy Plc (SSE), ScottishPower Energy Networks Ltd (SPEN), Northern Powergrid (NP), Electricity North West Ltd (ENW), Western Power Distribution (WPD) and UK Power Networks (UKPN) [43]. Currently, the local DNO needs to be informed when any source of electricity generation is connected to the grid. For systems producing less than 3.7kW, only a notification of the DNO is required, while for larger power generators an approval preceded by a network study is necessary [24]. Alike TNOs, DNO companies rely on charging electricity producers and suppliers to use their medium to low voltage wires. Again, the regulator (Ofgem) is responsible of determining the maximum amount of revenue which the DNOs can collect from their consumers [32]. These price controls have been set using the RIIO-ED1 model and have been defined for the period running from the 1st of April 2015 to the 31st of March 2023.

2.1.3 Limitations

Having studied the structure as well as the different key participants of today's electricity grid (Sections 2.1.1 and 2.1.2 respectively), it is becoming apparent that the current energy path, as it is now, is not suited to support the three ongoing trends identified in Section 1, which are Electrification, Decentralisation and Digitalisation.

The first major constraint, is the vertical integration of the grid, which is centred around large power plants. In 2017, still 50.0% of electricity generated in the UK came from fossile-fuel plants [44], while 20.8% was produced from nuclear power stations [44]. This centralised generation which is typically performed in low population density areas, therefore requires the transportation of electricity across significant distances to geographically reach the demand. The transmission network consists of over 8,700km of high voltage cables [45, 46], while electricity is also transfered along 827,040km of medium and low voltage lines (distribution network) [47]. As explained in Section 2.1.1, there is the presence of significant resistive heating of the current flowing in the cables. Hence, electrical system's experts from Imperial College London and Sohn Associates have estimated in 2014, that the overall electricity transportation losses accounted for: 4.2-4.9% of energy supplied in urban networks; 4.9-6.4% in semi-urban areas; and 6.0-9.1% in rural regions [48]. Another study requested by the UK Parliament and carried by the Citizens Advice Bureau has further revealed that "about 1.7% of the electricity transferred over the transmission network is lost" [49, 50]. In addition, a "further 5.0-8.0% of the electricity transferred over the [various regional] distribution networks is [also] lost" [50–52]. Based on Ofgem's calculations for the "societal cost" of energy losses, it is estimated that almost £1.3 billion perished in 2018 due to grid inefficiencies [53]. Ofgem's "societal cost" includes the "value of the electricity lost, the cost of providing the additional transportation capacity on the transmission and distribution networks and the costs of the environmental impacts associated with the additional generation that is needed to cover losses" [54].

The second limitation affecting the current grid is related to its lack of flexibility. Currently, the electricity network does not possess any large scale energy storage capacity due to its exorbitant development cost and limited engineering feasibility. Therefore, as mentioned in Section 2.1.2, electricity generation is dictated by demand and requires a second-by-second matching to guarantee system stability [33]. However, as can be seen in Figure E.1 in Appendix E, the average daily load profile for a representative British household is extremely uneven. A load profile, comprises of the power consumption of a load (e.g. household) expressed in Watts (W) over a 24 hour period. The power consumption is typically measured every half-hour as this is the latest Smart Meter (SM) standard (detailed in Section 2.2.1), but its granularity can vary depending on the data source.

As displayed in Figure E.1 from Appendix E, a conventional domestic load profile shows a first medium consumption increase between 8:00 and 12:00, before peaking to its maximum value from approximately 18:00 to 21:00. Therefore, in order to ensure that this peak-time demand is met, the current generators are designed to have a power output capacity marginally superior to the peak load. This implies that, outside of peak hours the generators only operate at a fraction of their maximum designed capacity as no energy storage is available. In fact, according to Dr. H. Farhangi, it is estimated that approximately 20% of the total generation capacity solely serves to meet peak demand [52]. This major grid inefficiency is viewed by the Ofgem as the most important issue to solve in the near future [55]. If the current grid model remains unchanged, the regulating body has predicted that over the next decade, the UK will need more than £100 billion of capital investment in its electricity generation and transmission infrastructure to accommodate the projected 19% rise in electricity demand by 2030 [55–57].

The third disadvantage of the current electricity grid, is the unidirectionality of its structure. As previously exposed in Section 2.1.1, the energy and its associated data, flows majorly in a single direction: from generators down to the end-user [58, 59]. Indeed, the standard electricity meters installed in households or businesses do not support two-way communication between suppliers/DNOs and the customers [60–62]. This characteristic therefore hinders the spreading and integration of Distributed Energy Resources such as the installation of domestic or commercial Solar Panels and wind turbines. Furthermore, the standard meters, unlike SMs which are discussed in the following Section 2.2.1, do not permit to have automated half-hourly demand measurements. They rely on the user who is tasked of reporting its consumption to the suppliers only on a monthly, quarterly or even bi-annually basis [61]. As detailed in Section 2.1.2, the efficiency of the Balancing Mechanism and the Balancing and Settlement Code is highly dependant on the accuracy of the demand forecasts for each half-hourly Settlement Period [2]. Hence, relying on monthly historical consumption data from standard meters, considerably reduces the predictions' accuracy for the BM. This in turn requires greater efforts from the SO to balance the grid and incurs higher settlement charges to the different market participants. Ultimately, this rise in balancing and settlement costs triggers down to the consumer who will face increased electricity rates and thus higher energy bills.

2.2 Smart Grid Initiatives

As described in Section 2.1, the electricity grid remains relatively inefficient, and under its current form is not best suited to tackle the growing challenges brought by Electrification, Decentralisation and Digitalisation (Section 1). Nevertheless, a range of smart grid initiatives are in progress. This Section 2.2 presents the most promising state-of-the-art projects being developed, with a particular focus on technologies close to market (less than 5 years) or already deployed.

2.2.1 Smart Meters

In order to overcome the issues associated with standard electricity meters (Section 2.1.3) and gradually shift towards a smarter electricity grid, the British Government launched the Smart Metering Program (SMP) in 2011. Its initial aim was to ensure that "every home and small business in the [UK] is offered a smart meter by the end of 2020" [63]. The SMP is currently in the second phase of its delivery. In the first stage, the Government instated commercial and regulatory frameworks to support smart metering, ensuring the proper functioning of the system, and protecting the privacy of the customers [63]. The second phase, the meter rollout, began in November 2016 and should run at least until the end of 2020. This is the period during which households and small businesses receive their SMs, which are installed by their electricity supplier [63, 64]. As of the 31st of December 2018, 12.65 million SMs were in operation in households, representing 25% of all domestic meters [63]. Similarly, smaller non-domestic sites saw the installation of 1.12 million SMs, accounting for 35% of all non-domestic meters [63].

Smart Meters are a new generation of meters which give consumers half-hourly information on their energy consumption (expressed in pounds and pence) [64]. This half-hourly demand is also automatically transmitted to the customer's supplier through the Data Communications Company (DCC) [64,65]. This data is then aggregated by the DNOs to determine the exact volumes of energy moving across the various parts of their distribution network at each point in time [62]. For users (retail market), SMs effectively put an end to estimated billing and allow the customers to access a broader range of energy tariffs with more specific time periods, replacing the traditional dual peak/off-peak rates [44, 64, 65]. At a wholesale market level, SMs also allow to more accurately predict the consumption for each half-hourly Settlement Period, thus reducing the system imbalance and associated costs at the gate closure. As explained in Section 2.1.3, this permits the more efficient running of the grid, and ultimately a reduction in end-user energy tariffs [64]. Furthermore, SMs are central to the UK's shift to a more flexible energy network [65]. Indeed, their ability to communicate with a measurement device within a micro-generator [44] opens up new sources of flexibility and promotes customer engagement in the electricity market [64]. This enables a shift from the traditional consumer role, to a "prosumer" position. The term "prosumer" refers to a user both locally producing and consuming energy (e.g. roof mounted Solar Panels) [66].

2.2.2 Renewable Energies

In 2007, the European Union leaders agreed on a binding legislation for all EU members regarding climate and energy targets for the year 2020. This plan, entitled the *Climate and Energy Package* [67] and enacted from 2009 onwards, defined the 20–20-20 targets to be met. These are:

- the reduction by 20% of the greenhouse gas emissions based on 1990 levels;
- the fact that 20% of the EU energy supply must come from renewable energy sources;
- a 20% increase in energy efficiency of each national electricity network.

Renewable energy production capacity has been constantly increasing in the UK since the year 2000 [44]. Additionally, following the establishment of these European directives [67], GB saw a considerable uptake of electricity generation from wind and solar sources. In fact, in 2017 wind and solar supply rose by 29.1% from a year earlier to reach a total output of 61.5TWh [44]. This came thanks to an increase in wind and solar capacity of 22.6% and 7.3% respectively (with respect to 2016). Great Britain has in fact surpassed the EU targets, as in the second quarter of 2018 its renewables accounted for 31.7% of the national energy production [44].

In the near future, these trends are set to be bettered, as renewable energy sources, particularly at a local scale (e.g. domestic or office building installations), undergo continuous performance improvements as well as price reductions. This is especially true for Solar Panels (PVs), which have seen their price per power output fall by approximately 20% every year since 2011 [68]. In June 2018, the average solar energy cost was estimated to be approximately £1.8 per W. Nowadays, PVs are technologically extremely consistent and can operate at maximum capacity over long time scales measured in multiple years if not a full decade. Their main limitation actually comes from the amount of solar irradiance they receive, making it difficult to further improve their efficiency. The latest innovation developed in 2012 and put on the market three years later, consists in bifacial PVs. These effectively capture light both directly from the sun as well as from the surrounding reflecting surfaces. This technology is claimed to be able to improve by up to 50% the efficiency of PVs, however it is still not widely spread [69]. In the UK, the main constraint to the implementation of local panels arose from the energy metering system as explained in Section 2.2.1. However, with the current rollout of Smart Meters allowing two-way communication, an exponential rise of their integration into households is to be expected, reinforcing the ongoing trend of Distributed Energy Resources detailed in Section 2.2.4.

2.2.3 Demand Side Response

One of the most advanced smart grid initiative to date, is Demand Side Response (DSR). This technology is identified by Ofgem as the first of three "new flexibility methods" [70,71]. It is seen as an essential characteristic of current and future smart grid systems, giving the possibility to an energy supplier to control the electricity consumption at the consumers' premises. As defined by the UK Government, DSR is a "way in which users can participate in a smart energy system, shifting the time that they use energy, or turning their consumption up or down in response to [Price Signals (PSs)]" [72]. Said PSs are described as "financial incentives that influence the behaviour of generators and end users" [73]. This innovation once again relies on Smart Meters and their half-hourly energy demand readings for a "live" assessment of the user's consumption. The fact that it does not require the use of any other smart grid installation such as PVs or batteries, explains this technology's advanced market penetration. The principal aim of DSR is therefore to impact consumer behaviour through "time-of-use" tariffs, and thus benefit the overall system by helping to balance supply and demand [70]. Indeed, as discussed in Section 2.1.3, one of the main limitations of the current grid is the peak time demand occurring during the 18:00-21:00 period.

One of the UK leaders in DSR is the new electricity supplier Octopus Energy which began trading in 2016 [74]. To take full advantage of the SM capacities, this company launched *Agile Octopus* in 2018. To replace the traditional and inefficient on/off peak double tariff scheme commonly applied by other suppliers (e.g. Economy 7), Octopus Energy offers a pricing profile to its customers. This system implemented directly in their SMs, provides a "time-of-use" tariff to the users with half-hourly rates based on daily load profiles [74]. This therefore allows the customers to adjust their consumption to the times when the wholesale price of energy is cheapest and the strain on the grid lowest. Additionally, Octopus Energy also guarantees that the electricity supplied is generated by renewable sources, thus further promoting the idea of a smart grid, integrating low carbon energy generation coupled to consumption control.

2.2.4 Distributed Energy Resources

The second primordial "new flexibility method" [70,71] stated by Ofgem, is the integration of Distributed Energy Resources into the electrical grid. DERs refer to low carbon electricity generated locally at individuals' households or offices. This type of energy flexibility is mainly dependent on the reduction in cost of solar and wind power and its presence is thus expected to increase dramatically in the coming years following the ongoing trend of cheapening PVs. Additionally, through the use of local matching (described in Section 2.2.7), it has the potential to significantly reduce energy transmission and distribution losses (see Section 2.1.3) by shortening the distances between the energy generators and the loads (consumption). Diminishing losses would ultimately improve the grid efficiency and reduce its overall operational cost, therefore reducing the energy bills of the end-users. On the wholesale market level (above 11kV to 415/230V transformers), DER consists of renewable energy sources on an industrial or aggregator scale. On the retail market level which is the "interface" between customers and suppliers/DNOs (415/230V network), DER is supported by local energy generation at both residential and Small and Medium Enterprise (SME) scale [57].

In 2018, DERs accounted for 30% of the UK's energy mix, and according to the Crown Commercial Service they are expected to increase to 71% by 2030 [56]. In order to better assess their integration into future smart grids, the Smart Energy Cities (RM6108) program was launched in 2019 by the Crown Commercial Service. The aim of this project is to get increased access to data to make informed decisions and consider the cities' energy needs in a solution based approach rather than as individual product areas. These Smart Energy Cities encompass smart street lights, Electric Vehicle charging, as well as renewables. Additionally, the Smart Cities will include sensors to monitor electricity usage, pollution, temperature and other environmental factors [56].

Another ongoing program in the UK focussing on DERs, is the Smart Energy Islands project led by Hitachi Europe Ltd and funded by the European Regional Development Fund through a £10.8 million input [75]. This project based in the Isles of Scilly seeks to serve as a model smart grid by creating an intelligent network integrating DERs as well as EVs on an unprecedented scale. It is constituted of 100 solar powered homes which are expected to deliver 448kW of energy, along with 190 businesses with energy monitoring and control systems. Additionally, 10 of the households will be smart homes using supplementary smart technologies such as batteries and air source heat pumps. A platform will also be developed to manage electricity throughout the islands by balancing supply, storage and consumption, allowing the islands to increase their energy independence [75].

2.2.5 Storage

The last principal "flexibility method" depicted by Ofgem and the UK Government in their 2017 report on *Upgrading Our Energy System* [71], is energy storage. This technology implies the use of batteries or other forms of storage such as water gravity pumps to stock electricity when it is plentiful, or when the power generated is too important for the network cables to carry. This stored electricity can then be fed back into the system at peak demand times using a smart controller. Hence, such technology offers considerable opportunities for load balancing in micro-grids, especially when integrated into a system including Distributed Energy Resources such as PVs. In addition, with the latest uptake of EVs on the roads in the UK (69% year on year growth in 2018 [76]), more and more re-purposed Lithium-Ion batteries are becoming available for stationary storage systems. Thus, their price is expected to continue dropping in the coming years [77], rendering domestic storage an even more attractive option for smart micro-grids.

However, batteries remain the weakest link of the smart-grids. Indeed, their charge and discharge behaviours are highly non-linear, and their properties such as the battery capacity and State Of Charge (SOC) degrade due to ageing and heating amongst others. The paper *Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment* by Bolun Xu et al [4] proposes a semi-empirical lithium-ion battery degradation model to assess the battery cell life with respect to life cycles. Similarly, the article *Modeling Lithium Ion Battery Degradation in electric vehicles* [3] exposes a new ageing model for Lithium Ion batteries, founded on theoretical models of crack propagation. Eventhough battery performances over time are still not perfectly understood and require additional models to be developed, they still represent a major opportunity to improve the current grid's inefficiencies.

The leading company on the UK's smart electricity storage market is Moixa [78]. Their state-of-the-art Moixa Smart Battery [79] is suited for domestic applications and connected to both household PVs and the grid. Its internal software (developed and owned by Moixa) allows the battery to be charged when solar power generation exceeds household consumption, and then deplete at peak demand times. It also offers the novel possibility of charging from the grid at night when electricity rates are cheap [78], effectively acting as an automated DSR. Additionally, Moixa also develops a cloud-based software platform called GridShare that connects storage devices to the grid. GridShare enables smart battery management by analysing energy generation at the storage location, as well as consumption patterns, weather forecasts and available "time-of-use" electricity tariffs [80]. Moreover, GridShare also includes a platform for aggregating storage systems, thus acting as a virtual power plant [80], helping balance grid supply and demand. The business model of Moixa relies on the selling of batteries coupled to a monthly customer subscription for users of the GridShare platform [78, 80]. Moixa is also involved in the Smart Energy Islands project (see Section 2.2.4), as it supplies the batteries along with the GridShare software to 10 "smart" households [75].

2.2.6 Vehicle-to-Grid Implementation

As mentioned in Section 2.2.5, sales of EVs are currently booming in the UK. Indeed, they now represent more than half of the new vehicle registrations [81], and totalled 209,000 cars [82] on the UK roads as of April 2019. Furthermore, the UK Government has recently committed to electrify 25% of its vehicles by 2023 [83]. Due to their relatively high battery capacities of up to 100kWh (Tesla Model S P100D [84]), they constitute a serious challenge for the grid and its overload. However, the presence of significantly large batteries also provides the opportunity for large scale DSR through the implementation of Vehicle-to-Grid (V2G) systems. As per stationary storage, V2G consists in feeding back energy from EVs into the grid via two-way chargers. The aim is once again to alleviate peak demand as well as counter the "flat" (spread over the day and out of sync with peak demand) electricity production of renewable energy sources [85,86]. Numerous V2G projects are currently in development in Great Britain, but will still require a couple of years to become fully operational.

The Ofgem, funded in 2016 the My Electric Avenue program [87]. This three-year project seeks to determine the capacity provided by EV charging DSR from both domestic and commercial chargers [87]. The preliminary results showed that when flexible chargers were used, at least 60% more EVs could top up using the lower voltage electricity grids, without requiring any network infrastructure upgrade [87]. Flexible charging consists in allowing EVs to be charged at periods when there is less strain on the electricity grid. This requires EV users to use "time of use" tariffs available via smart meters, to identify the off-peak time and lowest energy price periods. In parallel, Ofgem has also conducted a research in 2018 on charging infrastructure [83]. Following this study, it has proposed reforms that will free up existing grid capacity to allow new generators and on-site power production to get connected to the grid more quickly to locally provide sufficient energy for EV chargers.

Other consortium projects related to this topic are currently running, such as Vehicle-to-Grid Britain [76] regrouping: DNOs, Nissan (car manufacturer) as well as Energy Systems Catapult (ESC) amongst others. This study seeks to better understand EV users' behaviours and develop the necessary V2G charging infrastructure accordingly, including smart chargers for DSR integration. In addition, another initiative driven by ScottishPower Energy Networks Ltd is the Charge project [88]. This program became in 2018 an Ofgem Electricity Network Innovation Competition (NIC) sponsored project. The DNO has identified two main issues with the policy drive from the UK Government to reach non-fossil fuelled transport by 2050. The first one is the unrestricted domestic charging infrastructure installed without prior notification. Indeed, this reduces the spare capacity on existing grid assets, and as the EV uptake progresses, this will lead to overloads requiring network reinforcements [88]. Their second point is regarding new connections for public EV charge points. These will require a serious upstream reinforcement of the grid to facilitate the transition to electrified transport [88]. In order to reduce the lead time for bringing new charging capacity in line with EV demand (currently growing at half the pace of EV deployment [76]), the Charge project proposes a novel charging network solution. The objective is to merge transport and electricity planning to assess where charge points will be required by users and how their location will impact the grid infrastructure. The preliminary results of the Charge initiative show potential savings of £135m by 2030 and £795m by 2050 in charging infrastructure costs. CO2 emissions are also said to be potentially reduced by 0.9 million tonnes by 2030 and 5.66 million tonnes by 2050 [88].

Other actors are also involved in the integration of V2G technology. Indeed, the electricity supplier Octopus Energy currently proposes the OctopusGo scheme for its customers, with extremely cheap night rates to charge their EVs [74]. Furthermore, mainstream auto manufacturers such as Peugeot are deploying new DSR technologies directly into their cars, with the possibility of delaying the vehicle's battery charging via a timer (available on the Peugeot 508 Hybrid [89]).

2.2.7 Flexibility Market and Local Matching

The uptake of numerous novel smart grid technologies has therefore enabled the appearance of a new local energy flexibility market based on local matching. Piclo in their whitepaper, define local matching as "the netting off of demand and generation between one or more end-users and a generator that are served by the same part of the distribution network and within the same settlement period" [73]. Additionally, this so called "flexibility market" enables owners of Distributed Energy Resources (e.g. storage operators, EV users, prosumers) to trade their flexibility in electricity supply or demand to the System Operator, but more commonly to another market participant at a local distribution level [90]. The opening of the electricity market has therefore led to the creation of a range of flexibility trading initiatives, the most promising of which are detailed in this section.

One of these projects is the Dynamic Demand 2.0 [91] developed by Open Energi [92] and launched in 2011. This software automates and optimises a system of DERs to reduce energy costs and provide "live" flexibility to enable a fully renewable energy network. The platform is able to co-ordinate a large scale of DERs and then trade the various flexibilities across the energy markets. Through Dynamic Demand 2.0, Open Energi currently manages over 3,500 assets spread over 400 sites, including utilities, developers and industrial technologies [92–94]. Note that the Open Energi diagram in Figure A.1 in Appendix A, provides a complete overview of the different types of energy flexibilities currently existing [5].

On a similar concept, Moixa's GridShare platform (detailed in Section 2.2.5) enables businesses to get involved in the flexibility market [80]. Indeed, companies equipped with Moixa's battery are able to respond to local constraints such as an EV charging station's rapid demand increase. Such system has the benefit of providing an additional source of income to the participating businesses, as well as eliminating through this local matching the need for costly transmission upgrades to bring power to the newly created loads (e.g. EV charger) [80].

In addition to Open Energi and Moixa's products, the Smart Energy Cities project described in Section 2.2.4 also seeks to take full advantage of the flexibility market. Indeed, one of the project's outcomes will be the creation of a catalogue function in the electricity flexibility market of the cities involved [56]. This will simplify the route to purchase commoditised energy products for the different market participants, thus further opening up the market and increasing competition.

Following onto this increasing flexibility trading trend, some more traditional market participants such as DNOs have taken action. A prime example is that of UK Power Networks which has defined a Flexibility Roadmap [95, 96]. It consists in a plan for a more flexible and lower cost future network, affecting its 8.2m electricity customers. Indeed, UKPN has estimated that by 2023 the market for flexibility on its distribution network could be worth over 200MW, equivalent to the current demand of approximately 130,000 homes [96]. Additionally, UKPN has identified three major benefits from this future rise in grid flexibility, which are [95]:

- Lower electricity costs thanks to a deferral of the capital expenditure associated to an upgrade of its cables;
- New revenue opportunities from flexibility tenders (bids or demand) for the retail market participants with DERs;
- A stronger network enabled by the reduction of peak demand thanks to DERs.

In order to make the most of these opportunities, UKPN is developing its DER flexibility through the Piclo Flex platform created and managed by Piclo (formerly known as Open Utility) [95].

Piclo Flex [97] is an independent marketplace for the trade of smart grid flexibility services on the wholesale market level. Piclo have created a software platform where all flexibility providers can access the flexibility bids. Their dashboard displays future predicted congested areas in the distribution network, due for example to transformer maintenance services or large events drawing more electricity than usual. These tenders which display the required power and contract duration are visible in advance, therefore allowing flexibility sellers to plan for future revenue opportunities [98]. The buyer is the DNO which has identified the future need in a particular area, and buys following an auction the energy from the qualified DER providers located in proximity of that congested area [97]. Piclo is currently working with all 6 UK DNOs and the trade is open to all flexibility sellers larger than 0.5MW [73, 97]. In September 2017, they have received £1.9 million in funds from the UK Government Department for Business, Energy and Industrial Strategy (BEIS) for their flexibility marketplace [97]. The aim of Piclo Flex is to make, as defined by Piclo, "peer-to-peer electricity trading a reality" [97]. This has emerged as a promising way to promote DERs whilst helping to take some strain off the grid's higher voltage levels, and thus permit significant transmission costs' savings.

2.2.8 Novel Business Models

As mentioned in the opening lines of this report (Section 1), the evolution of the electricity landscape in GB has led to the apparition of novel business models. In the whitepaper *Local Grid Charging: Exploring the incentivisation of local energy* [73], Piclo states that despite the large interest of market participants in the Piclo Flex platform (see Section 2.2.7), "the growth potential of this local matching opportunity is being hindered by legacy network charging mechanisms that offer no financial incentives to either generators or end-users" [73].

The current system used by the DNOs, consists in defining Distribution Use of System (DUoS) charges to energy suppliers, to recover the costs associated to the transportation of electricity in the distribution network to reach the end-user. These charges are then passed on by the suppliers to their customers [73]. DNOs also issue credits to any generator exporting electricity to the local grid. However, these credits are determined on the assumption that the local energy produced is entirely consumed by the end-users locally, hence providing a saving to the grid. This estimated grid saving is then directly used to determine the value of the credits. However, not all generators are locally matched in practice. This charging method therefore assumes that production on the distribution level always offsets demand at higher transmission levels [73]. In reality, if generators are in supply-heavy locations or are generating outside of peak demand hours, they actually provide surplus energy and increase the strain on the grid [73]. In these cases, with the current DUoS charges, end-users still fund generator credits even though the generators are providing no benefit to the network and even adding to its operational costs. Moreover, there is also no incentive to encourage more local generation in high-demand areas [73].

To overcome this inefficient charging scheme, Piclo proposes two Locational DUoS business models in its whitepaper [73]. The first one, Model 1, consists in removing the current DUoS credits provided to supposedly local-matching generators. Instead, end-users that matched their consumption with local generation would be charged a lower "matching DUoS" rate [73], paid using the credits normally given to the generators. The total amount recovered through this alternative DUoS charging would not change, but simply be reallocated. For this model to work, it would require a method to share the savings through discounted rates between the matching end-users and local generators [73]. Model 2 on the other hand slightly modifies the allocation of DUoS to generators and end-users. Indeed, a percentage of the savings made from the diminished reinforcements required for the network along with the reduced high transmission losses would be spent to increase the discount allocated to local matching. Therefore, generators would still receive DUoS credits for matched generation, but end-users would also pay a lower "matching DUoS" rate for their locally match energy consumption [73]. The main advantages of these two models are their fairness and scalability. However, as identified by Piclo, the price signals proposed are relatively low, which might not be sufficient to affect the user behaviour [73]. In their white paper, Piclo also study the potential of Network Replicating Private Wires (NRPWs) and Virtual Private Wires (VPWs), but both of these incentivisation methods are said to have poor scalability due to their important initial setup costs [73].

2.2.9 Data Availability

All of the smart grid initiatives rely on the use of Smart Meter data as previously detailed in Section 2.2.1. The Commercial Crown Service expects a leap of 4000% in Smart Meter data production between 2010 and 2020 [56], which could be used to improve the grid efficiency via the multiple smart grid projects. The half-hourly consumption data in the SMs is stored for 13 months in the actual meter (also stores 2 years of daily consumption) [64]. However, the access to the current data generated by SMs is still extremely restricted. Indeed, only the energy suppliers can make direct usage of their customer's consumption. The other stakeholders have to go through the three following protection layers to get hold of this data:

- The General Data Protection Regulation (GDPR), which is an EU regulation enforced since May 2018 [99];
- The 1998 UK specific Data Protection Act (DPA), which regulates the processing of personal data, and as stated by the Information Commissioner, places "obligations on organisations who wish to process personal data and giving individuals rights in respect of their own personal data" [100];
- The approval of the Data Communications Company managing the output data from the SMs.

To address this major constraint, the Government and Ofgem have launched the Energy Data Taskforce [58] which is run by Energy Systems Catapult. The aim is to deliver recommendations on how the industry and public sector can work together to improve data availability and transparency (results from this report are expected to be delivered by the end of 2019) [58]. Previously, the ESC has also produced the *ESC Energy Data Review* [58] which is a data model and catalogue that provides a "whole-system snapshot" of the current data landscape [101]. Five main issues with today's electricity data landscape have been identified. Firstly, the systems and organisations are fragmented and there are few examples of high quality centralised data repositories. This goes along with the added fact that the data standards and protocols are inconsistent and the data sets often incomplete. Furthermore, the report also highlights the rigidity of data privacy rules and raises the lack of incentives for data sharing or quality assurance [58, 59].

The *ESC Energy Data Review* [58] also explains the potential benefits of a more transparent energy data framework. The overall efficiency of the energy system would be improved and as mentioned in Section 2.2.1, it would also ameliorate the demand forecasting capabilities, thus allowing for a more effective DER response. Improved data visibility and access would also allow an increase in the number of market competitors, thus leading to the desired ultimate aim of reduced energy tariffs for end-users.

3 Problem Motivation and Specification

Following onto this exhaustive literature review (Section 2) on the current grid's limitations and impossibility to satisfy future demand governed by the three trends of Electrification, Decentralisation and Digitalisation, it became clear that significant benefits can stem from the modelling of smart micro-grids. Keeping in mind the ultimate objective of delivering a future software able to quantify the ROI of SG initiatives for all stakeholders, the development of the initial simulation model prioritised robustness and flexibility to support the future iterations of the model.

The extensive study of Smart Grid initiatives carried in Section 2 has also put into light some major limitations affecting the implementations of smart energy projects. As depicted in Section 2.2.5, the main difficulties to assess the benefits of smart micro-grids are mainly related to the connected energy storage devices. These form what can be termed the "weak link" of the smart energy loop. Indeed, as depicted in Section 2.2.2, the micro-generators such as PVs and wind turbines now operate consistently over long time scales, even reaching a decade for PVs [69]. In fact, they function near their maximum capacity and as efficiently as the materials employed allow. Moreover and most important of all, their sources of inefficiencies are well understood by researchers and the energy market participants [68]. As detailed in Section 2.2.2, the principal source of uncertainty regarding the performance and efficiency of PVs, is the actual irradiance from the sun [69]. A similar statement can also be made regarding the performance of wind turbines, which are, as explained by O. Florin and R. Eugen in their *Efficiency assessments for some state of the art wind turbines in the coastal environments of the Black and the Caspian seas* [102] now majorly restricted by their environmental factor rather than the technological one.

Regarding energy storage however, this statement in drastically different. Indeed, numerous papers [3, 4] have already attempted to model the characteristics of batteries, but they still remain the greatest source of uncertainty in smart grids. Additionally, to the author's best knowledge, no previous research combining battery ageing simulations with a scalable smart micro-grid has already been published.

In the scheme of the long term aim of producing an ROI quantifying software, this paper thoroughly describes in Section 4 the development procedure and validation of a robust and scalable smart micro-grid simulation model. However, it is believed that the main source of novel insights which will stem from this research will concern the impact of battery characteristics in a smart grid environment. Hence, the results and critical discussion carried in Section 5 focus on a parametric study of the battery variables and their impact on the grid's ROI. The principal metric to assess their non-linear impact on the micro-grid is selected to be the smart grid's daily energy consumption drawn from the distribution network.

4 Simulation Model

4.1 Model Overview

4.1.1 Software and Environment Selection

As depicted in Section 1 and further explained in the extensive literature review (Section 2), a Smart Grid consists of numerous entities interacting with each other, forming a closely tied and interconnected network. To model this multi-agent system, it was therefore necessary to select an appropriate simulation environment, keeping in mind the restricted time frame of less than 4 months to conduct this research. The results of comparative studies on the advantages and limitations of the different agent-based modelling softwares available (AnyLogic [103] and Mosaik [104] amongst others) were examined [105–108], such as that of R.J. Allan and its *Survey of Agent Based Modelling and Simulation Tool* [106], as well as the work of M. Pipattanasomporn et al. on *Multi-agent systems in a distributed smart grid: sesign and implementation* [108]. Additionally, the option of Model-Based Design (MBD) was also studied.

MBD consists in a technique to visually address complex network problems associated, for example, to the creation and usage of a mathematical model, as well as the design of complex control, signal processing, or communication systems. From the underlying model, it is then possible to "derive an executable specification" [109] which permits to simulate the real behaviour of the system modelled. Model-Based Design is one of the preferred methodology applied to the design of embedded software in the power industry [94, 109].

Exposed to these multiple simulation options, and considering the short time scale as well as the overall project's aim of producing a robust and user-friendly framework for future projects, it was decided to opt for the Simulink® [110] environment developed by MathWorks®. Simulink is a block diagram environment specifically produced to support multi-domain simulations and MBDs. It includes a Graphical User Interface (GUI), solvers, as well as customisable block libraries allowing the modelling and simulation of dynamic systems such as a Smart Grid [111]. Moreover, Simulink's integration with MATLAB® enables a straight-forward incorporation of MATLAB algorithms into the models. It also gives the possibility to easily export simulation results to MATLAB for further analysis [111], such as a potential micro-grid optimisation.

This model-based approach propagated by MathWorks through Simulink, is extensively used in the power industry research. Indeed, papers such as a *Feasibility Analysis of the Positioning of Superconducting Fault Current Limiters for the Smart Grid Application Using Simulink and SimPowerSystem* by U.A. Khan et al. [112], or the *Intelligent energy management system simulator for PHEVs* *at municipal parking deck in a smart grid environment* by P. Kulshrestha et al. [113] have employed Simulink and particularly the SimPowerSystems™ toolbox for their analysis. In the report from A. Bergmann on the *Benefits and Drawbacks of Model-Based Design* [114], the author identifies the main benefits of using Simulink, which are:

- A Graphical User Interface allowing for simple user understanding as well as making it suitable for documentation purposes, hence considerably reducing the documentation costs [114];
- A library of pre-implemented mathematical models under blocks available from an extensive library [111, 114];
- A hierarchical structure and automatic bug detection, allowing for rapid in-system debugging [114];
- The presence of a specific Simscape Electrical™ (formerly SimPowerSystems) providing component libraries for modelling and simulating electrical power systems [115].

On the other hand, two principal drawbacks are associated to the use of this environment. The first one is due to the platform's independence. Indeed, if code execution time is to be optimised in future projects, it will necessitate the download of device-specific libraries, hindering the porting on another target [114]. The second constraint is related to the limited functions implemented in the Simulink model blocks. If particular functionalities not present in the library are necessary for future research, it will require the coding of proprietary blocks in C-code [114]. It is worth mentioning that the current project did not necessitate the creation of specific blocks as the required ones were all present in the Simscape Electrical library.

4.1.2 Method

Simulink offers three different methods to solve the system modelled. These are the following:

- Continuous: using a variable-step solver such as ODE15s [116];
- Discrete: discretising the electrical system to determine a solution at fixed time steps [116];
- Phasor solution: mainly used to study electromechanical oscillations of power systems [117].

For this research, it is the latter option, the phasor mode, which was used to build the simulation micro-grid presented in Section 4.1.3. Indeed, for the purpose of this project only the quasi-steady behaviour of the system is of interest rather than the transients which are necessary for the study of network stability [118]. In phasor mode, the system components such as loads and transformers are designed to have a very high ban-width, which allow them to move rapidly from one condition to another. Using this quasi-steady method therefore ignores the transient response, and the steady-state response is equivalent to a load-flow [119, 120].

A load-flow study, also termed as power-flow, corresponds to the numerical analysis of the flow of power in an interconnected network. It involves determining all of the states of the system, i.e. (complex) voltage and current, at all the different network nodes [121]. Once the magnitudes and phases of voltage and current are known, it is then possible to calculate the different active, reactive and apparent powers which flow through the system [117, 121].

As its name suggests, the Simulink phasor mode implemented through the Powergui block [116] only computes voltages and currents as phasors. Phasors are complex numbers representing a sinusoidal function whose amplitude, angular frequency and initial phase angle are time-invariant [121]. In load-flow studies, these functions are the sinusoidal voltages and currents at a particular frequency, arising from Alternating Current (AC) generation. Phasors can be expressed either in cartesian coordinates with a real and imaginary part, or in polar coordinates with an amplitude and phase [117]. With the phasor solution method, only a reduced set of algebraic equations rather than the complete differential equations from the state-space model are solved. Therefore, unlike the continuous and discrete methods, the phasor mode does not require a specific solver, considerably reducing the simulation times [117,121]. The main limitation of this solution method remains the fact that the system's solution is calculated only at a single frequency. For this research, the frequency was selected to be 50Hz as it is the targeted operating frequency of the entire UK electricity network [38]. In real-life however, the frequency value will fluctuate between its two stability thresholds of 49.5Hz and 50.5Hz [37]. These variations affect to a minor extent the voltages, currents and power flowing through the system, and these fluctuations are not taken into consideration in this paper.

4.1.3 Scale, Systems and State Variables

The micro-grid model built for this project is displayed in Figure 4.1 below. As mentioned in Section 4.1.2, this model operates with a phasor solution method at a frequency of 50Hz. The network, developed on the base of H. Mita's *Simplified Model of a Small Scale Micro-Grid* [122], comprises of two main subsystems connected together through an agent. This agent corresponds to an 11kV to 230V linear transformer replicating the role of a typical secondary substation (e.g. pole-mounted transformer) found in the UK grid.

The *primary subsystem* (red background in Figure 4.1) also known as the macro-grid, represents the portion of the distribution network between the primary (132kV to 11kV transformer) and secondary substations (11kV to 230V transformer) [1] as depicted in Figure 2.1. This portion of the grid model operates at the UK's standard constant grid voltage of 11kV [7] and comprises of three phases. As can be seen in Figure 4.1, the primary subsystem includes two agents replicating the primary substation as well as the typical light industrial loads found at this level of the grid [8,9] (see Section 4.2 for more details on the individual blocks).

The *secondary subsystem* (green background in Figure 4.1) on the other hand, represents a local micro-grid single-phase circuit operating at a constant voltage of 230V [9]. This subsystem which replicates a typical smart micro-grid found downstream of a secondary substation, integrates three types of agents: Domestic Loads, PVs and a Battery (refer to Section 4.2 for additional details on underlying agent subsytems).

Please note that the number of each agent (one battery, two PVs and three loads) displayed in Figure 4.1 is arbitrary and does not represent the exact individual number of each entity used when performing simulations.

In addition to these agents, the secondary subsystem also includes a battery controller which itself is not considered as a fourth agent. This object was modelled as a separate entity to the battery, to provide an abstraction layer in the model for an easier adjustment to future projects. In total, the model includes six different agents as well as a single object which are each characterised by a range of attributes:

- *Three-Phase Source* – represents the low voltage side (11kV) of a primary substation [8]. Its corresponding attributes are: the generator type; the configuration of its three internal

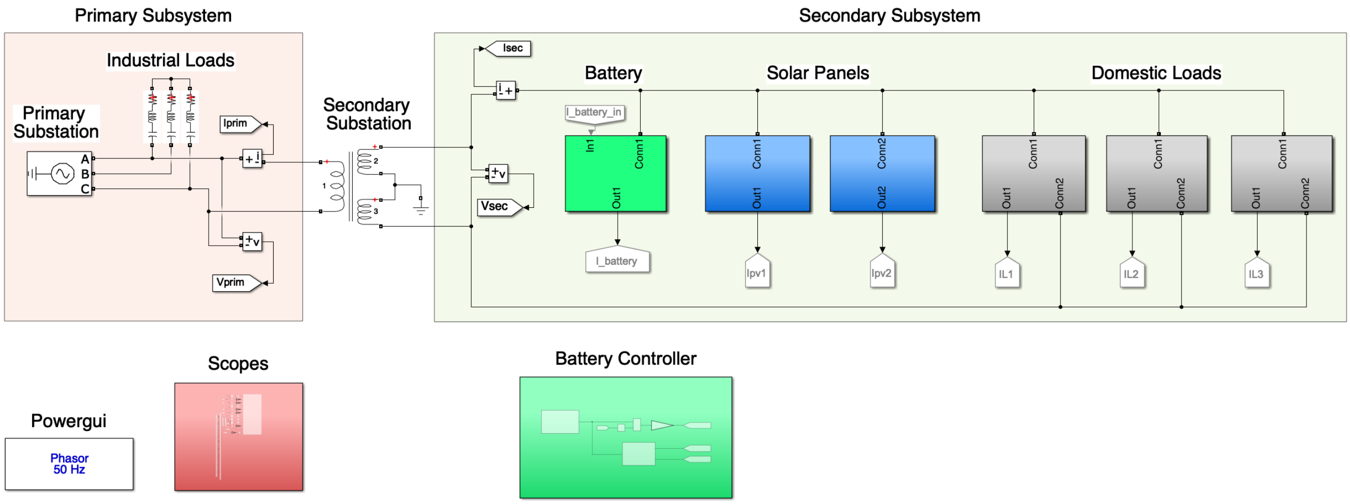


Figure 4.1: Simulink block diagram of the simulation macro/micro-grid model.

voltage sources; the phase-to-phase voltage; the phase angle of the first phase; and the voltage frequency which is fixed to 50Hz as an ideal model of the real grid [37].

- *Series RLC Loads* – enact the role of the light industrial loads consuming energy from the grid at an 11kV voltage. They are described by the following attributes: the load type; the nominal voltage and frequency (50Hz); the active power consumption; the inductive reactive power; and the capacitative reactive power.
- *Linear Transformer* – replicates the secondary substations converting the 11kV input electricity into 230V rated energy. The transformer's attributes are: its number of windings; the nominal power and frequency (50Hz); the voltage, resistance and inductance of each winding; and the overall magnetisation resistance and inductance of the block.
- *Loads* – represent the households consuming electrical power from the grid. These Loads possess a number of attributes which are: their load profile based on historical data [6]; the voltage magnitude which in this case is the constant 230V micro-grid value [8]; the voltage phase; the internal resistance; the initial current amplitude, phase and frequency (the latter selected to be 50Hz). Each Load agent also contains a hierarchical structure of component objects, which are described later in Section 4.2.
- *Solar Panels* – replicate the PV assets themselves, which are expected to become the most common type of Distributed Energy Resources in the near future, as explained in Section 2.2.2. They are characterised by the following attributes: their power generation profile based on historical data [122]; the voltage magnitude (230V) and phase; the internal resistance; the initial current amplitude, phase and frequency (of 50Hz). This agent is also constituted of multiple components presented in Section 4.2.
- *Battery* – as its name suggests, this agent represents a local energy storage capacity which can be found in households or commercial buildings. This battery is determined by the subsequent attributes which are: the initial amplitude, phase and frequency (50Hz) of its Controlled Current Source (CCS). Like the Loads and PVs, the battery also possesses a range of components detailed in Section 4.2.
- *Battery Controller* – supplements the battery agent and models its physical characteristics. The Controller also replicates to a certain extent, the embedded command softwares found in controlled energy storages [79, 80]. This behavioural object includes the following attributes: the storage capacity; the charge and discharge currents' magnitude and phase; the

current upper and lower saturation limits; the minimum and maximum capacity thresholds for respectively, battery charge and discharge; and the initial storage SOC.

Table 4.1 below provides a summary of all entities present in the model along with their corresponding attributes. Note that the "categorical" attribute type corresponds to arrays of qualitative data with values from a finite set of discrete nonnumeric data, as defined in Simulink [123]. Note also that all "cell array" types contain solely numeric data [124].

Table 4.1: Simulink model entities and their characterising attributes.

Entity	Attribute Name	Attribute Type	Description
Three-Phase Source	Generator type	categorical	generator type of the voltage source
	Configuration	categorical	internal connection of 3 internal voltage sources
	Phase-to-phase voltage	double	internal phase-to-phase voltage (V_{RMS})
	Phase angle of phase A	double	phase angle of voltage generated by phase A (°)
	Frequency	double	source frequency (Hz)
Series RLC Load	Load type	categorical	load type selection
	Nominal voltage	double	nominal load voltage (V_{RMS})
	Nominal frequency	double	nominal load frequency (Hz)
	Active power	double	load active power (W)
	Inductive reactive power	double	load inductive reactive power L (vars)
	Capacitive reactive power	double	load capacitive reactive power C (vars)
Linear Transformer	Pn	double	nominal power rating (VA)
	Nominal frequency	double	nominal transformer frequency (Hz)
	Three windings	boolean	select between 2 or 3 windings transformer
	Winding voltage	double	winding nominal voltage (V_{RMS}) of each winding
	Winding resistance	double	winding resistance (Ω)
	Winding inductance	double	leakage inductance (H)
	Magnetisation resistance	double	resistance (Ω) simulating the core active loss
	Magnetisation inductance	double	inductance (H) simulating the core reactive loss

Table continued on next page...

Table 4.1: Continued from previous page.

Entity	Attribute Name	Attribute Type	Description
Load	Data specification	categorical	method of table and breakpoint specification
	Table data	cell array	load profile time output values (s)
	Breakpoints specification	categorical	breakpoint specification (explicit/even spacing)
	Breakpoints 1	cell array	load profile active power output values (W)
	Gain6	double	negative inverse of micro-grid voltage (V^{-1})
	Vsec	double	secondary voltage phase (Im)
	Resistance	double	branch resistance (Ω)
	Initial amplitude	double	CCS initial peak current (A)
	Initial phase	double	initial CCS phase (°)
	Initial frequency	double	initial CCS frequency (Hz)
Solar Panel	Data specification	categorical	method of table and breakpoint specification
	Table data	cell array	load profile time output values (s)
	Breakpoints specification	categorical	breakpoint specification (explicit/even spacing)
	Breakpoints 1	cell array	load profile active power output values (W)
	Gain5	double	inverse of secondary grid voltage (V^{-1})
	Vsec	double	secondary voltage phase (Im)
	Resistance	double	branch resistance (Ω)
	Initial amplitude	double	CCS initial peak current (A)
	Initial phase	double	initial CCS phase (°)
	Initial frequency	double	initial CCS frequency (Hz)
Battery	Initial amplitude	double	CCS initial peak current (A)
	Initial phase	double	initial CCS phase (°)
	Initial frequency	double	initial CCS frequency (Hz)

Table continued on next page...

Table 4.1: Continued from previous page.

Entity	Attribute Name	Attribute Type	Description
Battery Controller	Capacity	double	battery capacity (Ah)
	Isec	double	secondary current (Re & Im)
	Vsec	double	secondary voltage (Re & Im)
	Limit output	boolean	set current integral output limits (yes/no)
	Upper saturation limit	double	maximum value of current integral (A)
	Lower saturation limit	double	minimum value of current integral (A)
	Initial condition	double	internal initial value of current integral (A)
	Switch1 threshold	double	minimum battery SOC to allow discharge (%)
	Switch2 threshold	double	maximum battery SOC to allow charge (%)
	Constant1	double	initial SOC of battery at simulation start (%)

4.2 Blocks and Subsystems

In the previous Section 4.1.3, a general overview of the micro-grid and its components was presented. To understand in greater depth the logic and mathematical models underlying this research, this section describes the specific processes of entities in more details, starting with the Simulink blocks utilised.

4.2.1 Simulink Blocks

Three-Phase Source

As mentioned in Section 4.1.3, the Three-Phase Source Simulink block was employed to model the typical primary substations found on the UK macro-grid. In the case of the "real" network, these substations are transformers which convert electricity from a 132kV voltage to a derated 11kV value [125]. However, as these transformers only allow current to flow from the high voltage side to their lower voltage windings [8], and as this paper does not focus on the high voltage network above primary substations, it was deemed a reasonable approximation to model this substation as an ideal voltage source with no impedance. Additionally, the block parameters (detailed in Table 4.1) were selected to best emulate the characteristics of the "real" transformers. Indeed, the three internal voltage sources are connected in a Y configuration to an internally grounded neutral [126]. The electricity output of the block is defined as three perfect sinusoidal voltages and currents, each separated by a 120° phase shift and operating at the "real" grid's targeted frequency of 50Hz [37]. The output voltage for each phase also has a Root Mean Square (RMS) value of 11kV as per the "real" network [9].

As explained in *A Dictionary of Physics (6 ed.)* [127], for an electric Alternating Current, the RMS value corresponds to the equivalent amount of Direct Current (DC) which would "produce the same average power dissipation in a resistive load" [127]. Additionally, the relationship between the RMS and peak values of a perfect sinusoidal function such as the AC voltage or current from the model can be determined as follows.

The constant periodic sinusoidal voltage can be defined as $V(t) = V_{peak}\cos(\omega t)$ where V_{peak} is the maximum value of the waveform and ω is its angular frequency [128]. The RMS voltage is then given by the analytical expression [128]:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V_{peak}^2 \cos^2(\omega t)\, dt} \tag{4.1}$$

where T is the function's period and is related to the angular frequency by $\omega = \frac{2\pi}{T}$. Integrating the above equation by parts and using the following trigonometric identity $\cos^2(\theta) = \frac{\cos(2\theta)+1}{2}$ yields the expression:

$$V_{RMS} = \sqrt{\frac{V_{peak}^2}{2T}\left[\frac{\sin(2\omega t)}{2\omega} + t\right]_0^T} \tag{4.2}$$

Further substituting the integral limits of 0 and T then gives:

$$V_{RMS} = \sqrt{\frac{V_{peak}^2}{2T}\left[\frac{\sin(2\omega T)}{2\omega} + T\right]} \tag{4.3}$$

Finally, recalling that $\omega T = 2\pi$, the resulting relationship between V_{RMS} and V_{peak} is:

$$\boxed{V_{RMS} = \frac{V_{peak}}{\sqrt{2}}} \tag{4.4}$$

It is worth noting that the same equation applies for the current waveform. In addition, in the micro-grid model, all the voltages and currents measured using the Simulink measurement blocks are outputted as peak values [129]. Therefore, the relationship displayed in Equation 4.4 has been extensively used to convert these values into the energy industry's standard RMS measurements. As stated previously, Equation 4.4 was obtained by assuming that the electricity delivered by the three-phase voltage source behaves as an ideal sinusoidal function. In practice however, due to the continuous switching of loads on the grid, some transients are generated. These will affect the shape of the voltage and current waves flowing inside the network, and thus the power consumption and generation of the different connected entities [37]. Nevertheless, as this research does not focus on the stability of the grid and its associated losses, the approximation made to derive Equation 4.4 was deemed valid.

Series RLC Load

In Section 2.1.1, it was explained that some light industrial loads operated on the 11kV distribution network as part of the UK national grid. To replicate these loads, the Simulink Series RLC Load block was employed. Even-though this industrial consumption is not the focus of the micro-grid model and does not significantly affect the downstream electricity flow to the region of interest, Simulink requires the presence of some type of resistance between the three-phase voltage source and the linear transformer. Hence, in order to develop a more realistic model, three series RLC loads were implemented, one on each phase of the primary subsystem (see Figure 4.1). The three loads were selected to be of constant active and reactive power type, with an active power consumption of 10kW based on the British light industry average presented in the *Modelling demand profiles in the I&C sector* report from the University of Bath and Element Energy [130]. As expected, the blocks were also set to operate at an 11kV RMS voltage and a nominal frequency of 50Hz. Finally, the inductive and capacitative reactive powers were kept to Simulink's default values of 100 var (volt-ampere reactive) [131] for both parameters. Due to the specificity of these two variables, historical data is extremely scarse or not available. Following a rapid parametric study of their influence on the power consumption of the series RLC loads, it was apparent that these two parameters did not significantly influence the power demand. Hence, Simulink's default values were considered to be the most sound quantities to use.

Linear Transformer

To connect the primary three-phase circuit together with the secondary single-phase subsystem (refer to Figure 4.1), a Simulink linear transformer block was employed, effectively replicating a secondary substation typically found on the UK grid. In a similar way to that of an actual pole-mounted transformer, this block allows current to flow in both directions [8, 132], from the 11kV primary side to the 230V secondary part as well as in the opposite way. The nominal power of the transformer was selected to be 25kVA in order to remain slightly above the maximum achieved value of the product of secondary current and voltage (when no battery is operating). As stated by MathWorks, this parameter does not have an "impact on the transformer model when the Units parameter is set to SI"(default) [132]. However, in the case of the "real" grid, transformers are designed to have a nominal power as close as possible to the product of maximum secondary current and voltage of the secondary grid they are connected to (including future connection predictions) [8, 37].

For the simulation model, the transformer was also configured to have three windings with two secondary winding output ports connected to the ground, as per industry standards [8]. The principal winding was parametrised with an RMS nominal voltage of 11kV, while both windings 2 and 3 were selected to have a voltage of 115V (RMS) to neutral, thus setting the secondary micro-grid voltage to 230V. As explained in Section 2.1.1, this 230V voltage corresponds to the standard domestic value present in the UK network.

In addition, as again this research does not focus on grid losses, the modelling of an ideal transformer was deemed as a reasonable approximation. As such, to implement this idealisation, the winding resistances and inductances (of all three windings) were set to 0, and the magnetisation resistance and inductance to infinity as per MathWorks' guidelines [132]. This ideal modelling also had the desired effect of significantly reducing the simulation time, from 30 seconds to less than 2 seconds.

Cables

For this micro-grid model, the electrical connections linking the different blocks and agents were modelled as ideal, as this paper does not seek to study the grid's electrical losses. For the case of the actual UK national grid however, the cable losses are not negligible. Indeed, as stated in

Section 2.1.3, they account for the majority of the 4.2-9.1% [48] of the generated energy lost in the overall network every year. These losses are proportional to the square of the current intensity flowing through the cables, as demonstrated in Equation 2.2 [20].

4.2.2 Subsystems

In order to model the three different secondary grid (green background in Figure 4.1) agents along with the battery controller, it was necessary to build specific subsystems for each entity. These are described in this section.

Domestic Loads

For the modelling of the domestic loads such as those of typical households, an equivalent circuit was designed and is displayed in Figure 4.2 below. This circuit, which is connected to the rest of the micro-grid through connectors 1 and 2 (see Figure 4.2), is based on the principles of Norton's theorem [133]. This theorem, which is the converse of Thevenin's theorem, states that: "any linear electrical system with only voltage sources, current sources and resistances can be replaced at its terminals by an equivalent current source connected in parallel with an equivalent resistance" [133]. Additionally, "this equivalent current is [that] obtained at the terminals of the network when [these] are short circuited" [133]. Similarly, the "equivalent resistance is [given by] the resistance obtained at the system's terminals with all its voltage sources short circuited and all its current sources open circuited." [133]

Following this theorem, Norton's equivalent circuit can thus be employed to model any system of linear sources and impedances at a given frequency. In the case of this micro-grid simulation model, a Simulink Controlled Current Source block [134] with an AC source type was used and placed in parallel with a resistance. The initial amplitude and phase angle of this CCS were set to 0, and its operating frequency defined to be 50Hz. Additionally, the parallel resistance was selected to be $10^6\Omega$. This value corresponds to the threshold beyond which a further resistance increase only has a negligible impact on the current flowing through the equivalent circuit.

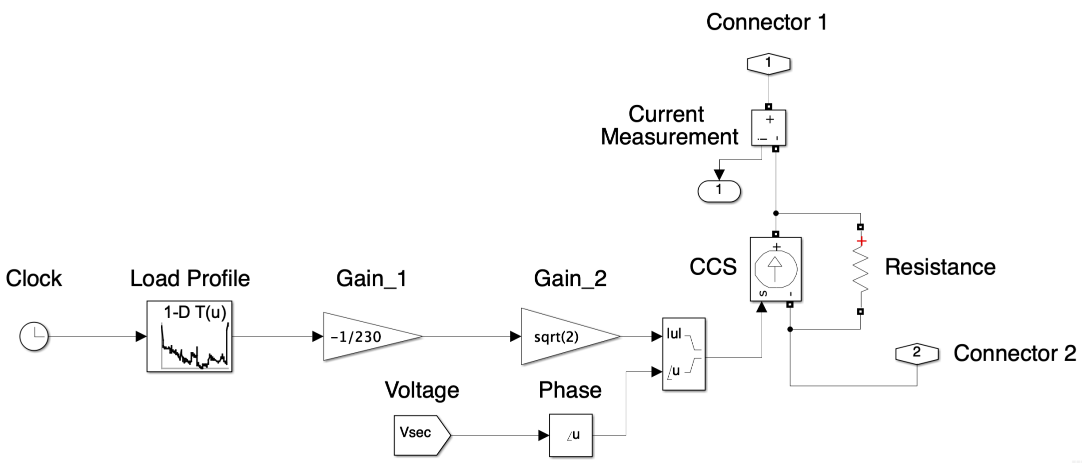


Figure 4.2: Simulink block diagram of the domestic load subsystem.

As the Simulink CCS block requires a current phasor (complex number) input signal (port "s" of CCS block in Figure 4.2) to drive the equivalent current source, it was necessary to convert the power from the load profile data into a current phasor (previously explained in Section 4.1.2). To achieve this, the power first needed to be transformed into an RMS current value.

In AC circuits, the instantaneous power p is defined as the product of the instantaneous voltage v and the instantaneous current i [135]. Assuming, as for the demonstration of Equation 4.4, that the waveforms of the voltage and current are both sinusoidal with the same frequency, the following expression for v can be written [135]:

$$v(t) = V_{peak} \sin(\omega t + \theta_v) \tag{4.5}$$

where V_{peak} is the maximum value of the voltage waveform in volts (V), ω its angular frequency in radians per second (rad.s^{-1}) and θ_v its initial phase-shift in radians. Similarly, i can be expressed as [135]:

$$v(t) = I_{peak} \sin(\omega t + \theta_i) \tag{4.6}$$

where I_{peak} is the maximum value of the current waveform in amperes (A), ω its angular frequency in rad.s^{-1} and θ_i its initial phase-shift in radians. Multiplying Equations 4.5 and 4.6 together thus yields the following expression for the instantaneous power:

$$p = V_{peak} I_{peak} \left[\sin(\omega t + \theta_v) \sin(\omega t + \theta_i)\right] \tag{4.7}$$

Applying the product-to-sum trigonometric identity [135] which is:

$$\sin A \sin B = \frac{1}{2} \left[\cos(A - B) - \cos(A + B)\right] \tag{4.8}$$

and noting that the phase difference between the voltage and current waveforms can be expressed as $\theta = \theta_v - \theta_i$, then Equation 4.7 becomes:

$$p = \frac{V_{peak} I_{peak}}{2} \left[\cos\theta - \cos(2\omega t + \theta)\right] \tag{4.9}$$

Furthermore, according to the expression derived in Equation 4.4, the peak values of the voltage and current are related to their respective RMS values through a factor of $\sqrt{2}$. Hence, the above expression can be displayed as:

$$p = V_{RMS} I_{RMS} \cos\theta - V_{RMS} I_{RMS} \cos(2\omega t + \theta) \tag{4.10}$$

This equation reveals that p is the difference of two terms. The first term is constant, while the second term is a time varying sinusoid. As the phasor solution mode employed for the micro-grid only considers the mean value of the power over time, the instantaneous power of the sinusoid can be simplified to:

$$p = V_{RMS} I_{RMS} \cos\theta \tag{4.11}$$

Additionally, only a single-phase is present in the secondary subsystem of the simulation model, implying that there is no phase difference between the voltage and current waveforms. Hence, $\theta = 0$ and the power is simply expressed as:

$$\boxed{p = V_{RMS} I_{RMS}} \tag{4.12}$$

Making use of Equation 4.12, the power from the load profile was therefore divided by the secondary circuit voltage of 230V (Gain 1 in Figure 4.2). It is to be noted that this Gain 1 is negative to take into account that the power from the load profile corresponds to a consumption rather than a generation. Having converted this power into an RMS current value, it was then necessary to further transform it into a current phasor. Such feat was achieved by multiplying the RMS value with a factor of $\sqrt{2}$ (Gain 2 in Figure 4.2), thus outputting the current's peak value, as derived in Equation 4.4. The final step to transform this peak current value into a complex phasor was then carried through the use of a magnitude-angle to complex signal block [136]. The inputted magnitude consisted in that of the peak current value, while the phase was taken from the micro-grid voltage measurement (Vsec in Figure 4.2) to ensure that both current and voltage were in-phase. The current phasor output was then fed into the CCS, generating the desired single-phase AC current.

Solar Panel

The Solar Panels were replicated using a similar equivalent circuit to that of the domestic loads, as can be seen in Figure 4.3 below.

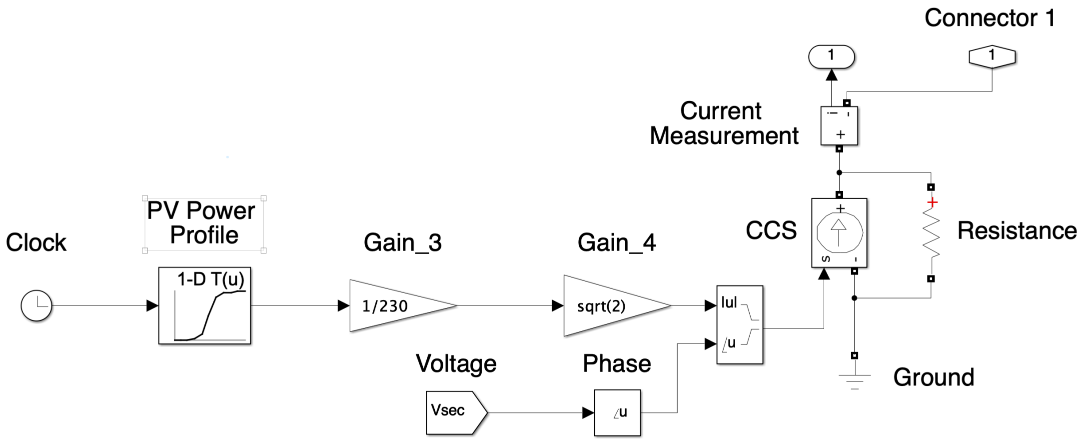
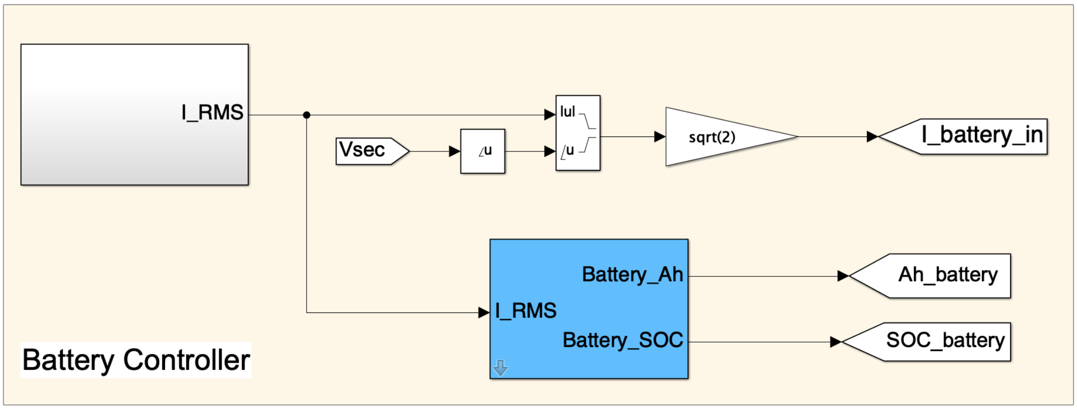


Figure 4.3: Simulink block diagram of the solar panel subsystem.

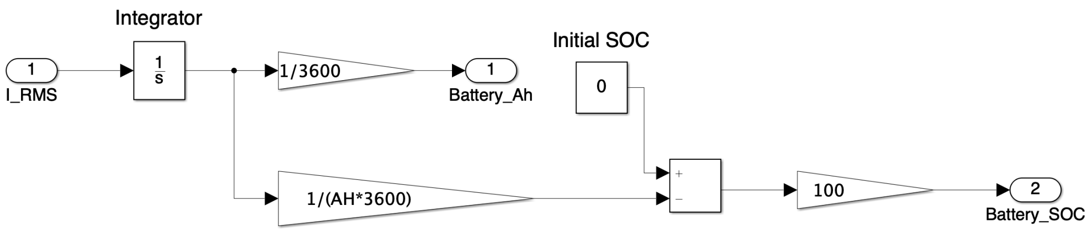
There are three principal differences between this subsystem and the one employed for the loads. Firstly, the input data is a Simulink theoretical PV power profile [122] instead of the load profile used for the household demand. Secondly, the gain converting the power data to an RMS current value is positive (Gain 3 in Figure 4.3), as to account for the fact that in this case power is generated to rather than drawn from the micro-grid. Thirdly, as this model represents a generator delivering power in a single direction (to the micro-grid), the CCS is grounded rather than in parallel with the other micro-grid agents.

Battery and Battery Controller

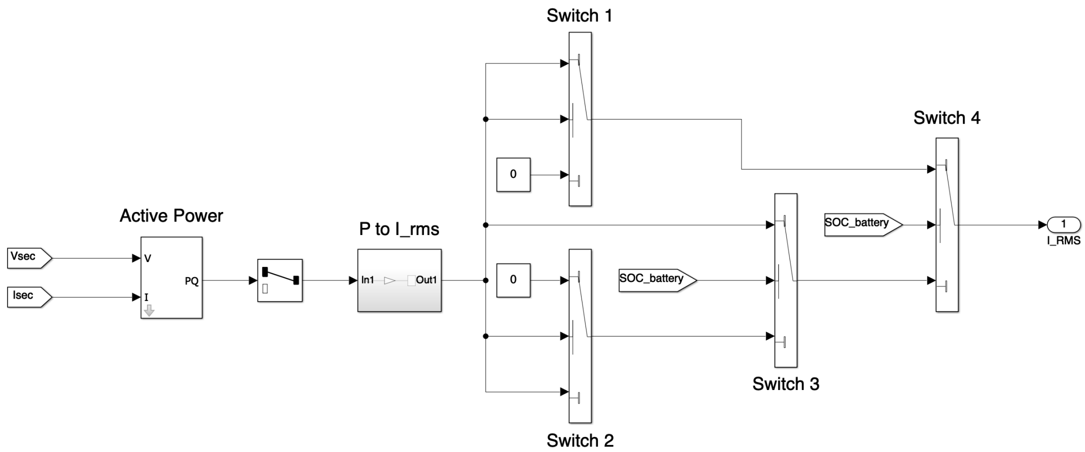
The battery subsystem (green block inside secondary system in Figure 4.1) was also modelled using an equivalent circuit based on Norton's theorem [133]. A block diagram of this circuit can be found in Figure B.1 of Appendix B. As for the loads and the PV model, the AC type CCS was initialised with zero amplitude and phase, and a 50Hz frequency. The resistance connected in parallel to the CCS was also selected to have a value of $10^6\Omega$. The input current phasor fed into the CCS was determined from the output of the general battery controller displayed in Figure 4.4a (`I_battery_in` tag). To achieve this output, it was first necessary to convert the peak voltage and current values of the electricity in the secondary system, into an active power value (displayed in Figure 4.4c). This was done using the Simulink Active & Reactive Power block [137]. The active power was then converted to an RMS current value using the same procedure outlined previously, base on Equation 4.12. It was also made possible to control the maximum and minimum value of this RMS current, effectively simulating the maximum charge and discharge currents achievable by a battery. This RMS current was then fed into a series of switches (see Figure 4.4c) which allow to control the State Of Charge interval in which the battery can operate. From this RMS current value, it was then possible to determine the instantaneous SOC of the battery by using a Simulink integrator block [138] (Figure 4.4b) which calculates the integral of its input signal.



(a) First layer of the battery controller subsystem.



(b) Capacity and SOC battery controller subsystem (blue block in Figure 4.4a).



(c) Charge and discharge current battery controller subsystem (light grey block in Figure 4.4a).

Figure 4.4: Simulink block diagrams of the subsystems constituting the battery controller.

Indeed, the SOC of a battery can be expressed in terms of its current i flowing inside and its total capacity Q such that [139]:

$$SOC = 100\left(\alpha - \frac{1}{Q}\int_0^t i\left(t\right)dt\right) \tag{4.13}$$

where α corresponds to the initial SOC of the battery (value between 0 and 1). In the model, this value was varied thanks to the implementation of a Simulink constant block (Initial SOC in Figure 4.4b). Note that the integral term in Equation 5.1a corresponds to the instantaneous battery capacity (outputted to `Battery_Ah` tag in Figure 4.4b). Having determined this instantaneous SOC, its value was fed back to update the threshold of switches 3 and 4 in Figure 4.4c, effectively closing the battery controller loop. It is worth mentioning that the instantaneous RMS current value obtained (`I_RMS` tag in Figure 4.4c) had to be converted to a current phasor (Figure 4.4a) before being inputted into the CCS of the battery subsystem (input `I_battery_in` in Figure 4.1).

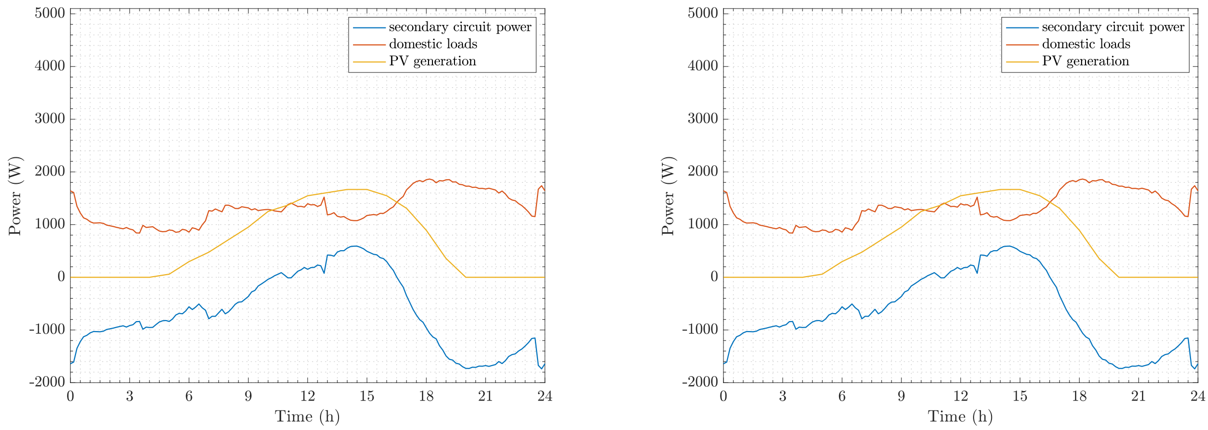
4.3 Validation

As no historical nor empirical data from a similar micro-grid was available with sufficient granularity, the model was validated analytically. For this purpose, a simpler micro-grid model was built, a diagram of which can be found in Figure B.2 in Appendix B. This model included a single PV block connected to a secondary system with three different domestic loads. The data for the PV power generation profile was taken from a standard profile provided by Simulink [122]. The three household loads on the other hand were taken from the *Household Electricity Survey* [6] and are presented in Appendix C.

A MATLAB script (`FYP_analytical_test` attached in Appendix D) was written and included the mathematical expressions derived in Sections 4.2.1 and 4.2.2 which underly the Simulink blocks as well as the specifically designed subsystems employed to build the micro-grid model (Figure 4.1). In addition to Equations 4.12 and 4.13, it was necessary to mathematically model the role of the secondary substation transformer in the micro-grid. Recall from Section 4.2.1 that the linear transformer was assumed to be ideal in the simulation model. Thus, it was possible to replicate its role using the principle of conservation of energy as indicated in the paper *The mathematical model of the power transformer considering the parasitic capacitances* [140]. The conservation of energy in a linear transformer can be expressed as follows:

$$V_{primary} \times I_{primary} = V_{secondary} \times I_{secondary} \tag{4.14}$$

where V is the RMS voltage value and I the RMS current value of the respective primary and secondary sides of the transformer. Note that in the case of the micro-grid model (Figure 4.1), the primary side corresponds to the higher 11kV distribution network, while the secondary part of the transformer relates to the two windings providing a 230V voltage to the battery, PVs and loads. Having determined all the mathematical tools to replicate the micro-grid model, the 24 hour PV generation power profile along with the three domestic load profiles were inputted into the validation simulation grid as well as the `FYP_analytical_test` MATLAB script. The total power seen by the secondary side of the transformer was then plotted using the output of both the simulation and the script. As expected, these two plots were identical, as can be seen in Figures 4.5a (analytical method) and 4.5b (simulation method) below. These results are not surprising as the simulation model is ideal and relies on the exact same mathematical statements as those used in the MATLAB script. This therefore validated the model micro-grid.



(a) Analytical calculations using the `FYP_analytical_test` MATLAB script (Appendix D).

(b) Simulation using the validation model (Figure B.2 in Appendix B).

Figure 4.5: Validation case plots of the analytically derived and simulated power outputs of the secondary grid. Note that the "domestic loads" are presented as an absolute value and count as negative power drawn from the grid in practice. The "secondary circuit power" corresponds to that seen by the transformer (a negative value indicates that power consumed is greater than that generated).

4.4 Initialisation

In order to perform the simulations using the micro-grid model exposed in Figure 4.1, some initialisation parameters were defined. Note that these parameters have been detailed throughout Section 4.2, and are summarised in Table F.1 in Appendix F. In addition, a total of 40 domestic loads were introduced into the micro-grid, relying on the data from the *Household Electricity Survey* [6] (as per the validation model in Section 4.3). These loads included a mixture of flats (varying in sizes between 0-49sq m and 50-99sq m), mid and end-terraced households (sizes between 50-99sq m and 100-159sq m). Some of the flats were also specified to have electric primary heating, while others did not have electric heating at all. Note that these load profiles are daily averages over a full-year and thus do not include seasonality effects. The mix was selected to be as representative as possible of a typical domestic building located in an urban area as this is believed to be the most promising location for smart grid implementations. The solar panel generation profile on the other hand, used theoretical data generated by Simulink [122] due to the lack of granular PV data openly available. This data is said to be representative of a solar panel power output supplying a dozen households [122]. Three PVs with identical generation profiles were therefore selected for the simulation. The characteristics of the battery, which was expected to be the main source of non-linearity in the simulation model, were varied by altering the different parameters exposed in Tables 4.1 (Section 4.1.3) and F.1 (Appendix F).

5 Results and Discussion

As previously mentioned in Section 1 and further supported by the unprecedented literature review (Section 2), this project was motivated by the simulation of a smart micro-grid. Hence, as described in detail in Section 4.2, the model developed is highly flexible and easily scalable. Indeed, even-though the agents have been termed as “Solar Panels” or “domestic loads”, and have been assigned particular generation and load profiles from both Simulink [122] and the *Household Electricity Survey* [6], it is entirely possible to model other types of micro-grid generators and loads (e.g. wind turbine generators, commercial loads). The main variables to modify for this “adaptation”, are the inputted power supply and demand profiles which are converted to RMS current phasors as explained in Section 4.2. The same also holds true for the battery agent, which with further and more specific parametrisation can replicate the behaviour of Electric Vehicles and Vehicle-to-Grid systems.

It is also worth noting that even-though the parameters used for the simulations presented in this paper are specified to best model the UK mainland electricity network, the framework developed is not solely limited to an implementation in the UK. Indeed, the comparative study between the China Southern Power Grid and the National Grid Plc revealed that similar network utilisation rates were measured for both grids between 2009 and 2014 [15]. Thus, large scale energy network savings are also to be accomplished in other networks around the globe. As previously stated, this simulation model was developed with flexibility and scalability in mind. Therefore, to gain novel insight on smart grid implementation in the grid of interest, it solely requires the input of appropriate parameters characterising said grid. A potential other network to study is the China Southern Power Grid [15].

As previously explained in Section 3, it stems from the literature review that the main difficulties in implementing smart micro-grids arise from the storage capacities. Indeed, numerous papers such as *Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment* by Bolun Xu et al. [4] have already attempted to model the characteristics of batteries, especially their ageing and temperature dependancy. Following onto the outline from Section 3, the rest of this section will focus on the results of a parametric study on the battery and battery controller models described in Section 4.2.2. Indeed, as explained in Section 3, no previous significant research time has been spent on assessing the impact of battery characteristics in a smart micro-grid environment (below the 11kV to 230V transformers as displayed in Figure 4.1). Therefore, this paper exposes novel insights regarding the non-linearity of batteries in smart micro-grids.

To measure this storage impact, a range of parameters in the battery and controller models were altered when running the simulations. As mentioned in Section 3, the main metric to quantify this role of the battery was logically taken to be the smart grid's daily energy consumption drawn from the distribution network (above the secondary substation). To measure this metric, two Simulink measurement blocks [129] were employed and outputted the instantaneous current (`Isec` tag in Figure 4.1) as well as the instantaneous voltage (`Vsec` tag in Figure 4.1) measured at the low voltage side of the linear transformer. These peak value measurements were then processed, by applying Equation 4.12, and a power "load" profile was outputted via a Simulink scope [141] (similar to those displayed in Figure 4.5). The load profile was then integrated using the trapezoidal rule embedded in the `trapz` MATLAB function [142]. This permitted to output a single value of the daily energy consumption of the micro-grid for each 24 hour simulation. This metric was selected as it quantifies the amount of power drawn by the micro-grid from the higher distribution network above the secondary substation. Indeed, as has previously been explained in Section 2, it is at this particular distribution level (above the 11kV to 230V transformers) that the energy losses and thus associated costs are the most important [48]. Furthermore, this metric is ideal to support the two network costs charging methods (Locational DUoS Methods 1 and 2) proposed by Piclo in their whitepaper [73]. Indeed, it measures only the electricity drawn from the distribution grid without offsetting the excess supply generated by the PVs during the day (supply which exceeds both the loads consumption as well as the battery capacity). Thus, this metric truly measures the amount of energy that the micro-grid consumes when there is not enough power generation for micro-grid local matching. This metric therefore solutions the issue raised by Piclo in their paper *Local Grid Charging: Exploring the incentivisation of local energy* [73], regarding the question of how to measure locally matched supply and demand.

With this principal metric defined, the parametric study of the battery characteristics and its impact on the micro-grid was carried. Four main independent parameters were tested. These are:

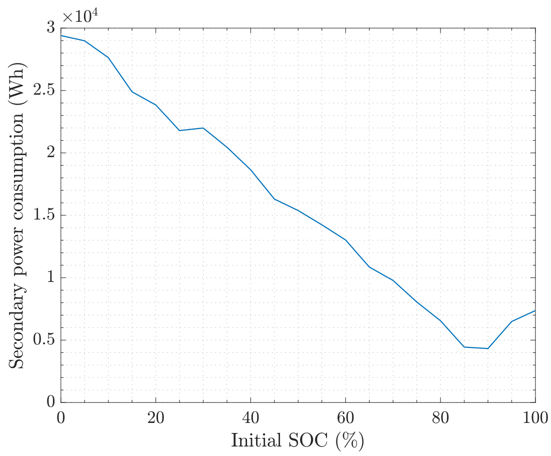
- the battery total capacity measured in Ah;
- the initial State Of Charge of the battery at the beginning of the simulation (hour 00:00 of the day) measured in % (see Equation 4.13 in Section 4.2);
- the maximum charging current that can flow into the battery measured in A;
- the maximum discharging current that can flow out of the battery in A.

The capacity, charge and discharge current parametric tests were also performed at 3 different initial SOC conditions, respectively 0, 50 and 100%. The following Table 5.1 summarises the value of the four parameters employed for each of the four tests.

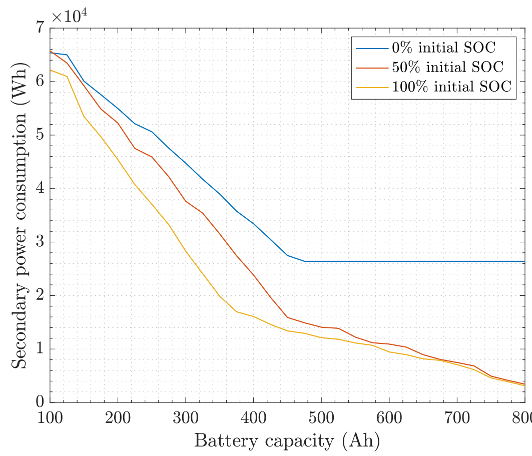
Table 5.1: Parameters' values for the parametric study of four different battery variables.

Test Parameters	Capacity (Ah)	Initial SOC (%)	Charge Current (A)	Discharge Current (A)
Capacity	-	0/50/100	100	100
Initial SOC	450	-	100	100
Charge Current	450	0/50/100	-	100
Discharge Current	450	0/50/100	100	-

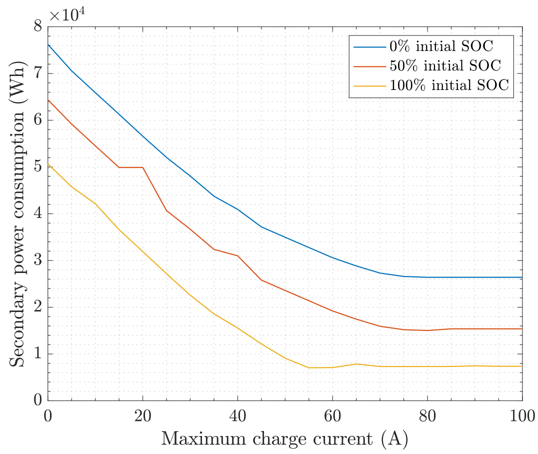
The results of this parametric study are presented in Figure 5.1 below. As can be seen from the four plots in Figure 5.1, the battery is a significant source of non-linearity in the model, thus revealing the necessity for the use of simulations. The variable with the least non-linear effect on the



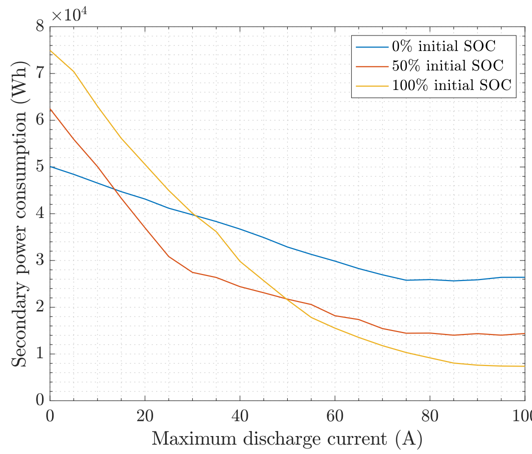
(a) Varying initial SOC.



(b) Varying battery capacity for three different initial SOCs.



(c) Varying maximum charge current for three different initial SOCs.



(d) Varying maximum discharge current for three different initial SOCs.

Figure 5.1: Evolution of the secondary power consumption of the micro-grid with varying battery model parameters.

power consumption is the initial SOC (Figure 5.1a). Indeed, as visible from Figure 5.1a, the power consumed by the grid decreases linearly with an increasing initial SOC. The observation follows what was to be expected, as the additional initial SOC allows the battery to supply energy to the loads in the morning, before the PVs start generating sufficient power to meet demand. Beyond an initial SOC of 87% however, the previously described trend reverses, indicating a point of optimum initial SOC at a value between 85% and 87%. This observation can be explained by the fact that above an initial SOC of 87%, the battery will saturate (fully charged) before peak demand time when absorbing the excess power from the PVs during daytime. This can therefore be seen as a loss of PV generation which is not locally matched with the loads.

For the three other parameters, some highly non-linear trends are clearly visible. For the varying battery capacity (Figure 5.1b) starting the day with no charge, the grid consumption decreases gradually with increasing capacity until it plateaus for a capacity greater than 450Ah. This once again indicates the presence of an optimum battery capacity of 450Ah for this particular parametric configuration. For non-zero initial SOCs however, it can be seen that the consumption follows a non-linear trend tending to zero with a kink around a 370Ah and 440Ah capacities for respectively 100% and 50% initial SOCs. This plateau and two kinks observed, indicate that beyond these capacity values, the battery will have saturated, restricting the potential for local matching and thus the micro-grid efficiency. Non-linearity response is even greater when the saturation limits of the maximum charging and discharging currents are altered. As visible in Figure 5.1c, regardless of the initial battery charge, an increase in maximum charge current is clearly desirable in order to reduce the energy drawn from the macro-grid. Indeed, in Figure 5.1c all three curves see a non-linear decrease with increasing maximum current, before plateauing to constant consumption values. This observation again displays the opportunity for a micro-grid energy asset optimisation using this simulation model. Indeed, after the charging current reaches a value of 55.0A, 75.0A and 80.0A for respectively the 100%, 50% and 0% initial SOCs, the batteries in their respective configurations saturate before peak demand, thus diminishing the efficiency of the micro-grid. A similar trend is visible in Figure 5.1d with the variation of maximum discharge current. It is clear that the micro-grid's efficiency is improved by increasing the discharge current saturation threshold. However, it is interesting to see that at low discharge currents (below 15A), the lower the initial SOC is, the greater the efficiency. This can be explained by the fact that at low discharge currents, the batteries with an initially higher charge will not have the time to deplete before absorbing excess PV power. Thus they will saturate earlier than initially less charged storage devices. This trend then reverses as the discharge saturation increases.

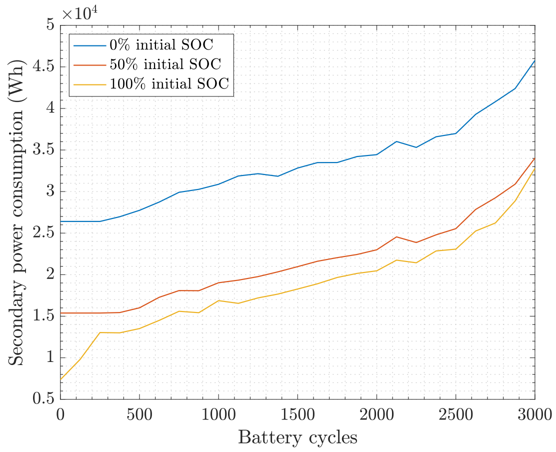


Figure 5.2: Evolution of the secondary power consumption of the micro-grid with battery life cycles [3,4].

To study the effects of ageing, the evolution of secondary power consumption with battery life cycles was researched. First an empirical model of the variation of a Lithium-Ion battery capacity (expressed as a % of its maximum capacity) with number of cycles was taken from the paper *Modelling of Lithium-Ion Battery Degradation for Cell Life Assessment* [4]. This capacity against life cycles plot can be found in Figure H.1 in Appendix H. The data from this plot was then inputted into the battery model, giving the plot in Figure 5.2 above. The non-linear behaviour of the battery model is clearly visible in Figure 5.2. As expected, an increase in battery life (cycles) causes the battery to lose capacity, thus saturating before peak demand which in turn leads to a reduction in micro-grid efficiency (increase in energy consumed from the macro-grid). It can be seen that as the battery ages further, the micro-grid consumption starts to increase more rapidly. This can be a significant issue with used batteries converted from an EV type to stationary storage [3].

6 Conclusion

This industrial research paper has proposed an extensive literature review on the current electrical landscape in the UK, exposing the main limitations of today's network. The grid was depicted as vertically integrated as well as unidirectional. This structure founded on large power plants with no strategic geographical positioning, requires an important high voltage transmission network, thereby incuring energy transportation losses as high as 9.1% [48] of total the generated power.

This work has also put in light the multiple smart grid initiatives being undertaken following the rollout of Smart Meters. Through a thorough analysis of this evolving energy landscape, it was explained that the three trends of Electrification, Decentralisation and Digitalisation acted in a virtuous circle, permitting a rapid shift towards a Smart Grid. A wide range of technologies on or close to the market were studied, ranging from Demand Side Response to Distributed Energy Resources. These were described as providing new revenue streams for the exponentially increasing number of market participants, thus allowing for the development of novel business models. The most promising of these emerging incentivisation plan is believed to be the Locational DUoS from Piclo [73]. Moreover, this paper exposed the convergence of all these initiatives towards the common objective of maximising grid efficiency, thereby reducing losses and thus end-user costs.

This in-depth research however, revealed that the greatest challenges opposing the wide spread of SG initiatives were both metering data protection, and most importantly, the absence of knowledge regarding energy storage in a smart micro-grid environment.

Being the stepping stone for the development of a future software quantifying the Return On Investment of SG initiatives, this paper sought to present the design and implementation of a robust, flexible and scalable smart micro-grid model. This was achieved by applying equivalent circuit models to replicate the micro-generators, energy storages and loads present on a local electrical network. Following its analytical validation, this model was then instrumental in gaining novel insights on the non-linear behaviour of batteries integrated into a smart micro-grid.

Indeed, through a parametrical study of the battery model, it became apparent that the energy storage's non-linear behaviour significantly affects the efficiency of its containing grid. Furthermore, by employing model simulations, some optimisation opportunities were identified. The use of the micro-grid power consumption metric proved to be ideal for the future implementation of Piclo's Locational DUoS methods. Based on the novel insights of this work, it is clear that the model designed offers great opportunities for capturing the complexity of a SG. However, it still has to fully mature from its theoretical application to a model encapsulating all the necessary parameters to provide business value. Hence, a set of novel directions is delivered in the following Section 7.

7 Future Work

7.1 Added Business Value

The results discussed in Section 5 have proved that the smart micro-grid simulation model depicted in this paper offers significant opportunities for the implementation of optimisation algorithms. Furthermore, the decision made to use Simulink provides the possibility to easily export the output power profiles to MATLAB for further analysis. The application of some of MATLAB's Optimization Toolbox™ [143] functions would prove to be extremely useful to determine the optimum configuration of the micro-grid. Indeed, a further step towards the concretisation of the Return On Investment software, would be to determine the micro-gri's agent mix providing the lowest amount of consumption from the macro-grid. Once this step is achieved, an extensive research on the calculation of DNO costs would be required. This would permit to quantify the DUoS charges currently applied as part of the Common Distribution Charging Methodology (CDCM) [73]. Then, the two different Locational DUoS incentivisation models proposed by Piclo in their white paper [73] could be implemented, effectively permitting to quantify the potential gains brought by these two methodologies with respect to the current charging scheme. Similarly, other incentivisation methods could also be studied through this quantitative approach.

As mentioned in Section 2.2.8, two other alternative charging schemes are already in use for exceptional circumstances, and are described by Piclo in their white paper [73]. The first one is the Network Replicating Private Wire which is a subset of the Private Wires. These Private Wires correspond to a special agreement between a micro-grid generator and a consumer, typically of industrial type. It consists in supplying electricity directly from the local generator to the customer via privately owned wires [73]. This allows the energy producer and the consumer to be exempt from certain charges associated to the carbon footprint, supply and network costs of electricity transmission and distribution. These physical wires however, are extremely rare due to their significant incurred costs. Hence, NRPW replicate these physical connections by using existing assets owned and maintained by the local DNOs. The generators can effectively supply electricity under contract to independent customers by connecting themselves to the DNO's network where there is spare capacity [73]. The other option is by using Virtual Private Wires. These work in a similar way to NRPWs. However, instead of requiring new connections to the DNOs network, part of the spare capacity on this DNO's system is virtually allocated to the generator. This generator can then supply customers "directly" without requiring a reinforcement of the distribution infrastructure [73]. Ideally, a study of all four incentivisation methods (two Locational DUoS, the VPW and the NRPW) would be performed using a scaled up version of the model developed in this work. There would also be the possibility of testing hybrid versions combining the four incentivisation methods, always in the aim of improving the grid's efficiency and reducing the end-user's bills.

To add additional business value to the project launched with this paper, the exact cost of all grid assets could also be determined. This would involve modelling the price evolution with energy capacity of every DER present in the model. It is worth noting that this further research would lead to an additional major source of non-linearity within the model. Indeed, an example is the current price of Lithium-Ion batteries which is not proportional to the device's energy capacity [77]. Therefore, it is expected that an optimisation of the asset prices instead of the micro-grid's consumption (as discussed in Section 6) could lead to a relatively different optimum grid agent mix. Indeed, a discrepancy between the two different optimums, one measured in price per kW and the other in kW consumption only could be found. This would be an invaluable study for the energy market authorities such as Ofgem. Indeed, they would be expected to attempt to make the two optimums converge, thus ensuring that the most efficient grid is indeed the cheapest one for the customer.

On a shorter timescale, it would also be interesting to integrate the latest half-hourly pricing profiles made available by Octopus Energy [74]. These could be compared to the traditional single energy tariffs or the latest Economy 7 on/off peak price signals, to determine the cost savings that the customers can make through DSR. If this tool proves that the Octopus Energy profiling scheme does indeed allow customers to make significant savings, it could be used for marketing purposes by the energy supplier to attract new clients. This study would also expose the new market opportunities presented by electricity price profiling and half-hourly consumption measurements, thus further opening up the energy market and driving customer bills down.

7.2 A More Realistic Model

In parallel with the multiple opportunities the model offers for deriving financial incentives, the Simulink environment also permits to implement some less theoretical blocks. Indeed, the SimScape library includes a parametrised Lithium-Ion Battery block [139] based on empirical charge, discharge, ageing and thermal response data. This block also allows for the integration of experimental data into the model. However, the Lithium-Ion Battery block can only run in continuous or discrete solution modes (no phasor mode) [139]. Hence, a severe model review and important change of design strategy would be required in order to perform transient simulations.

A shift to a transient model (continuous or discrete) would nonetheless also present some upsides. Indeed, it would permit to quantify the different losses associated to loads and supplies being out of phase. It would also permit to study the entire system over a more realistic 49.5-50.5Hz frequency range rather than the ideal 50Hz value from the phasor mode. In addition, the impact on the network of loads and generators switching on and off could also be assessed. This shift to a transient model would therefore allow to perform an in-depth loss study of the entire micro-grid model, making the simulations more representative of the actual physical network.

On a short term, a loss analysis can also be performed on the current phasor grid model. In a first stage losses could be estimated using empirical data and applying correction factors to the simulation outputs. At later stages, for more in-depth studies, the Simulink's Pi Section Line blocks [144] could be implemented to connect the different agents together. These blocks are said to replicate the physical properties of cables along with their associated losses due to heating resistance effects as well as magnetisation impedance [144].

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A Demand Response Diagram

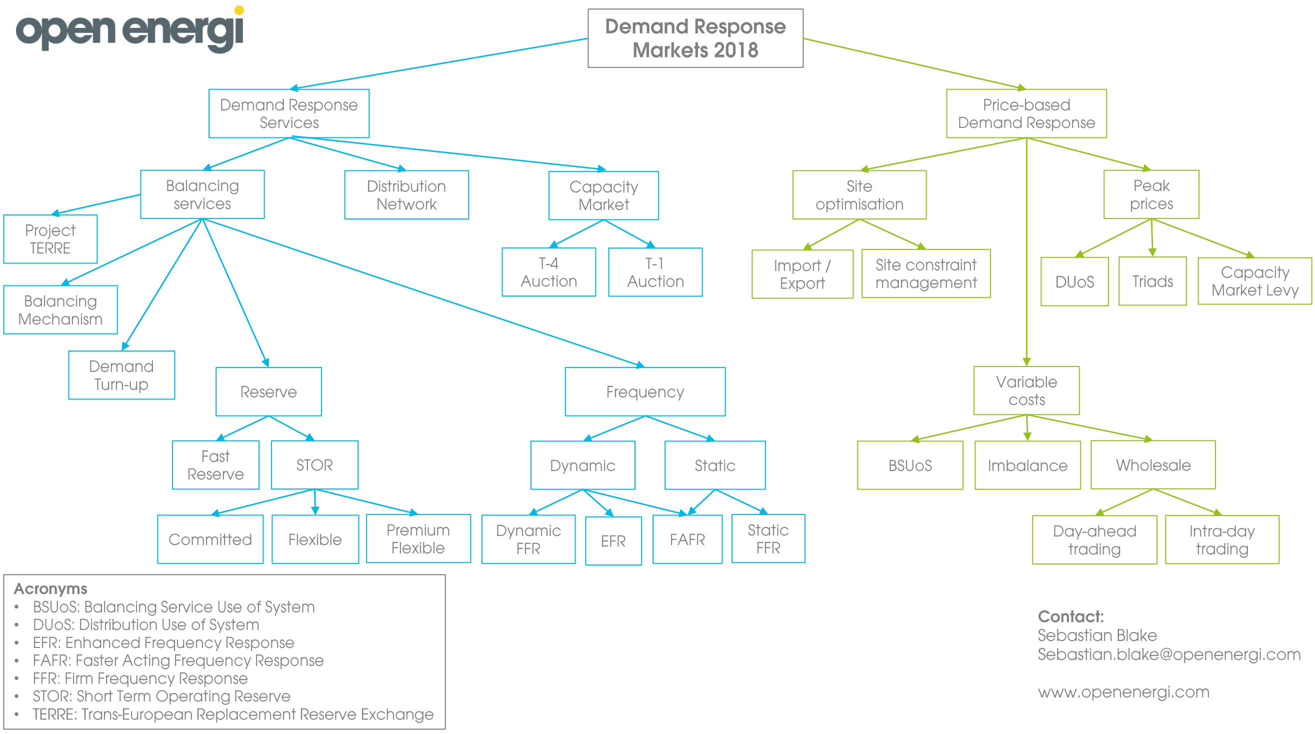

Figure A.1: Open Energi diagram of the different types of demand response available in the market as of 2018 [5].

B Simulink Block Diagrams

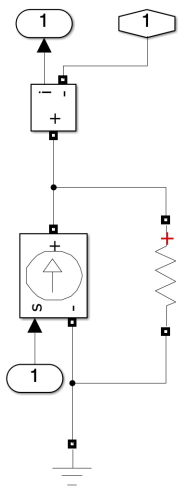

Figure B.1: Simulink block diagram of the battery subsytem.

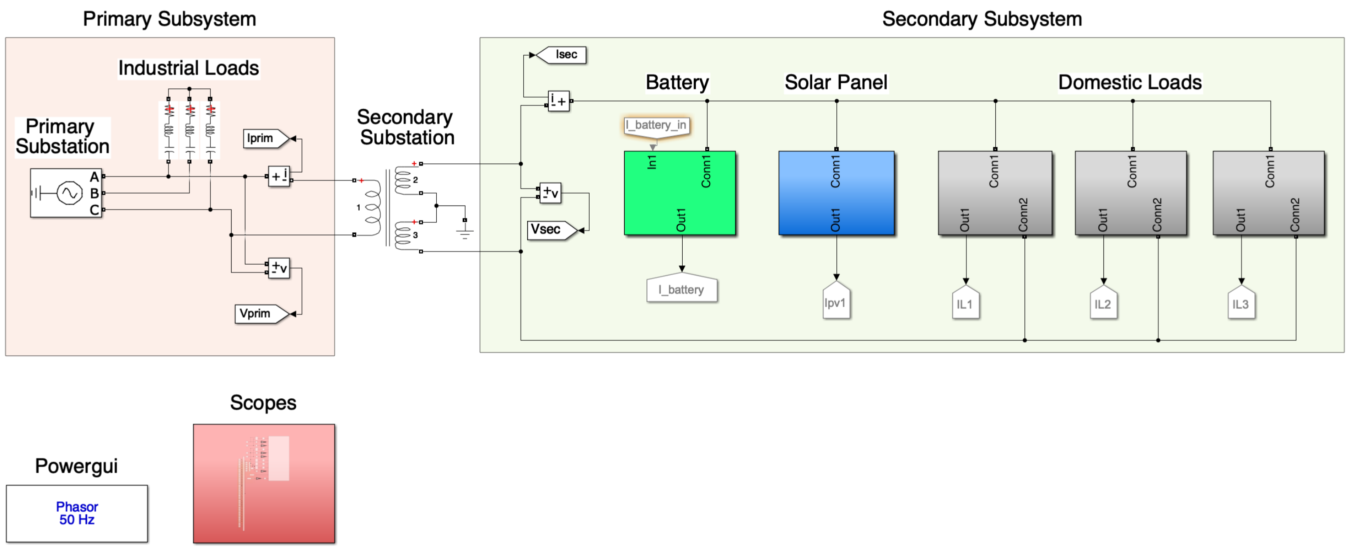

Figure B.2: Simulink block diagram of the simplified model micro-grid used as a validation test-bed.

C Validation Case Load Profiles

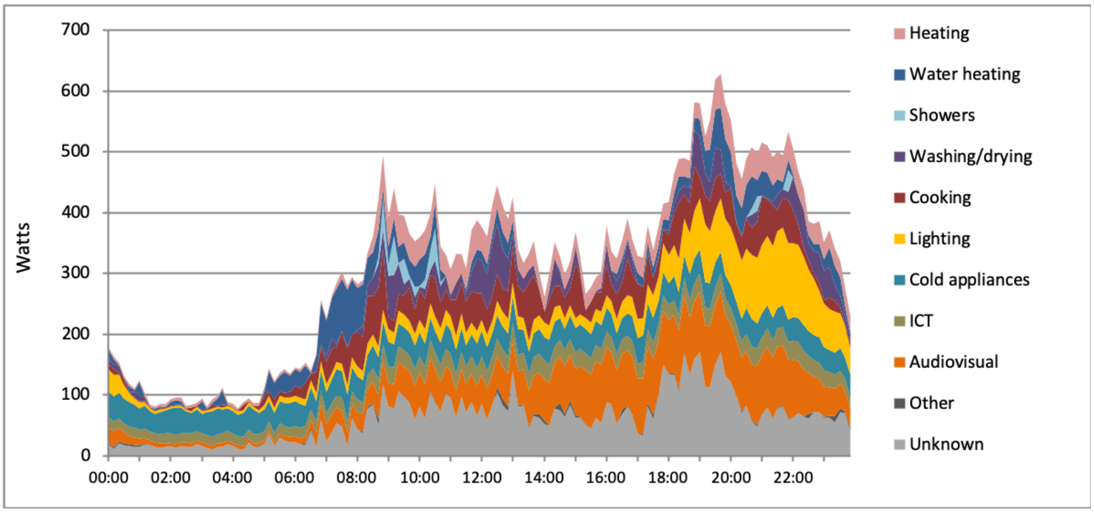

Figure C.1: Yearly average of a 24h load profile of a typical 50-99m^2 flat in the UK [6].

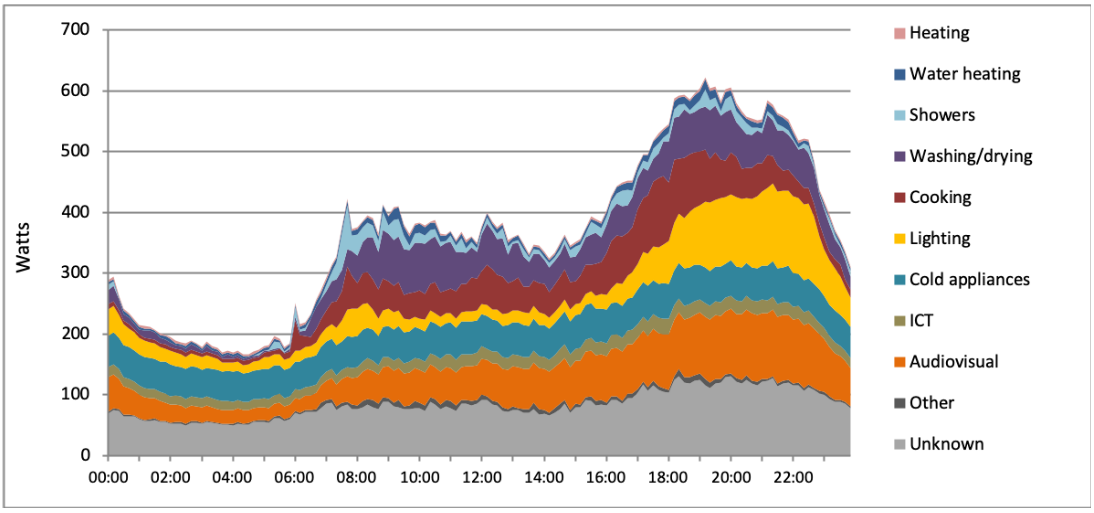

Figure C.2: Yearly average of a 24h load profile of a typical 50-99m^2 mid-terrace household in the UK [6].

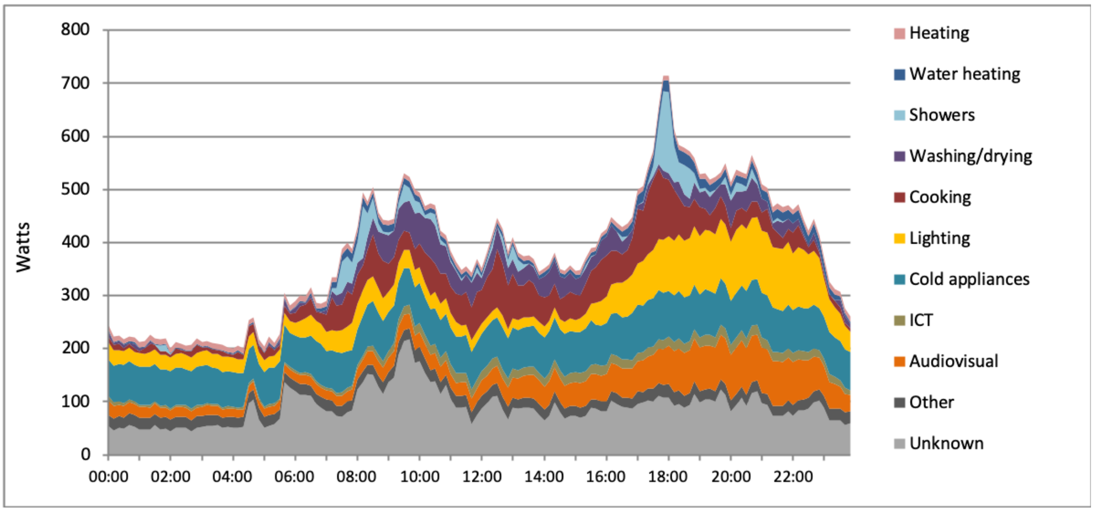

Figure C.3: Yearly average of a 24h load profile of a typical 50-99m^2 bungalow household in the UK [6].

D Validation Case MATLAB Script

```
%% FYP Analytical Test
%
%by Cesar Maklary.
%
%Script to verify analytically the results of the Simulink model
%power_microgrid_v3_analytic.slxc
%
%The simulink model needs to run before this script to output the scope
%data under the structure name Scope_analytical.

%clear house but not workspace variables
close all
clc

%plot settings
set(0,'DefaultLineLineWidth', 1);
set(0,'defaulttextfontsize',14);
set(0,'defaultaxesfontsize',14);
set(0,'defaulttextinterpreter','latex');
set(0,'defaultAxesTickLabelInterpreter','latex');
set(0,'defaultLegendInterpreter','latex');

%% Load Profiles
%24h period split in intervals of 600s (timescale in hours)
t=xlsread('Domestic_data_all_x3.xlsx',1,'B2:EQ2')/3600;
%Domestic load from All houses with 3 sizes (1.0-49m2, 2.50-99m2 3.
%100-149m2)
P_A=xlsread('Domestic_data_all_x3.xlsx',1,'B3:EQ5');
%Default PV load data
load('default_PV_data.mat');
%Select PV data every 600s (default in file in 60s)
for i=1:length(P_A(1,:));
    P_PV(i)=SPD_1min(1+10*(i-1))/3;
end

%% Secondary Power Calculations
Vsec=230; %secondary circuit voltage (V)
R=1e6; %resistance of loads to model ideal current sources (Ohms)
%convert power loads to RMS currents for controlled current source
%(P=I_rms*V_rms)
I_A=P_A/Vsec;
I_PVin=P_PV/Vsec;
```

```
%total RMS currents at node closest to + side of secondary transformer (A)
I_load=I_A(1,:)+I_A(2,:)+I_A(3,:)-3*Vsec/R; %total loads current
I_PVout=I_PVin-Vsec/R; %total PV current
I_sec=I_PVout-I_load; %summation of current

%calculate power from RMS current and transformer voltage (W)
P_load=I_load*Vsec; %power loads output
P_PVout=I_PVout*Vsec; %power PV output
P_sec=I_sec*Vsec; %power secondary circuit

%% Plots
%analytical plot
figure(1)
plot(t(1:end),P_sec(1:end))
hold on
plot(t(1:end),P_load(1:end))
plot(t(1:end),P_PVout(1:end))
hold off
box on
grid minor
%title('Power Analytical Calculations')
xlabel('Time [h]')
ylabel('Power [W]')
xlim([0 24])
xticks([0:3:24])
ylim([-2000 5100])
legend('secondary','loads','PV')
set(gca,'XMinorTick','on','YMinorTick','on')

%simulation plot
figure(2)
plot(sec_p.time,sec_p.data)
hold off
box on
grid minor
%title('Power Simulink Model')
xlabel('Time [s]')
ylabel('Power [W]')
xlim([0 24])
xticks([0:3:24])
legend('secondary','loads','PV')
set(gca,'XMinorTick','on','YMinorTick','on')
```

E Typical British Household Load Profile

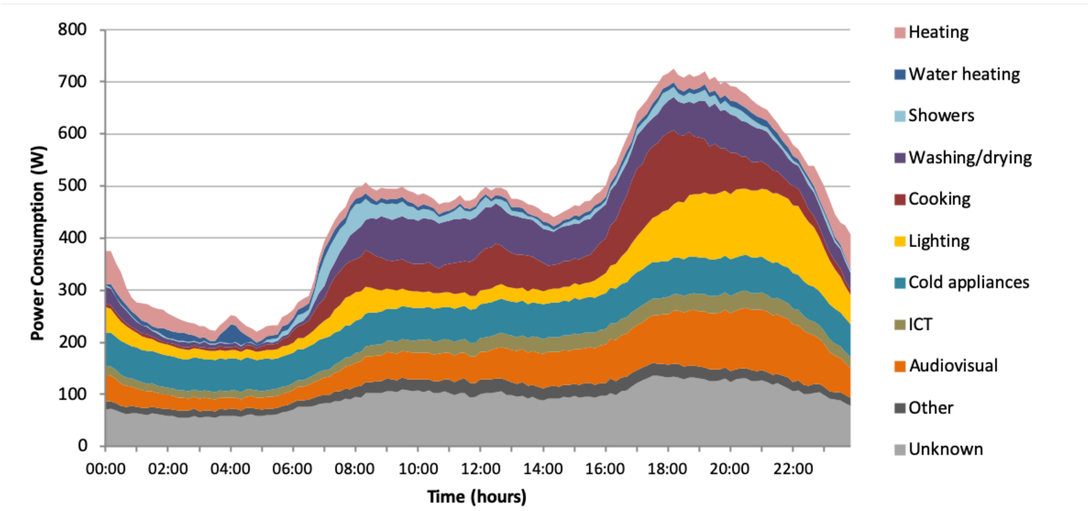

Figure E.1: Daily average load profile for a representative UK household monitored as part of the *Household Electricity Survey* [6].

F Simulation Parameters

Table F.1: Parameter values for entities in the micro-grid simulation.

Entity	Attribute	Value	Units	Source
Three-Phase Source	Generator type	swing	n/a	Simulink
	Phase-to-phase voltage	Yg	n/a	Simulink
	Phase angle of phase A	0	°	ENA
	Frequency	50	Hz	NGESO
Series RLC Load	Load type	constant Z	n/a	Simulink
	Nominal voltage	1000	V_{RMS}	ENA
	Nominal frequency	50	Hz	NGESO
	Active power	10^6	W	Element Energy
	Inductive reactive power	100	var	Simulink
	Capacitive reactive power	100	var	Simulink
Linear Transformer	Nominal power	25	kVA	ENA
	Nominal frequency	50	Hz	NGESO
	Winding 1 voltage	11	kV	ENA
	Winding 1 resistance	0	Ω	Simulink
	Winding 1 inductance	0	H	Simulink
	Windings 2 & 3 voltage	115	V	ENA
	Windings 2 & 3 resistance	0	Ω	Simulink
	Windings 2 & 3 inductance	0	H	Simulink
	Magnetisation resistance	Inf	Ω	Simulink
	Magnetisation inductance	Inf	H	Simulink
Load	Table data	load profile	s	NES
	Breakpoints 1	load profile	W	NES
	Gain6	$\frac{-1}{230}$	V^{-1}	Simulink
	Resistance	10^6	Ω	Norton
	Initial amplitude	0	A	Simulink
	Initial phase	0	°	ENA
	Initial frequency	50	Hz	NGESO

Table continued on next page...

Table F.1: Continued from previous page.

Entity	Attribute	Value	Units	Source
Solar Panel	Table data	generation profile	s	Simulink
	Breakpoints 1	generation profile	W	Simulink
	Gain5	$\frac{1}{230}$	V^{-1}	Simulink
	Resistance	10^6	Ω	Norton
	Initial amplitude	0	A	Simulink
	Initial phase	0	°	Simulink
	Initial frequency	50	Hz	NGESO
Battery	Initial amplitude	0	A	Simulink
	Initial phase	0	°	ENA
	Initial frequency	50	Hz	NGESO
	Resistance	10^6	Ω	Norton
Battery Controller	Capacity	100 - 800	Ah	Bolun et al.
	Upper saturation limit	0 - 100	A	Millner
	Lower saturation limit	(-100) - 0	A	Millner
	Initial condition	0	A	Simulink
	Constant1	0 - 1	%	Simulink

G Principal UK Grid Characteristics

Table G.1: Characteristics of the UK electricity grid [7–9].

Network	Source	Output Voltage (V)	Frequency (Hz)	Phase
Transmission	Generators	25,000	50	3
	Step-up Transformers	400,000	50	3
	TNOs	132,000	50	3
	Grid Supply Points	132,000	50	3
Distribution	DNOs	230	50	3
	Heavy Industries	33,000	50	3
	Light Industries	11,000	50	3
	Secondary Substations	11,000	50	3
Supplier	Domestic & Commercial Users	230	50	1/3

H Battery Ageing

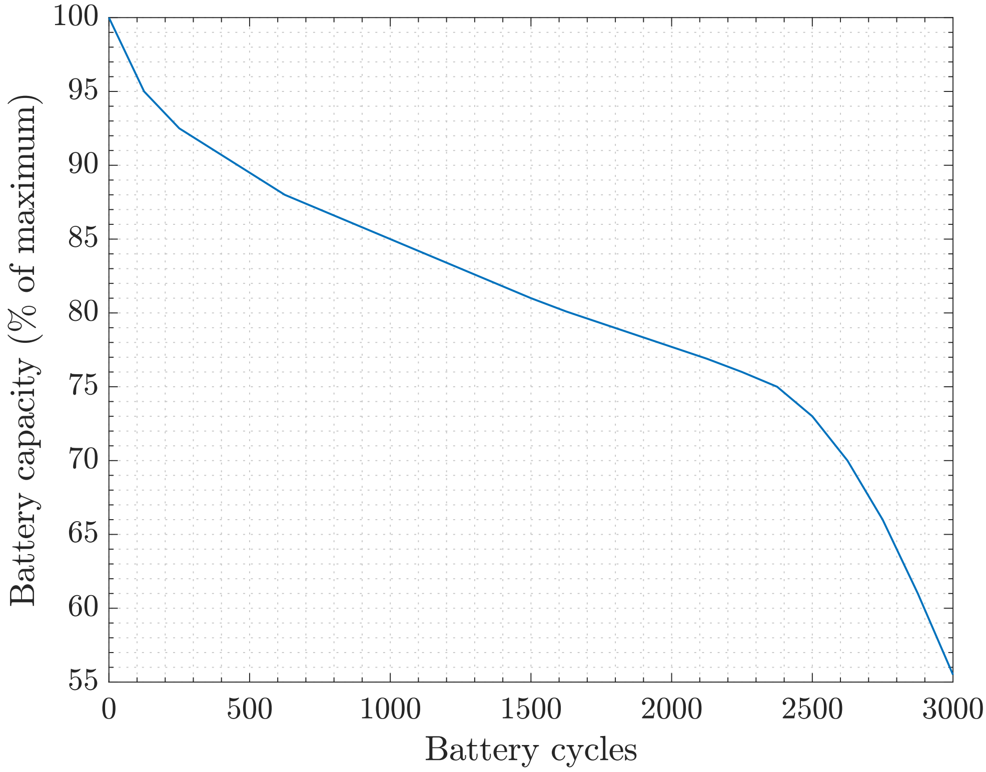

Figure H.1: Typical evolution of a Lithium-Ion battery capacity with life cycles [4].