Department of Mechanical and Aerospace Engineering

Assessing Grid-level Storage Requirements in a Future Net-Zero Carbon UK Energy System

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Signed: Malamatenia Patouni Date: 17/08/2021

Abstract

Much research has been done regarding the energy future worldwide. Climate change has emerged along with its consequences to the environment. Countries are now facing a challenge to mitigate this phenomenon and change their attitude over their energy generation and consumption.

Towards this direction, many countries have been motivated and have officially agreed to act by reducing carbon emissions or even eliminating them until 2050. This pathway consists of an intermediate critical year, i.e., 2030 and several targets that need to be achieved.

Altering the traditional types of electricity generation by renewable energy sources satisfies this ambition. However, due to the nature of renewables and their excessive production, energy storage facilities are vital to be incorporated with them.

This MSc thesis examines three aspects regarding the future electricity: demand and generation, along with the distribution of it in the UK. 2017 was taken as a benchmark for every projection. A simple Excel model was created, based on two different scenarios, in order to calculate the future electricity demand and supply.

Projections for 2030 and 2050 were found in literature and then adjusted to the respective reference data. Specifically, a scalar for net electricity demand and scalars for potential future energy supply sources were found and then multiplied by the initial half-hourly data.

The results were plotted to present these future demand-supply profiles and then according to these, the storage capacity was calculated. Finally, two different types of storage were assessed and discussed in terms of applicability and feasibility.

Acknowledgements

With the present MSc thesis, my study in Sustainable Engineering: Renewable Energy Sources and the Environment, here at the University of Strathclyde, Department of Mechanical and Aerospace Engineering (MAE), is concluded. Due to the last, I would like to warmly thank all of those who stood next to me by supporting my effort with valuable knowledge throughout this difficult period of pandemic.

Firstly, I would like to thank my family who provided me with the opportunity to educate and further enrich my background by constant support. In addition, it is critical to mention the whole academic personnel of the department who contributed to several queries that occurred during the individual project.

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Table of contents

List of Figures

List of Tables

1.0 Introduction

Nowadays, the carbon emissions have posed a significant threat to the planet and therefore environmentally friendly solutions, regarding the mitigation of this phenomenon, are urgent. Towards this direction, agreements have been established among countries worldwide, such as the Paris Agreement. It declares that countries will keep global warming up to 1.5 degrees, by reducing emissions by at least 45%, compared to 2010 levels, until 2030. The final target is countries to reach net-zero carbon emissions until 2050 [1].

1.1 Background

The UK government's aim to reduce greenhouse gas emissions by 80% by 2050 faces major difficulties, including a change of the UK electrical infrastructure on a scale that was never seen before. Markets are to deliver and integrate important amounts of intermittent renewable generation along with less flexible nuclear and Carbon Capture and Storage (CCS) plants, as part of this effort, while fields of the transportation and heating sectors are expected to be electrified [2].

Recently, studies have shown that by 2050 the electricity generation will be solely from renewable energy sources. The current state of each renewable source contribution is shown at the pie chart below.

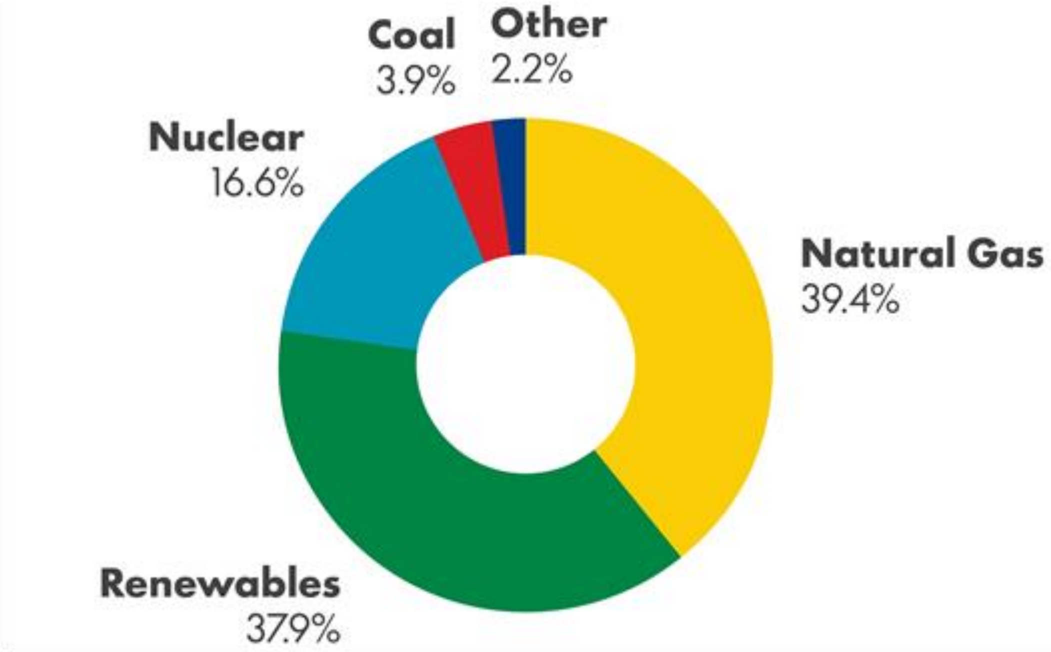

Figure 1: UK Energy Mix 2020 *[3]*

Due to the large contribution of gas combined cycle power plants (CCGT) to the grid, carbon dioxide emissions are relatively high, imposing the need of renewables, so as to reach the global targets. Especially, the UK seems to have warmly adopted the idea of a fully renewable future by investing not only to the evolution of renewables, but also to units for potential storage facilities [4].

Research has shown that although UK has invested in storage energy projects, there is still need for upgrading and increasing them, with regards to the increased needs for electricity. On a distributed and centralised basis, storage technologies can be used at multiple scales. Energy storage technology development varies by industry; some are well-developed, while others are still in the early phases of development [5].

1.2 Aims and Objectives

This MSc thesis aims to present the projections of national net demand for electricity and the corresponding electricity generation for the whole UK. These projections are based on a reference year, that was used as a benchmark, to calculate the aforementioned demand-supply profiles. In addition, the next target of this project is to assess the energy storage required for 2030 and 2050, in accordance with the previous profiles, to support the needs for electricity of the national grid. Finally, after assessing the energy storage a third goal is set and it accounts for potential storage systems.

As far as the objectives of this dissertation are concerned, a brief overview of demand and supply projections is theoretically presented. The next objective is to identify the renewable energy sources that could potentially supply the national grid. Another goal is to provide a theoretical overview of grid-level storage assessment, as well as an analysis of trending energy storage systems. Furthermore, energy storage capacity for both years is determined, along with possible future types of storage. Last but not least, the feasibility and applicability of the suggested storage systems is evaluated.

2.0 Literature Review

2.1 Demand Profile Projections and Supply

A variety of publications address several aspects of hourly demand projection. The majority of research concentrates on single-sector or consumer load curve projections, while others are restricted to regional load curves. Further research focuses on specific aspects of future system load, namely the load duration curve or the system peak load. Nevertheless, there are only three approaches now reported in literature for continuous hourly prediction of national scale load curves over a full year, to the extent known [2].

The first is a trend-extrapolation of load shape transformation's historical data. [6] analyse historical load curves for daily, weekly, and seasonal periodicity. The results are incorporated into a load curve trend extrapolation, which takes into consideration assumptions regarding total annual demand evolution. Macroeconomic impacts, technical developments, or temperature-related effects on the load curve are not considered, as this assumes that previous technology shifts would remain unmodified in the future. [7] expands on this technique by conducting a regression analysis using hourly German load data from 2006 to 2011, taking into account economic trends, public holidays and vacations, unexpected occurrences, and the growth of population. The introduction of new technologies on the market is not specifically considered.

Regarding the second type, there is an emphasis on certain appliances or events. [8] projects the future national demand taking into account the widespread use of electric vehicles and heat pumps. Hourly simulated load profiles indicate their usage pattern. The degree to which the load curve is transformed, is largely determined by the yearly electricity demand, regardless of the impact of ambient temperature.

The third type of research is based on a complete design of the future load curves. Based on empirical data, [8] establishes user specific load profiles of typical consumer groups across the industrial, tertiary, and residential sectors. These profiles are combined to create the total load curve, which is then scaled to generate the annual national demand. Because the spread of new technologies is not expressly considered, [9] follows the same method but focuses on the impact of rising market penetration of electric vehicles and heat pumps. [10] performs a regression analysis using historical load data, taking into account workdays, temperature, and day light. Future changes in consumer behaviour, such as working hours or opening hours in the business sector, are factored into the load profiles generated with a final goal to generate electricity demand projections.

Regarding the supply side, it is essential to follow the demand and match with it, during relatively short timescales and, given the limited alternatives for storage, it is observed a lack of flexibility in terms of providing the load with the demanded electricity at any time [2]. In addition to this, sometimes there are no communications between the consumers and the electricity suppliers, which make it more difficult for researchers to determine the supply profiles. Nevertheless, the technology and control evolution with applications, such as smart grids, have contributed to the more effective creation of supply profiles [11].

As years go by, the implementation of renewables, especially wind and solar, gives the opportunity to smart grids to evolve and get upgraded. This happens because of the fact that with the continued deployment of the two previous sources, the supply may change dramatically in a single day, and therefore supply profiles can become more dynamic charging profiles. By making a profile smart charging, it is possible to achieve significant peak shavings which lead to the degradation of the grid's fluctuations. However, it is noteworthy to remember that the combination of reduced minimum load, peak load, reduced utilization along with powerful ramp rates, that are stored, make it more challenging for supply profiles to be identified [12].

2.2 Hybrid Nuclear-Renewable Energy Systems

Nuclear power and renewable energy sources are both essentially carbon-free energy sources and have emerged as viable solutions to the reduction of environmental footprint and energy security issues. As a result, several countries have begun to invest in nuclear and renewable energy as a way to minimise reliance on crude oil commerce, improve energy security, reduce price fluctuations associated with imported fossil fuels and alleviate environmental damage. Although both energy sources have their own challenges, they are still a preferable solution for electricity generation, especially when they form a hybrid system.

In fact, renewable energy technologies used at a national level can make a significant contribution to a country's socio-economic growth. Relevant infrastructure and appliances, even in rural and isolated regions that are not connected to the grid, may significantly improve the quality of life. Nuclear power on its own may not be able to meet global energy demand, but it may not be possible to do so without it. A future global energy mix that emphasises on renewable sources and opposes to large scale nuclear power deployment would have severe economic and environmental consequences. In spite of its debatable reputation, nuclear power is sustainable, reliable and efficient, and multiple studies have recommended that it must be included in the energy mix [13].

In general, renewable energy sources are characterized by variability of generation, as it can be observed by the electricity production of wind turbines and photovoltaics. High penetration of these resources implies a flexible grid and, as a result, alternative generators, such as nuclear-renewable energy systems, can supply outputs at the required rates [14].

This kind of hybrid nuclear-renewable energy systems can provide several benefits. First of all, it contributes to the competitiveness of renewable energy and an environmentally friendly growth of green energy for future electricity generation. In addition, by upgrading the grid infrastructure to support grid-scale energy storage and dispatch, intermittent renewable energy can have a high grid penetration. Moreover, increased energy conversion efficiency will be achieved by improved integration of smart control and heat management technologies [13]. Finally, combining nuclear with renewable energy into a standalone hybrid energy system would allow a nuclear plant to operate at its full capacity, while at the same time to meet the demand for flexible generation rates and the production of both energy and ancillary services, and low-carbon co-products [14].

2.3 Grid-Level Storage

Energy storage is one of most important technological solutions for integrating intermittent renewable generation with electrified transportation and heating demand, as the power system in the UK, and the world, changes rapidly.

Regarding the generation side, renewable energy requirements are hastening the transition from dispatchable, slow-ramping large power plants to smaller non-dispatchable renewable energy resources, like wind and solar power plants. Electric vehicles, demand response, as well as metering systems are being improved in a similar way. Changes on both the supply and demand sides are causing uncertainty about the resources needed to keep the electrical grid in balance. For instance, many prominent renewable sources are unpredictable and intermittent, which can result in fluctuations during electricity generation, as well as unanticipated changes in power availability [15].

As for the demand-side, significant proportion of electric vehicles can cause increase or decrease in grid loads. In general, such additional risk has been addressed by operating reserves or any other auxiliary services, that can correct short-term imbalances quickly. However, due to grid change, the size and capacity needed to meet the new grid are likewise unclear, and can differ depending on region, season and weather patterns; as a result, it is not easy to estimate or define resource availability [15]. Such technologies that secure power system's flexibility are crucial to reaching renewable energy integration targets without putting at risk the efficiency, reliability and the cost-effective operation of the grid. Grid-scale energy storage is commonly thought to have the ability to give this additional flexibility [16].

There are several grid-scale energy storage systems that function on varying time intervals with an extent from seconds to hours. Such technologies are pumped hydroelectric storage (PHS), batteries, supercapacitors, flywheels, compressed air energy storage (CAES) and superconducting magnetic energy storage (SMES). More specifically, in the UK there are currently 39 installed storage systems which consist of different technologies [17]. There are several fundamental characteristics of typical grid-scale energy storage systems, such as the energy storage capacity (in TWh), which is the amount of energy that can be stored, along with energy and power density which indicate the rated storage energy per unit volume (in Wh/L) and the maximum available power per unit volume (in W/L), respectively [15].

Another feature that needs to be considered is the charge and discharge duration, which is the time needed for storage unit to fully charge or discharge. In accordance with discharge duration of storage unit, it is essential to know the typical amount of power that can be discharged within this period, which is the typical power output (in MW). The required time for the storage facility to start providing the power output, called response time, is another characteristic crucial for the application of the storage unit. In addition, storage's lifetime (in years or cycles) points out the total number of years or cycles of its continuous operation. Moreover, the roundtrip efficiency (in %), demonstrates the ratio of energy discharged by the system to the energy required, including losses, to charge the system over each cycle. Last but not least, the capital cost (in $/kWh) plays an important role in choosing a specific storage unit and shows the upfront investment costs of the system per unit of energy storage capacity.

It is vital for energy storage to meet a number of requirements when it is connected to a grid, which is supported by renewables. Common grid-services regarding the stability of provided power, regulation services, voltage control, usage of the power that is produced during off-peak hours to serve the load (energy arbitrage) and load balancing are important as demand and supply fluctuates during a year [15].

All things considered, the grid-scale storage can assist in mitigating the phenomena of intermittent, unstable and non-dispatchable power sources in various ways. Large-scale energy storage is able to prevent losses of load by services which provide enough energy capacity to meet peak power demand, along with services that improve power quality and suppress power output fluctuations. In times that there is lack of wind and solar energy to match the demand, storage can facilitate time-shifting of loads. Another important use of storage in renewable energy systems, is to compensate for voltage rises (or falls) induced by substantial increases (or decreases) in power availability, for instance those caused by resource intermittency. Storage that is co-located with a renewable power source is frequently used to perform this function. For example, co-locating storage with wind farms has been proven to help control power levels and stabilise production in response to market or operational conditions [18].

2.4 Design of Energy Storage

Energy storage systems consist of three different stages: charge, in which the storage unit absorbs the electrical energy from energy sources, storage, in which the facility converts the electrical energy to other types of energy, like mechanical or electrochemical, to store it, and discharge, which is the opposite procedure of charge, and the storage unit injects the stored electrical energy back to the system. As energy storage is only a storehouse of energy rather than a perfect energy source, there are always losses at each stage of the storage process. Equation (1) defines the energy delivered to the system considering the energy generated by the sources and the losses during power outages.

$$E_{generate} - \Delta E_{loss} = E_{out} \tag{1}$$

Energy losses are described by equation (2)

$$\Delta \mathrm{E}_{loss} = \Delta \mathrm{E}_{ch} + \Delta \mathrm{E}_{st} + \Delta \mathrm{E}_{disch} \tag{2}$$

where, $\Delta \mathrm{E}_{\mathrm{ch}}$, $\Delta \mathrm{E}_{\mathrm{disch}}$ and $\Delta \mathrm{E}_{\mathrm{st}}$ are the losses during charge, discharge and storage mode, respectively.

In fact, an essential parameter in electrical storage is the efficiency of each stage, which indicates the energy flow in the system. Equations (3) and (4) describe the efficiencies of charge and discharge stage, respectively.

$$\eta_{ch} = \frac{E_{st}}{E_{ch}} \tag{3}$$

$$\eta_{disch} = \frac{E_{st}{}^{*}}{E_{disch}} \tag{4}$$

It needs to be mentioned that energy losses as well as the efficiency of storage depend on the time needed among charging and discharging, so the efficiency of this stage can be calculated by equation (5).

$$\eta_{st}(t) = \frac{E_{st}{}^{*}}{E_{st}} \tag{5}$$

The total energy storage efficiency is given by equation (6)

$$\eta_{total} = \frac{E_{out}}{E_{generate}} = \eta_{ch} \times \eta_{disch} \times \eta_{st}(t) \tag{6}$$

The stored energy is represented by E_{st}*, while Est is the existing energy from this part. $E_{generate}$, E_{out}, E_{ch}, and $E_{dischare}$ describe the generated energy, the output, the energy during the charge and discharge step, respectively [19].

2.5 Batteries

Batteries are gaining attention recently, because they present a number of attractive advantages, like fast response, modularisation, high efficiency, flexible installation and large lifespan. More specifically, grid-level energy storage has become a field of application for batteries, because they should comply with large-scale and complex needs of the power grid. Hence, energy efficiency and densities, power, lifetime, and capacity should be taken into consideration. In addition to this, issues regarding load levelling, peak shaving, frequency regulation and other grid services (e.g., emergency response) should be investigated further before deciding to connect a Battery Energy Storage System (BESS) with the grid.

There are various types of batteries currently on the market, but still lithium-ion batteries are dominating due to their significant merits. For instance, they can achieve efficiencies higher than 95%, energy densities up to 200 Wh/kg, as well as up until 3000 cycles at a depth of discharge (DOD) of 80%. Due to their high energy densities, lithium-ion batteries seem to be promising when combining them with renewable energy sources in terms of grid-level storage of energy.

The principles of operation of lithium-ion batteries are based on the existence of two electrodes, anode and cathode, and a medium that is called electrolyte. During the charge state, electrons move from cathode to anode via the electrolyte, whereas during discharge process happens the vice versa. The operation of a lithium-ion battery is shown at Figure 2 below.

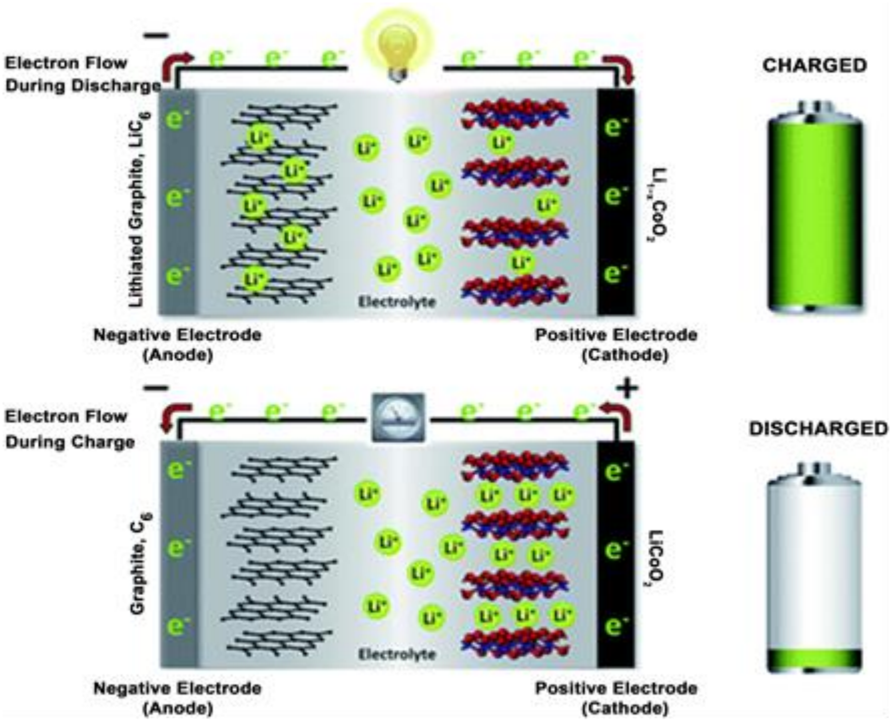

Figure 2: Illustration of the working principle of Lithium-Ion Batteries

The energy which is stored in batteries comes from electricity converted from a large-scale power network into a form that can be saved and be converted back into electricity in case it is needed. As the power grid needs energy storage systems that balance demand and supply, gravimetric energy density, along with high efficiency and long cycle life should be taken into account. Moreover, the reliability and cost efficiency of these systems are also crucial for large-scale power grid applications. That is why, it is mandatory to know the calendar life of lithium-ion batteries, because when either maintenance or replacement arises, the cost is significantly high. Storage duration and periodical discharge rate refer to calendar life, along with temperature, and they need to be measured in advance, as they cause losses during battery's self-discharging.

However, there are some disadvantages and challenges which make lithium-ion batteries deterring in terms of their wide-scale use. One of them corresponds to their high cost, which is related to the shortage of certain raw materials used for batteries' manufacture, such as nickel, lead and lithium. In addition to that, lithium-ion batteries consist of materials which when they come in contact with the electrolyte, are flammable and highly active. For these reasons, batteries should pass several safety tests, including electrical, environmental, and mechanical, before using them for grid-scale energy storage.

The applications which use batteries follow the concept of storing energy when the demand is covered by the supply and cover with vacant power the grid when it is necessary. The necessity of batteries appears when peak load has to be covered by peak shaving and load levelling. Also, unprecedented fluctuations of the output power may occur and as a result, batteries are due to smooth the generated power from renewable energy sources and diminish these fluctuations. A way to achieve this is to adjust the output profiles of either the wind or solar energy, for instance.

In order for a grid network to operate properly and steadily, sufficient power and energy are prerequisites. That leads to utilisation of hundreds or even thousands of batteries, which need to be properly managed in terms of how they are going to distribute the power. The key feature to accomplish this is the implementation of an appropriate power management strategy. The strategy that will be formulated, will take into consideration a few aspects, such as reliable function, cost-effectiveness, work, and storage safety, as well as durable stability. When batteries are place in stacks, it is compulsory to find a way to satisfy the needs of grid-level energy storage. It is worth mentioning that the total current capability increases in case of parallel connection, whereas the total voltage increases in series connection. In fact, this raises a severe challenge regarding stability, safety, voltage operation and cycle life [20].

2.6 Pumped Hydro Storage

Future electricity systems will integrate a large number of intermittent renewable energy sources, presenting challenges for ensuring high efficiency during operation and planning of these systems. Therefore, it is vital for energy storage to be flexible and able to accommodate the variability of renewable energy sources output and support the system by providing frequency regulation and capacity. Pumped storage can serve this purpose due to its rapid response to weather conditions or fluctuations and its ability to comply with large loads. In addition to that, one of the main advantages of pumped-hydro storage is its infinite technical lifetime. However, the reliance on topography of the region, large use of land and the initial capital needed are the most important disadvantages.

Pumped storage power plant's operation is based on controlling the level of water on an upper reservoir and the output frequency of voltage. The upper reservoir holds water, which during the generation mode flows through the hydropower plant in order to generate electricity. With regards to storage, the water is pumped from the lower reservoir into the upper one, using the same generators and turbines operating reversibly when there is lack of electricity. It is noteworthy that the height difference between the upper and lower tank is important to generate a larger amount of mechanical energy. A typical pumped storage plant is shown below in Figure 3.

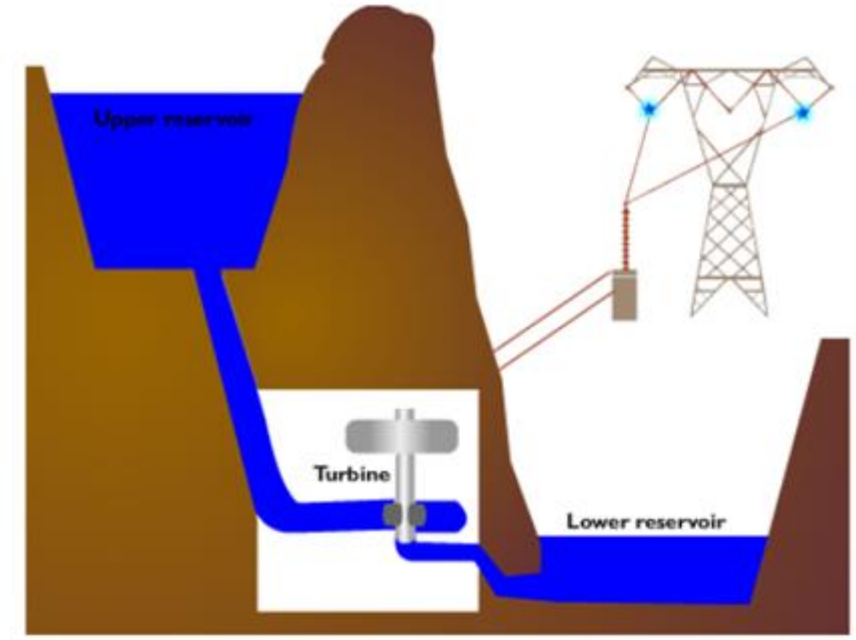

Figure 3: Typical Pump Storage Plant

When the water flows from the upper tank to the discharge tank, the motor acts as a turbine and converts gravitational power to mechanical power. The potential power relies on the water head and its flow rate can be found using the formula:

$$P_h = \rho g H Q_w \tag{7}$$

where the output mechanical power of the turbine is expressed as:

$$P_{PT} = \eta \rho g H Q_w \tag{8}$$

P_{PT} is the total output mechanical power from the turbine in Watts, η is the turbine efficiency, ρ is the volume density of water (kg/m^3), g is the gravitational acceleration (m/s^2) due to the height of the upper reservoir. Q_w is the water flow rate passing through the turbine (m^3/s) and H is the effective head of water across the turbine (m).

The efficiency of the pump-turbine is a fixed value in all operating modes, turbine and pump, and it can be usually around 70-85% [21].

3.0 Analysis

In this MSc thesis, the data for future electricity demand were examined based on 2017's electricity consumption data, that were acquired from ELEXON Portal and National Grid. The downloaded EXCEL data set consisted of 17,520 half-hourly data. The whole UK was taken as research area, as it complies with the target of this project, which was the future demand-supply profiles projection in national scale. Towards this direction, an estimation for these profiles was made for 2030 and 2050, following the methodology presented below.

3.1 Data Acquisition

The first step of the methodology was to search for valid data regarding forecast of national net demand in 2030 and 2050. Projections of UK's national net demand for both years were found in several references, as it is shown at Table 1 and Table 3. However, after comparison of the aforementioned data, DUKES and National Grid were considered to give more valid and accurate values. It is worth mentioning that, in this set of data some contributions were neglected. More specifically, interconnectors and inflows from other countries, such as France, the Netherlands and Ireland were not taken into consideration. Also, ELEXON Portal assigned zero to any negative values received from National Grid in the data set [22].

In a similar way, future supply projections for 2030 and 2050 were obtained from DUKES [23], Climate Committee's 2017 Report [24] and National Grid [25]. Based on these data it was decided that supply of electricity in the UK during the years 2030 and 2050 will be from some specific sources. In particular, for 2030, electricity will be provided by wind energy, solar energy, nuclear powerplants and small number of CCGT plants. By the end of 2050, UK's electricity generation will be fully decarbonised, so it is assumed that the supply will be only from renewable energy sources, i.e., wind (onshore and offshore) and solar energy, along with nuclear power plants.

For 2017, which was the reference year, the plot of supply and demand of electricity is shown at Figure 4. It needs to be mentioned that only wind, solar, nuclear, and other renewables' contribution to that year's supply, such as biomass and hydro, is plotted.

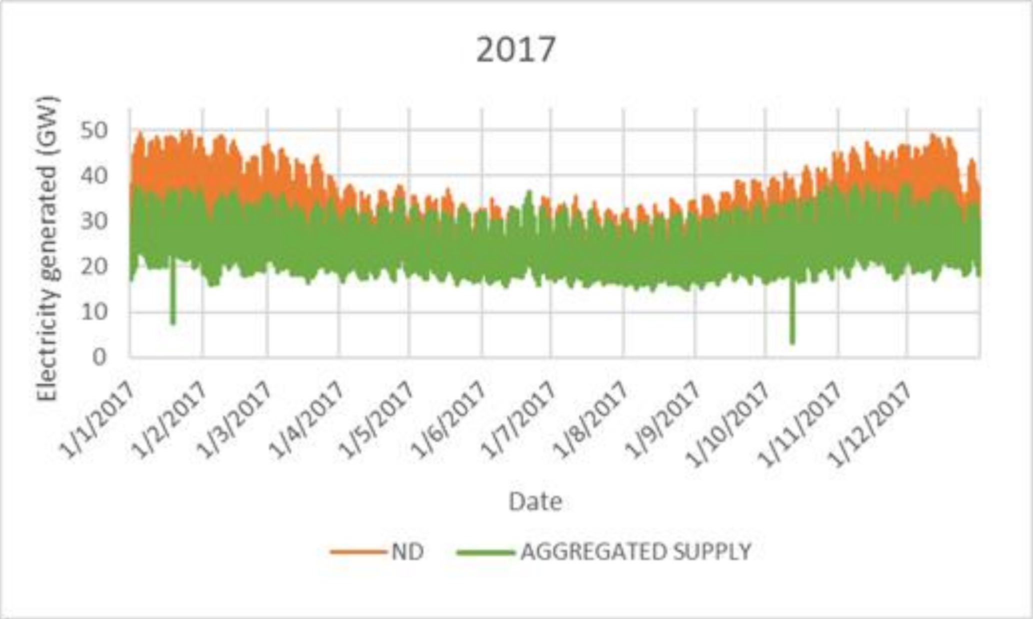

Figure 4: National Demand and Supply of the reference scenario

3.2 Net National Electricity Demand-Supply Profiles

The generation of future electricity demand – supply profiles were based on the following methodology. After gathering projections for electricity demand (in TWh) in 2030 and 2050, as well as projections for the aforementioned sources of electricity supply in these years, a number of scalars was calculated. For future wind supply, onshore and offshore, in total 6% of curtailment was considered [24]. These scalars were multiplied by the half-hourly data, giving the desired profiles.

The coefficients were calculated by applying the following formula:

$$\mathrm{r} = \frac{\text{Final value} - \text{Initial value}}{\text{Initial value}} + 1 \qquad (9)$$

where initial value (in TWh) refers solely to 2017 and final value (in TWh) corresponds to either 2030 or 2050 depending on the scalar that was to be calculated.

3.3 Scenarios

To investigate UK’s future electricity demand – supply profiles for 2030 and 2050, two different scenarios were examined. The criterion that was used to divert these two scenarios was the fossil fuel prices; namely, low prices (LP) and high prices (HP), as it was suggested by DUKES. Although, DUKES had recommended some other classifications, in this thesis’ framework only low and high prices classifications were considered [23].

3.3.1 Low Prices Scenario

At this scenario low fossil fuel prices were taken into consideration to create the demand-supply profiles for 2030 and 2050, respectively. DUKES data were provided in an Excel file until 2040, so for 2030 the values that were taken were exactly from the spreadsheet. However, for 2050 trend interpolation was used based on a fourth order polynomial to predict the values needed to create the 2050 profile. The values that were used as inputs to this trend started from 2008 up to 2040. By finding the aforementioned values, the respective scalars were calculated and then the initial data were multiplied by them.

In order to verify the 2050 data calculated by using the trend, a cross-check from credible literature was conducted. [26] and [2] give similar results to the ones that derived from the Excel model.

Afterwards, the demand-supply profiles, created for the low prices' scenario, were plotted and they are presented in the next section. More specifically, for each year, the results are depicted into two different graphs; one includes the national net demand and electricity generated by each source, and the other includes the net national demand along with the aggregated supply.

Table 1: Projections for LP Scenario

	2017 (in TWh)	**2030 (in TWh)**	**2050 (in TWh)**	**Reference**
National Electricity Demand	298.1	350	650	[24], [27]
Generation by type				
Nuclear	64	55	124	[23]
Wind (Onshore/Offshore)	50	120	361	[23]
Solar	11.5	25	72	[23]
Gas (CCGT)	134	67	0	[23]
Renewables	94	228	480	[24]

Table 2: Scalars for LP Scenario

Scalars (r)	**2030**	**2050**
ND	1.17	2.18
Nuclear	0.86	2.25
Wind	2.4	7.22
Solar	2.17	6.26
Gas (CCGT)	0.5	0

3.3.2 High Prices Scenario

At this scenario, on the contrary, high fossil fuel prices were taken into account to create the demand-supply profiles for 2030 and 2050, respectively. Following the same procedure as it was described previously, the respective scalars were calculated and finally the initial data were multiplied by them.

In terms of verification of the estimated values, a cross-check from credible literature was conducted. [26] and [2] give similar results to the ones that derived from the Excel model. At that point, the demand-supply profiles, created for the high prices' scenario, were plotted and they are shown in the next section. For both years, 2030 and 2050, the results are depicted into two different graphs; one includes the national net demand and electricity generated by each source, and the other includes the net national demand along with the aggregated supply.

The scalars calculated for both scenarios, along with an accumulative table of all the projections, are shown below.

Table 3: Projections for HP Scenario

	2017 (in TWh)	**2030 (in TWh)**	**2050 (in TWh)**	**Reference**
National Electricity Demand	298.1	350	650	[24], [27]
Generation by type				
Nuclear	64	55	124	[23]
Wind (Onshore/Offshore)	50	130	368	[23]
Solar	11.5	25	73.5	[23]
Gas (CCGT)	134	49	0	[23]
Renewables	94	244	490	[24]

Table 4: Scalars for HP Scenario

Scalars (r)	**2030**	**2050**
ND	1.17	2.18
Nuclear	0.86	2.25
Wind	2.6	7.36
Solar	2.17	6.39
Gas (CCGT)	0.37	0

From Table 1 and Table 3 it is noticed that nuclear power plants' capacity presents a substantially fall in 2030. This is due to the fact that 15 operational nuclear power plants will have been taken off by 2030, which correspond to 35% reduction of electricity generation. However, new nuclear power plants are to be developed, as well as the upgrade of the existing ones [28].

3.4 Storage Assessment

To assess the required storage capacity to support the grid at a national scale, the aggregated supply was found. The net electricity was found by adding the electricity generated from each source, i.e., solar energy, wind energy, nuclear power plants and gas (CCGT). The next step was to determine the excess electricity that occurred during a full year and needs to be stored. Therefore, the difference between aggregated supply and national demand was calculated for each half-hourly data. The sign of this difference indicates whether there is excess electricity or not, i.e., the positive sign shows this excess, whereas the negative one points out the shortage of required energy to cover the needs of the grid for electricity.

Furthermore, the aforementioned difference's sign outlines the charge and discharge state of the storage system. When the difference is greater than zero, it means that the storage facility is charged with the respective excess electricity. On the other hand, when the difference is less than zero, the storage unit is discharged. Another feature of the storage unit that needs to be defined is the ramp rate. The ramp rate is the average rate of either charging or discharging of the storage system per half hour. It was essential to calculate the ramp rate, so as to have a good approximation of the storage system's size and behavior.

Based on the methodology of this thesis, the average charge and discharge rate in a whole year were calculated, as well as the corresponding ramp rates of each state.

The maximum difference between aggregated supply and demand was calculated by using a moving window to scan a set of data, importing the Excel sheet to MATLAB. The timestep of this window was assumed to be 14 calendar days or 672 half-hourly segments. The aim of the process was to keep the maximum number of the difference during the first iteration and then compare it with the one obtained from the next iteration and finally keep the maximum amongst them. The same procedure was repeated until the last scan of data, so as to find the maximum of all. The total maximum was then multiplied by 30 days and by 24 hours to find the storage capacity in TWh. The product occurred was multiplied by a coefficient of 1.05 which indicates the worst-case losses and amounts to approximately 5% per day [29].

To make the problem more realistic, two types of storage were dimensioned; pumped storage and batteries. The methodology regarding the pumped storage was based on [21] and for the batteries, by retrieving a set of manufacturers' data, as shown at Appendices , some detrimental steps were followed to estimate the number of batteries needed.

As it was presented at [21] and by using Dinorwig hydropower station as a benchmark, the quantity of respective pumped storage plants was calculated.

Table 5: Storage characteristics for LP Scenario

2030		
Total capacity	12289.79 MW	9.29 TWh
Average charge rate (MW)	2995.78	
Average discharge rate (MW)	11882.42	
Average charge ramp rate (MW/30min)	1.66	
Average discharge ramp rate (MW/30min)	6.60	
2050		
Total capacity	56273.76 MW	42.54 TWh
Average charge rate (MW)	12999.17	
Average discharge rate (MW)	24967.77	
Average charge ramp rate (MW/30min)	7.22	
Average discharge ramp rate (MW/30min)	13.87	

Table 6: Storage characteristics for HP Scenario

2030		
Total capacity	12657.4 MW	9.57 TWh
Average charge rate (MW)	3082.82	
Average discharge rate (MW)	12995.70	
Average charge ramp rate (MW/30min)	1.71	
Average discharge ramp rate (MW/30min)	7.22	
2050		
Total capacity	58208.1 MW	44.01 TWh
Average charge rate (MW)	13382.78	
Average discharge rate (MW)	24881.27	
Average charge ramp rate (MW/30min)	7.43	
Average discharge ramp rate (MW/30min)	13.82	

The amount of energy to be stored for 2030 scenario and low fossil fuels' prices, as show at Table 5, is 9.29 TWh which corresponds to 12,289.79 MW. This is a vast amount of energy to be stored and therefore it was decided to split this quantity into 70% that goes to pumped storage and 30% that is sent to batteries. Consequently, 8,602.85 MW are to be stored via pumped hydro storage and 3,686.94 MW with batteries, respectively.

As far as pumped storage is concerned, an already existing pumped hydro storage system was taken into consideration as a benchmark, i.e., Dinorwig Power Station. The specifications of this Power Station are depicted at Table 9 at Appendices. It was also considered the maximum charge and discharge power rate of storage were equal [30].

Based on [21], the Dinorwig's current nominal capacity (CN) in MW was estimated:

$$C_N = 6\ \text{generators} \cdot 288\ {}^{\text{MW}}/_{\text{generator}} = 1{,}728\text{MW} \tag{10}$$

If for 1,728 MW 6 generators are required, then for 8,602.85 MW it was calculated that 30 generators are required. Hence, given the 6 generators of Dinorwig's Power Station, 24 generators will be essential eventually. This corresponds to 4 additional pumped storage plants likewise Dinorwig's Power Station.

Afterwards, the generated power was assumed to be 1,728 MW. The required mass of water, during the discharge state, is given by the formula:

$$\text{D}_{\text{cap}} = \frac{\text{P}_{\text{gen}}}{\text{g} \cdot \text{H}_{\text{eff}} \cdot \text{D}_{\text{is,rate}} \cdot \text{n}_{\text{gen}}} = \frac{1728 \cdot 10^6}{9.81 \cdot 536 \cdot 390 \cdot 0.8} = 1053.3\text{m}^3 \tag{11}$$

On the other hand, during the charge state, the flow rate is calculated as follows:

$$\text{Flow rate} = \text{F}_{\text{rate}} = \frac{\text{P}_{\text{gen}} \cdot \text{n}_{\text{gen}}}{\text{g} \cdot \text{H}_{\text{eff}}} = \frac{1728 \cdot 10^6 \cdot 0.8}{9.81 \cdot 536} = 262{,}905.6\ {}^{\text{m}^3}/_{\text{s}} \tag{12}$$

The calculated flow rate corresponds to 6 generators in total.

Then, based again on [21], if a reference time of 16 secs is considered, then the required electrical energy along with the maximum capacity can be assessed using the equations below:

$$\text{Required Electrical energy} = \text{T}_{\text{ref}} \cdot \text{P}_{\text{gen}} = \frac{16}{3600} \cdot 1728 \cdot 10^6 = 7.68\text{MWh} \tag{13}$$

$$\text{Maximum Capacity} = \frac{\text{Energy}}{\text{Voltage}} = \frac{7.68\text{MWh}}{18\text{kV}} = 426.7\text{Ah} \tag{14}$$

Regarding the percentage of energy that was determined to be stored at batteries, it corresponds to 2.79 TWh. From the respective manufacturer's data for a battery that is presented at Appendices (Figure 13) it was found that the battery's capacity (Q) is 138 Ah and the open-circuit voltage (Voc) is 12.8 V. Thus, the capacity of the battery in Wh units is:

$$\text{C} = \text{Q} \cdot \text{V}_{\text{oc}} = 138 \cdot 12.8 = 1.8\text{kWh} \tag{15}$$

Since each battery can store 1.8kWh, it was calculated that for storing 2.79 TWh, the number of required batteries is:

$$\text{Number of Batteries} = \frac{2.79 \cdot 10^{12}}{1.8 \cdot 10^3} = 1{,}550{,}000{,}000 \tag{16}$$

By following the same methodology, the respective values were calculated and presented at the table below. At this point, it is worth mentioning that for both scenarios of 2050, it was decided to split the quantity of energy to be stored into 80% for pumped storage plants and 20% for batteries, respectively. The results are presented on the table below.

Table 7: Recommended Storage Capacity

Type of Storage		**2030 HP**	**2050 LP**	**2050 HP**	**2030 LP**
Pumped Storage	Total Capacity (TWh)	6.38	32.41	35.21	6.19
	Number of Power Stations	5	26	26	4
Batteries	Total Capacity (TWh)	2.87	8.51	8.8	2.79
	Required number	1,594,444,444	4,727,777,778	4,888,888,889	1,550,000,000

4.0 Results and Discussion

By following the methodology described at the previous chapter, demand-supply profiles were created for both years, i.e., 2030 and 2050, for HP scenario, in accordance with the projections presented at the tables previously.

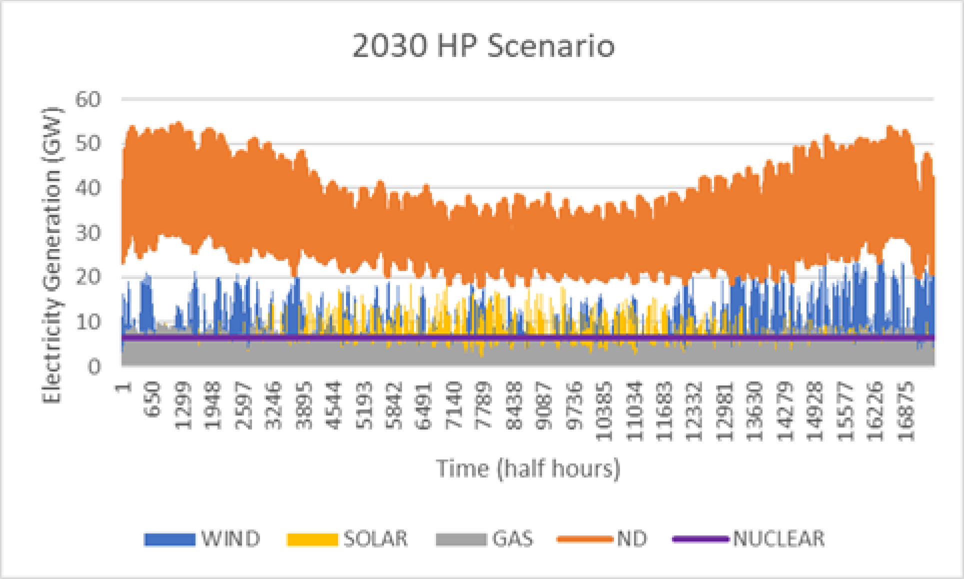

Figure 5: Demand-Supply Profile by source for 2030 HP Scenario

At Figure 5 the HP scenario for 2030 is shown and the x-axis the time is depicted in half-hourly segments, while y-axis depicts the national demand for electricity that needs to be covered, as well as the future electricity generated by each source, in terms of power.

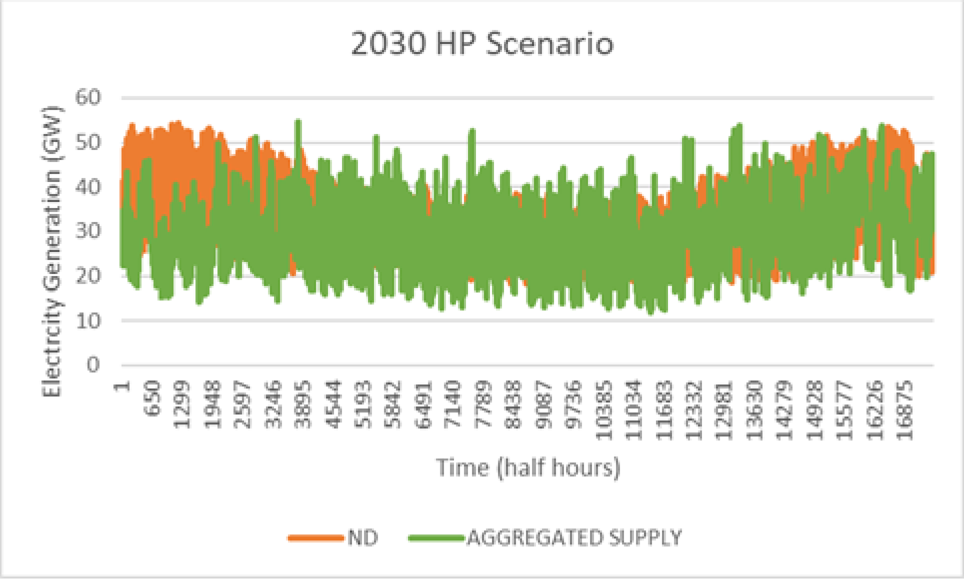

Figure 6: Demand-Aggregated Supply Profile for 2030 HP Scenario

Figure 6 represents the national demand projected for 2030, along with the aggregated supply which resulted by adding the electricity generation provided by each source.

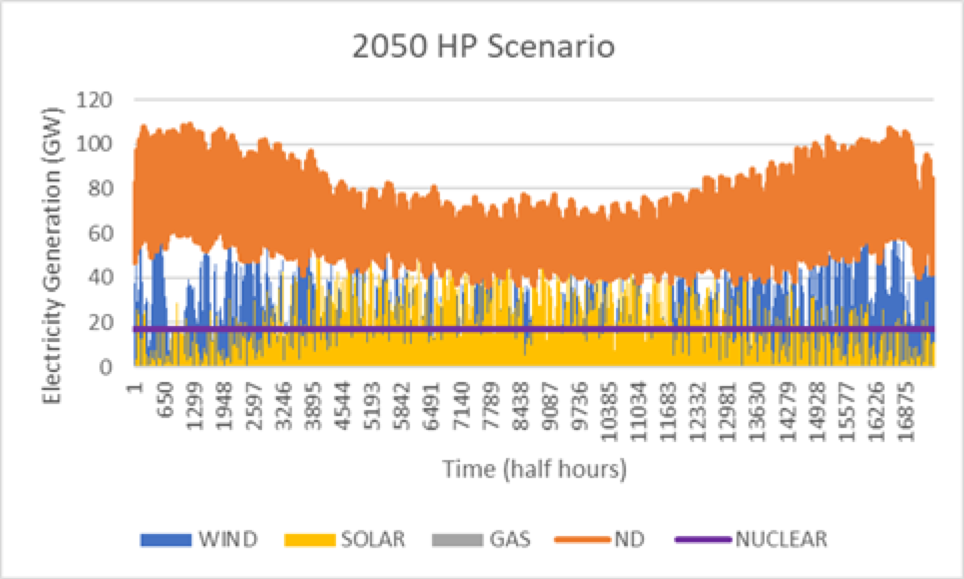

Figure 7: Demand-Supply Profile by source for 2050 HP Scenario

At Figure 7 the HP scenario for 2050 is shown and the x-axis the time is depicted in half-hourly segments, while y-axis depicts the national demand for electricity that needs to be covered, as well as the future electricity generated by each source, in terms of power.

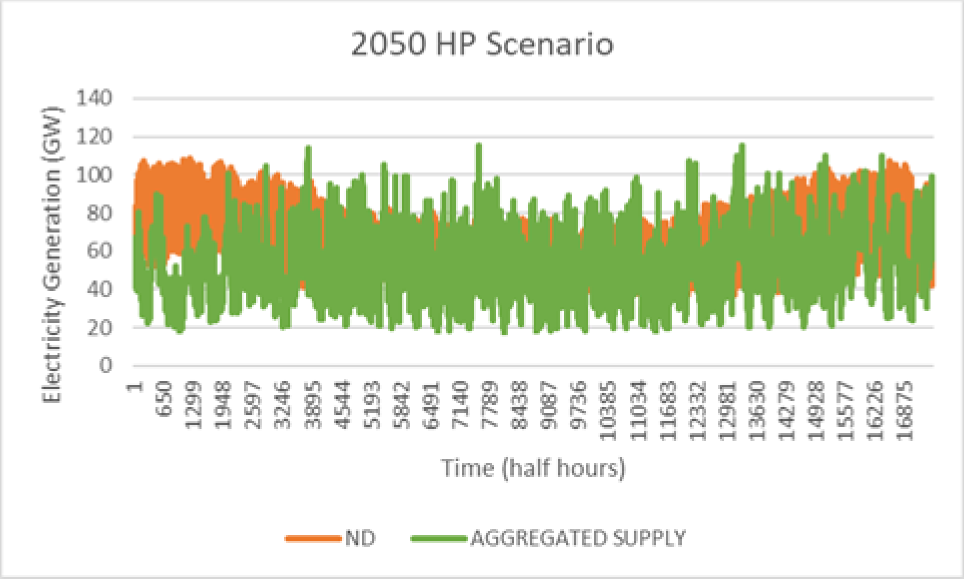

Figure 8: Demand-Aggregated Supply Profile for 2050 HP Scenario

Figure 8 shows the national demand projected for 2050, along with the aggregated supply which resulted by adding the electricity generation provided by each source.

Similarly, the projected demand and supply profiles for the LP scenario in both years, are illustrated below.

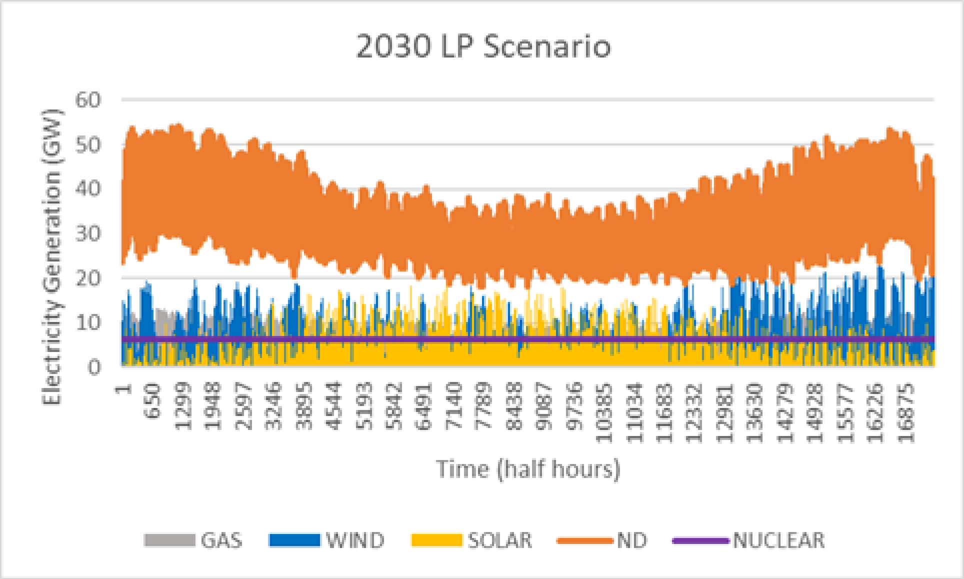

Figure 9: Demand-Supply Profile by source for 2030 LP Scenario

Figure 9 demonstrates the LP scenario for 2030. At the x-axis the time is depicted in half-hourly segments, while y-axis depicts the national demand for electricity that needs to be covered, as well as the future electricity generated by each source, in terms of power.

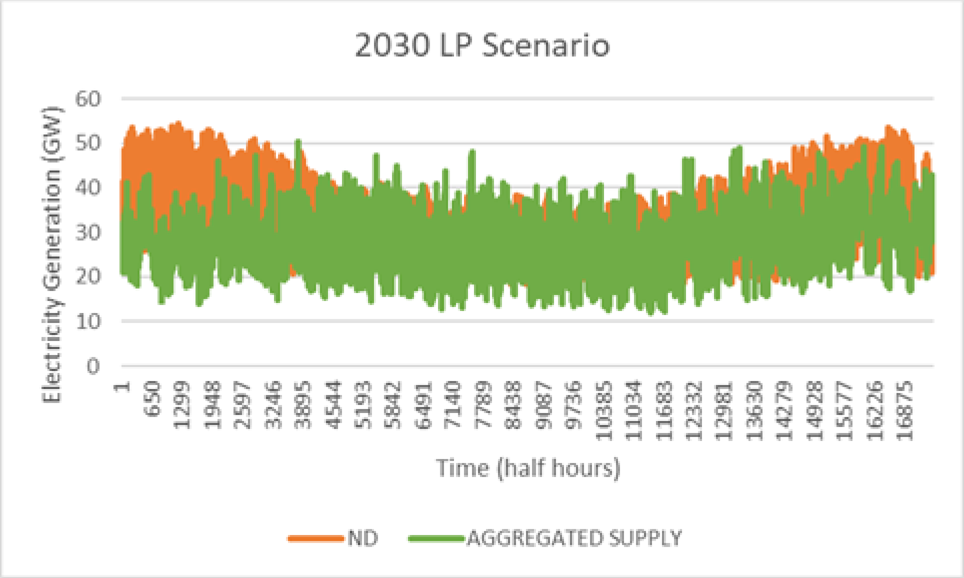

Figure 10: Demand-Aggregated Supply Profile for 2030 LP Scenario

Figure 10 presents the national demand projected for 2030, together with the aggregated supply which occurred by adding the electricity generation provided by each source.

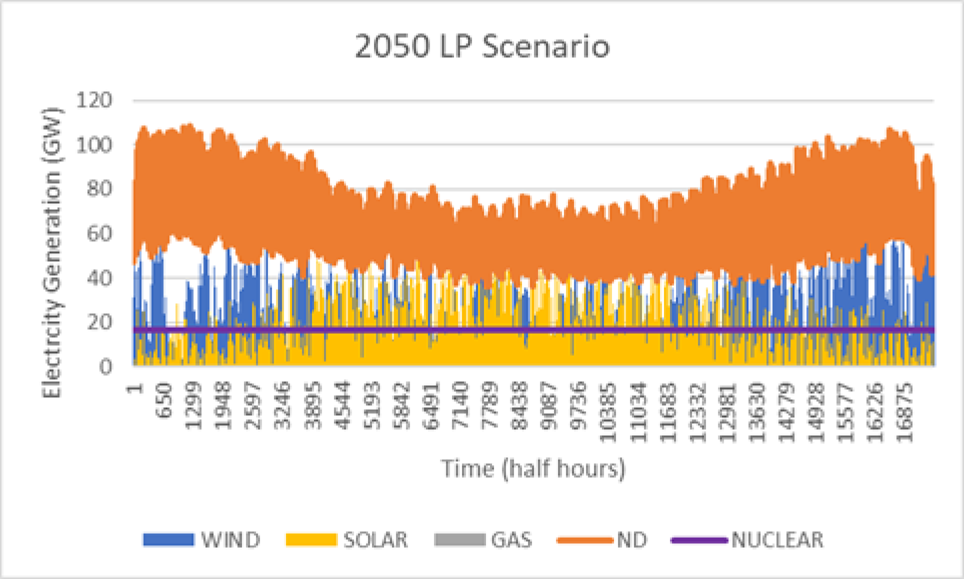

Figure 11: Demand-Supply Profile by source for 2050 LP Scenario

Figure 11 demonstrates the LP scenario for 2050. At the x-axis the time is depicted in half-hourly segments, while y-axis depicts the national demand for electricity that needs to be covered, as well as the future electricity generated by each source, in terms of power.

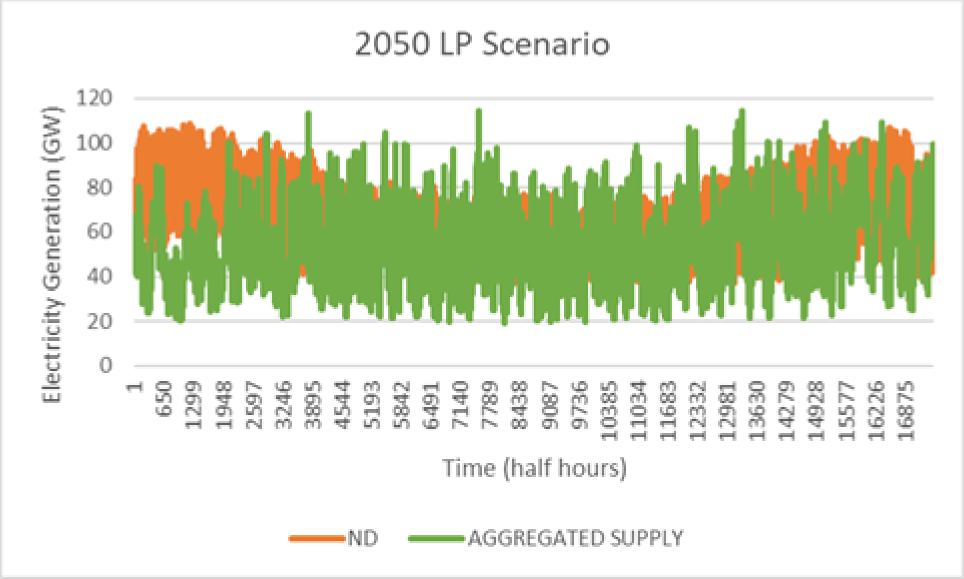

Figure 12: Demand-Aggregated Supply Profile for 2050 LP Scenario

Figure 12 presents the national demand projected for 2030, together with the aggregated supply which occurred by adding the electricity generation provided by each source.

In general, based on the graphs presented above, supply and demand does not match every time in a full year, due to the nature of sources that are chosen to support the demand. To be more specific, wind and solar are renewable energy sources which are affected by weather conditions, such as adequate wind and solar radiation, and their power generation is not steady throughout the year. When the supply surpasses the demand, there is a potential to store the excess energy and use it during peak hours, when the supply is not enough to meet the grid load. Also, it needs to be mentioned that 2017's respective profiles (Figure 4) do not match, as in that year the electricity supply coming from renewables accounted less than 36% of UK generation.

According to the methodology suggested to the previous chapter, the capacity of energy to be stored for both scenarios in 2030 and 2050 was calculated and it is presented at the table below. The excess energy (storage capacity) was calculated by subtracting demand from supply for each segment and then find the maximum value of this difference. Remarkably, during the winter months, electricity demand seems to have its peak, whereas during summer months there is excess energy and there is the potential to store it and be exploited afterwards.

Table 8: Storage Capacity for both scenarios in both years

Scenarios	**Year**	**Storage Capacity (TWh)**
Low Prices	2030	9.29
	2050	42.54
High Prices	2030	9.57
	2050	44.01

The above values for storage capacity were verified based on National Grid's projections [31]. Particularly, National Grid projects 9.36 TWh total capacity of storage in 2030 and 51.12 TWh storage capacity for 2050, regardless of any scenario. The deviation of values projected for 2050 arises from the fact that in this thesis' framework only wind, solar and nuclear contribute to 2050's electricity generation, while in reality more renewable energy sources will contribute to 2050's electricity generation, while in reality more renewable energy sources will contribute to it, which, on the other hand, have been considered from National Grid.

It can be observed that during the transition to a net-zero carbon emissions future, a large amount of storage capacity is required, regardless of the examined scenario. Particularly, the capacity of storage soars from approximately 9 TWh in 2030 to almost 45 TWh in 2050. This difference between 9 and 45 TWh can be justified due to the increase of renewables connected to the grid, which compared to the traditional coal or gas power plants' output, their output is much greater. Another reason contributing to this large difference is the implementation of new technologies, such as wind generators with improved efficiencies and control strategies. This means that the power output is effectively controlled and adapted to the electricity needs of the grid. Increased storage capacity is an indicator of the amount of excess energy generated from renewables, as the target for the UK grid is to be 100% renewable by the end of 2050.

In general, in 2050, electricity supply will be achieved by more renewable energy sources than the three that are considered in this dissertation. More specifically, renewables like tidal, wave, biomass, and gas, along with coal power plants with carbon capture and storage (CCS), will also have an important contribution to future electricity production. The implementation of these additional sources support the supply side resulting in the rise of supply by a percentage that remains to be thoroughly investigated.

Concerning the demand side, projections about an increased value have been made. To be more specific, scientists talk about almost double electricity demand until 2050, in comparison with the one in 2017. This accounts for increased needs for electricity due to the electrification of vehicles and heating, for instance, and the use of alternative fuels, with hydrogen to be a pioneer. Also, from Table 8 it is noticed that regarding the HP scenario, the storage capacity, in both years, is larger than the capacity found for the LP scenario, during the same period. An explanation could be that the higher the prices of fossil fuels are, the greater the motivation for utilisation of renewables is.

In terms of storage, the results occurred for pumped hydro storage look slightly more sensible than the ones for batteries (Table 7). As a result, additional storage techniques have to be investigated to support the batteries as one storage option. The techniques that are recommended at this MSc thesis concern the energy distribution to supercharges in order to charge electric vehicles and to appropriate facilities for hydrogen production. Electric vehicles are a trend that spreads worldwide and towards a net-zero carbon emissions future, they are about to dominate the market. Since the quantity of these increases, it is certain that more and more power stations will be essential. Moreover, hydrogen becomes popular as an alternative fuel and state-of-the-art concept to store excess energy that can be exploited. Finally, as it was mentioned at literature review section, there are currently various installed stand-alone energy storage projects in the UK, which can be potentially upgraded to support the future needs for electricity storage.

5.0 Conclusions and Future Work

All in all, this study set out to provide an overview of the UK’s electricity demand projection in the upcoming years, towards a net-zero carbon emissions future energy system. In accordance with the demand projections, the supply was determined based on the targets that UK has set for electricity generation to be 100% from renewables until 2050. British electricity is going to be fully decarbonised until then and by integration of renewables to the grid, the generated energy will significantly rise. Therefore, the need to store this amount of energy for potential future use derives from the respective excess energy which occurs.

In this thesis’ framework, it was observed that demand and supply profiles do not always match. However, there are days throughout the year when supply surpasses the demand and that is why the excess energy needs to be stored. In addition to this, the stored energy will contribute to the grid supply in order to decarbonise it, as it was presented at this project. Furthermore, several technologies to store this energy were suggested and a couple of them were dimensioned, i.e., pumped hydro storage and batteries. The results indicated that these two types of storage are not enough to support the grid in terms of saving energy for future use. Consequently, additional energy storage units need to be investigated and in accordance with the respective feasibility studies to be dimensioned.

In terms of the future work, the main field of study could be the analysis of the additional energy storage units, regardless of pumped storage and batteries. This could lead to a more practical and feasible approach regarding the distribution of the stored energy. Another aspect for future research is the improvement of current storage configurations with the implementation of additional technologies, such as control systems, to improve the efficiency of storage unit and therefore the performance of the grid. Last but not least, the design of demand side management strategies for peak power reduction, improved reliability and degradation of carbon dioxide emissions is also recommended for future work.

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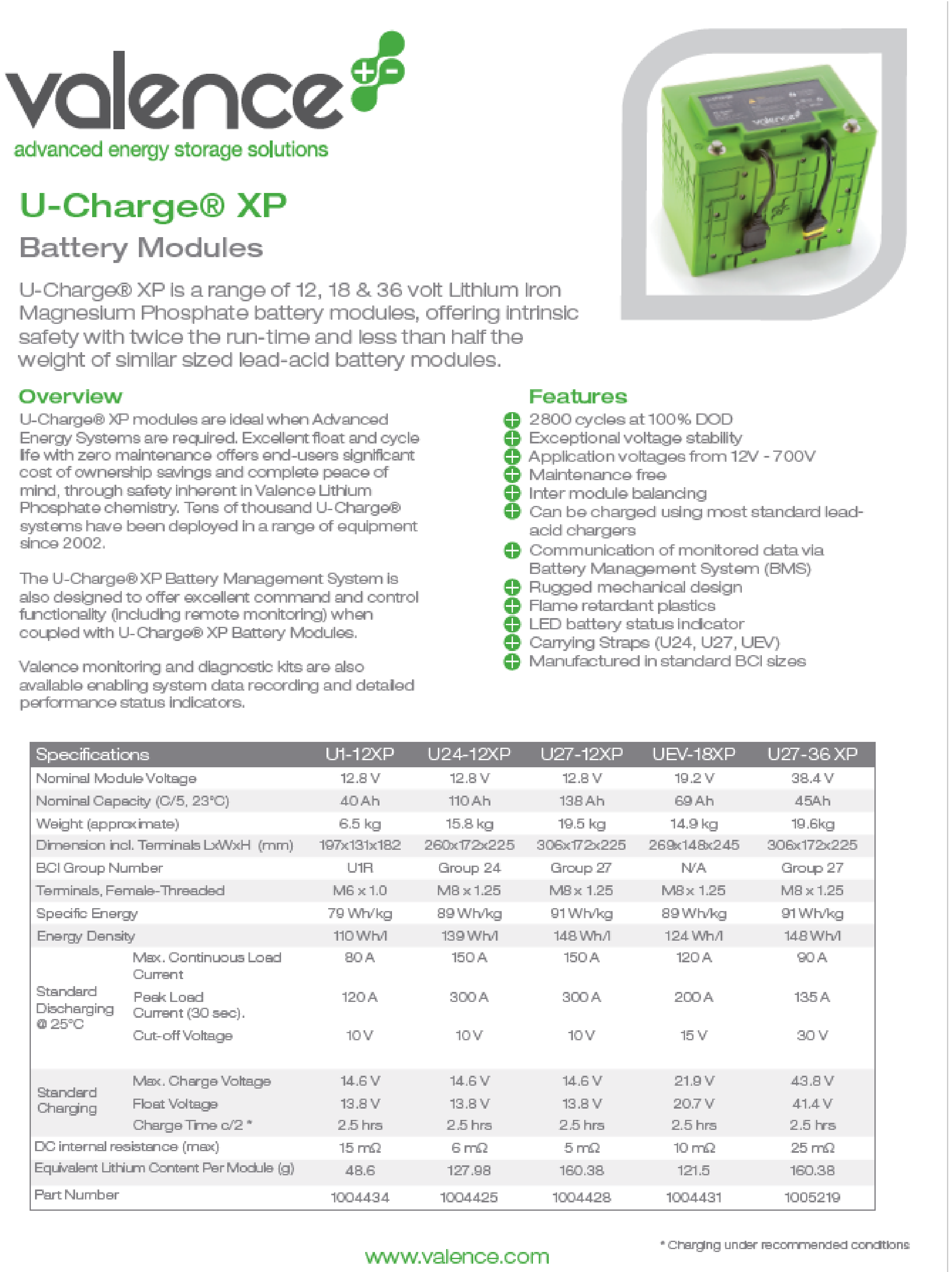
Appendices

Table 9: Dinorwig Power Station's characteristics

Dinorwig Power Station	
Dimensions of Surge Pond (m)	80x40x14
Effective Head (m)	536
Distance of Power Station inside mountain (m)	750
Depth of Turbine Hall below top level of Llyn Peris (m)	71
Number of Generators	6
Generator/Motor Rating (MVA)	330/312
Terminal Voltage (kV)	18
n_{gen}	80%
Discharge Rate (m^3/s)	390
Total time of a full cycle (h)	12
Average full unit over all heads (declared capacity) (MW)	288
Synchronous Speed (rpm)	500



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U-Charge® XP

Battery Modules

U-Charge® XP is a range of 12, 18 & 36 volt Lithium Iron Magnesium Phosphate battery modules, offering intrinsic safety with twice the run-time and less than half the weight of similar sized lead-acid battery modules.

Overview

U-Charge® XP modules are ideal when Advanced Energy Systems are required. Excellent float and cycle life with zero maintenance offers end-users significant cost of ownership savings and complete peace of mind, through safety inherent in Valence Lithium Phosphate chemistry. Tens of thousand U-Charge® systems have been deployed in a range of equipment since 2002.

The U-Charge® XP Battery Management System is also designed to offer excellent command and control functionality (including remote monitoring) when coupled with U-Charge® XP Battery Modules.

Valence monitoring and diagnostic kits are also available enabling system data recording and detailed performance status indicators.

Features

- 2800 cycles at 100% DOD
- Exceptional voltage stability
- Application voltages from 12V - 700V
- Maintenance free
- Inter module balancing
- Can be charged using most standard lead-acid chargers
- Communication of monitored data via Battery Management System (BMS)
- Rugged mechanical design
- Flame retardant plastics
- LED battery status indicator
- Carrying Straps (U24, U27, UEV)
- Manufactured in standard BCI sizes

Specifications		U1-12XP	U24-12XP	U27-12XP	UEV-18XP	U27-36 XP
Nominal Module Voltage		12.8 V	12.8 V	12.8 V	19.2 V	38.4 V
Nominal Capacity (C/5, 23°C)		40 Ah	110 Ah	138 Ah	69 Ah	45Ah
Weight (approximate)		6.5 kg	15.8 kg	19.5 kg	14.9 kg	19.6kg
Dimension incl. Terminals LxWxH (mm)		197x131x182	260x172x225	306x172x225	269x148x245	306x172x225
BCI Group Number		U1R	Group 24	Group 27	N/A	Group 27
Terminals, Female-Threaded		M6 x 1.0	M8 x 1.25	M8 x 1.25	M8 x 1.25	M8 x 1.25
Specific Energy		79 Wh/kg	89 Wh/kg	91 Wh/kg	89 Wh/kg	91 Wh/kg
Energy Density		110 Wh/l	139 Wh/l	148 Wh/l	124 Wh/l	148 Wh/l
Standard Discharging @ 25°C	Max. Continuous Load Current	80 A	150 A	150 A	120 A	90 A
	Peak Load Current (30 sec).	120 A	300 A	300 A	200 A	135 A
	Cut-off Voltage	10 V	10 V	10 V	15 V	30 V
Standard Charging	Max. Charge Voltage	14.6 V	14.6 V	14.6 V	21.9 V	43.8 V
	Float Voltage	13.8 V	13.8 V	13.8 V	20.7 V	41.4 V
	Charge Time c/2 *	2.5 hrs	2.5 hrs	2.5 hrs	2.5 hrs	2.5 hrs
DC internal resistance (max)		15 mΩ	6 mΩ	5 mΩ	10 mΩ	25 mΩ
Equivalent Lithium Content Per Module (g)		48.6	127.98	160.38	121.5	160.38
Part Number		1004434	1004425	1004428	1004431	1005219

* Charging under recommended conditions

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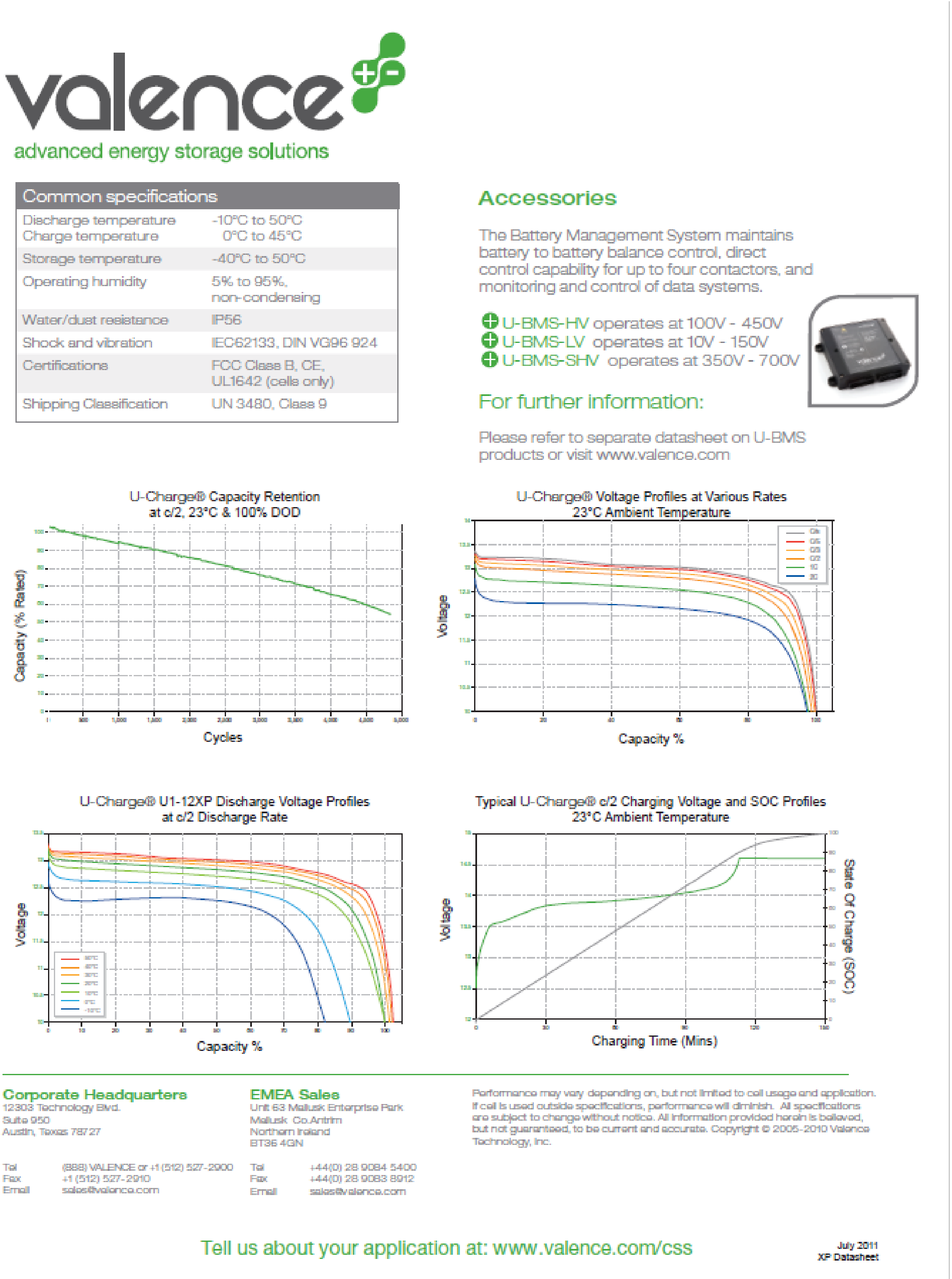
Figure 13: Battery Datasheet 1/2



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Common specifications	
Discharge temperature Charge temperature	-10°C to 50°C 0°C to 45°C
Storage temperature	-40°C to 50°C
Operating humidity	5% to 95%, non-condensing
Water/dust resistance	IP56
Shock and vibration	IEC62133, DIN VG96 924
Certifications	FCC Class B, CE, UL1642 (cells only)
Shipping Classification	UN 3480, Class 9

Accessories

The Battery Management System maintains battery to battery balance control, direct control capability for up to four contactors, and monitoring and control of data systems.

- U-BMS-HV operates at 100V - 450V
- U-BMS-LV operates at 10V - 150V
- U-BMS-SHV operates at 350V - 700V

For further information:

Please refer to separate datasheet on U-BMS products or visit www.valence.com

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Performance may vary depending on, but not limited to cell usage and application. If cell is used outside specifications, performance will diminish. All specifications are subject to change without notice. All information provided herein is believed, but not guaranteed, to be current and accurate.

Tell us about your application at: www.valence.com/css

July 2011
XP Datasheet

Figure 14: Battery Datasheet 2/2