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Technical Appraisal of a Wind-Thermal Energy Storage System in Scotland

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Signed: Ewan Millan Date: 26/08/20

Abstract

This research details the modelling of a wind-thermal energy storage system in Scotland using the tool EnergyPLAN. The central aim of the research is the construction of the model, alongside the additional aims of calculating the wind resource potential of an area of Scotland and identifying the optimum thermal energy storage configuration and material to be used in the system.

The Literature Review establishes the need for energy storage to provide flexibility to grid scale electricity systems and recognises the gap in thermal energy storage for electricity generation. Different methods of thermal energy storage are investigated along with their suitability for electricity generating applications in wind-thermal energy storage systems.

To calculate the wind resource potential of an area of Scotland, data from the Global Wind Atlas, the tool HOMER Pro and equations relating to Hellman's Power Law are used. The thermal energy storage configuration and material are selected based on their ability to provide high working temperatures, high heat capacity and a high thermal conductivity over a long lifetime through many thermal cycles.

The results of the EnergyPLAN modelling show that the integration of the thermal energy storage with a wind resource generally improves the flexibility of the electricity generating system. However, this reaches a limit, with increases in the energy and power capacity of the thermal energy storage not considerably improving the flexibility of the system, whilst incurring higher costs. The limitations of the study are discussed, especially those arising from the use of EnergyPLAN and the research concludes with how this work could be improved upon in the future.

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1. Introduction

1.1 Background and Problem Definition

1.1.1 Changing Energy Systems and the Need for Flexibility

Electricity generation has long been achieved by the burning of fossil fuels. Coal, oil and natural gas offer a source of fuel that is dispatchable and highly energy dense, and their use over the last few hundred years has been a driving force behind the industrialisation and development of countries across the world. Now, amidst the backdrop of increasingly dire warnings of the severity of the climate crisis, predominantly caused by the polluting nature of fossil fuels, these energy systems are changing.

One key change is the increasing use of renewable sources of energy, due to their lack of greenhouse gas emissions. In Scotland, the past 20 years have yielded significant changes in renewable energy use, especially intermittent wind energy. The fraction of gross electricity met with renewables increased from 13.2% to 54.9% between 2005 and 2018, with wind energy responsible for the largest increase jumping from 2.6% to 40.2% (Scottish Goverment, 2020). The Scottish and UK Government recognise the economic and environmental benefits of these new sources of electricity and have set targets of 100% gross electricity consumption to come from renewable sources in Scotland by 2020 (Scottish Government, 2017a) and up to one third of UK electricity to be generated by offshore wind farms by 2030 (Department of Business, Energy and Industrial Strategy, 2019). These ambitious targets are accompanied by a myriad of laws, targets and other pieces of legislative agenda that conjure an image of a future Scottish/UK energy system that is heavily reliant on renewables.

However, renewable sources of energy are beset by their own issues that must be addressed if a low carbon energy future is to be achieved. Wind power alone cannot act as the baseload of a grid scale electricity generation system because of its intermittent nature (Suberu, Mustafa and Bashir, 2014). This presents a major barrier to increased penetration of wind power in the Scottish energy mix, which currently stands at 40% gross consumption and is unable to meet the national demand at small timescales of seconds and minutes. Other issues associated with variable sources of renewable energy include power quality, insufficient transmission infrastructure, market and regulatory factors, and a range of grid stability problems, among others. To address intermittency and increase penetration of wind into the energy mix, it is widely recognised that some degree of "flexibility" must be incorporated into the renewable energy systems. One method of achieving such flexibility at a grid scale is through energy storage.

1.1.2 Energy Storage and the Thermal Energy Storage Gap

Energy storage can allow intermittent energy to be captured and stored when demand is low and released when demand is high. This addresses the problem of unmatched demand from a consumer perspective and the problems arising on the grid from the use of intermittent renewables from a grid operator perspective. Energy storage methods are diverse with each solution offering different advantages, disadvantages, and overall suitability to different energy systems. Energy storage methods are usually divided into four groups: Electrochemical, Electromagnetic, Mechanical and Thermal/Thermodynamic. Figure 1 shows a tree diagram of the four categories of energy storage, further divisions, and individual examples of each method. Figure 1 is based on information from (Evans, Strezov and Evans, 2012; Argyrou, Christodoulides and Kalogirou, 2018).

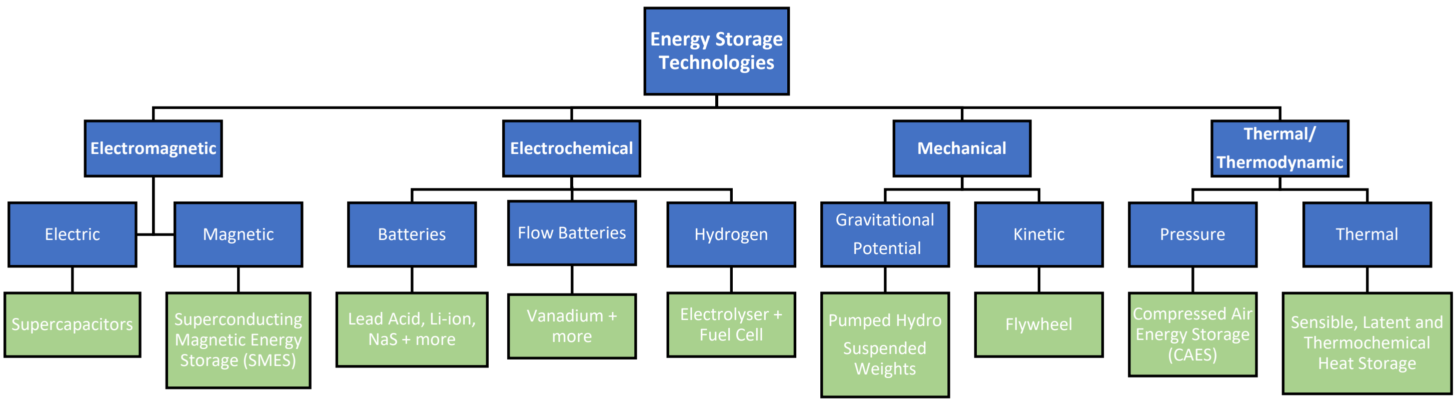

Figure 1 – Tree diagram showing the different categories of energy storage methods

Upon consideration of the relevant literature concerning grid scale energy storage in the UK, the author believes there is a significant gap regarding the use of thermal energy storage (TES). Before detailing the technical aspects of different TES systems, the suitability of TES for grid-scale electricity generation yet its absence from real world electric grids and energy policy will be presented. In their research on behalf of the European Association of Energy Storage, (Teller et al., 2013) discuss selected methods of energy storage, broken down in a similar fashion to Figure 1. The methods are compared on their suitability for five applications within grid scale energy storage: Conventional Generation, Renewable Generation, Distribution, Transmission and Customer Services. Of the methods investigated, only electrochemical (such as batteries) and thermal energy storage are rated as either suitable or possible for all five applications.

Yet even as TES's advantages as an energy storage technology is recognised, other technologies tend to be preferred. This is in part due the relative novelty of TES for utility-scale electricity generation (referred to as Electric TES) compared to more established technologies like pumped hydro. Global energy storage capacity is presented in Figure 2, taken from (Argyrou, Christodoulides and Kalogirou, 2018). Here, pumped hydro's dominance as the favoured energy storage technology is obvious, with it representing 96% of the world energy storage capacity compared to TES's ~2%, 169GW compared to 3.2GW.

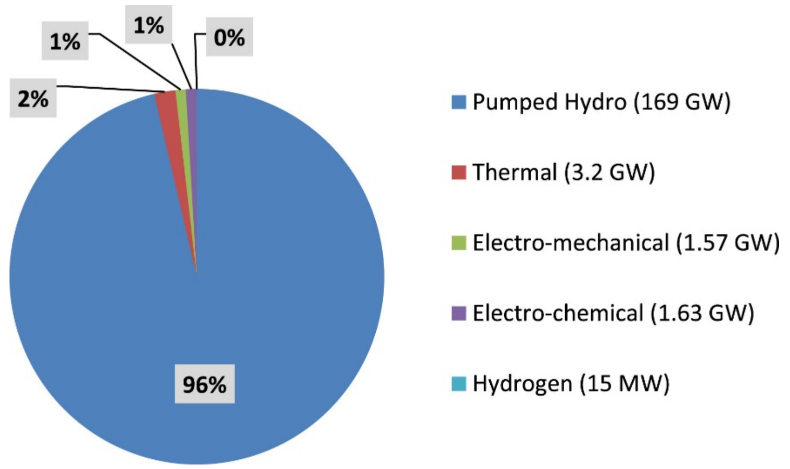

Figure 2 - Energy storage methods share of global energy storage capacity

Moreover, of the 3.2GW of TES capacity in the world, 75% of this is in Concentrating Solar Power thermal plants, a kind of electricity generation that is unsuitable for use in Scotland, as will be detailed in Section 2.2.2. This could explain why in the Scottish Government's 2017 energy strategy publication, they acknowledge the importance that energy storage will have in any future Scottish energy system, yet make no mention of the potential role of Electric TES specifically (Scottish Government, 2017b).

1.2 Aims

The central aim of this research is to construct a model of a Wind-Thermal Energy Storage (WTES) system in Scotland. A WTES system is a specific kind of Electric TES system that has its initial energy supplied by a variable wind resource. WTES systems will be discussed in more detail in Section 2.3. The WTES system's performance will be analysed in EnergyPLAN to measure its ability to address the issues arising from the use of variable sources of renewable energy established in the Introduction, and that will be further discussed in the Literature Review. Alongside this main aim, the research has smaller aims to be achieved in order to successfully build a WTES system model. Specifically, these smaller aims pertain to the calculation and modelling of the wind and TES components of the WTES system. The aims of this research are:

- To construct a model of a Wind-Thermal Energy Storage (WTES) system in Scotland, and investigate its operation and influence on a larger energy system.
- To calculate the wind resource potential of an area of Scotland
- To review TES options and identify the optimum storage configuration and medium for the WTES system.

1.3 Structure of the Thesis

This research is split into the following Sections: Literature Review, Methodology, Case Study and Results, and Conclusions and Future Work. The Literature Review develops the concept of flexibility and the role of energy storage in electricity systems presented in the Introduction. The Literature Review then assesses the TES options for use in a WTES system, describing the various characteristics of sensible, latent and thermochemical heat storage, and their suitability for utility-scale electricity generation. The Literature Review then goes on to briefly describe existing WTES systems and their parameters before evaluating potential wind speed data sources that could be used in the construction of the WTES model. The Literature Review concludes with the assessment of modelling tools to be used to construct and analyse the WTES system.

The Methodology is split into three subsections. The first, Wind Resource Potential, describes the mathematics required to calculate the energy available from wind in a chosen area of Scotland. The second, TES Selection, identifies the optimum TES configuration and storage medium to be used in the WTES model and discusses their defining thermal properties. The third subsection, Modelling the WTES system in EnergyPLAN, details how the WTES system is constructed in EnergyPLAN, the modelling tool selected. This includes the technical and economic parameters of the wind resource and TES components of the system, alongside the technical and economic parameters of the larger energy system that it is a part of. The Case Study and Results section is split into two subsections. The first, Wind Resource Potential, describes the carrying out of the work outlined in the likewise named Methodology subsection. The second, EnergyPLAN Modelling Results, presents and discusses the results of the analysis of the WTES model in EnergyPLAN. The final section, Conclusions and Future Work, summarises and concludes the research presented here and identifies potential ways of improving the research in any future work.

2. Literature Review

2.1 Flexibility and Energy Storage in Future Electric Grids

The first section of this Literature Review will expand upon some of the ideas established in the Introduction. Namely, the problems caused by the use of variable renewable sources in an electricity grid and how energy storage can be used to address these problems.

The most serious consequence arising from an energy system with a large penetration of stochastic renewable energy concerns the balancing of supply and demand. All generation must be matched by consumption in order to keep the grid operational, measured, in bulk, by grid frequency. Research suggests unproblematic renewable energy grid penetration reaches a maximum limit of approximately 20% gross electricity consumed when no significant action is taken to improve the flexibility of the grid (Denholm et al., 2010). Even so, such figures of approximately 20% are achieved only after exhausting other means such as operational, market and regulatory changes that favour the generation and consumption of renewable electricity (Castillo and Gayme, 2014). If penetration of renewable energy is to be achieved to a degree that supports a system largely or wholly dependent on variable low-carbon sources of generation, more significant action must be taken to introduce flexibility into the system.

Flexibility can loosely be defined as the ability of a power system to exploit its resources in order to match supply and demand. Flexibility is not a novel concept, with energy systems having adopted supply-side mechanisms of adjustment since their inception (Akrami, Doostizadeh and Aminifar, 2019). Supply-side mechanisms usually include altering the output of thermal power plants and using back-up power generation systems as contingency, though such action fails to match supply and demand at small time scales (~milliseconds). In the UK, the National Grid employs various "ancillary services" in order to stabilise the grid frequency within 1% of 50Hz (National Grid, 2020). However, these measures are generally thought not to offer the degree of flexibility that is required to maintain the stability of the UK grid beyond a renewable energy penetration of approximately 20%; some other method must be implemented.

Many studies have focused on what technologies, operational regimes, and policy frameworks (or combinations thereof) help to introduce flexibility into an electricity generating system. Energy storage is often identified as the most promising solution (Denholm and Hand, 2011; Yekini Suberu, Wazir Mustafa and Bashir, 2014). Fundamentally, energy storage enables supply and demand to be balanced when generation and consumption do not necessarily happen at the same time. Energy storage is considered highly flexible given its ability to stabilise the grid at the both small and large timescales of seconds and hours: studies have shown that energy storage can be highly adept at acting as a frequency regulator because of its potential fast ramping and charging/discharging abilities (Mohler and Sowder, 2014). Moreover, the potential large capacities associated with energy storage enable it to be an effective option for load shifting on an hour-by-hour basis (Evans, Strezov and Evans, 2012). Additionally, the introduction of energy storage into existing grids has proven to free up generation capacity, that was originally earmarked as back-up, to be used as part of the baseload (Cochran et al., 2013). However, these features are very much dependent on the method of energy storage employed. As detailed in the introduction, the author believes there is a gap in the study of Electric TES.

2.2 Thermal Energy Storage

2.2.1 TES Introduction

This section of the Literature Review will detail how different methods of TES operate and the parameters of each method that define its suitability for Electric TES. The most suitable applications of Electric TES are referred to by (Chen et al., 2009; Argyrou, Christodoulides and Kalogirou, 2018) as “energy management” applications, meaning it will take advantage of TES’s potential large energy capacity for applications such as load shifting. This is in contrast to some other, faster acting energy storage technologies like batteries that perform “power quality” functions like voltage and frequency regulation.

TES works by heating a storage medium during the charging phase and releasing the heat when the energy is needed during the discharging phase. There are multiple different kinds of TES, yet each configuration shares some basic components: a storage medium, a container tank, inlet/outlet connections and usually a Heat Transfer Fluid (HTF). The different kinds of TES can be categorised into three groups based on the behaviour of the storage medium: Sensible Heat Storage, Latent Heat Storage and Thermochemical Energy Storage.

2.2.2 Sensible Heat Storage

Sensible Heat Storage (SHS) involves heating a storage medium which can be either liquid or solid without the material undergoing any phase or chemical composition change. The energy storage capacity, Q_S, stored in such materials follows Equation 1 (Zhang et al., 2016):

$$Q_S = mc_p\Delta T \qquad \textit{Equation 1}$$

Here, m is the mass of the storage medium, c_p the specific heat capacity at a constant pressure and ΔT the temperature range of the storage medium during the charging and discharging processes. SHS is regarded as relatively low cost, given the storage media employed are materials that are widely available like water and salts, among many others as we will come to discuss. It is the most well developed and utilised method of TES, with everyday examples such as domestic hot water tanks showing the existing widespread use of SHS.

When it comes to selecting the storage material for an SHS system, there are some general criteria that the storage material should meet (Khare et al., 2013):

- Thermo-physical Properties: High energy density, high thermal conductivity, long term thermal cycling stability and high heat capacity
- Chemical Properties: long term chemical stability, non-toxic, non-flammable, non-explosive and non-corrosive

- Economic Properties: Cheap and Abundant materials
- Environmental Properties: Low CO_2 footprint

Table 1 displays a selection of common solid and liquid SHS technologies at 20°C with their corresponding thermal properties (Hamdhan and Clarke, 2010; Zhang et al., 2016; Dinker, Agarwal and Agarwal, 2017; Koçak and Paksoy, 2019).

Table 1 - Selected SHS Media Thermal Properties at 20°C

Storage Medium	**Type**	**Energy Density (kJ/m^3)**	**Specific Heat Capacity (kJ/kg/K)**	**Temperature Range (°C)**	**Thermal Conductivity (W/m.K)**
Water	Liquid	4175.88	4.18	0-100	0.61
Concrete	Solid	1933.80	0.88	200-400	1.28
Sand	Solid	1600	0.80	200-500	0.25
Sandstone	Solid	1562	0.71	200-550	1.8
Alumina Beads	Solid	2447	0.920	120-700	30
Iron	Solid	3650.25	0.465	200-400	59.3
Nitrate Salts	Liquid	2992	1.6	265-565	0.52
Sodium	Liquid	1105	1.3	270-530	71

Note that the selected storage media with a temperature range starting at 200°C were assigned this value in order to classify them as “high temperature” storage materials, but they could feasibly reach a minimum temperature lower than 200°C (Zhang et al., 2016).

A defining feature of SHS storage mediums are their low energy densities. Consequently, to enable a SHS system to store utility-scale quantities of energy, the storage medium and container facility must be considerably large. Figure 3 shows a SHS facility in Denmark with a 75,000m^3 water tank acting as the storage medium providing hot water for a local district heating system (Marstal District Heating, 2020). This can lead to siting issues with TES systems and a larger storage facility tends to result in larger thermal losses (Kousksou et al., 2014). Moreover, large facilities are generally more difficult and costly to manage (Kousksou et al., 2014). This has led a number of researchers to identify new TES storage methods that try to avoid the construction of large container tanks. Underground TES uses existing geophysical features such as caves as the container tank (Reed et al., 2018) and Borehole TES also moves the container tank underground for seasonal-length TES through the use of manmade boreholes (Wołoszyn, 2018).

Figure 3 - Marstal Solar Thermal District Heating Scheme, water container basin circled

SHS systems have the marked advantage of being able to produce a large ΔT. That is, a high temperature can be derived from SHS, especially solid media SHS, which has the benefit of potential coupling to thermal turbines, enabling Electric TES (Zhang et al., 2016). The high thermal conductivities of SHS materials is another attractive feature. Thermal conductivity dictates how efficiently and how fast the storage materials charge and discharge, an important property if energy is required on small timescales.

It is worth noting that SHS is often used in Concentrating Solar Power systems (CSP) with the storage medium, often molten salt, heated by parabolic solar mirrors or troughs (Yang et al., 2010; Alva, Lin and Fang, 2018). These systems have proven to increase the penetration of variable solar power and they are important parts of electrical grids in countries like Spain (Martín et al., 2015). CSP systems are not perfect and are affected by their own operational characteristics and issues (Gil et al., 2010) but they are excluded from this work for different reasons. Rather, they are excluded due to the fact that this paper is researching TES systems for potential deployment in Scotland, which, unfortunately, does not have the required weather conditions to facilitate CSP plants.

2.2.3 Latent Heat Storage

The second category of TES technologies is Latent Heat Storage (LHS). LHS involves the absorption and release of heat that occurs when the storage medium undergoes a phase change. The materials used as a storage medium in such systems are called Phase Change Materials (PCM). The storage capacity, Q_L, stored in an LHS system using PCMs follows Equation 2 (Zhang et al., 2016):

$$Q_L = m\int_{T_L}^{T_m} C_{PCM,s}dT + m\Delta H_m + m\int_{T_m}^{T_H} C_{PCM,l}dT \qquad \textit{Equation 2}$$

Here, T_m is the melting point of the PCM, and T_H and T_L are the respective highest and lowest temperatures reached either side of the phase change process, represented by the phase change enthalpy ΔH. $C_{PCM,s}$ and $C_{PCM,l}$ are the specific heats of the PCM in its solid and liquid state, yet if the phase change is completed isothermally (as it often near enough is), Equation 2 can be simplified to Equation 3:

$$Q_L = m[C_{PCM,s}(T_m - T_L) + \Delta H_m + C_{PCM,l}(T_H - T_m)] \qquad \textit{Equation 3}$$

As is clear from Equations 2 and 3, LHS systems will involve SHS to some extent on either side of the phase change. This is shown in the melting process in Figure 4 as the two non-horizontal lines (Enescu et al., 2020). Energy is added to the PCM in order to increase its temperature to the phase change temperature, $T_{phase\ change}$, at which any additional energy added contributes to its isothermal phase change. Beyond this, extra energy can be added and stored as sensible heat in the PCM in its liquid form. If Figure 4 were reversed this would show an exothermic freezing process yet would be guided by the same principles of sensible and latent heat storage outlined in Equations 2 and 3.

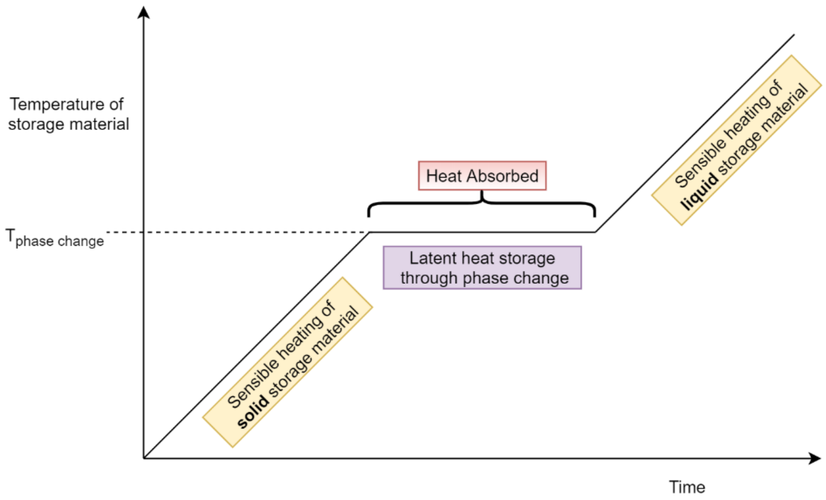

Figure 4 - Simple graph to show how energy is stored as both sensible and latent heat in a PCM

The phase change of LHS systems can be that of a solid-liquid or liquid-vapour/gas transition, with solid-solid crystalline phase transformation a less common, yet still possible process (Regin, Solanki and Saini, 2008). The solid-liquid transition PCMs are the most regularly employed given the superior latent heat available compared to solid-solid PCMs, and they avoid the large volumes contingent with liquid-vapour/gas PCMs (Fernandes et al., 2012).

Categorisation of LHS systems is usually done through classification of the PCM they use, usually as organic, inorganic, or eutectic. Organic PCMs are generally a safe, chemically inert, and stable PCM choice although have comparably poor thermal properties (Kousksou et al., 2014). Inorganic PCMs generally have superior latent heat of fusion and thermal conductivity compared to their organic counterparts, however, some are more toxic and more likely to corrode the LHS system they are a part of (Kousksou et al., 2014). Eutectics are mixtures of organic and inorganic substances, combined to produce a new substance with different thermal properties than either of the constituent substances (Kousksou et al., 2014). When it comes to selecting a PCM for an LHS system, there are some general criteria that the PCM properties should meet. Some of these criteria are shared with SHS materials (Fernandes et al., 2012; Kousksou et al., 2014):

- High latent heat of fusion per unit mass, in order to store as much latent energy as possible in the PCM
- High specific heat, in order to store considerable additional energy in the sensible heating of the PCM
- Small volume changes during phase transition
- Melting point within the desired operating temperature range
- High thermal conductivity so the charging and discharging thermal gradients are small.
- Contain non-poisonous, non-flammable, non-explosive substances
- Inexpensive and available in large quantities

Table 2 lists some selected solid-liquid PCMs and their corresponding thermal properties (Gil et al., 2010; Dinker, Agarwal and Agarwal, 2017). Table 2 contains only solid-liquid PCMs given their superior thermal properties.

Table 2 - Selected LHS Solid-Liquid PCM Thermal Properties

PCM	**Type**	**Melting Point (°C)**	**Heat of Fusion (kJ/kg)**	**Thermal Conductivity, when liquid (W/m.K)**
Paraffin wax (C_{13}–C_{18})	Organic	32	251	0.214
Polyglycol E600	Organic	22	127.2	0.189
$MgCl_2 \cdot 6H_2O$	Inorganic	117	168.6	0.570
$NaNO_3$	Inorganic	307	172-199	0.5
$CaCl_2 \cdot 6H_2O$	Inorganic	29	190.8	0.54
$KNO_3/NaNO_3$	Inorganic	220	100.7	0.56
NaCl	Inorganic	800	492	5
$LiNO_3/KNO_3/NaNO_3$	Eutectic	121	310	0.52

Comparing Table 2 to Table 1, the poor thermal conductivity of PCMs compared to SHS materials is clear, especially when considering organic PCMs. The thermal conductivity of LHS systems can be improved by modifying heat exchangers, for example, with embedded metallic foams or external finned tubes, among other changes (Jegadheeswaran and Pohekar, 2009; Fernandes et al., 2012). Figures for energy density of individual PCMs were unavailable, but it is well established in the literature that the PCMs of LHS systems generally have greater energy densities than SHS materials (en Zalba et al., 2003; Castell and Solé, 2014). This means that LHS systems are considerably more compact than SHS systems. For example, SunAmp is Scottish private company that manufactures LHS systems for use in domestic and industrial settings. Figure 5 is an image of the company's UniQ 3 product, an LHS unit with a capacity of 3.5kWh (SunAmp, 2018). SunAmp claim this product's high energy density is able to provide significant fuel savings while being small enough to be installed within a domestic dwelling.

Figure 5 - SunAmp's UniQ 3 LHS system

Identifying the ideal PCM for a project is a difficult process. Take, for example, NaCl in Table 2, which has a vastly superior thermal conductivity compared to the other PCMs, 5W/m.K compared to the others' which are all less than 0.6W/m.K. This potentially makes it an attractive option for use in an LHS. Yet NaCl's improved conductivity comes with the disadvantage of having a melting point of 800°C, making it a more expensive and complex PCM to handle compared to those with a lower melting point. This trade-off between desirable and undesirable thermal properties is a defining feature when choosing a PCM for an LHS system.

2.2.4 Thermochemical Heat Storage

Thermochemical heat storage involves a reversible chemical reaction that is used to store and release heat. The storage capacity Q_{Th}, stored in such a reaction follows Equation 4 (Zhang et al., 2016):

$$Q_{Th} = m\alpha\Delta H_r \quad \alpha \leq 1 \qquad \textit{Equation 4}$$

Here, m is the mass of the material, α is the "conversion" and ΔH_r the endothermic heat of reaction. Equation 5 is another way of describing thermochemical reactions, albeit in an untechnical fashion.

$$A + B \leftrightarrow C + heat \qquad \textit{Equation 5}$$

Here, substances A and B are combined together forming substance C and energy in the form of heat. The configuration here shows the system discharging in an exothermic reaction, if it were to be reversed (as shown by the ↔ symbol) that would constitute the system charging in an endothermic reaction.

Thermochemical heat storage is the least developed of the three kinds of TES yet there is a comprehensive effort to find which application it is most suitable. There is considerable interest in thermochemical heat storage because it potentially has the largest energy density and efficiency out of itself, SHS and LHS (Van Berkel, 2005; Kousksou et al., 2014). Moreover, thermochemical storage tends to have very low energy losses at ambient temperatures compared to other TES systems, asserting its potential for use in long term, seasonal length energy storage (Zhang et al., 2016). Table 3 shows a selection of thermochemical heat storage reactions (Gil et al., 2010). Note the very large energy densities available from the reactions, compared to SHS and LHS materials in Table 1 and Table 2.

Table 3 - Selection of Thermochemical Heat Storage Reactions

Compound	**Reaction**	**Energy Density (GJ/m^3)**	**Reaction Temperature (°C)**
Hydroxides e.g.	$Ca(OH_2) \leftrightarrow CaO + H_2O$	3.0	500
Calcium Carbonate	$CaCO_3 \leftrightarrow CaO + CO_2$	4.4	800-900
Iron Carbonates	$FeCO_3 \leftrightarrow FeO + CO_2$	2.6	180
Metal Hydrides	$metal\ xH_2 \leftrightarrow metal\ yH_2 + (x-y)H_2$	4.0	200-300

Research into the commercialisation of thermochemical heat storage focuses on reducing the costs of building such systems and making them more economically viable in general (Fernandes et al., 2012). They are also beset with lifetime issues: the compounds themselves deteriorate and they corrode the wider TES facility they are housed significantly faster than SHS and LHS (en Zalba et al., 2003; Kousksou et al., 2014). Thermochemical heat storage is still very much in the research and development phase, with no working prototypes of it being used as a utility-scale TES option. Being able to produce any meaningful technical content about thermochemical energy storage appears to require a knowledge of chemistry that the author does not hold. For these reasons, thermochemical energy storage is not considered an option for the TES in this paper.

2.2.5 Electric TES

In this paper, the TES system to be modelled as part of the larger energy system will be chosen in Section 3.3. First, it will be beneficial to identify qualifying criteria and examples of TES systems being used at a utility scale to generate electricity, to know where the selection process should be focused and avoid any unrealistic scenarios. As stated above, thermochemical energy storage systems are not considered because of their relative developmental infancy.

Electric TES systems must meet the main criteria of having a large working temperature range, in order to be coupled to electricity generating thermal turbines. This also means the storage medium must be stable at high temperatures, especially for longer periods if the medium is to store energy for hours or days at a time. For utility scale Electric TES, the storage medium must also have considerable power and energy capacity in order to meet the large demands from the electric grid. Upon consulting the literature considering the criteria the storage system must meet, it is apparent SHS technologies are the most realistic choice for Electric TES in Scotland. SHS technologies can more readily meet the high temperatures required to generate electricity than LHS technologies. SHS media also meet the criteria of being stable at high temperatures for a long time to a better degree than PCMs. SHS and LHS systems are both able to meet the required energy and power capacities since they are both scalable technologies, however, it is easier to scale SHS systems given the simpler technology compared to LHS systems.

The theoretical suitability of SHS over LHS for Electric TES is backed up when considering real world work on Electric TES. The majority of such applications are in the development phase, but the potential of SHS for Electric TES is recognised in the literature (Chen et al., 2009). There are private companies in countries such as Germany, the USA and France working to prove the economic viability of Electric TES systems using SHS. For instance, Storasol is a German private company that is developing storage of thermal energy in sand, gravel and other solid media that is coupled to a thermal power plant for on demand generation of electricity (Storasol, 2020). This is just one of many Electric TES systems using SHS materials in the development phase by commercial entities (EPRI, 2019; Lumenion, 2020; Malta Inc., 2020) that stand alongside academics studying similar systems (Laing et al., 2011; Bergan and Greiner, 2014; Okazaki, 2020). Therefore, when choosing which TES method to use in Section 3.3, only SHS technologies will be considered.

2.3 Wind-Thermal Energy Storage Systems

The aim of this section of the literature review is to identify examples of a WTES system and explore their operational characteristics. As stated in Section 1.2, the construction of such a WTES system is the central aim in this research. This section will be relatively brief for two reasons. First, there are a limited number of examples of such a system either being researched or implemented into an existing energy system. Second, this section will focus only on how the WTES systems operate, not the reasons why WTES has been chosen or work pertaining to the individual wind and TES components of the larger WTES system.

There is an important distinction between WTES systems and more general Wind-Energy Storage systems. There are numerous examples of investigations of such systems in the literature and they follow similar formats: the researchers identify issues with wind power generation and that energy storage could be a potential solution to these issues. They carry out a review of possible energy storage options and then model a select few to examine their effectiveness in addressing the issues at hand (Zhao et al., 2015; Caralis et al., 2019; Guo et al., 2020). However, in such research, it is rare to have TES systems offered as a potential solution. Compressed Air Energy Storage (CAES) systems are sometimes suggested as a form of TES, but in the context of this research, CAES does not qualify as TES (Sullivan, Short and Blair, 2008; Sundararagavan and Baker, 2012). Moreover, when TES is considered to be coupled to wind turbines, often it is to be part of the heating supply and not the electricity supply. Integrating TES with an existing CHP plant and wind energy resource is a common subject matter among researchers seeking to improve the performance of a district heating system (Leahy, Connolly and Buckley, 2010; Bloess, Schill and Zerrahn, 2018). This research will not be focused on modelling such systems and instead, will focus on modelling a WTES system used only within the electricity supply i.e. Electric TES.

As mentioned, there are only a small number of examples of such WTES systems in the literature.
(Guo et al., 2020) describe how TES is introduced into a wind energy system in order to reduce the levelized cost of electricity. In fact, presented here is a hybrid solar-wind-TES system. However, since the wind resource is a component alongside solar which is also a variable energy source, the author is qualifying it as a WTES system. In this configuration, the researchers use the fairly common two-tank system, featuring a hot and cold tank to separate the TES medium before and after it has been passed through a heat exchanger to produce steam to drive a power block. The medium and HTF used in this system is molten salt which is heated by an electric resistance heater. Figure 6 is a much-simplified version of the system, focusing on the wind resource aspect and how the TES is heated.

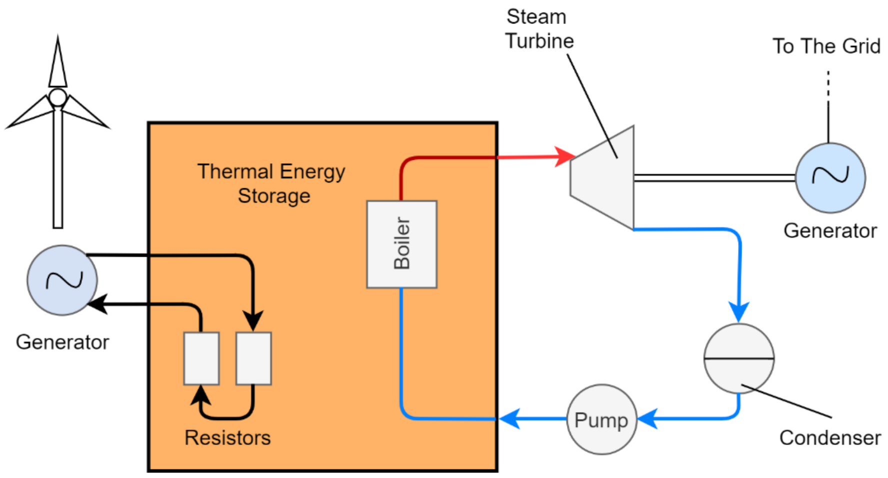

Figure 6 - Simplified WTES system using electric resistors to heat the storage medium

Similarly, (Forsberg et al., 2017) study storing excess electricity in the form of thermal energy in specially developed bricks. Here, the researchers are mainly focused on the economic impact of high production of variable wind power when demand is low and look towards TES as a low-cost method of avoiding an electricity price collapse. Like (Guo et al., 2020), the bricks are heated using an electric heater therefore the system can be depicted in the same way as Figure 6. The HTF employed in this instance is air.

(Okazaki, Shirai and Nakamura, 2015) describe how TES is used to solve issues of dispatchability and high curtailment rates with wind power generation. The particular WTES system detailed here produces heat from the wind using a friction-based heat generator the researchers call a "light electric brake". No particular TES medium is specified but "salts" are suggested as an option. The researchers report that the WTES system is more economical for improving dispatchability of wind energy generation than similar Wind-Battery Energy Storage systems. The "heat-generator" method of converting the energy available from the wind into thermal energy is depicted in Figure 7.

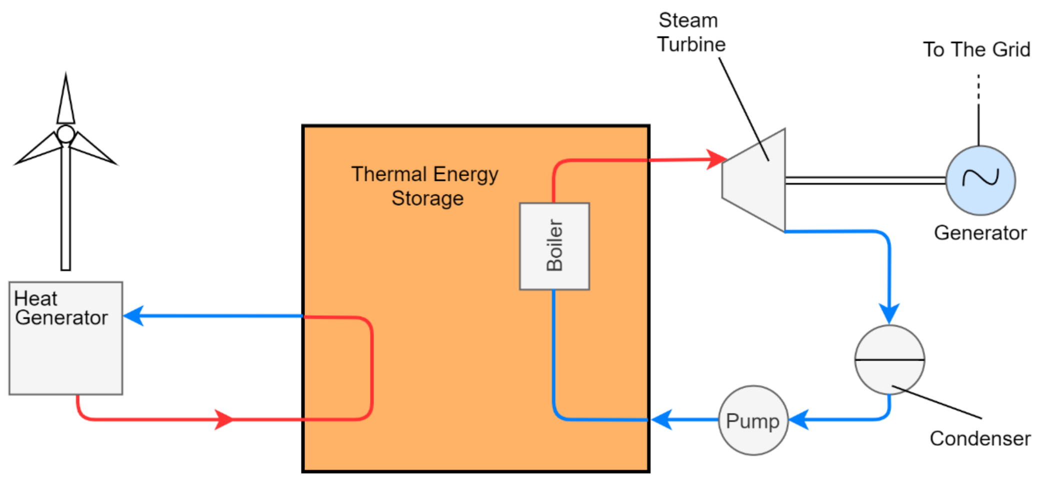

Figure 7 - Simplified WTES system using a heat generator to heat the TES medium

The heat generator method is also mentioned in (Enescu et al., 2020) as an option that avoids the inefficient conversion of electricity to heat that is involved in the systems depicted in Figure 6. However, this removes the electricity generating capacity of wind turbines, so will likely have limited use in specialised WTES applications. Direct heat generation can be achieved using friction as mentioned, or through the fairly novel method of electromagnetic induction. Electromagnetic induction is employed by (Okazaki, 2020), using Eddy current resistive heating in either a HTF or the storage medium itself. The Eddy currents are produced by an alternating magnetic field by rotating a static magnetic field. Here, the rotating motion comes from the rotation of the wind turbine blades. Similarly, (Karasu and Dincer, 2018) detail electromagnetic induction as the heat generation method in a WTES system. The researchers claim the method has better energy conversion efficiencies compared to the other methods detailed here, yet concede the technology is considerably more complex and expensive to construct and operate. An electromagnetic induction system can also be depicted as in Figure 7.

This review of existing WTES systems for electricity generation shows the concept is novel yet technically and economically viable. According to the author's knowledge, this research is the first time a WTES system in Scotland has been studied. In the literature, there is particular attention given to the development of individual components of the systems, like the method of heating the storage medium and the WTES system's wider influence on the energy system it is part of.

2.4 Wind Data Sources

Pertinent to the construction of the WTES model is the input of energy available from wind. The precise method of how this will be calculated will be covered in Section 3.2, but first, an appropriate source of wind speed data must be identified. Much research that includes the calculation of a wind energy resource uses data measured by the researchers (Ozdamar et al., 2005; Belabes et al., 2015). Since this is not a feature of this paper, existing data must be downloaded. Ideally, the potential data would be of the form of hourly wind speeds at a chosen height in a chosen area. The data in this form would allow for the simplest analysis to be made to calculate the energy available from the wind. However, upon a review of the available sources, it becomes clear that the wind data used will be of a different form.

When reviewing the available sources, they must be filtered to include only detailed wind speed data and data that covers the UK. This identified Global Wind Atlas and CEDA (Centre for Environmental Data Analysis) from the Met Office as the most suitable sources of detailed UK wind speed data (DTU and World Bank Group, 2018; Met Office, 2020). The New European Wind Atlas was also considered but it offers very similar data to the Global Wind Atlas, just differing in the methodology used to collect the data (NEWA, 2019). Investigating the sources further, Global Wind Atlas was found to outperform CEDA in a number of metrics. Primarily, the data available from Global Wind Atlas is much simpler to access and requires little processing to get it in the form of data that can be usefully used to calculate the wind resource potential of a chosen area. CEDA data, while precise, requires interpolation in order to create continuous wind speed data from discreet point source data measured by individual weather stations. This extra step is not required when accessing equally precise Global Wind Atlas data. For this reason, Global Wind Atlas will be used in this research.

Global Wind Atlas offers wind speed data of any desired area, selected by the user. The data available comes in two files, the rudimentary Plot Data file and more extensive

Generalised Wind Climate file (GWC). The Plot Data offers basic wind speed data such as monthly average wind speed and power density of the chosen area. These are not sufficient to calculate the wind resource potential of an area of Scotland, this must be done using data from the GWC. The GWC contains wind speed data in the form of Weibull parameters, variables that are part of the Weibull function, at certain reference heights. The Weibull function is a wind speed frequency distribution which is commonly used to succinctly describe wind resource potential. The GWC and the properties of the Weibull function and parameters will be described in more detail in Section 3.2. For now, it is sufficient to establish that the data available in the GWC can be used to accurately calculate the wind resource potential of a chosen area in Scotland.

2.5 Software Selection

2.5.1 Review of Modelling Tools Available

To simulate a WTES system and be able to investigate its operational performance, an energy system modelling tool must be employed. Given the number of options when it comes to energy modelling tools, identifying which to use is subject to a literature review. First, the key aspects of the WTES system to be modelled and investigated must be established. The two key aspects of the proposed WTES system are the wind power and integrated TES. This system will need to be modelled as a constituent part of a larger energy system (since the WTES system will be part of the energy network in Scotland) so will need to model at a regional/local scale. Importantly, the tool should be adept at modelling electricity from renewable sources and the tool should be used by a considerable number of people. This should hopefully point towards the existence of material and users online that could assist in the author's use of the tool. Additionally, if the tool is open access, this would enable the research to be replicated by others more easily.

To aid in the identification of suitable energy modelling tools, a number of reviews of such tools were consulted. In their extensive 2010 review, (Connolly et al., 2010a) first recognized 68 energy system modelling tools, but narrow down to 37 for further analysis focusing on tool properties, applications, and users. First, the tools that have a high number of users and are initially free to download are identified: HOMER (HOMER Energy LLC), RETscreen (National Resources Canada), energyPRO (EMD International A/S), EnergyPLAN (Aalborg University), Invert (Vienna University of Technology) and ORCED (Oak Ridge National Laboratory) all meet this initial criteria. Next, the tool "types" are identified. From their descriptions, the type of tool employed in this research should be a Simulation tool, defined: "simulates the operation of a given energy-system to supply a given set of energy demands" and a Bottom Up tool, defined: "identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives" since the purpose of the tool is to investigate the operation of specific technologies. Of the initial six, HOMER, EnergyPLAN, Invert and ORCED fit these additional criteria.

The typical applications of the tools are then explored. HOMER and EnergyPLAN are unconstrained by a "Specific Focus" whereas Invert and ORCED are mainly used to model the dispatch of electricity and the heat sector, respectively. Therefore, these two tools are disqualified as they are specialised in an undesired area of energy modelling. Both EnergyPLAN and HOMER have the ability to model the electricity sector and at the regional/local scale, the desired sector and scale. Considering the information from the most extensive review of tools available, HOMER and EnergyPLAN are identified as the most promising modelling tools for the system being researched in this paper.

More recently, (Lyden, Pepper and Tuohy, 2018) conduct a review of energy modelling tools used in community scale energy systems. They include a focus on energy storage, which is also a topic of focus in this paper. A less extensive review, the authors analyse the properties and application of 13 tools, screened from 51. When filtering for "Practical Considerations" the tools COMPOSE, DER-CAM and EnergyPLAN each share the properties of being free and being mainly used for academic purposes. All three are all able to model TES, an important aspect of this research. However, EnergyPLAN exceeds the user-friendliness and support available than both COMPOSE and DER-CAM. The paper also includes HOMER in its investigation and report that HOMER is also unable to model TES so was disqualified.

This review of energy modelling tool reviews identifies EnergyPLAN as the most promising tool for this paper, given it is free, user friendly, is able to model high penetration of renewable energy and TES, at a regional/local scale and is supported by a selection of training videos and user manuals.

2.5.2 EnergyPLAN

EnergyPLAN can be described as a deterministic energy modelling tool (Connolly et al., 2010b; Prina et al., 2018). That is, an EnergyPLAN model with the same inputs will always produce the same outputs. Its inputs are usually demand, energy sources, costs and regulation strategies (Krajačić et al., 2011; Marczinkowski and Østergaard, 2018). EnergyPLAN can model the electricity, heat and transport sectors, or combinations of these sectors and will always model the operation of the system over a period of one year in one hour timesteps. EnergyPLAN is not an automatic optimisation tool, rather it simulates the performance of a pre-selected energy system configuration. Optimising with EnergyPLAN is possible, however, it must be done manually (Østergaard, 2015) or through pairing with another tool (Pina, Silva and Ferrão, 2013).

To further verify that EnergyPLAN is suitable to model the desired WTES system, a brief review of uses and applications of EnergyPLAN was completed. The authors of (Østergaard, 2015) identify "integration of renewable energy in the energy system" and "high renewable energy scenarios" as the most common areas of study in their review of the use of EnergyPLAN, in line with the focus of this research. In the same paper, flexibility is discussed as a concept to be incorporated into existing and future energy systems. How to measure flexibility in EnergyPLAN is the topic of several research papers into energy systems with both renewable and conventional generation (Denholm and Margolis, 2007; Nunes, Farias and Brito, 2015). These researchers use Equation 6 to measure flexibility.

$$Flexibility = 1 - \frac{MIN\{e_1,\ldots,e_i,\ldots,e_{8784}\}}{MAX\{e_1,\ldots,e_i,\ldots,e_{8784}\}} \qquad Equation\ 6$$

Here, e_i is the total electricity production of the conventional generation components in a system in the i^{th} hour of the year. The variable i can take on values between 1 and 8,784, the number of hours in a year over which EnergyPLAN completes the simulation. MIN and MAX identify the minimum and maximum value of conventional generation production in a system out of all the hourly values. Equation 6 will produce a value between 0 and 1 which is the factor of which conventional generation production can be reduced because renewable sources of energy can take its place. EnergyPLAN has been used to model wind energy penetration specifically (Lund, 2005) and TES in a number of applications, including solely within the electricity sector (Tarroja et al., 2012; Child and Breyer, 2016; Marczinkowski and Østergaard, 2019). From this research, it is clear that EnergyPLAN will be suitable to model the desired WTES system in this paper.

2.5.3 EnergyPLAN Wind Distribution – HOMER

There is one issue with EnergyPLAN, concerning the wind distribution to be used in the upcoming model. EnergyPLAN requires hourly wind speed data to be in the format of wind power normalised to the capacity of the wind resource. The normalisation of wind speed to power is simple enough (and will depend on the features of the wind turbine employed), the issue lies with the prerequisite hourly wind speed which Global Wind Atlas does not supply. As discussed in Section 2.4, Global Wind Atlas provides wind speed data in the form of Weibull Parameters and some select data on average wind speeds. Some method of producing synthetic hourly wind speed data from the available information in the GWC must be used.

Generation of synthetic wind speed data is an active area of research in wind energy engineering. However, upon a review of the relevant literature it is apparent that the mathematics employed to generate synthetic wind data is well beyond the scope of this work (Turner et al., 2011; Naimo, 2014; Chen and Rabiti, 2017). Instead, a tool will be used to generate the synthetic data. A review of such tools in the same fashion as Section 2.5.1 is not feasible given that their use is not widespread in the literature. After an extensive search of potential tools, it can be concluded the most viable option is HOMER (a software repeatedly mentioned in Section 2.5.1). HOMER has the capability to generate synthetic wind data from inputs that can be calculated from the Global Wind Atlas data (HOMER Pro). The operation of HOMER in the generation of synthetic data will be detailed in Section 3.2 Wind Resource Potential.

3. Methodology

3.1 Methodology Introduction

The central aim of this research is to create an EnergyPLAN model of a WTES system in Scotland. This Methodology section will describe how this model is constructed and is split into three parts: Wind Resource Potential, Selection of Thermal Energy Storage and Modelling of the WTES System in EnergyPLAN.

Pertinent to this model, is the input of energy available from wind. As discussed in Section 2.4, Global Wind Atlas provides wind speed data in the form of Weibull parameters at certain reference heights. The first part of Section 3.2 details the mathematics used to extrapolate these parameters to a height other than the reference. The second part details the input of the required wind speed data from this calculation and the GWC into HOMER to generate synthetic wind speed data. Section 3.2 also includes the processing of this information from pure wind seed data into normalised wind power data ready to be inputted into EnergyPLAN

Section 3.3, Selection of Thermal Energy Storage, will concern the identification of the suitable TES technology to be integrated with the wind energy system. This will not include the novel design and modelling of a TES system. Instead, using information from the literature review - and from further research into technologies utilised for Electric TES - the technical and economic parameters of the most suitable system will be identified for modelling in EnergyPLAN.

Lastly, Section 3.4 will describe the construction of the WTES model in EnergyPLAN. The first subsection details the sizing of the different components of the EnergyPLAN model. The following subsection details the information needed for the model to replicate the Scottish energy system as precisely as possible. This includes information such as conventional generation fuel ratios and fuel CO_2 content. The last subsection regards the costing of the system, from component capital and maintenance costs to the import and export prices of the External Market.

3.2 Wind Resource Potential

3.2.1 Weibull Distribution and Parameters

When calculating the energy available from a wind turbine, two models are conventionally required. First, the turbine power curve; a wind speed-power relation using Equation 7 (Belabes et al., 2015) with the limits of cut-in speed, rated power and cut-out speed imposed by the features of the chosen turbines.

$$P = \frac{1}{2} A\rho C_p V^3 \qquad \textit{Equation 7}$$

Here, P = power, A = area swept by the blades, ρ = air density, C_p = power coefficient and V = wind speed. Equation 7 shows the importance of wind speed in the model, given power is proportional to wind speed cubed. Bear in mind that power coefficient C_p is different than specific heat capacity c_p from Equation 1.

Second, the two-parameter Weibull distribution; a density function of the wind speed distribution in a specified area, at the specified height. The name "two-parameter" refers to the characteristic parameters that define the curve, called the scale factor c and shape factor k. The Weibull distribution is shown in Equation 8 (Belabes et al., 2015).

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp(-\left(\frac{v}{c}\right)^{k}) \qquad \textit{Equation 8}$$

Here, the two-parameter nature of the density function is evident, with scale factor c (in units of m/s) and the dimensionless shape factor k the only variables besides wind speed affecting the variable f(v), the probability of likelihood of any speed v. As discussed in Section 2.4, Global Wind Atlas supplies wind data as Weibull parameters, in the form of in a frequency distribution table. However, this data only corresponds to certain heights, and it is unlikely that the chosen turbines will be at this exact height. Therefore, a method of calculating the Weibull parameters at different heights must be used.

3.2.2 Hellmann's Power Law

Hellmann's Power Law is most commonly employed when extrapolating wind speed data from the anemometer height (where the measurement takes place) to the desired height, shown in Equation 9 (Belabes et al., 2015). The simple equation describes the vertical gradient in the horizontal wind speed. Wind speeds tend to increase with height – until approximately 1,000m - as a result of the atmospheric thermal gradient and friction forces introduced by the terrain (Bañuelos-Ruedas, Ángeles Camacho and Rios-Marcuello, 2011)

$$\frac{v}{v_0} = (\frac{h}{h_0})^n \qquad \textit{Equation 9}$$

Here, v is the wind speed at the desired height, h; v_0 is the wind speed at anemometer height, h_0. The index n is the surface roughness length or coefficient, a measure of the effect of the surrounding terrain on the wind speed and can range from ~0 to 3. Table 4 shows a range of terrains and the approximate corresponding roughness length (Manwell, McGowan and Rogers, 2010). In much research, n is estimated and not measured (Ozdamar et al., 2005; Kaabeche, Belhamel and Ibtiouen, 2011) with assumptions regularly landing on a value between 0.1 and 0.143 – the latter often invoked as a "standard" value for low roughness terrain (Ucar and Balo, 2008; Albani, Ibrahim and Yong, 2019).

Table 4 - Selected Terrains and their corresponding roughness coefficient

Terrain Description	**Surface Roughness Length, n (m)**
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Rough pasture	0.010
Crops	0.05
Few trees	0.1
Many trees, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
City centre, tall buildings	3

Following Hellmann's Power Law, the Weibull parameters can be extrapolated to the desired height through the equations listed below (Justus and Mikhail, 1976).

$$c(h) = c_0 \left(\frac{h}{h_0}\right)^z \qquad \textit{Equation 10}$$

$$k(h) = k_0\left[\frac{1-0.088\ln(h_0/10)}{1-0.088\ln(h/10)}\right] \qquad \textit{Equation 11}$$

$$z = \frac{[0.37 - 0.088\ln(c_0)]}{[1-0.088\ln(h/10)]} \qquad \textit{Equation 12}$$

Equation 10 is of a similar form as Equation 9, calculating the scale factor c of the Weibull distribution at the desired height h, extrapolated from the scale factor c_0 at the anemometer height h_0. This extrapolation is facilitated through the index z which is detailed in Equation 12. The Weibull shape factor k at height h is calculated using Equation 11 and k_0, shape factor at anemometer height.

Finally, the last unknown variable used in Equation 7 is the power coefficient, C_p. The power coefficient is a measure of how efficiently a turbine converts the kinetic energy in the wind into useful electrical energy. C_p varies with wind speed and pitch angle of the turbine blades, however this will not be investigated in this paper. Unfortunately, wind turbine C_p data is considered confidential commercial information and is generally unavailable to the public. However, the C_p of different wind speeds can be estimated from its relationship with the tip speed ratio, λ. Equation 13 shows how λ for the chosen turbines can be calculated for different wind speeds.

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} = \frac{\left[\frac{\text{rotational speed (rpm)}*\pi*D}{60}\right]}{\text{wind speed}} \quad \textit{Equation 13}$$

Here, the rotational speed refers to the turbine rotor and will either be a constant value or have a range of values if the turbine is geared. To estimate the varying C_p values from the λ values, a generic C_p-λ curve can be consulted as shown in Figure 8 (Manwell, McGowan and Rogers, 2010). Therefore, using Equation 13 and Figure 8, the C_p values for different wind speeds can be estimated.

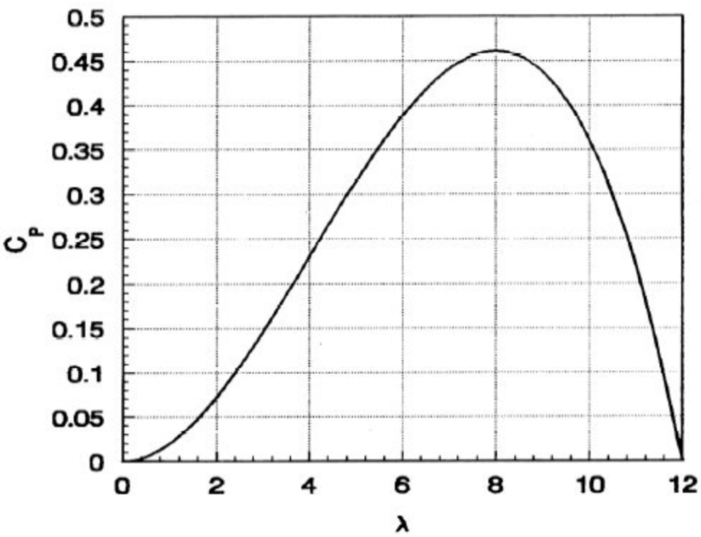

Figure 8 - Generic Cp-λ used to estimate the power coefficient at different wind speeds

There exist other methods of wind speed extrapolation including variations of the power law and other methods based on entirely different mathematics (Gualtieri, 2019). However, these methods are generally used in research focusing on the statistical technique used in extrapolation. This is not the focus of this research and these methods are beyond the scope of the work. The data available from Global Wind Atlas and Hellmann's Power Law outlined in Equations 9-12, will be sufficient to calculate the Weibull distribution of the wind speed in the desired area.

3.2.2 Generating Synthetic Wind Distribution

As discussed in Section 2.5, HOMER Pro will be used to produce hourly wind speed data over a time period of one year. HOMER Pro requires four variables in order synthetically generate the data, all of which can be calculated from data available from Global Wind Atlas or estimated:

- Weibull shape factor k
- 1-hour Auto-correlation factor – a measure of how much the wind speed in one time step depends on the wind speed in the previous time step.
- Diurnal Pattern Strength – a measure of how much the wind speed depends on the time of day.
- Hour of Peak Wind Speed – the hour of day that on average is the windiest.

The procedure to calculate Weibull shape factor k using the data available from Global Wind Atlas has been covered in Section 3.2.1. As for the remaining three variables, HOMER Pro claims the 1-hour Auto-Correlation factor is usually between 0.8-0.95 with areas of complex and simple landscape corresponding to smaller and larger values, respectively (HOMER Energy, 2016; Brett and Tuller, 1988). This factor can be calculated using methods of statistical analysis that are unnecessarily complex for this research and estimation of the value will suffice (Cavallo, 2010).

A feature of Diurnal Pattern Strength (DPS) is its tendency to increase with height. That is, the peak wind speed in a specified area tends to be later in the day as the anemometer height increases (Tian et al., 2020). As with the 1-hour Auto-Correlation factor, the calculation of DPS for synthetic wind data is an active area of research, with no one method proving to be applicable to all scenarios (Carapellucci and Giordano, 2013). In this research it will again suffice to estimate this value and HOMER Pro states the DPS is usually between 0.0-0.4, with a "standard" value of 0.25 (HOMER Energy, 2016). When making this estimation, consideration should be made with regards to the variation in DPS with height as mentioned. Lastly, the Hour of Peak Wind Speed can be found from the Global Wind Atlas data. This figure will also give insight into what value should be estimated for DPS i.e. if the Hour of Peak Wind Speed is late in the day for high turbines, the DPS should be estimated as larger than 0.25.

Finally, the EnergyPLAN distribution requires the wind speed data to be converted to wind power, normalised to the turbine rated power and formatted as a set of values, one for each hour of the year, between 0-1. Once completed, this artificial wind speed data, synthesized using values from Global Wind Atlas and HOMER Pro, is fit for use in EnergyPLAN.

3.3 Selection of Thermal Energy Storage

3.3.1 Criteria

In Section 2.2.5, some basic criteria were established regarding the desired properties of the material to be used in the TES system for generating electricity. To recap, these criteria were:

- The material must be able to store energy at a high temperature, in order to be coupled to thermal turbines that require working temperatures ~600°C to operate (Fernandes et al., 2012). This can be interpreted as having a large ΔT according to Equation 1.
- The material will have to be stable at high temperatures. That is, it must not have any mechanical structural problems, or undergo any chemical decomposition or phase change at high temperatures. This must be the case through many thermal cycles and over a long period of time.

- The material must have a high thermal conductivity. This is a measure of the charging and discharging capabilities of the material.

This led to the identification of solid SHS materials as the preferred choice, given they outperform LHS and liquid SHS in the three main criteria presented here. The aim of this section is to identify the optimum solid SHS material and TES system configuration for Electric TES from the literature.

3.3.2 TES System Configuration – Packed Bed

Regarding system configuration, the author believes that the best choice for this particular setup, is that of a packed bed system. A packed bed is a container tank filled with a solid SHS material made up of discreet, small particles, often called a "filler". Thermal energy is transferred to the filler through the Heat Transfer Fluid (HTF) when charging and from the filler when discharging. Packed beds are generally cylindrical, however, in the literature there is particular attention given to the study of the thermal properties of different geometries of packed beds (Mertens et al., 2014). The filler can be any solid material with examples of sand, crushed rocks and pebbles in the literature (Mawire et al., 2009; Bruch, Fourmigué and Couturier, 2014; McTigue, Markides and White, 2018). The HTF is often a gas with instances of air, argon and supercritical carbon dioxide found in the literature (White, McTigue and Markides, 2016; McTigue and White, 2018; McTigue, Markides and White, 2018) alongside less common liquids, mainly synthetic oils (Bruch, Fourmigué and Couturier, 2014).

Packed beds are generally considered to be more compact than other SHS container tanks, especially the commonplace two-tank system used in many SHS systems using molten salt. The use of an axial air flow as the HTF means packed beds are unable to charge and discharge at the same time, unlike some energy storage systems. This should be considered when constructing the model in EnergyPLAN. In this paper, the HTF will be air, given its simpler handling and cheaper costs compared to other gases (Johnson et al., 2018). Air does have a poorer heat capacity compared to some synthetic oils and other gases, which should translate as the system having a lower than optimum efficiency (Mertens et al., 2014). The air will be heated using an electric heater powered by the wind turbines, similar to the electrical resistor heaters in Figure 6 in Section 2.3. Another negative impact on efficiency will be the irregular charging of the packed bed filler. (McTigue, Markides and White, 2018) found that irregular charging periods, such as those caused by a variable renewable energy source, reduce the roundtrip thermal efficiency of packed bed storage systems.

A feature of packed beds is the formation of a thermocline across the storage material. A thermocline is a thermal gradient introduced and maintained by the axial flow of the HTF. The existence of a thermocline improves the charging and discharging efficiencies of the TES system, and avoidance of its degradation is an active area of research (Geissbühler et al., 2019). This leads to packed bed systems having relatively large roundtrip thermal efficiencies compared to other SHS configurations (Strasser and Selvam, 2014; Mostafavi Tehrani et al., 2017; Johnson et al., 2018).

3.3.3 SHS Material – Alumina Beads

Regarding storage material, based on the Literature Review and Table 1, the author believes that the best choice for this particular setup is alumina beads (aluminium oxide, Al_2O_3). Sintered alumina beads have a high working temperature of up to 700°C , high thermal conductivity, high mechanical and thermal stability at high temperatures over many thermal cycles and a high heat capacity (Anderson et al., 2015). This meets the qualifying criteria outlined in Sections 2.2.5 and 3.3.1. Table 5 shows the thermal properties of alumina beads (Koçak and Paksoy, 2019; Alumina Energy, 2020).

Table 5 - Thermal Properties of Alumina Beads

Energy Density (kJ/kg)	**Specific Heat Capacity (kJ/kg.K)**	**Working Temperature, ΔT (°C)**	**Thermal Conductivity (W/m.K)**	**Lifetime**
2447	0.920	120-700	30	30+ years

Alumina beads are found to have high storage efficiency (low heat loss), especially when the packed bed container is an insulted carbon steel tank (Cascetta et al., 2015). They have a large lifetime, 30+ years is usually quoted as the highest possible lifetime for a SHS material (Argyrou, Christodoulides and Kalogirou, 2018). Alumina beads are slightly more expensive than some other similar SHS materials, but they are environmentally low impact and are relatively simple to handle. The selection of alumina beads as the storage material is bolstered by the literature, where alumina beads have been regularly investigated as a filler material in packed bed high temperature SHS (Cascetta et al., 2015; Koçak and Paksoy, 2019).

Figure 9 shows the general schematic of a packed bed heat storage system using alumina beads as the filler. Figure 10 is a combination of Figure 9 and Figure 6 from Section 2.3, showing the alumina beads packed bed storage system integrated with wind turbines that will be modelled in EnergyPLAN. The electric air heater heats the air using electrical resistors. The gradient of colours from red to yellow is to show relatively different temperatures of the alumina beads, the existence of which forms a thermocline.

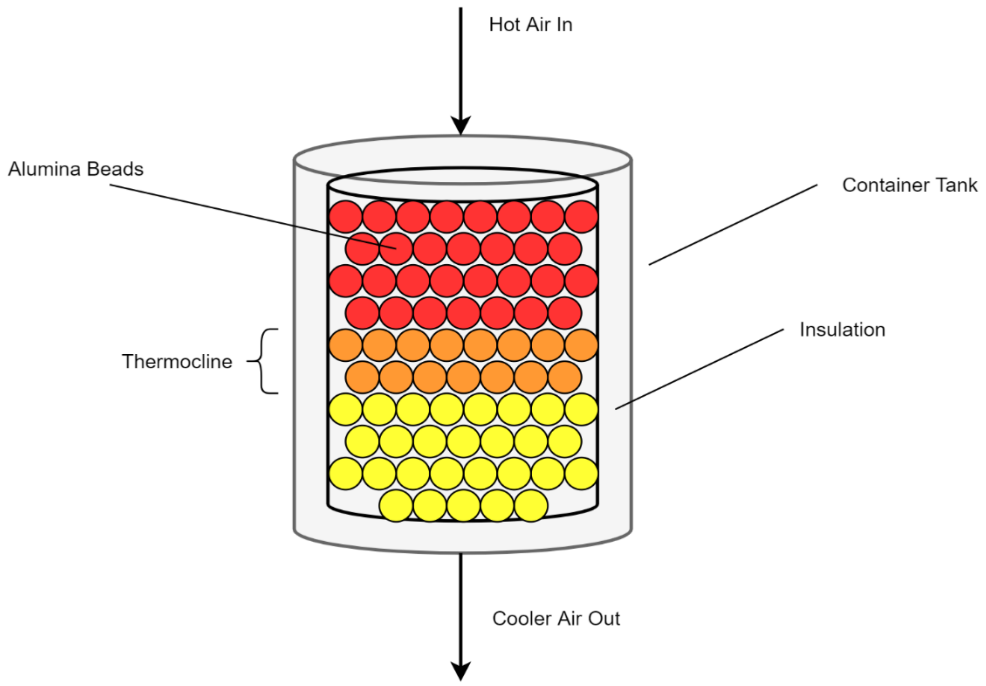

Figure 9 – General schematic of an alumina beads packed bed SHS system

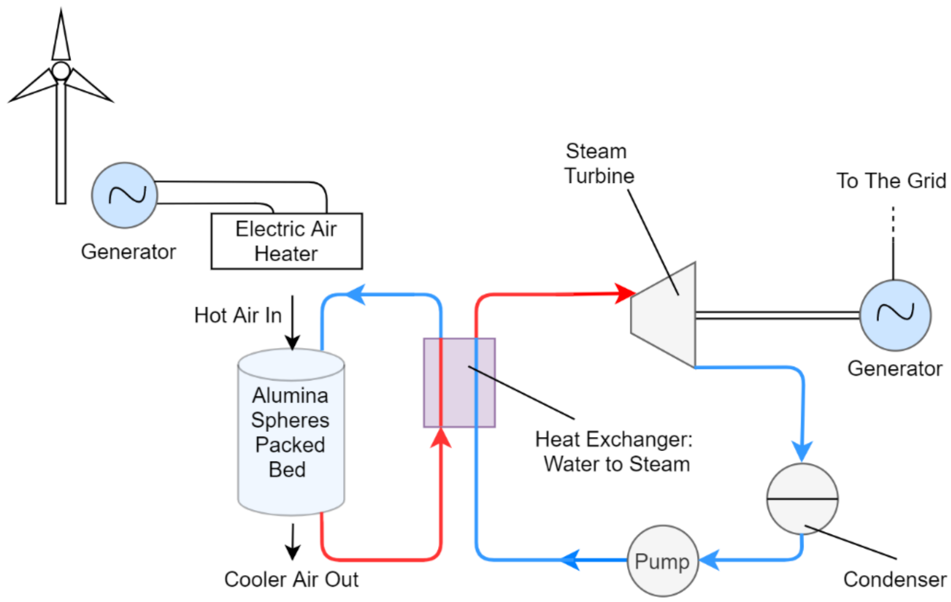

Figure 10 - Schematic of alumina beads packed bed SHS system within a WTES system

Identification of the technical and economic parameters to model the packed bed TES system in EnergyPLAN will be covered in the next section.

3.4 Modelling of the WTES System in EnergyPLAN

3.4.1 Background and Schematic

This section will detail how the information pertaining to the wind resource potential and to the TES parts of the project will be combined and modelled in EnergyPLAN. The WTES system will be modelled in a larger energy system, as this is how it would work in reality, and the interactions between different parts of the system are crucial aspects of its operation. This model will as closely resemble Scotland as possible, using economic and technical data that relates to Scotland or the UK. The main elements of the larger energy system model will be an electricity demand, conventional fossil fuel generation and an external market, alongside the wind power and TES components of the WTES system. The system will be very simplified compared to any real model of the Scottish energy system, as in this case, the interest is in the basic function of the

WTES within a larger system, that therefore does not need to be unnecessarily complex. A schematic of the simplified system is shown in Figure 11.

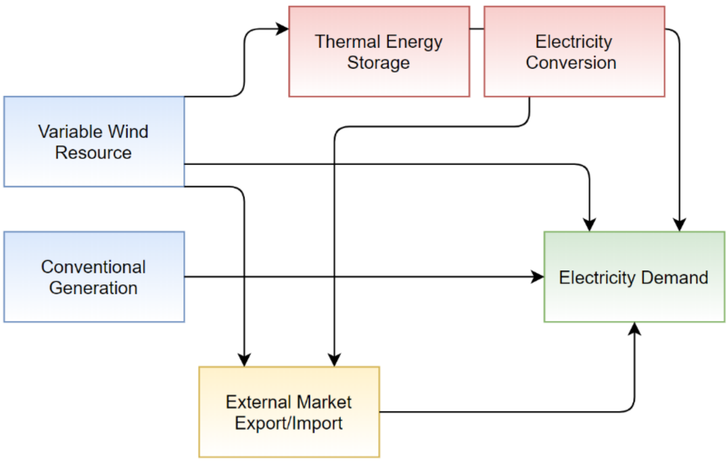

Figure 11 - Schematic of desired simplified EnergyPLAN model

Figure 11 shows the absence of the heat and transport sectors from the system. In reality, the larger energy system would include these sectors, but since the WTES system would have no effect on these sectors, they can be omitted. Note the lack of connection between the conventional generation or the External Market and the TES. It is crucial that EnergyPLAN does not allow any excess energy produced or imported by the conventional generation or the External Market to be stored in the TES. The TES must be isolated apart from its connection to the variable wind resource in order to accurately model a WTES system.

3.4.2 Sizing and System Components

The first step in constructing the EnergyPLAN model is to determine the electricity demand. Ideally, the total demand would be a figure representing a small part of the Scottish electricity system. Scotland had a total electricity demand of 24.15TWh in 2018 (Scottish Goverment, 2020) so a demand of 0.5TWh/year was selected to represent a small yet significant part of the Scottish electricity system. This figure is somewhat arbitrary as what matters more is the sizing of the electricity generation sources relative to the demand and to one another. The distribution of this total is calculated according to the distribution file provided with EnergyPLAN, “hour.electricity.”. This total demand paired with “hour.electricity” results in an average electricity demand of 56MW and a maximum and minimum of 88MW and 29MW respectively.

Next, the conventional generation, wind resource and storage must be sized. The operational strategy of EnergyPLAN means that in order for the storage option to be adequately utilised, the system must be very renewable energy heavy. However, in the interest of building a replication of Scotland’s energy system - and exploring the interactions between different elements of the system - the sizes will also ensure that all components have an important role to play.

The conventional generation is represented by PP1 (Power Plant 1) in EnergyPLAN. PP1 is intended to act as a CHP plant, supplying both electricity and heating demand. The use of a CHP plant in this model to generate only electricity is unproblematic as no heating demand is included in the simple EnergyPLAN system. PP1 is assigned a capacity of 25MW, enabling it to supply a considerable portion of the electricity demand, but still enabling the majority of the supply to be met with renewables. The efficiency of PP1 depends on the kind of power plant that it is representing. In Scotland in 2018, 15.7% of electricity was generated using fossil plants of which 15.1% is from natural gas and 0.6% is from fuel oil (Scottish Goverment, 2020). The UK Government cite an average efficiency of 48.8% for Combined Cycle Gas Turbine (CCGT) plants in the UK, so this value is used for the efficiency of PP1 (Department of Business Energy and Industrial Strategy, 2020).

The wind resource is defined by four factors: the total wind capacity, the stabilisation share, the correction factor and the distribution. The precise capacity will depend on the chosen model of turbine, which will be covered in Section 4.2. Recall, the capacity of the wind resource must be large in comparison to PP1 in order for EnergyPLAN to fully utilise the storage system. The stabilisation share represents how much of the installed renewable capacity contributes to grid stability services like frequency regulation. This is assigned a value of 0% as renewable sources are not able to effectively contribute to grid stability as has been discussed in Section 2.1. The correction factor adjusts the generation capacity but is not required for this model as the full capacity of the turbines should be used. Calculation of the distribution has been detailed in Section 3.2.

EnergyPLAN has many options for modelling the TES system. The most suitable is the Rockbed storage, which is described as "high temperature electricity storage" in the EnergyPLAN manual, which is an accurate description of what the author has been referring to as Electric TES. Throughout this report, "Rockbed storage" is referring to Electric TES. The storage is defined by six factors: charging capacity, discharging capacity, energy capacity, heat loss per hour, fuel in/steam out ratio (effectively efficiency) and share of PP1 that the Rockbed output has access to. The effect of changing the charging, discharging and energy capacity will be investigated in Section 4.2. These factors are dependent on cost, with many TES systems costed according to their power and energy capacity (i.e. £/kW or £/kWh). As for the remaining three factors, the share of PP1 that the Rockbed storage has access to is set at 100%, to ensure the Electric TES is utilised as much as possible, however, this is recognised as unrealistic and will be discussed further in Section 4.2. The loss per hour associated with an alumina beads packed bed SHS system can be found in the literature. Values range between <0.5-3% of thermal energy loss per hour, depending on the particular configuration of the packed bed and the fraction of capacity utilised in each charging cycle (Johnson et al., 2018; McTigue, Markides and White, 2018). A value of 1.5% heat loss per hour is assigned to the energy model plan, as it is within this range, is similar to a study that used a packed bed configuration (Koçak and Paksoy, 2019), and is within the range cited by more general reviews of TES systems (Argyrou, Christodoulides and Kalogirou, 2018). As for the fuel in/steam out ratio, which can be viewed as the efficiency of the system, TES systems in general report a relatively low value. Reviews of TES systems state 30-60% efficiency and when considering the use of air as an HTF and the irregular charging periods expected with a WTES system, the efficiency was estimated at the low value of 40%. Comparing to Figure 10, the "Electricity Conversion" component is contained within the Rockbed storage. Table 6 gives a short summary of the parameters that define the electricity generating components of the EnergyPLAN model.

Table 6 - Summary of the electricity generating components of the EnergyPLAN model

Parameter	**Value**
PP1 Capacity	25MW
PP1 Efficiency	48.8%
PP1 distribution	Hour.electricity.txt
Wind Distribution	*To be calculated in Section 4.2*
Wind Capacity	*To be determined in Section 4.3*
Charging Capacity	*To be investigated in Section 4.3 (10s of MW)*
Discharging Capacity	*To be investigated in Section 4.3 (10s of MW)*
Energy Capacity	*Dependent on Cost, will be discussed in Section 3.4.4 (1s of GWh)*
Heat Loss per Hour	1.5%
Share of PP1	100%
Fuel in/Steam Out Ratio (efficiency)	40%

3.4.3 Additional Information and EnergyPLAN Model Operation

EnergyPLAN requires some more information to be inputted in order to flesh out and accurately model the system. As discussed in Section 3.4.2, in Scotland, natural gas and oil produce 15.1% and 0.6% of gross electricity. This can be represented in the Supply → Fuel Distribution tab using a fixed ratio of fuels of 151:6. The CO_2 content of the fuels, in Supply → CO2, can be ascertained to be 50.28kgCO_2/GJ for natural gas and 69.72kgCO_2/GJ for oil (DEFRA, 2007; Department for Business Energy and Industrial Strategy, 2019). The costs of these fuels are 2.78 £/GJ for natural gas and 1.67 £/GJ for fuel oil (Bloomberg, 2020; Ofgem, 2020). There are no taxes or handling costs included in the system.

The final component of the EnergyPLAN model is the External Market. The External Market exists for excess electricity production to be exported for a profit and for electricity to be imported in the case of a dearth in supply, at a cost. Like other components, the External Market requires a price distribution: one entry for each hour of the year, of the market value of 1MWh of electricity. Such data for UK prices can be downloaded from the Nord Pool website (Nord Pool, 2020). 2019 data is used in the model, as it is the most recent full year. The operation of Rockbed storage and the External Market in EnergyPLAN is where the model runs into a major issue. As outlined in the EnergyPLAN manual, in the case of excess electricity production, the model will prioritise selling the electricity on the External Market over storing it in the Rockbed (Lund and Thellufsen, 2019). This cannot be overcome by any definitive means in EnergyPLAN (such as a different operating strategy) so must be dealt with by restricting the model transmission capability, to a figure of 5MW. This results in the diminished capacity of the connection to the External Market. This is largely unrepresentative of the Scottish energy system as Scotland is connected to other parts of the UK and to Europe with transmission cables with capacities that exceed 1GW (SSE, 2016; SP Energy Networks, 2020). However, this is the only method of ensuring that the Rockbed storage is fully utilised. The External Market is not assigned any addition, multiplication or elasticity factors as the model does not need to include any increase in CO_2 or fuel prices or consider how imports and exports affect the market.

This restriction of the transmission capacity will ensure that in every situation that is ran, Critical Excess Electricity Production (CEEP) will be reached. CEEP is the amount of electricity that had to be exported from the energy system but could not because the required transmission capacity was not available. The regulation strategy that is chosen as response to CEEP is number 7, "Reducing power plant in combination with RES1 (wind)", as it is the strategy that favours reduction in PP1 supply alongside the wind resource, as opposed to other strategies that just reduce the wind output.

Lastly, EnergyPLAN contains two options for simulating the model. The Market Economic simulation option focuses on reducing costs and will be discussed in Section 3.4.4 shortly. The Technical simulation option in EnergyPLAN simulates the operation of the model, prioritising reducing the use of fossil fuels and meeting electricity demand using the wind resource and the Rockbed storage. This simulation strategy can be used to investigate the utilisation of the Rockbed storage and the integration of the wind energy into the system through measuring flexibility, as shown in Equation 6. The Technical Simulation also ensures that there exists no connection between PP1 and the Rockbed Storage, so the integrated WTES system desired is successfully constructed in EnergyPLAN.

3.4.4 Costing the Components

PP1, the wind resource and the Rockbed require costing data, both a capital investment cost and an Operations and Maintenance cost (O&M). Costs for natural gas and fuel oil have been established in Section 3.4.3. Many of the upcoming references used in costing the components of the EnergyPLAN model originally quote the prices in US Dollars or Euros, and they are often not up to date. To address this, every price that will be cited in this section has been converted to Great British Pounds and adjusted for inflation (if needed). Foreign markets having different prices than what could be expected in the UK has not been accounted for.

(The UK 2050 Calculator, 2020) states that CCGT power plants can cost between 776-1040 £/kW with an O&M cost of between 1-7%. Similar data is quoted by (EIA, 2016), 806 £/kW and an O&M cost of ~3%. Therefore, the cost data inputted to EnergyPLAN for PP1 is 800 £/kW and an O&M of 3%. Wind turbine capital cost is quoted by (Renewable Energy Agency, 2012) as 1.71 million £/MW and by (WindIndustry.org, 2020) as between 1.1 million – 1.7 million £/MW. Regarding O&M costs, (Renewable Energy Agency, 2012) give a figure in £/kWh, and using the value of 0.19TWh/year of wind energy produced a year from EnergyPLAN this works out to an O&M cost of 1.6-3.2% of investment. Similarly, (Blanco, 2009) quote an O&M cost in €/kWh, which comes out to 1.35-2.1% of investment. Therefore, a reasonable choice for wind turbine O&M costs is 2%. For Rockbed storage, (Glatzmaier, 2011) breakdown the costs of a high temperature molten salt SHS system into individual components that comes out to 12.10 £/kWh. Another study, (Mostafavi Tehrani et al., 2017) states 14.80 £/kWh is the cost for a Single Medium Thermocline with a carbon steel tank as the container (a categorisation of TES system that alumina beads packed bed would fit into). Yet this method uses concrete as the filler, considering alumina beads are a more expensive storage medium than concrete, the cost is assigned as 15 £/kWh. No information could be found that pertained specifically to O&M costs of Electric TES using SHS. Referring to the values of 3% and 2% for PP1 and the wind resource, a Rockbed O&M cost of 3% was inputted in EnergyPLAN.

In EnergyPLAN, the Rockbed cost data is only linked to the energy capacity of the system not the power capacity. Therefore, the energy capacity will be changed along with the power capacity. This is to simulate higher costs associated with more powerful equipment. The Market Economic simulation in EnergyPLAN has the goal of reducing fossil fuel use while also ensuring a system that is run at as low a cost as possible. Finally, a "standard" interest value of 3% is assigned to the EnergyPLAN model (Connolly, 2015). Table 7 summarises the cost data for the EnergyPLAN model:

Table 7 - EnergyPLAN Cost Data

Parameter	**Cost**
PP1 Investment	800 £/kWh
PP1 O&M	3% of investment
Wind Investment	1.7 million £/MW
Wind O&M	2% of investment
Rockbed Investment	15 £/kWh
Rockbed O&M	3% of investment
Natural Gas	2.78 £/GJ
Fuel Oil	1.67 /GJ

4. Case Study and Results

4.1 Case Study Introduction

In this section, the methodology outlined in Section 3 will be applied to a hypothetical Wind-Thermal Energy Storage system in Scotland. The Case Study will be split into two subsections: Wind Resource Potential Case Study and EnergyPLAN Modelling Results.

The aim of Section 4.2, Wind Resource Potential Case Study, is to calculate the energy available from the wind using the data available from Global Wind Atlas and Equations 8-13, as outlined Section 3.2 of the Methodology. These energy yield figures will then have losses applied to compare with figures from ScottishPower to validate the results. The validated results will be inputted to HOMER Pro to generate synthetic wind speed data to be used in the EnergyPLAN Model.

Section 4.3, EnergyPLAN Modelling Results, presents and discusses the results of the Technical and Market Economic simulations carried out in EnergyPLAN. The influence of the WTES system on the flexibility of the larger system is investigated alongside the operation of the TES when its energy and power capacity parameters are changed. The effect of the WTES on the system CO_2 emissions and costs are also investigated.

4.2 Wind Resource Potential Case Study

4.2.1 Weibull Parameters

Upon accessing Global Wind Atlas to download wind speed data, one must first identify the area from which the data will be taken. Here, there are two choices: an area that already has wind turbine/wind farm development or an area without (but presumably still with promising wind speed resources). The former choice of an area already containing wind turbines is preferred because it immediately gives credence to the project by linking it with the realities of the current energy system. Further, it avoids any questions such as those over the lack of Environmental Impact Assessment or adequate transmission infrastructure that could delegitimise the work. The site chosen overlaps with the area of the Whitelee wind farm in southern Scotland, shown in Figure 12. Figure 13 below shows the same area with the wind speed data layer enabled.

Figure 12 - The area in Global Wind Atlas chosen for the wind speed data

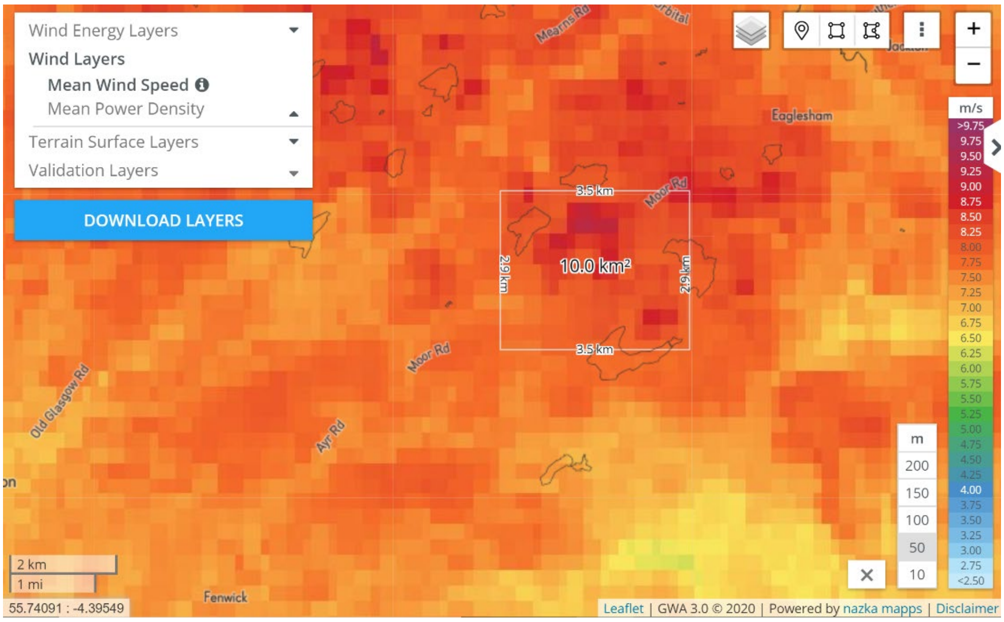

Figure 13 - the same area in Global Wind Atlas with wind speed data overlain

An important aspect of WTES system are the wind turbines. The type of wind turbine employed will have an effect on the total power produced according to the features of cut-in speed, cut-out speed, rated speed and rated power. To identify a turbine to be used in this system, a review was completed of the six largest onshore wind farms in Scotland, and what turbines are used at each. The results are shown in Table 8.

Table 8 - Largest wind farms in Scotland and what turbines are in use

Farm	**Operator**	**Turbine Make**	**Rating**
Whitelee	Scottish Power	Siemens SWT-2.3	2.3 MW
Clyde	SSE	Siemens SWT-2.3	2.3 MW
Crystal Rig	Fred Olsen Renewables	Nordex N80 and Siemens SWT-2.3	2.5 MW
Black Law	Scottish Power	Siemens (2.3MW definitely)	54 x 2.3 MW, 11 x 1.67 MW, 23 x 2 MW,
Hayard	SSE	Siemens SWT-2.3	2.3MW
Farr	Ventient	Bonus B82/2300 (Subsidiary of Siemens)	2.3 MW

(Fred Olsen Renewables, no date; Power Technology, no date; ScottishPower, 2020; The Wind Power, 2020c, 2020b, 2020a)

The most commonly used turbine at the six largest wind farms is the Siemens SWT-2.3. Given that it is also the turbine used at Whitelee wind farm, this will be the turbine chosen to be a part of the WTES system. Table 9 lists the relevant parameters of the Siemens SWT-2.3 Turbine. Figure 14 is the power curve associated with the Siemens SWT-2.3 turbine (The Wind Power, 2018).

Table 9 - Features of Siemens SWT 2.3 Turbine

Feature of Siemens SWT 2.3 Turbine	**Value**
Cut-in speed	3.5m/s
Rated speed	13m/s
Cut-out speed	25m/s
Rated Power	2.3MW
Hub Height	65m
Diameter	90m

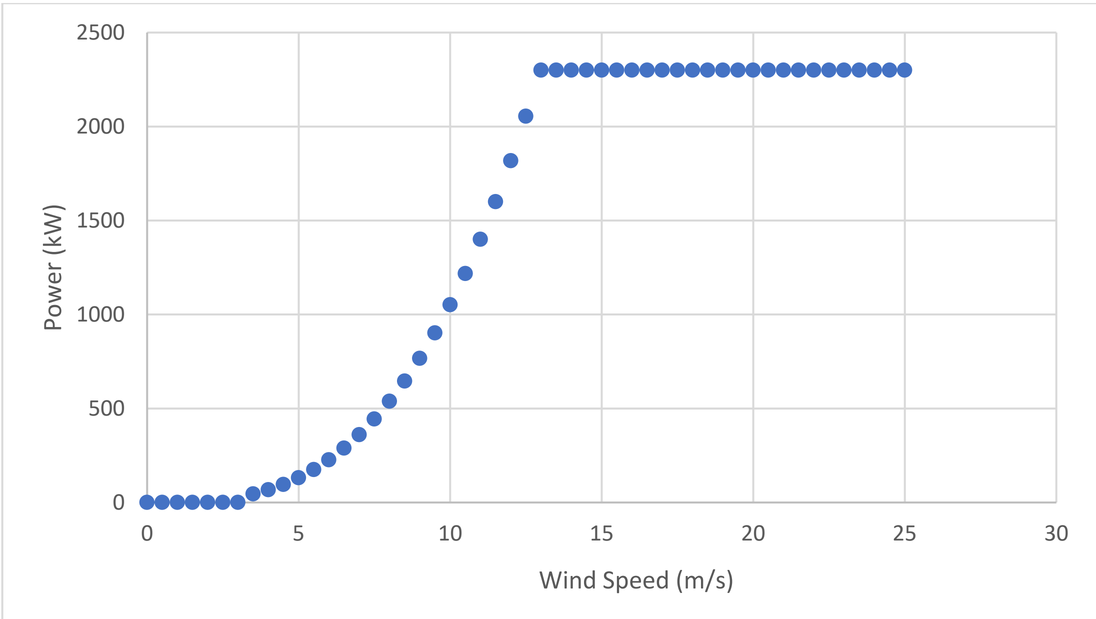

Figure 14 - Power curve of the Siemens SWT-2.3 turbine

When the GWC file from Global Wind Atlas has been downloaded some processing of the data is needed before the equations from Section 3.2 can be utilised. As discussed, the file provides Weibull shape and scale factors in form of a frequency distribution at certain reference heights, h_0 and roughness coefficients n. The reference height of 50m is chosen as it is closest to the height of the Siemens SWT-2.3 turbine. As for roughness coefficient, referring to Table 4 the coefficient for this terrain at Whitelee wind corresponds to a value of 0.1. Since the GWC supplies Weibull data at a reference roughness of 0.1 this eliminates the need to modify the data from the reference roughness coefficient data supplied.

From the frequency distribution table, an average shape and scale factor at n = 0.1 and h_0 = 50m called the reference shape and scale factor can be calculated as k_0 = 2.018 and c_0 = 8.568m/s. Using Microsoft Excel, Equations 10-12 with h = 65m can be applied to calculate k(h) = 2.073 and c(h) = 9.069m/s. Moreover, using Equation 13 and Figure 8 the power coefficient of the turbine at different wind speeds can be estimated. The Microsoft Excel function "WEIBULL" produces a Weibull distribution of wind speeds, shown in Figure 15, with a wind speed bin size of 1m/s.

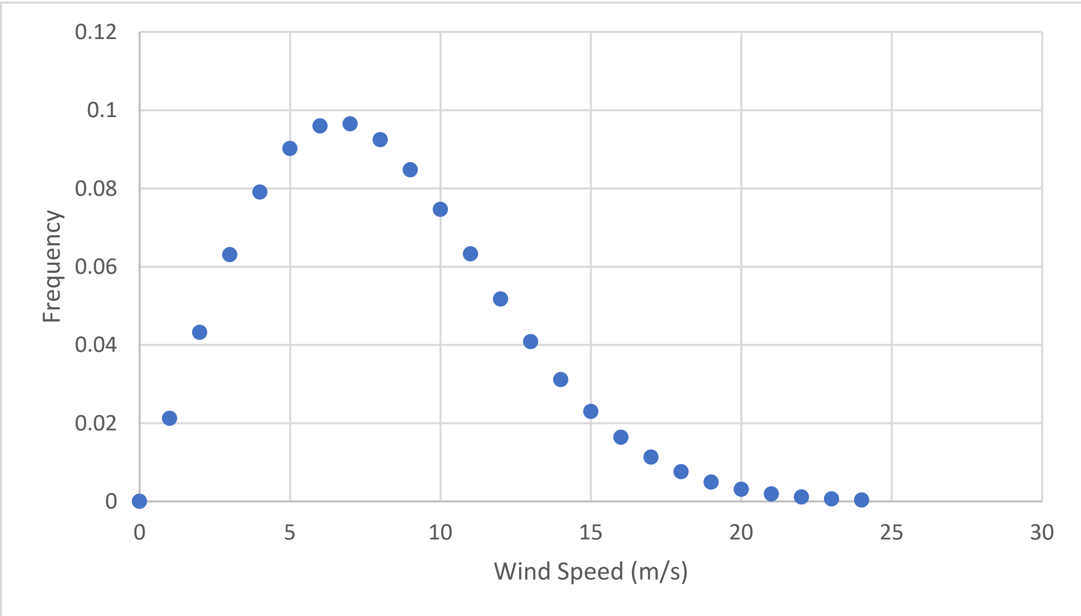

Figure 15 - Weibull distribution of wind speed at chosen area at height of 65m

Equation 7 can then be used to calculate the energy produced by one wind turbine. First the variables must be defined using the available data from the calculations and information about the turbine. The frequency of wind speeds from the Weibull Distribution data can be extrapolated to the number of hours per year at such wind speeds. The swept area can be calculated from the diameter of the blades to be 6,361.73m^2 and the air density can be taken as a standard value of 1.225kg/m^3 (Belabes et al., 2015). This completes the calculation of the necessary variables. Taken together, Equation 7 calculates the energy available over one year from one wind turbine at the site to be 8,291,723.69kWh

This figure is not particularly relevant on its own, however, it along with loss considerations can be compared to figures from ScottishPower of the Whitelee wind farm to check the calculations and validate the results. Assuming the WTES system will include more than one turbine, there are many sources of energy loss in the energy extraction from the wind:

- Wake losses – wake losses are caused by the downstream disturbance of wind by a turbine in front of others in a wind farm. Much consideration is given to the placement of wind turbines in arrays since the avoidance of excessive wake losses is a relatively simple way of increasing the energy yield of a wind farm (Hwang et al., 2015; Yang et al., 2019). Measurement of wake losses can be completed using a variety of mathematical techniques that vary in complexity, however, it will suffice to estimate wake losses at 15% of the energy yield (Manwell, McGowan and Rogers, 2010; Schallenberg-Rodriguez, 2013).
- Availability – availability losses concern a reduction in energy produced due to turbine downtime for maintenance. Research has shown that such downtime leads to an 11% decrease in energy production (Harman, 2010). This figure also covers turbines failing in extremely windy conditions.
- Operating Efficiency – operating efficiency losses are the energy losses caused by sub-optimal control systems, misaligned components, and other electrical issues. These can be estimated as the relatively smaller value of 2% energy reduction (Harman, 2010; Colmenar-Santos et al., 2014)
- Generator Losses – generator losses encompass many different, smaller losses that occur during the generation of electricity, including: gearbox, windage, ball bearing, copper, Eddy current, hysteresis and stray load loss. Research has shown that such losses can reduce the energy yield of a wind turbine by 9% (Inoue et al., 2005)

There exist other losses that do no need to be applied in this case. Ageing is the general deterioration of performance of turbines over time, however since the effect is poorly understood and not the focus of the paper it will not be included. In Section 3.2, Hellmann's Power Law describes the vertical gradient of horizontal wind speed which, in theory, could be applied to the large vertical distances covered by the turbine blades. This could potentially lead to losses and other deterioration problems by introducing wind shear on the blades (Albani, Ibrahim and Yong, 2019). This is a highly specialised loss effect that will not be included in this system, however, the author is aware of its implications. Other potential losses are due to minor features of the operation of a wind turbine such as blade fouling which will be omitted in this study due to time limitations.

Combining the relevant losses,

True Energy Yield = Ideal Energy Yield * (Wake Effect * Availability * Operating Efficiency *Generator Losses)

True Energy Yield = Ideal Energy Yield * (0.85 * 0.89 * 0.98 * 0.91) = Ideal Energy Yield * 0.675

This figure can be used to validate the energy yield and losses calculation. ScottishPower claim that the Whitelee wind farm with its 215 turbines, generates electricity for 298,837 homes at an average of 4,266kWh consumption per household (ScottishPower, 2020). Combining these figures, one of ScottishPower's turbines at Whitelee produces, in one year:

(298,837 * 4,266) / 215 = 5,929,482.06 kWh

Applying the loss factor calculated above to the ideal energy yield figure of 8,291,723.69kWh, gives

8,291,723.69 * 0.675 = 5,596,913.49 kWh

An approximately 6.1% difference in yield, which is a similar figure to that claimed by Scottish Power, indicating the energy yield calculation is a success and the data can be transferred to HOMER Pro for synthetic wind speed data generation.

4.2.2 HOMER Pro

As covered in Section 3.2.2, the data from Global Wind Atlas can now be transferred to HOMER Pro to generate synthetic wind speed data. Specifically, HOMER Pro requires average monthly wind speed figures, which are supplied in the GWC file from Global Wind Atlas. As for the required accompanying variables, the calculations outlined above have identified k(h), the Hour of Peak Wind Speed is available from the GWC and the 1-hour Auto-Correlation Factor and the Diurnal Pattern Strength can be estimated. The figures are listed in Table 10.

Table 10 - variables required for HOMER Pro to generate synthetic wind speed data

Variable	Value
Weibull Shape Factor, k(h)	2.073
1-hour Auto Correlation Factor	0.90
Diurnal Pattern Strength	0.25
Hour of Peak Wind Speed	21 (9pm)

The 1-hour Auto-Correlation Factor is estimated at 0.90, as simple topographies correspond to higher values in the range of 0.80-0.95, in keeping with the assumed simple topography represented by the estimated surface roughness coefficient value of 0.1, which is smaller than the "standard" value of 0.143. The Diurnal Pattern Strength is estimated at 0.30 as this is slightly higher than the quoted "standard" value by HOMER Pro (HOMER Energy, 2016), which is to be expected with a wind speed height of 65m and an Hour of Peak Wind Speed of 21. Inputting this data into the software (as part of a simple energy model that has no bearing on the results of the synthetic wind data) produces a data set of wind speeds that can be exported from HOMER Pro.

Finally, this data must be altered before it can be used in EnergyPLAN. EnergyPLAN requires wind speed data to be in the form of normalised power fraction data, as discussed in Section 3.4. To produce this, the wind speed data was cubed since Power $\propto$ (Wind Speed)^3 according to Equation 7, and then normalised to the highest possible power output. The resulting hourly wind speed-power distribution is ready for use in EnergyPLAN, and is shown in Figure 16.

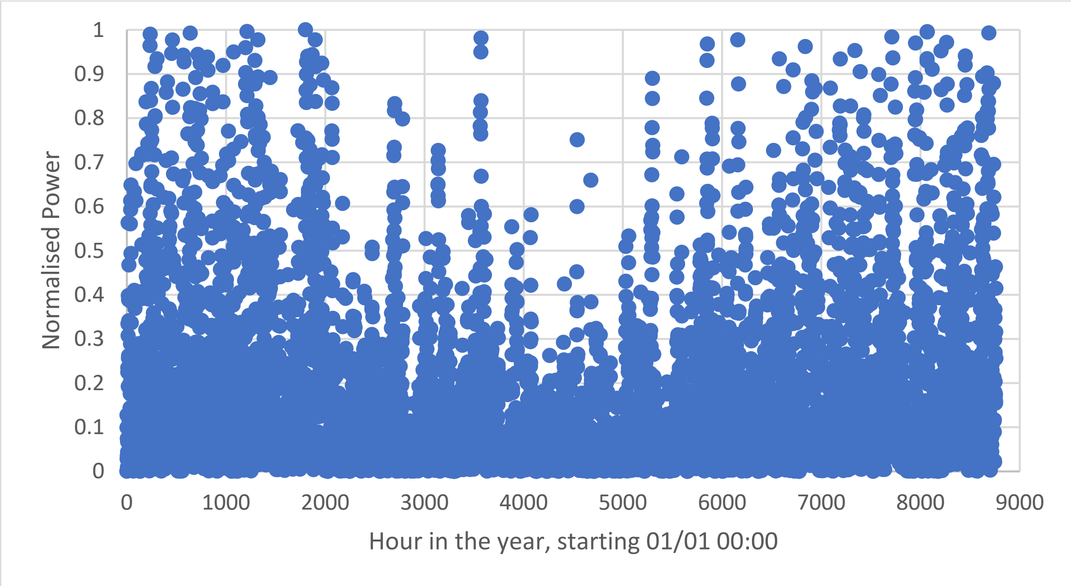

Figure 16 - Normalised power distribution from synthetic wind speeds

4.3 EnergyPLAN Modelling Results

4.3.1 Introduction and Results

This section will combine the wind power distribution work completed in Section 4.2 and the EnergyPLAN modelling work completed in Section 3.3 to investigate the operation of the WTES system within the wider EnergyPLAN model. To do so, the charging and discharging capacity will be altered to explore the influence the WTES system has in the model. As touched upon in Section 3.4.4, the cost data for the Rockbed storage only applies to the energy capacity, so to ensure that the increase in power capacity of the Rockbed storage is represented in the costing data, there will be a corresponding increase in energy capacity.

The final input of the wind resource capacity in EnergyPLAN can now be assigned. In Section 4.2, the turbine chosen to be part of the WTES system was the Siemens 2.3 SWT. This turbine has a rated capacity of 2.3MW so the total wind resource capacity has to be a multiple of 2.3MW. The only other condition, as outlined in Section 3.4.2, is that the wind resource capacity must be considerably large. This is to create the renewable energy heavy system that is required in order for EnergyPLAN to fully utilise the Rockbed storage component. Therefore, the wind resource was assigned a capacity of 92MW, representing 40 wind turbines.

The Technical Simulation will measure the operation of the Rockbed storage, the influence the Rockbed storage has on the flexibility of the system as well as any changes in CO_2 emissions. The Market Simulation will measure the influence the Rockbed Storage has on the total system cost. The simulations are not meant to optimise the system in any way. Rather, they are meant to simulate its operation and produce the values of certain parameters to analyse how the system operates. Tables 11 and 12 show the results of the Technical and the Market Economic simulations. Note that the system also includes the 25MW of PP1 and, 92MW of rated wind and a 5MW connection to the External Market. In EnergyPLAN, under the Simulation tab, the Rockbed regulation strategy selected was number 1.

Table 11 - First part of EnergyPLAN modelling results

Simulation Number	**Rockbed Charge/ Discharge Capacity (MW)**	**Rockbed Energy Capacity (GWh)**	**Max Flexibility**	**Average Flexibility**
1	0	0	100%	22%
2	10	1	100%	28%
3	20	2	100%	32%
4	30	3	100%	36%
5	40	4	100%	40%
6	50	5	100%	40%
7	60	6	100%	42%

Table 12 - Second part of EnergyPLAN modelling results

Simulation Number	**Rockbed Average Storage (MW)**	**Rockbed Max Storage (MW)**	**Rockbed Average Steam Out (MW)**	**Rockbed Max Steam Out (MW)**	**CO2 Emissions (Mt)**	**Costs (£million)**
1	0	0	0	0	0.135	23
2	22	570	3	10	0.12	24
3	34	1003	3	20	0.111	25
4	40	1250	3	30	0.099	27
5	38	1335	3	40	0.091	28
6	38	1339	3	50	0.091	29
7	37	1339	3	60	0.091	30

4.3.2 Flexibility Results and Discussion

Regarding flexibility, the author's original plan was to measure the Maximum Flexibility, according to Equation 6. That is, the maximum fraction of PP1 that is able to be ramped down in favour of renewable generation. However, even in the case without storage the Maximum Flexibility is 100%, indicating that at some point during the one year simulation, there was enough wind power to entirely meet the electricity demand, which is plausible. For this reason, the Average Flexibility will be used as a measure of the influence of storage on the flexibility of the system. The Average Flexibility is calculated from the annual average value of PP1 capacity. For example, take Simulation 2, which had an average PP1 capacity of 18MW. So, on average, PP1 can reduce its capacity by 28% over the whole year, giving the system Average Flexibility of 28%. Note, this figure of 28% can also be interpreted as the share of gross electricity consumption that comes from renewable sources. In Section 2.1, it was stated unproblematic renewable energy grid penetration reaches a maximum limit of approximately 20% gross electricity consumed when there is no storage in the system. Since the system in this simulation includes 1GWh and 10MW of storage energy and power capacity, this does not contradict the earlier statement.

The system has some intrinsic flexibility even without storage, with the 92MW of wind giving the system an Average Flexibility of 22%. Imports from the External Market will technically also contribute to Average Flexibility since they will cause a reduction in PP1 output. However, the restricted transmissions capacity means that imports as well as exports will be considerably small, so it can be assumed that most of the flexibility will come from the WTES system. Again, note that this figure of 22% exceeds the 20% limit of unproblematic renewable energy penetration. Since this simulation included no storage, it is expected that the system would have some issues balancing supply and demand. This is confirmed by the warnings that EnergyPLAN displayed upon completion of the simulations, including warnings of PP1 and the wind resource overcapacity. In reality, if this energy could not be consumed or exported, this would cause major problems for the grid.

The integration of the TES system with the wind resource considerably increases the Average Flexibility (by 8%) and increasing the Charge/Discharge Power Capacity gradually improves it as well (in increments of 2-4%). However, the flexibility only increases up to a point, with it somewhat plateauing at 40-42% when storage Power Capacity reaches 40MW. Increasing the capacity beyond this point indicates that the TES system will become oversized and its increased capacity has little additional positive effect on the flexibility of the system. The increased capacity will incur higher costs and will be more difficult to maintain so accurate modelling should take place to find the optimum size of the TES system before implementation of such a system in real life.

4.3.3 Rockbed Operation Results and Discussion

The Average Rockbed Storage reveals a similar result, as the figures gradually increase with increasing Power and Energy Capacity but plateau around 40MW as well. Interestingly, the Maximum and Average Steam Out from the storage are perhaps not what would be expected for a WTES system. As discussed in Section 2.2.5, TES is more suited to “energy management” applications: high energy capacity, longer duration storage services that rely on TES’s advantages of being able to store large quantities of energy for a long time and avoid its disadvantage of having a poor response time and inefficient operation. The low Rockbed Average Steam Out figures of 3MW yet the Rockbed Max Steam Out figures reaching as high as they can in each configuration potentially indicates that the storage is generally being used sparingly yet when it is used, it is to meet peak demands, much like the operation of storage systems that focus on “power quality” services like batteries. However, the full usage of the potential Power Capacity of the TES systems in each simulation indicates that the WTES system has become an important part of the larger energy system.

4.3.4 CO_2 Emissions and Costs Results and Discussion

The CO_2 Emissions follow a similar pattern as the Average Flexibility and Rockbed Storage results, with a marked decrease in emissions, from 0.135Mt CO_2 in a system with no storage to 0.091Mt CO_2 at the usual plateau power capacity of 40MW, a decrease of 32.6%. However, the desire for such reductions – and for flexibility – must consider the associated costs of adding storage into the system. The Market Economic simulation reveals the cost of each simulation, values that are not subject to the same plateauing effect as the other results. The costs continue to climb in each simulation as the energy capacity of the TES increases, without it having a significant effect on the Average Flexibility or the CO_2 Emissions. This again stresses the importance of sizing the TES system, as an oversized system results in very high costs, meaning it would be more difficult to recover the investment cost through the profitable operation of the TES system.

4.3.5 Influence of Wind on Flexibility and Modelling Limitations

Interestingly, when the wind resource capacity was altered this appeared to have more of an effect on the flexibility of the system than the storage. Table 12 shows the results of Technical simulations ran when PP1 capacity was 25MW, storage energy and power capacity were held at 2GWh and 20MW respectively, and the connection to the External Market was 5MW. The wind resource capacity increases in increments of 11.5MW, or 5 turbines, and starts at 92 MW. The Maximum Flexibility was not included as it has been established that it will reach and stay at 100%

Table 13 - EnergyPLAN modelling results when wind resource capacity was changed

Simulation Number	Wind Capacity (MW)	Average Flexibility	CO2 Emissions (Mt)	Costs (£million)
1	92	32%	0.111	25
2	103.5	40%	0.092	26
3	115	46%	0.084	28
4	126.5	54%	0.074	29
5	138	60%	0.066	30

Table 12 shows that when the wind capacity is increased, it has a much more significant impact on the flexibility of the system than the storage has. Increasing the capacity from

92MW to 138MW, almost doubled the flexibility of the system from 32% to 60%. Moreover, the increasing wind capacity is not subject to the same plateauing effect that the Rockbed storage is and it leads to better CO_2 emission reductions and similar costs as the increases in Rockbed storage. However, this highlights a limitation of the research. Flexibility was defined early on as the ability of conventional generation sources to reduce their generating output. As can be seen from Table 12, increasing the wind resource capacity facilitates this very well, but will not offer the same flexibility features as storage such as load shifting or security of supply on a timescale of hours. Furthermore, if increasing the capacity of the wind resource was preferred over a shorter timescale, “power quality” energy storage method, the system would forego an enhance capability to perform ancillary services like frequency regulation.

In addition to a more nuanced definition of flexibility, the model has other limitations and assumptions that should be addressed. First, since the transmission capacity was restricted to stimulate the interaction between the wind and TES components (thereby creating the WTES system), the model lost the ability to measure another financial metric: profit. The restricted transmission capacity made any profit figures very small and unrepresentative of what would be expected if the capacity was at a level one would expect for the size of the system modelled. This would have given more useful insight into the economic implications of the iterations of the system beyond their costs. Another inaccuracy was the assumption of the Rockbed storage having access to 100% of PP1. In reality, the storage would likely have limited access to the thermal plant’s capacity, especially if an already existing thermal plant was used. Additionally, there was no consideration for the operation costs associated with reducing PP1’s capacity. This would also have a negative effect on PP1’s efficiency as thermal turbines operate most efficiently when producing power at their rated capacity.

5. Conclusions and Future Work

5.1 Conclusions

This research has detailed the construction and investigation of a Wind-Thermal Energy Storage system in Scotland. The need for energy storage in the wider electricity system to provide flexibility and enable the integration of variable sources of renewable electricity was established. Thermal energy storage was found to have particular characteristics that made it an attractive option for long-term energy management applications. Despite this it was found to be rarely used to generate utility-scale electricity but is gaining popularity among researchers and electricity providers alike.

The wind resource potential for an area in Scotland was identified using data downloaded from Global Wind Atlas. This data along with mathematics relating to Hellmann's Power Law and utilisation of the modelling tool HOMER Pro was used to generate synthetic wind data. The corresponding available energy from the wind was calculated according to limitations imposed by the chosen turbine parameters and was verified using energy data from ScottishPower of a wind farm in the same area. The different options for the TES method were investigated, eventually narrowing down to alumina beads packed bed sensible heat storage given the material's high thermal conductivity, high heat capacity and thermal and chemical stability. Therefore, the two smaller aims of the research, to calculate the wind resource potential of an area of Scotland and identify the optimum TES for use in the WTES, were achieved.

The central aim of the research was to construct a model of a WTES in Scotland. To model the WTES system within a wider energy system, the tool EnergyPLAN was used. The simulations revealed that the WTES improved the flexibility of a system with conventional fossil fuel generation from 22% to 42%, allowing wind power to be further integrated into the electricity supply. However, the sizing of the TES system was revealed to be an important aspect, as continually increasing the power capacity of the TES system beyond 40MW incurred higher costs – from £24million to £30million - but did not continue to improve the flexibility of the larger system. The use of the WTES system also had a positive effect on CO_2 emissions, reducing them from 0.135Mt to

0.091Mt, following a similar plateauing effect as the other results. Overall, the EnergyPLAN results indicate WTES systems' potential as a method of increasing the flexibility of energy systems whilst contributing to creating the low carbon energy systems of the future.

5.2 Future Work

There exists much scope for further work in this area, investigating related concepts and going into more detail in the concepts introduced here. The primary focus of any future work should be to do with the modelling. First, information estimates for the TES model were taken from a review of the literature. If the TES system could be modelled separately then factors like heat capacity, thermal conductivity and stability could be independently calculated. This means a more suitable storage system and material than the alumina beads packed bed system would likely be found. Moreover, improved knowledge of the storage system characteristics would likely result in more accurate parameters to be inputted to EnergyPLAN, increasing the credibility of the WTES model.

Similarly, the EnergyPLAN model could be improved upon by making it more extensive and representative of the Scottish energy system. For this paper, EnergyPLAN was a suitable choice to simulate the basic function of a WTES system and investigate its influence in a larger energy system. However, as discussed in Section 3.4, there are a number of issues with the system, namely, the need for the system to be very renewable energy heavy and to restrict the transmission line in order for the Rockbed storage to be used. Having a more detailed system would likely remove these problems, as EnergyPLAN is optimised for modelling energy systems on a larger, regional scale. Furthermore, more substantive results could be obtained i.e. regarding costs and profits. In the system presented, the effect of increasing the storage capacity on costs can be investigated but only whether they increase, decrease, or stay the same. Having a more representative model would result in more meaningful cost data, and the effects on cost could be investigated in more detail than if the results changed.

Finally, any future work on the subject of a WTES could also focus on integration of the TES with heating systems. Often in the literature, TES was used as part of district heating systems either separate from or alongside its electricity generating capacity. This addresses TES systems' major setback of having a poor efficiency when converting heat to electricity and has proven to be a very suitable application of TES. In summary, the work presented in this paper could be improved upon through the development of more in-depth models of both the individual WTES system and the larger energy system that it is a part of.

References

Aalborg University (no date) EnergyPLAN: advanced energy system analysis computer model. Available at: http://energy.plan.aau.dk/ (Accessed: 8 July 2020).

Akrami, A., Doostizadeh, M. and Aminifar, F. (2019) 'Power system flexibility: an overview of emergence to evolution', Journal of Modern Power Systems and Clean Energy. Springer Heidelberg, pp. 987–1007. doi: 10.1007/s40565-019-0527-4.

Albani, A., Ibrahim, M. Z. and Yong, K. H. (2019) 'Wind shear data at two different terrain types', Data in Brief. Elsevier Ltd, 25, p. 104306. doi: 10.1016/j.dib.2019.104306.

Alumina Energy (2020) Our Technology - ALUMINA PACKED BED THERMAL ENERGY STORAGE. Available at: https://www.aluminaenergy.com/technology (Accessed: 16 August 2020).

Alva, G., Lin, Y. and Fang, G. (2018) 'An overview of thermal energy storage systems', Energy. Elsevier Ltd, pp. 341–378. doi: 10.1016/j.energy.2017.12.037.

Anderson, R. et al. (2015) 'Packed bed thermal energy storage: A simplified experimentally validated model', Journal of Energy Storage. Elsevier Ltd, 4, pp. 14–23. doi: 10.1016/j.est.2015.08.007.

Argyrou, M. C., Christodoulides, P. and Kalogirou, S. A. (2018) 'Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications', Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 804–821. doi: 10.1016/j.rser.2018.06.044.

Bañuelos-Ruedas, F., Ángeles Camacho, C. and Rios-Marcuello, S. (no date) 4 Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region. Available at: www.intechopen.com.

Belabes, B. et al. (2015) 'Evaluation of wind energy potential and estimation of cost using wind energy turbines for electricity generation in north of Algeria', Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 1245–1255. doi: 10.1016/j.rser.2015.07.043.

Bergan, P. G. and Greiner, C. J. (2014) ‘A New Type of Large Scale Thermal Energy Storage’, in Energy Procedia. Elsevier Ltd, pp. 152–159. doi: 10.1016/j.egypro.2014.10.422.

Van Berkel, J. (2005) Storage of solar energy in chemical reactions. Thermal energy storage for solar and low energy buildings.

Blanco, M. I. (2009) ‘The economics of wind energy’, Renewable and Sustainable Energy Reviews, pp. 1372–1382. doi: 10.1016/j.rser.2008.09.004.

Bloess, A., Schill, W. P. and Zerrahn, A. (2018) ‘Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials’, Applied Energy. Elsevier Ltd, pp. 1611–1626. doi: 10.1016/j.apenergy.2017.12.073.

Bloomberg (2020) Energy. Available at: https://www.bloomberg.com/energy (Accessed: 21 August 2020).

Brett, A. C. and Tuller, S. E. (1988) The Autocorrelation of Hourly Wind Speed Observations, Source: Journal of Applied Meteorology.

Bruch, A., Fourmigué, J. F. and Couturier, R. (2014) ‘Experimental and numerical investigation of a pilot-scale thermal oil packed bed thermal storage system for CSP power plant’, Solar Energy. Elsevier Ltd, 105, pp. 116–125. doi: 10.1016/j.solener.2014.03.019.

Caralis, G. et al. (2019) ‘Analysis of energy storage systems to exploit wind energy curtailment in Crete’, Renewable and Sustainable Energy Reviews. Elsevier Ltd, 103, pp. 122–139. doi: 10.1016/j.rser.2018.12.017.

Carapellucci, R. and Giordano, L. (2013) ‘The effect of diurnal profile and seasonal wind regime on sizing grid-connected and off-grid wind power plants’, Applied Energy. Elsevier Ltd, 107, pp. 364–376. doi: 10.1016/j.apenergy.2013.02.044.

Cascetta, M. et al. (2015) ‘A study of a packed-bed thermal energy storage device: Test rig, experimental and numerical results’, in Energy Procedia. Elsevier Ltd, pp. 987–994. doi: 10.1016/j.egypro.2015.12.157.

Castell, A. and Solé, C. (2014) ‘Design of latent heat storage systems using phase change materials (PCMs)’, in Advances in Thermal Energy Storage Systems: Methods and Applications. Elsevier Inc., pp. 285–304. doi: 10.1533/9781782420965.2.285.

Castillo, A. and Gayme, D. F. (2014) ‘Grid-scale energy storage applications in renewable energy integration: A survey’, Energy Conversion and Management. Elsevier Ltd, pp. 885–894. doi: 10.1016/j.enconman.2014.07.063.

Cavallo, A. (2010) Stand-Alone and Hybrid Wind Energy Systems: Chapter 12 - Compressed air energy storage technologies for wind energy systems. Edited by J. K. Kaldellis.

Chen, H. et al. (2009) ‘Progress in electrical energy storage system: A critical review’, Progress in Natural Science. Science Press, pp. 291–312. doi: 10.1016/j.pnsc.2008.07.014.

Chen, J. and Rabiti, C. (2017) Synthetic Wind Speed Scenarios Generation for Probabilistic Analysis of Hybrid Energy Systems.

Child, M. and Breyer, C. (2016) ‘The Role of Energy Storage Solutions in a 100% Renewable Finnish Energy System’, in Energy Procedia. Elsevier Ltd, pp. 25–34. doi: 10.1016/j.egypro.2016.10.094.

Cochran, J. et al. (2013) Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy. Available at: www.nrel.gov/publications.

Colmenar-Santos, A. et al. (2014) ‘Simplified analysis of the electric power losses for on-shore wind farms considering weibull distribution parameters’, Energies. MDPI AG, 7(11), pp. 6856–6885. doi: 10.3390/en7116856.

Connolly, D. et al. (2010a) ‘A review of computer tools for analysing the integration of renewable energy into various energy systems’, Applied Energy. Elsevier Ltd, pp. 1059–1082. doi: 10.1016/j.apenergy.2009.09.026.

Connolly, D. et al. (2010b) ‘Modelling the existing Irish energy-system to identify future energy costs and the maximum wind penetration feasible’, Energy. Elsevier Ltd, 35(5), pp. 2164–2173. doi: 10.1016/j.energy.2010.01.037.

Connolly, D. (2015) Finding and Inputting Data into EnergyPLAN (The FIDE Guide). Available at: www.dconnolly.net.

DEFRA (2007) Guidelines to Defra's GHG conversion factors for company reporting Annexes updated June 2007.

Denholm, P. et al. (2010) The Role of Energy Storage with Renewable Electricity Generation. Available at: http://www.osti.gov/bridge.

Denholm, P. and Hand, M. (2011) 'Grid flexibility and storage required to achieve very high penetration of variable renewable electricity', Energy Policy, 39(3), pp. 1817–1830. doi: 10.1016/j.enpol.2011.01.019.

Denholm, P. and Margolis, R. M. (2007) 'Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems', Energy Policy, 35(5), pp. 2852–2861. doi: 10.1016/j.enpol.2006.10.014.

Department for Business Energy and Industrial Strategy (2019) 2018 UK greenhouse gas emissions, provisional figures.

Department of Business Energy and Industrial Strategy (2020) Chapter 5 Electricity.

Department of Business Energy and Industrial Strategy, U. G. (2019) Industrial Strategy Offshore Wind Sector Deal Walney extension offshore windfarm.

Dinker, A., Agarwal, M. and Agarwal, G. D. (2017) 'Heat storage materials, geometry and applications: A review', Journal of the Energy Institute. Elsevier B.V., pp. 1–11. doi: 10.1016/j.joei.2015.10.002.

DTU and World Bank Group (2018) Global Wind Atlas. Available at: https://globalwindatlas.info/ (Accessed: 21 August 2018).

EMD International A/S (no date) energyPRO. Available at: https://www.emd.dk/ (Accessed: 8 July 2020).

Energy Information Administration (EIA) (2016) Capital Cost Estimates for Utility Scale Electricity Generating Plants. Available at: www.eia.gov.

Enescu, D. et al. (2020) 'Thermal energy storage for grid applications: Current status and emerging trends', Energies. MDPI AG. doi: 10.3390/en13020340.

EPRI (2019) EPRI to Lead $5 Million DOE/NETL Project to Test Concrete Thermal Energy Storage Technology. Available at: https://www.globenewswire.com/newsrelease/2019/07/01/1876757/0/en/EPRI-to-Lead-5-Million-DOE-NETL-Project-to-Test-Concrete-Thermal-Energy-Storage-Technology.html (Accessed: 8 September 2020).

Evans, A., Strezov, V. and Evans, T. J. (2012) ‘Assessment of utility energy storage options for increased renewable energy penetration’, Renewable and Sustainable Energy Reviews, pp. 4141–4147. doi: 10.1016/j.rser.2012.03.048.

Fernandes, D. et al. (2012) ‘Thermal energy storage: “How previous findings determine current research priorities”’, Energy. Elsevier Ltd, 39(1), pp. 246–257. doi: 10.1016/j.energy.2012.01.024.

Forsberg, C. W. et al. (2017) ‘Converting excess low-price electricity into high-temperature stored heat for industry and high-value electricity production’, Electricity Journal. Elsevier Inc., 30(6), pp. 42–52. doi: 10.1016/j.tej.2017.06.009.

Fred Olsen Renewables (no date) Crystal Rig. Available at: https://fredolsenrenewables.com/windfarms/crystal-rig/ (Accessed: 1 July 2020).

Geissbühler, L. et al. (2019) ‘An assessment of thermocline-control methods for packed-bed thermal-energy storage in CSP plants, Part 1: Method descriptions’, Solar Energy. Elsevier Ltd, 178, pp. 341–350. doi: 10.1016/j.solener.2018.12.015.

Gil, A. et al. (2010) ‘State of the art on high temperature thermal energy storage for power generation. Part 1-Concepts, materials and modellization’, Renewable and Sustainable Energy Reviews, pp. 31–55. doi: 10.1016/j.rser.2009.07.035.

Glatzmaier, G. (2011) Developing a Cost Model and Methodology to Estimate Capital Costs for Thermal Energy Storage. Available at: http://www.osti.gov/bridge.

Gualtieri, G. (2019) ‘A comprehensive review on wind resource extrapolation models applied in wind energy’, Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 215–233. doi: 10.1016/j.rser.2018.12.015.

Guo, S. et al. (2020) ‘The multi-objective capacity optimization of wind-photovoltaic-thermal energy storage hybrid power system with electric heater’, Solar Energy. Elsevier Ltd, 195, pp. 138–149. doi: 10.1016/j.solener.2019.11.063.

Hamdhan, I. N. and Clarke, B. G. (2010) Determination of Thermal Conductivity of

Coarse and Fine Sand Soils, Proceedings World Geothermal Congress.

Harman, K. G. G. H. (2010) ‘Availability and Operating Efficiency-How well do wind farms actually perform?’, RenewableUK.

HOMER Energy (2016) HOMER® Pro Version 3.7 User Manual. Boulder, CO.

HOMER Energy LLC (no date) HOMER Pro. Available at: https://www.homerenergy.com/products/pro/index.html (Accessed: 8 July 2020).

HOMER Pro (no date) Wind Resource. Available at: https://www.homerenergy.com/products/pro/docs/latest/wind_resource.html (Accessed: 8 July 2020).

Hwang, C. et al. (2015) ‘Modelling and simulation of the wake effect in a wind farm’, Journal of International Council on Electrical Engineering. Informa UK Limited, 5(1), pp. 74–77. doi: 10.1080/22348972.2015.1109793.

Inoue, A. et al. (no date) IEEE PEDS 2005 A Calculation Method of the Total Efficiency of Wind Generator.

Jegadheeswaran, S. and Pohekar, S. D. (2009) ‘Performance enhancement in latent heat thermal storage system: A review’, Renewable and Sustainable Energy Reviews, pp. 2225–2244. doi: 10.1016/j.rser.2009.06.024.

Johnson, E. et al. (2018) ‘Thermal energy storage with supercritical carbon dioxide in a packed bed: Modeling charge-discharge cycles’, Journal of Supercritical Fluids. Elsevier B.V., 137, pp. 57–65. doi: 10.1016/j.supflu.2018.03.009.

Justus, C. G. and Mikhail, A. (1976) ‘Height variation of wind speed and wind distribution statistics’, Geophysical Research Letters, 3, pp. 261–264.

Kaabeche, A., Belhamel, M. and Ibtiouen, R. (2011) ‘Techno-economic valuation and optimization of integrated photovoltaic/wind energy conversion system’, Solar Energy, 85(10), pp. 2407–2420. doi: 10.1016/j.solener.2011.06.032.

Karasu, H. and Dincer, I. (2018) ‘Analysis and Efficiency Assessment of Direct Conversion of Wind Energy into Heat Using Electromagnetic Induction and Thermal Energy Storage’, Journal of Energy Resources Technology, Transactions of the ASME.

American Society of Mechanical Engineers (ASME), 140(7). doi: 10.1115/1.4039023.

Khare, S. et al. (2013) ‘Selection of materials for high temperature sensible energy storage’, Solar Energy Materials and Solar Cells, 115, pp. 114–122. doi: 10.1016/j.solmat.2013.03.009.

Koçak, B. and Paksoy, H. (2019) ‘Packed-bed sensible thermal energy storage system using demolition wastes for concentrated solar power plants’, in E3S Web of Conferences. EDP Sciences. doi: 10.1051/e3sconf/201911301014.

Kousksou, T. et al. (2014) ‘Energy storage: Applications and challenges’, Solar Energy Materials and Solar Cells, pp. 59–80. doi: 10.1016/j.solmat.2013.08.015.

Krajačić, G. et al. (2011) ‘Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction’, Applied Thermal Engineering, 31(13), pp. 2073–2083. doi: 10.1016/j.applthermaleng.2011.03.014.

Laing, D. et al. (2011) ‘Thermal energy storage for direct steam generation’, Solar Energy, 85(4), pp. 627–633. doi: 10.1016/j.solener.2010.08.015.

Leahy, M. J., Connolly, D. and Buckley, D. N. (2010) ‘Wind energy storage technologies’. doi: 10.2495/978-1-84564-/205-1.

Lumenion (2020) Lumenion High Temperature Storage System. Available at: https://lumenion.com/product-2?lang=en (Accessed: 8 September 2020).

Lund, H. (2005) ‘Large-scale integration of wind power into different energy systems’, Energy. Elsevier Ltd, 30(13), pp. 2402–2412. doi: 10.1016/j.energy.2004.11.001.

Lund, H. and Thellufsen, J. Z. (2019) EnergyPLAN Advanced Energy Systems Analysis Computer Model Documentation Version 15. Available at: https://www.energyplan.eu/wp-content/uploads/2019/09/EnergyPLAN-Documentation-Version15.pdf.

Lyden, A., Pepper, R. and Tuohy, P. G. (2018) ‘A modelling tool selection process for planning of community scale energy systems including storage and demand side management’, Sustainable Cities and Society. Elsevier Ltd, 39, pp. 674–688. doi: 10.1016/j.scs.2018.02.003.

Malta Inc. (2020) Malta's Electro-Thermal Energy Storage System. Available at: https://www.maltainc.com/our-solution (Accessed: 8 September 2020).

Manwell, J. F., McGowan, J. G. and Rogers, A. L. (2010) Wind Energy Explained: Theory, Design and Application.

Marczinkowski, H. M. and Østergaard, P. A. (2018) 'Residential versus communal combination of photovoltaic and battery in smart energy systems', Energy. Elsevier Ltd, 152, pp. 466–475. doi: 10.1016/j.energy.2018.03.153.

Marczinkowski, H. M. and Østergaard, P. A. (2019) 'Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands SamsØ and Orkney', Energy. Elsevier Ltd, 175, pp. 505–514. doi: 10.1016/j.energy.2019.03.103.

Marstal District Heating (2020) Marstal District Heating. Available at: https://www.solarmarstal.dk/ (Accessed: 8 August 2020).

Martín, H. et al. (2015) 'Promotion of concentrating solar thermal power (CSP) in Spain: Performance analysis of the period 1998-2013', Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 1052–1068. doi: 10.1016/j.rser.2015.05.062.

Mawire, A. et al. (2009) 'Simulated performance of storage materials for pebble bed thermal energy storage (TES) systems', Applied Energy. Elsevier Ltd, 86(7–8), pp. 1246–1252. doi: 10.1016/j.apenergy.2008.09.009.

McTigue, J. D., Markides, C. N. and White, A. J. (2018) 'Performance response of packed-bed thermal storage to cycle duration perturbations', Journal of Energy Storage. Elsevier Ltd, 19, pp. 379–392. doi: 10.1016/j.est.2018.08.016.

McTigue, J. D. and White, A. J. (2018) 'A comparison of radial-flow and axial-flow packed beds for thermal energy storage', Applied Energy. Elsevier Ltd, 227, pp. 533–541. doi: 10.1016/j.apenergy.2017.08.179.

Mertens, N. et al. (2014) 'Dynamic simulation of integrated rock-bed thermocline storage for concentrated solar power', Solar Energy. Elsevier Ltd, 110, pp. 830–842. doi: 10.1016/j.solener.2014.10.021.

Met Office (2020) 'CEDA - MIDAS Open: UK mean wind data'. Available at:

http://data.ceda.ac.uk/badc/ukmo-midas-open/data/uk-mean-wind-obs/dataset-version-201901/renfrewshire/00970_renfrew.

Mohler, D. and Sowder, D. (2014) ‘Energy Storage and the Need for Flexibility on the Grid’, in Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids. Elsevier Inc., pp. 285–292. doi: 10.1016/B978-0-12-407910-6.00023-5.

Mostafavi Tehrani, S. S. et al. (2017) ‘Annual comparative performance and cost analysis of high temperature, sensible thermal energy storage systems integrated with a concentrated solar power plant’, Solar Energy. Elsevier Ltd, 153, pp. 153–172. doi: 10.1016/j.solener.2017.05.044.

Naimo, A. (2014) ‘A Novel Approach to Generate Synthetic Wind Data’, Procedia - Social and Behavioral Sciences. Elsevier BV, 108, pp. 187–196. doi: 10.1016/j.sbspro.2013.12.830.

National Grid (2020) List of all balancing services. Available at: https://www.nationalgrideso.com/balancing-services/list-all-balancing-services (Accessed: 18 July 2020).

National Resources Canada (no date) RETScreen. Available at: https://www.nrcan.gc.ca/maps-tools-publications/tools/data-analysis-software-modelling/retscreen/7465 (Accessed: 8 July 2020).

NEWA (2019) New European Wind Atlas. Available at: https://map.neweuropeanwindatlas.eu/.

Nord Pool (2020) Historical Market Data. Available at: https://www.nordpoolgroup.com/historical-market-data/.

Nunes, P., Farias, T. and Brito, M. C. (2015) ‘Day charging electric vehicles with excess solar electricity for a sustainable energy system’, Energy. Elsevier Ltd, 80, pp. 263–274. doi: 10.1016/j.energy.2014.11.069.

Oak Ridge National Laboratory (no date) Oak ridge competitive electricity dispatch (ORCED) model. Available at: http://www.ornl.gov/sci/ees/pes/capabilities_ORCED.html (Accessed: 8 July 2020).

Ofgem (2020) Wholesale Gas Charts and Indicators. Available at: https://www.ofgem.gov.uk/data-portal/all-charts/policy-area/gas-wholesale-markets (Accessed: 21 August 2020).

Okazaki, T. (2020) 'Electric thermal energy storage and advantage of rotating heater having synchronous inertia', Renewable Energy. Elsevier Ltd, 151, pp. 563–574. doi: 10.1016/j.renene.2019.11.051.

Okazaki, T., Shirai, Y. and Nakamura, T. (2015) 'Concept study of wind power utilizing direct thermal energy conversion and thermal energy storage', Renewable Energy. Elsevier Ltd, 83, pp. 332–338. doi: 10.1016/j.renene.2015.04.027.

Østergaard, P. A. (2015) 'Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations', Applied Energy. Elsevier Ltd, pp. 921–933. doi: 10.1016/j.apenergy.2015.05.086.

Ozdamar, A. et al. (2005) 'An application of a combined wind and solar energy system in Izmir', Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 624–637. doi: 10.1016/j.rser.2004.06.002.

Pina, A., Silva, C. A. and Ferrão, P. (2013) 'High-resolution modeling framework for planning electricity systems with high penetration of renewables', Applied Energy. Elsevier Ltd, 112, pp. 215–223. doi: 10.1016/j.apenergy.2013.05.074.

Power Technology (no date) Clyde Windfarm, Scotland. Available at: https://www.power-technology.com/projects/clyde-wind-farm/ (Accessed: 1 July 2020).

Prina, M. G. et al. (2018) 'Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model', Energy. Elsevier Ltd, 149, pp. 213–221. doi: 10.1016/j.energy.2018.02.050.

Reed, A. L. et al. (2018) 'Solar district heating with underground thermal energy storage: Pathways to commercial viability in North America', Renewable Energy. Elsevier Ltd, 126, pp. 1–13. doi: 10.1016/j.renene.2018.03.019.

Regin, A. F., Solanki, S. C. and Saini, J. S. (2008) 'Heat transfer characteristics of thermal energy storage system using PCM capsules: A review', Renewable and

Sustainable Energy Reviews. Elsevier Ltd, pp. 2438–2458. doi: 10.1016/j.rser.2007.06.009.

Renewable Energy Agency, I. (2012) RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES Volume 1: Power Sector Acknowledgement. Available at: www.irena.org/Publications.

Schallenberg-Rodriguez, J. (2013) 'A methodological review to estimate techno-economical wind energy production', Renewable and Sustainable Energy Reviews, pp. 272–287. doi: 10.1016/j.rser.2012.12.032.

Scottish Goverment (2020) 'Scottish Energy Statistics Hub'. Available at: https://scotland.shinyapps.io/Energy/.

Scottish Government (2017a) Scottish Energy Strategy: The future of energy in Scotland. Edinburgh.

Scottish Government (2017b) Scottish Energy Strategy: The future of energy in Scotland.

ScottishPower (2020) About Whitelee Windfarm. Available at: https://www.whiteleewindfarm.co.uk/whitelee-windfarm-about-us (Accessed: 1 July 2020).

SP Energy Networks (2020) Western HVDC Link - SP Energy Networjs. Available at: https://www.spenergynetworks.co.uk/pages/western_hvdc_link.aspx (Accessed: 21 August 2020).

SSE (2016) Beauly-Blackhillock and Blackhillock-Kintore Reinforcement Projects Frequently asked questions and answers-Who is Scottish Hydro Electric Transmission (SHE Transmission)? How are Transmission network upgrades paid for?

Storasol (2020) High-Temperature Thermal Energy Storage Technology Description. Available at: https://storasol.com/en/technik/ (Accessed: 8 September 2020).

Strasser, M. N. and Selvam, R. P. (2014) 'A cost and performance comparison of packed bed and structured thermocline thermal energy storage systems', Solar Energy. Elsevier Ltd, 108, pp. 390–402. doi: 10.1016/j.solener.2014.07.023.

Sullivan, P., Short, W. and Blair, N. (2008) Modeling the Benefits of Storage Technologies to Wind Power. Available at: http://www.nrel.gov/analysis/winds/.

SunAmp (2018) 'UniQ Brochure'. MacMerry, Edinburgh: SunAmp. Available at: https://www.sunamp.com/wp-content/uploads/2018/11/Uniq-Brochure-V1.pdf.

Sundararagavan, S. and Baker, E. (2012) 'Evaluating energy storage technologies for wind power integration', Solar Energy, 86(9), pp. 2707–2717. doi: 10.1016/j.solener.2012.06.013.

Tarroja, B. et al. (2012) 'Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing', Energy. Elsevier Ltd, 42(1), pp. 546–562. doi: 10.1016/j.energy.2012.02.040.

Teller, O. et al. (2013) 'Joint EASE/EERA recommendations for a European energy storage technology development roadmap towards 2030', Joint European Association for Storage of Energy (EASE).

The UK 2050 Calculator (2020) CONVENTIONAL GAS ELECTRICITY GENERATION COST DATA. Available at: http://2050-calculator-tool-wiki.decc.gov.uk/cost_categories/4 (Accessed: 21 August 2020).

The Wind Power (2018) Siemens SWT-2.3-93. Available at: https://www.thewindpower.net/turbine_en_22_siemens_swt-2.3-93.php (Accessed: 1 July 2020).

The Wind Power (2020a) Black Law A. Available at: https://www.thewindpower.net/windfarm_en_1470_black-law-a.php (Accessed: 1 July 2020).

The Wind Power (2020b) Farr. Available at: https://www.thewindpower.net/windfarm_en_1446_farr.php (Accessed: 1 July 2020).

The Wind Power (2020c) Hadyard Hill. Available at: https://www.thewindpower.net/windfarm_en_1465_hadyard-hill-barr.php (Accessed: 1 July 2020).

Tian, L. et al. (2020) 'Numerical investigations into the idealized diurnal cycle of atmospheric boundary layer and its impact on wind turbine's power performance', Renewable Energy. Elsevier Ltd, 145, pp. 419–427. doi: 10.1016/j.renene.2019.05.038.

Turner, R. et al. (2011) 'Creating synthetic wind speed time series for 15 New Zealand wind farms', Journal of Applied Meteorology and Climatology, 50(12), pp. 2394–2409. doi: 10.1175/2011JAMC2668.1.

Ucar, A. and Balo, F. (2008) 'A seasonal analysis of wind turbine characteristics and wind power potential in Manisa, Turkey', International Journal of Green Energy, 5(6), pp. 466–479. doi: 10.1080/15435070802498101.

Vienna University of Technology (no date) Invert. Available at: https://invert.at/ (Accessed: 8 July 2020).

White, A. J., McTigue, J. D. and Markides, C. N. (2016) 'Analysis and optimisation of packed-bed thermal reservoirs for electricity storage applications', Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. SAGE Publications Ltd, 230(7), pp. 739–754. doi: 10.1177/0957650916668447.

Wołoszyn, J. (2018) 'Global sensitivity analysis of borehole thermal energy storage efficiency on the heat exchanger arrangement', Energy Conversion and Management. Elsevier Ltd, 166, pp. 106–119. doi: 10.1016/j.enconman.2018.04.009.

Yang, K. et al. (2019) 'Wind farm layout optimization for wake effect uniformity', Energy. Elsevier Ltd, 183, pp. 983–995. doi: 10.1016/j.energy.2019.07.019.

Yang, M. et al. (2010) 'Heat transfer enhancement and performance of the molten salt receiver of a solar power tower', Applied Energy. Elsevier Ltd, 87(9), pp. 2808–2811. doi: 10.1016/j.apenergy.2009.04.042.

Yekini Suberu, M., Wazir Mustafa, M. and Bashir, N. (2014) 'Energy storage systems for renewable energy power sector integration and mitigation of intermittency', Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 499–514. doi: 10.1016/j.rser.2014.04.009.

Zhang, H. et al. (2016) 'Thermal energy storage: Recent developments and practical aspects', Progress in Energy and Combustion Science. Elsevier Ltd, pp. 1–40. doi: 10.1016/j.pecs.2015.10.003.

Zhao, H. et al. (2015) 'Review of energy storage system for wind power integration support', Applied Energy. Elsevier Ltd, 137, pp. 545–553. doi: 10.1016/j.apenergy.2014.04.103.

Zhong, J. Q. et al. (2012) 'Finite-sample-size effects on convection in mushy layers', Journal of Fluid Mechanics, 704, pp. 89–108. doi: 10.1017/jfm.2012.219.