Department of Mechanical and Aerospace Engineering

Project

Analysis of the long-term deep energy storage requirements for Scotland in the National Grid's Future Energy Scenarios

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Signed: Aidan Nelson Date:18th August 2021

Abstract

The energy transition is changing the way we interact with energy. As our use of dispatchable fossil fuels shrinks and our use of variable renewable energy sources increase there will be a growing need to capture and store energy but the exact role this energy storage will play in the future is unclear. This project took the National Grid's net-zero Future Energy Scenarios, which cover all Great Britain and estimated the energy capacity requirement for Scotland accounting for its role as a large exporter of electricity. This was achieved using a high-level model that considered daily bulk energy supply and demand and calculated the required storage by considering the daily shortfall and excess in energy with hydrogen taken to be the storage method alongside a well-developed pumped hydro sector. Two of the three scenarios were found to require between 167GWh and 523GWh of hydrogen storage depending on the conditions simulated with this storage acting as an emergency back up full and means of additional flexibility. The third scenario which represents a higher use of hydrogen within the energy system was found to have a storage requirement of 1,675GWh to 1,847GWh and acted as a means of seasonal storage, with hydrogen levels depleting over the winter and replenishing in the spring and summer for the following winter. The role of large-scale hydrogen storage looks to be dependent on the energy system in which it operates but as this work was based around only a single dataset further work is required to draw robust conclusions.

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Abbreviations

CAES: compressed air energy storage

CCC: Climate Change Committee

DUKES: Digest of UK Energy Statistics

GB: Great Britain

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

SESH: Scottish Energy Statistics Hub

UK: United Kingdom

VRE: variable renewable energy

1. Introduction

This project seeks to investigate the required energy capacity and role of long-term deep energy storage in Scotland in several net-zero future scenarios.

1.1 Context

Society's relationship with energy is in the beginnings of profound change. For centuries the world's energy systems have developed around the extracting and burning of fossil fuels with this seemingly limitless reserve of energy driving rapid economic and technological growth. But in exploiting this resource vast quantities of carbon dioxide are being released into the atmosphere raising global temperatures resulting in damaging climate change. There is a growing concerted effort by world governments to minimise the dangerous effects of climate change with the landmark signing of the Paris Agreement committing 195 nations to limit the rise in average global temperatures to 2°C above pre-industrial levels and to pursue efforts to limit this to 1.5°C. [1] But the average temperature increase has already reached 1.02°C [2] above the preindustrial average, annual carbon emissions are now higher than when the Paris Agreement was signed, [3] and many technical challenges remain if this target is to be met.

The entire architecture of the energy system will need to change, from a model based on the extraction and unabated burning of fossil fuels as and when required to match the supply of energy to the demand for energy, to a model that makes use of variable renewable energy (VRE) sources such as wind and solar; capturing, storing, and utilising energy more efficiently and intelligently to allow not only supply to meet demand but also introduce flexibility that will allow demand to meet supply. The use of renewable sources is increasing dramatically around the world, but despite this the current global policies in place are forecast to result in a 2.7°C to 3.1°C temperature rise by the end of the century. [4] The use of renewable sources will need to continue to expand further and more aggressively, with one of the barriers faced being the ability to store enough energy to power society when the wind isn't blowing, or the sun isn't shining.

As the UK and Scotland, along with the rest of the world, endeavour to reach net zero there have been, and continue to be no shortage of reports, strategies, plans, route maps, policy prescriptions, targets and frameworks published by various bodies including government, trade bodies, interest groups, non-governmental organisations, and intergovernmental organisations, aiming to address many of the issues faced in the energy transition covering a wide range of aspects. The publications given in Box 1 come from the UK Government's advisory body, the Climate Change Committee (CCC), the UK and Scottish governments, the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), and consider the actions required to become a net-zero society. These reports outline pathways along which to transition as well as government strategies and plans. In all of these reports the need for energy storage is highlighted but the actual requirement for energy capacity is absent, even just an indication of the scale is completely lacking, and this is an issue identified by industry. A 2021 report into long term storage by Scottish Renewables, an industry trade body, identified this issue, stating: [5]

> *"While the [UK] White Paper identified the need for long duration storage, it did not elaborate on what storage was need or how much …" (Scottish Renewables, 2021)*

Box 1: Selection of publications on strategies and route maps to net zero energy systems at the Scottish, UK, and global levels.

'The future of energy in Scotland: Scottish energy strategy' (Scottish Government, 2017) [6]

'Securing a green recovery on a path to net zero: climate change plan 2018-2032 – update' (Scottish Government, 2020) [7]

'Clean Growth Strategy' (UK Government, 2020) [8]

'Energy white paper: Powering our net zero future' (UK Government, 2020) [9]

'The Ten Point Plan for a Green Industrial Revolution' (UK Government, 2020) [10]

'Sixth Carbon Budget' (CCC, 2020) [11]

'Global energy transformation: A roadmap to 2050' (IRENA, 2019) [12]

'Net Zero by 2050: A Roadmap for the Global Energy Sector' (IEA, 2021) [13]

The publications listed in Box 1 give values for different areas of the transition indicating ambitions and targets such at the requirement increase in energy efficiency, the necessary uptake of different renewable generation technologies and even the power capacity needed from energy storage as a means of flexibility. This focus on the power capacity over energy capacity when considering storage is consistently found in discussion around the energy transition with the monetary value of energy storage installations largely dictated by their power rather than the volume of energy they can store, but this is not to say there is no discussion around the required energy storage capacity as discussed in section 2. Despite this prioritisation of power, the ability to store large quantities of energy will likely be necessary in the future, particularly in Scotland with a high and increasing reliance on wind power coupled with a sizeable variation in seasonal demand with daily total energy requirements ranging from 516GWh to 174GWh in 2020. [14] This variation between summer and winter demand is currently met by the unabated burning of natural gas, but in a net-zero energy system that will not be possible, and an alternative would be required. The Scottish Renewables report mentioned above highlighted the need for greater planning with regards to energy storage capacity and identifies this area as requiring investigation and clarity from government and regulators. [5]

1.2 Aims and objectives

This project aims to investigate the need for energy storage with a focus on energy capacity rather than the power capacity which is currently prevalent in discussions surrounding energy storage. Centred on Scotland, this will consider the need for storage in providing energy security by putting a minimum value to the quantity of energy that will need to be stored to meet Scotland's day to day energy needs in three different possible future net-zero scenarios. Further to this the different roles required of these energy storage systems in theses scenarios will be discussed.

In the future, society will require energy, that is an absolute truth. But how this energy will be delivered is still largely uncertain. There is need for a long-term vision for what the energy system of the future will look like, and the Scottish Government has attempted to outline this vision in its 2017 energy white paper. [6] However, although long term potential futures are considered within their white paper the immediate steps to be taken were prioritised.

> *"Our focus is on the near term, rather than the full transition, as we prepare to make the major medium and long-term decisions in the next decade." (Scottish Government, 2017)*

We are now in that next decade and in the coming years decisions will need to be made by government, industry, and the public, both as consumers and member of their communities, that will dictate the direction society takes and the energy system that will emerge. To help inform these decisions, an understanding of the different components of the energy system must be developed, including energy storage in its various forms and the different roles it may take along with its interactions with the other components of the energy system. By better understanding the storage requirements in terms of energy capacity for these different scenarios, the effects, both positive and negative can be considered which will help decision makers weigh up the value of the choices they make as they direct society along a path for the decades ahead.

1.3. Methodology overview

To quantify the minimum long-term energy storage requirement a high-level model was constructed using Excel for three different potential net-zero futures. The National Grid publishes its Future Energy Scenarios annually and the three scenarios that achieve net-zero were used as the basis for these models with daily energy supply and demand profiles specific to Scotland constructed for these scenarios. [15] By comparing the supply and demand at a high-level daily excesses and shortages can be found and from this the minimum long-term storage required to guarantee bulk energy demand is always met.

This high-level approach makes several assumptions with the most significant being that any intraday variations between supply and demand, which may be significant, are met by other forms of flexibility such as demand side response, vehicle-to-grid services, smart charging and networks and utility scale batteries, all working at 100% efficiency, that absorb and reinject energy into the system. This simplification allows the model to work at a resolution of a day rather than half hourly, removing a plethora of variables and allowing the problem of supply and demand to be considered its simplest form. It considers only bulk generation and whether on any given day enough energy will be generated and from this how much energy will need to be stored to meet the shortfall. This work only considers a single modified 2020 dataset and does not aim to make hard conclusions or recommendations. It is intended as an insight into what long term storage may look like in Scotland for different net-zero futures given the complete lack of even an indication of the scale required in official government publications. This work also helps to identify areas that may be of value for further in-depth study, and as a tool for discussion surrounding the role of long-term storage in Scotland.

1.4. Report structure

Following this introduction, section 2 of this report will discuss the relevant background information which has been combined with the literature review. Section 3 then covers the modelling methodology in more depth building on the brief description given in section 1.3, with the results of this work then presented in section 4. These results along with their implications are discussed in section 5. Conclusions and areas for further study are then given in section 6.

2. Background and literature review

With increasing levels of variable renewable energy sources being integrated within energy systems, the role of energy storage in allowing this change is the subject of much ongoing discussion. The emergence of energy storage is often viewed as one of the key components that will need to be developed in the energy transition. But energy storage is nothing new and the development of the modern world largely came about by society's ability to utilise certain energy storage mechanisms. These energy storage mechanisms are the very thing we are now desperate to move away from: coal, oil, and gas.

The IEA defines energy security as: [16]

> *"… the uninterrupted availability of energy sources at an affordable price."*

Coal powered much of the Industrial Revolution, and by the definition above, brought energy security to the industrialised world. Cheap and abundant, coal could easily be stored anywhere, at home, in a factor, on a train, bringing a level of energy security that once obtained has never been relinquished. This energy security is vital to almost every aspect of modern life and one of the three considerations in the energy trilemma along with cost and the environment. [17] Scotland has now entirely moved away from coal but most energy still comes from oil and gas which fuel the transport and heat sectors respectively, which have proven difficult to decarbonise. [14] But there are pathways to achieve this such as the National Grid's net-zero Future Energy Scenarios. [15]

2.1. Applications of energy storage

Energy storage is a general overarching name, with energy storage coming in an array of forms from watch batteries to reservoirs of water, which can have many different applications. Many of these applications have emerged to completement the integration of renewables and to replace roles previously performed by fossil fuels. It is important to understand and clarify the different roles and to specify the focus of this project. The following list was adapted from a study into the future projected costs of electricity storage technologies: [18]

1. **Energy arbitrage**
2. Primary, secondary, and tertiary response
3. **Peaker plant replacement**
4. Black start
5. **Seasonal storage**
6. Transmission and distribution network investment deferral
7. Congestion management
8. Power quality and reliability

The aim of this project covers three of these to varying degrees: energy arbitrage, peaker plant replacement and seasonal storage. Energy arbitrage is very broad and can cover small domestic batteries acting as part of an aggregator service [19] as well as pumped hydro storage, which has historically been the primary application of these sites. It can also cover varying times scales from intraday to interday. This interday application is relevant to this project. The modelling method used works with a resolution of a day hence the intraday application doesn't feature, but energy arbitrage between days, weeks or even months, at which point it would be classified as seasonal storage, is the basics behind the model; take daily excess energy, store it, and return it on days of shortage. And as mentioned, energy arbitrage of electricity over months, for example to build a store in summer to sell in winter, would be considered seasonal storage. Peak plant replacement is then a storage systems ability to replace an existing plant, which are generally gas fired. At a fundamental level this is performing the same task as energy arbitrage, storing cheap energy, and returning it at a markup later. The only difference being the scale requirement for a storage system to replace a peaker plant is much larger than a storage system performing smaller scale energy arbitrage.

This study [18] classified four storage technologies as being applicable to all three of these applications: pumped hydro, compressed air energy storage (CAES), vanadium redox batteries and hydrogen. However it also projected the lowest cost for energy arbitrage and peaker plant replacements to be lithium-ion batteries, a technology that is not able to meet the third consideration, seasonal storage. Hydrogen was projected to offer the lowest cost for seasonal storage, but this was highly dependent on the number of cycles achieved ranging from 130USD/MWh to 1,500USD/MWh. Within Scotland, any storage system will be operating in a liberalised energy market and would need to be profitable and therefore factors such as this are major considerations for any energy storage development.

This study did not consider the stacking of revenues, whereby one system performs several roles and is paid for each. Consider a large hydrogen storage system, it could provide seasonal storage building hydrogen levels over months, but during this time act as peaker plant replacement or provide energy arbitrage as long as the general trend for its hydrogen levels during this time was up. The ability of energy storage operators to stack revenues is vital to allow these systems to be profitable and for decision makers to evaluate the lowest cost option because it is unlikely any system would provide only a single service. Considering the three applications given above, hydrogen was found to be the lowest cost option for seasonal storage with lithium-ion batteries the most cost effective for the other two. But if you required a single system to perform these three roles, lithium-ion batteries couldn't meet this need, and perhaps one of the other three applicable technologies when revenues are stacked would be the lowest cost option despite hydrogen being the best option for seasonal storage when considered in isolation.

IRENA provides detailed information for policy makers and industry on stacking and how the value of energy storage can be maximised and monetised within energy markets. This is set out in their 'Electricity Storage and Renewables: Costs and Markets to 2030' [20] and 'Electricity Storage Valuation Framework' [21] with accompanying tools available online. These documents highlight one of the issues often found when considering long term deep storage. These are key documents for policy makers, but only short-term storage is considered, largely because currently the value of energy storage is not in the actual amount of energy it can store but the power it can provide. However the previous study considered hydrogen to be applicable to all applications. If large scale energy storage is required these energy storage options that are currently not being considered in these documents will be operating within the energy market and could provide many of these services with the ability to stack revenues playing a critical role.

Whether classified as electricity storage, power-to-gas or as part of sector coupling, hydrogen is one of the primary options for storage which can make use of caverns or depleted gas fields. The other storage options identified for the application being considered was pumped hydro, CAES, and vanadium flow batteries. Although vanadium flow batteries are increasing in size, the World's largest located in China only has an energy capacity of 800MWh and so this option was deemed too small for the case being considered. [22] CAES requires the use of salt caverns, which Scotland does not have the required geology for, [23] or depleted oil and gas fields, although this is yet to be achieved. [24] Therefore the two methods that were modelled were pumped hydro for which there already operational sites in Scotland with plans for further development. Hydrogen storage would require the use of depleted oil and gas fields like compressed air storage; however hydrogen brings with it a multitude of applications and a level of intrinsic value.

2.2. Hydrogen energy storage

With hydrogen storage being the most viable option for meeting large long term energy storage requirements almost all of the literature examining this requirement considers hydrogen as the storage method. Predominantly this work considers the hydrogen storage requirements for Europe as a whole or is focussed on Germany with a large proportion of the research in this area coming from Germany. The north of Germany has the required geology for salt caverns and currently operates 31 caverns for the storage of natural gas. [25] They have the capacity to store 80 days' worth of natural gas, a store 17 times greater than the UK, [26] and so there is significant research and work going into how this natural asset can be utilised in the future, switch to hydrogen and becoming a hub or hydrogen.

Cebulla et al., [27] considered 17 studies into energy storage requirement and the values found ranged from 0.2TWh for Europe to 83TWh for Germany alone. The storage requirement is shown to be highly dependent and sensitive to numerous factors including the split of wind to solar generation. Cardenas et al., examined energy storage requirements for the UK, giving a figure of 43TWh with a 15% curtailment. Without this curtailment the storage capacity is found to increase to 116.5TWh. This overcapacity significantly reducing the total energy storage requirement is in keeping with the work of Rasmussen et al. [28] This figure of 43TWh is in keeping with the National Grid's Future Energy Scenarios [15] on which the models of this project are based, with a value between 12.1TWh and 51.0TWh however it would have been outside the range given in the 2020 values which ranged between 15.3TWh and 17.8TWh, [29] highlight that an understanding of the application of storage in this way is still developing.

The discussion on overproduction highlights one of the key benefits Scotland currently enjoys. Scotland already overproduces electricity generated over 150% of demand. [14] With a large renewable resource and an eager market in England and Wales where space and renewable generation is limited, Scotland is currently in a situation where it can produce as much electricity as it can with little worry about the economics of curtailment or the need for energy storage.

2.3. Pumped hydro storage

Pumped hydro storage has played a role in Scotland since 1965 and has 740MW of installed generation capacity with 13.4GWh or storage across two sites, Cruachan and Foyers. [30] Pumped hydro storage is a tried and tested method providing 99% of energy storage worldwide. [31] There are plans for several new pumped hydro installations in Scotland [32]–[34] and it is a sector that is supported by the Government who see it as having a key role to play in the future. [6] A well-developed pumped hydro storage system was assumed in the models created for this project with a total storage capacity of 55.9GWh and a generation capacity of 4.79GW. The largest of these sites is SSE’s planned Coire Glas site that would comprise more than half of the total energy capacity with 30GWh of storage. [32] Whether all these sites, or even any, get built is up for debate with no pumped storage has been built since privatisation.

3. Modelling methodology

This model is concerned with bulk energy and whether day to day Scotland will be able to generate or import sufficient energy to meet its needs in three different net zero future scenarios. Any intraday variation is assumed to be met by increased flexibility within the gird both on the demand side through methods such as smart charging and the supply side through utility scale batteries that can absorb and reinject energy into the network over short periods. The assumption is made that this is all 100% efficient, with this model solely focused on overall supply and demand. The transmission and distribution networks aren’t constrained in anyway. By making these assumptions it allows the most fundamental energy equation to be considered. Does supply meet demand? And if not, how much stored energy is required?

To model the potential minimum hydrogen storage requirements of Scotland in a net-zero 2050 based on the National Grid’s Future Energy Scenarios four steps were taken:

1. Construction of daily electricity and hydrogen demand for each scenario.
2. Construction of daily electricity generation by technology type for each scenario.
3. Estimation of hydrogen production capacity by method for each scenario.
4. Modelling of minimum hydrogen storage requirement in Excel for each scenario under different conditions by comparing daily supply and demand of both electricity and hydrogen.

This method will not produce a definitive and robust answer to how much hydrogen storage Scotland will need in the future. That will require study beyond the scope of this project.. This method is based solely on one dataset, adjusted to fit the three net-zero scenarios with two variables, wind level and interconnection, adjusted to explore how these changes influence the energy storage requirements. It is designed to give a glimpse into what a typical year might look like in a net-zero 2050 and how much energy storage may be required and the impact the different scenarios and directions society might take may have on this value. Ultimately this project is a first look at a question that currently has no answer, acting as a tool for discussion and highlighting areas worth further in-depth study within what is very broad subject.

3.1. Future energy demand profiles

Data provided in the National Grid’s Future Energy Scenarios indicate annual future energy demand but gives no indication of how this is distributed across a year. Therefore, the daily demand profile for Scotland in 2020 was used as a template to capture the weekly and seasonal variations. The daily demands for electricity, heat, transport, and the combined total are available through the Scottish Government’s Scottish Energy Statistics Hub (SESH) with the data for 2020 that was used for this model graphed in Fig.1. [14]

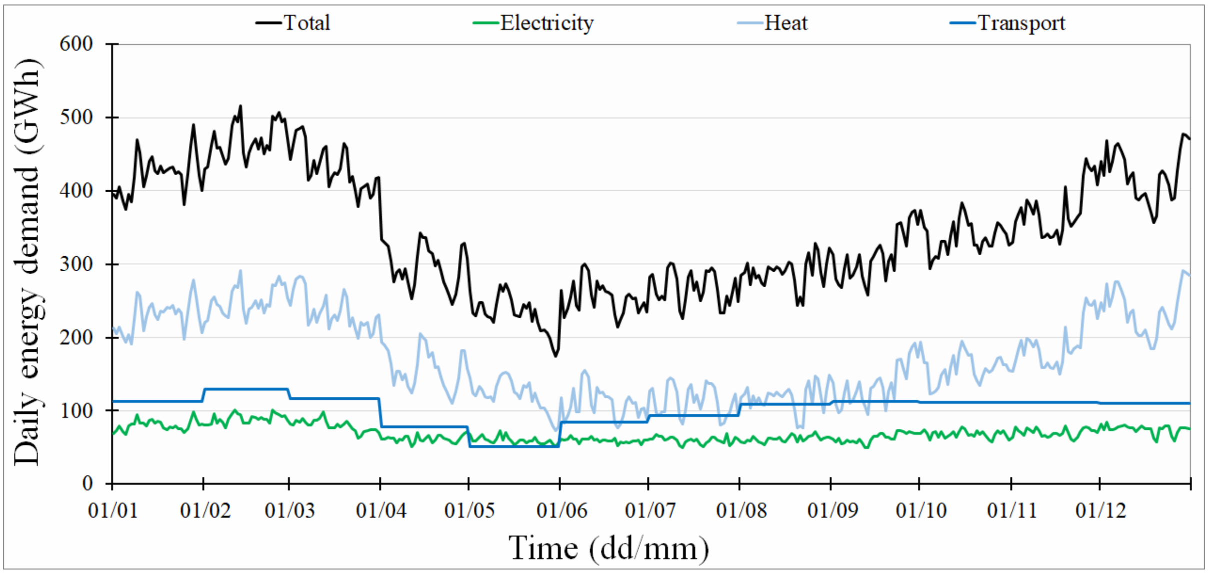


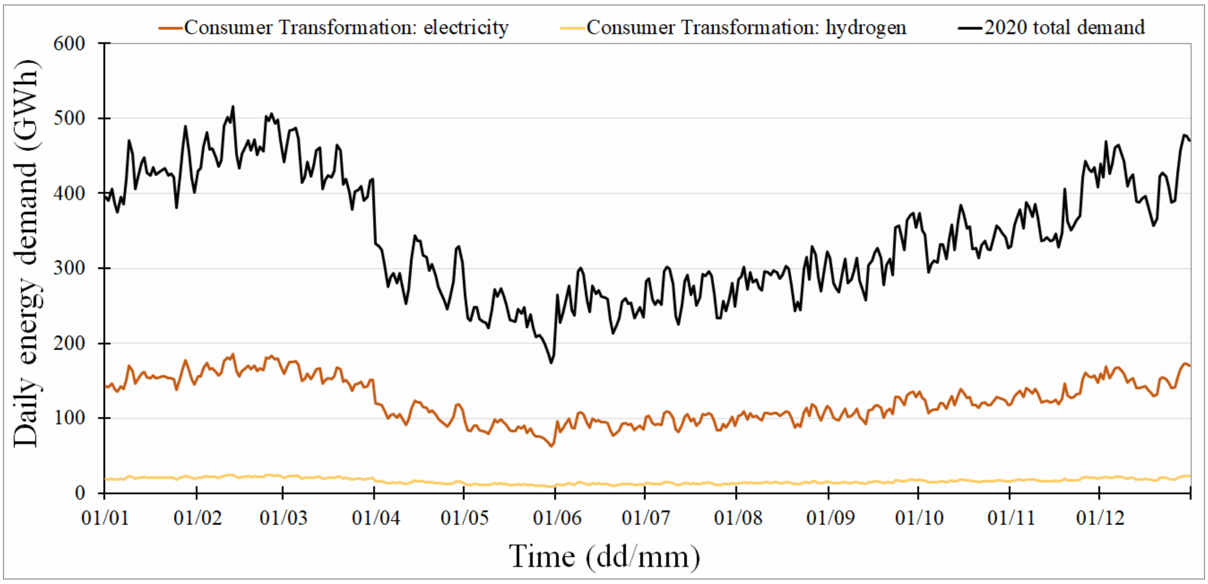
Fig. 1: Daily electricity, heat, transport, and total energy demand for Scotland in 2020. (Source: Scottish Energy Statistics Hub) [14]

A breakdown of the overall energy demand by fuel type taken from the National Grid for the future scenarios is shown in Table 1, [15] along with a calculated percentage of each scenarios total demand compared to the 2020 value. The total energy demand profile shown in Fig.1 was scaled according to the calculated percentages given in Table 1.

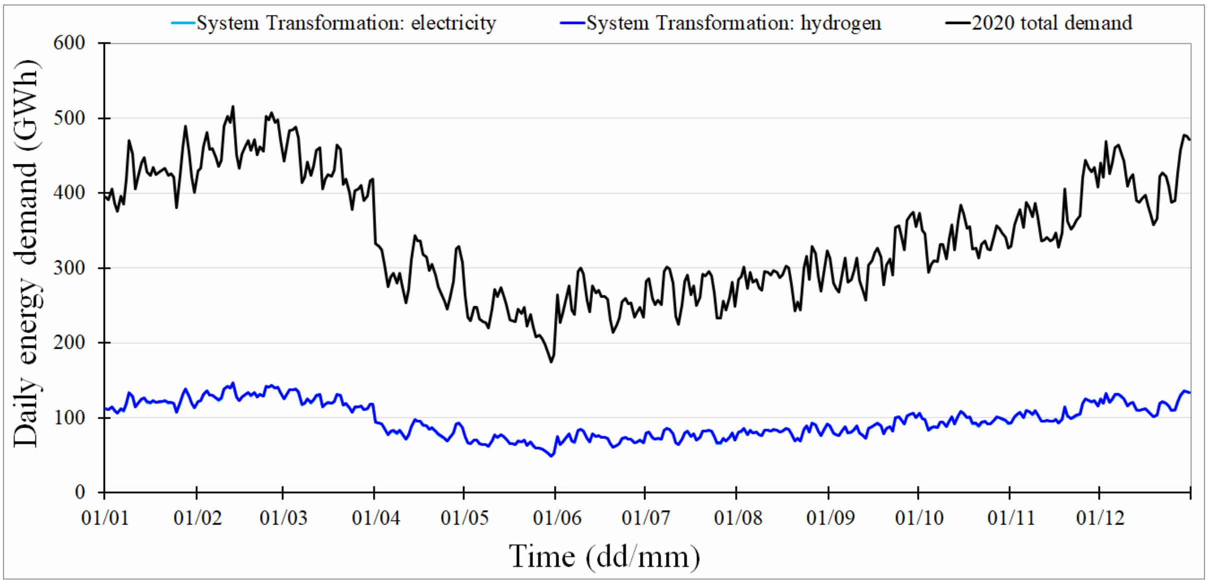
Table 1: Energy demand by fuel type in Great Britain in 2020 and for the National Grid's net-zero Future Energy Scenarios. (Source: National Grid: ESO) [15]

	GB energy demand (TWh)						
	Electricity	**Natural gas**	**Hydrogen**	**Oil/petroleum**	**Biofuels**	**Total**	
2020	258	567	0	496	48	1,369	100.0%
CT	494	13	65	0	17	589	43.0%
ST	388	10	389	0	13	800	58.4%
LTW	411	13	169	0	24	617	45.1%

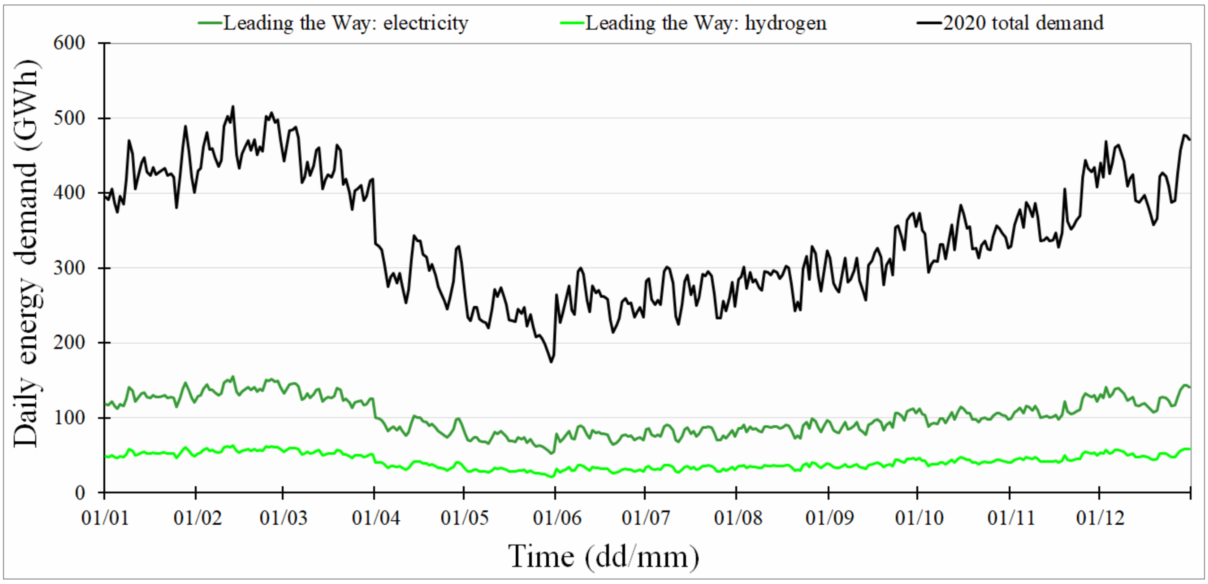
Today's energy system largely operates as three separate systems; electricity increasingly generated from renewables, heating fuelled by gas, and transportation fuelled by oil. In future net-zero scenarios these three systems are likely to become more intertwined and powered predominantly by electricity and hydrogen. Heating and transport demand will be met by both sources to varying degrees in the different scenarios. Therefore as these sources will play a role across the energy system both will use the overall energy demand as a template rather than considering electricity, heat, and transport separately. The electricity and hydrogen demand profiles were then found by scaling the total demand profile already found for that scenario by the percentage of the total energy demand for both electricity and hydrogen. These demand profiles are given in Fig.2 compared with the 2020 total energy demand. In the System Transformation electricity and hydrogen demand are almost identical and so it isn't possible to see both demand profiles in Fig.2(a). Natural gas and biofuels will play a small role in all the scenarios but have not been considered in this work.



(a) Consumer Transformation



(b) System Transformation



(c) Leading the Way

Fig. 2: Estimated daily electricity and hydrogen demand profiles for a typical year based on 2020 data. (Sources: Scottish Energy Statistics Hub) [14]

This approach doesn’t capture the variations in energy demand associated with each scenario. The System Transformation would likely have a larger seasonal variation than is modelled due to the lower building heating efficiency. Although it is modelled to always have a higher demand due to the nature of scaling it would likely be more closely aligned during the summer with a larger difference in winter demand.

3.2. Future electricity supply profiles

To find future electricity supply profiles for the future scenarios a similar process was used to that in section 3.1. The electricity generation profile for 2020 in Scotland was used as a template to scale a future increased generation capacity against. However, whereas daily demand data was available for Scotland only Great Britain (GB) level daily generation data was available and an approximation for Scotland had to be created. The assumed installed future electricity capacities were then compared to today’s values and used to scale each generation source within the daily electricity supply profile with some adjustments made to capacity factors.

3.2.1. 2020 Scottish electricity supply profile

Half hourly data by generation type is available for the GB network from Elexon who are responsible for managing the Balancing and Settlement Code. [35] This half hourly data was collated for each generation type to give an annual figure. Elexon doesn't provide solar PV data as this is connected at the distribution level and not metered. Solar PV data was taken from the University of Sheffield who work with the National Grid to model the solar PV generation entering the grid and provide historic data. [36] This data is presented in Table 2 along with the annual electricity generation by type for Scotland, [14] which is then calculated and expressed as a percentage of the GB total. CCGT and nuclear data wasn't available for Scotland at the time of writing, therefore the 2019 values were used, but this ultimately proves irrelevant as they do not play a role in the future scenario models and are only included here for completeness. The hydro figure given for Scotland is higher than the GB value. The source linked by SESH notes that the values given are yet to finalised which may account for the variation, or a part of this hydro generation may not be metered like the solar PV generation, either way it is unclear. The lower GB value was taken and a percentage of 91.98% attributed to Scotland based on this being the percentage of the GB hydro capacity located in Scotland. [37] These values are given in brackets.

Table 2: Annual generation data for 2020 for Great Britain from Elexon, and for Scotland from the Scottish Energy Statistics Hub. The adjusted hydro values discussed above are given in brackets. [14], [35], [36]

	Electricity generation (GWh)		
	GB	**Scotland**	**Scottish percentage (%)**
Coal	4,380	0	0.00
CCGT	94,934	6,045	6.37
Nuclear	47,378	12,226	25.81
Bioenergy and waste	17,984	2,342	13.02
Solar	12,050	353	2.93
Wind	54,661	23,183	42.41
Hydro	4,310	5,912 (3,964)	136.17 (91.98)
Other	1,638	451	27.53

Taking the percentages presented in Table 2 the Elexon half hourly data can be scaled to give an approximate representation of Scotland's electricity generation for 2020. Although the data provided by Elexon for wind doesn't include a breakdown of onshore and offshore this is given by SESH for Scotland with 19,783GWh from onshore generation and 3,429GWh from offshore generation. [14] The wind generation supply profile was split into onshore and offshore with this ratio. Fig.3 shows the electricity generation for the whole GB network in 2020, with the approximation for Scotland extracted from this shown in Fig.4.

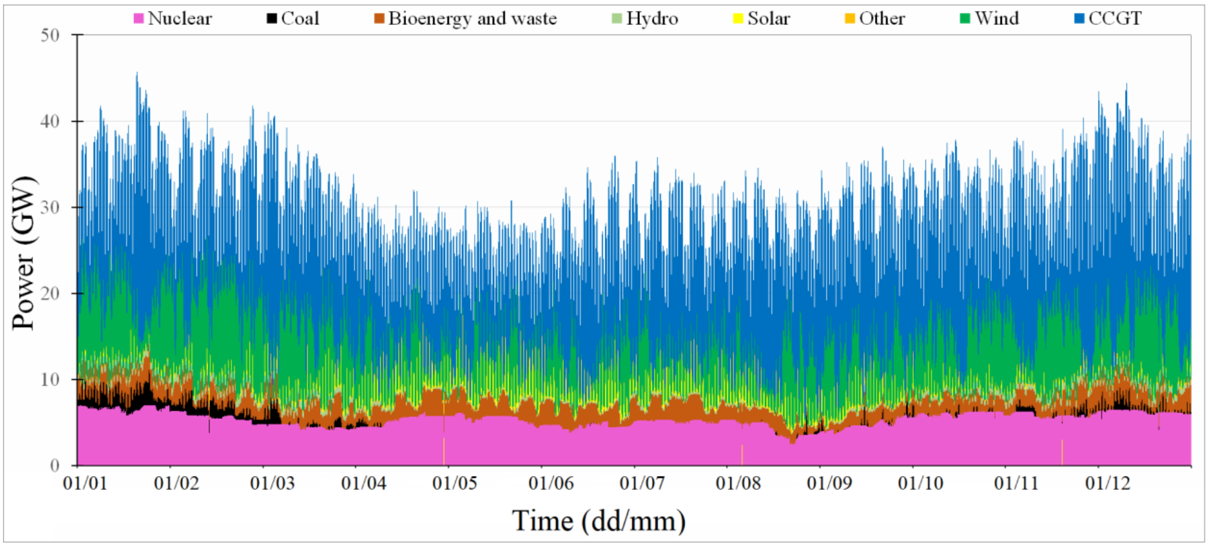


Fig. 3: GB electricity generation in 2020 by generation type. (Sources: Elexon & University of Sheffield) [35], [36]

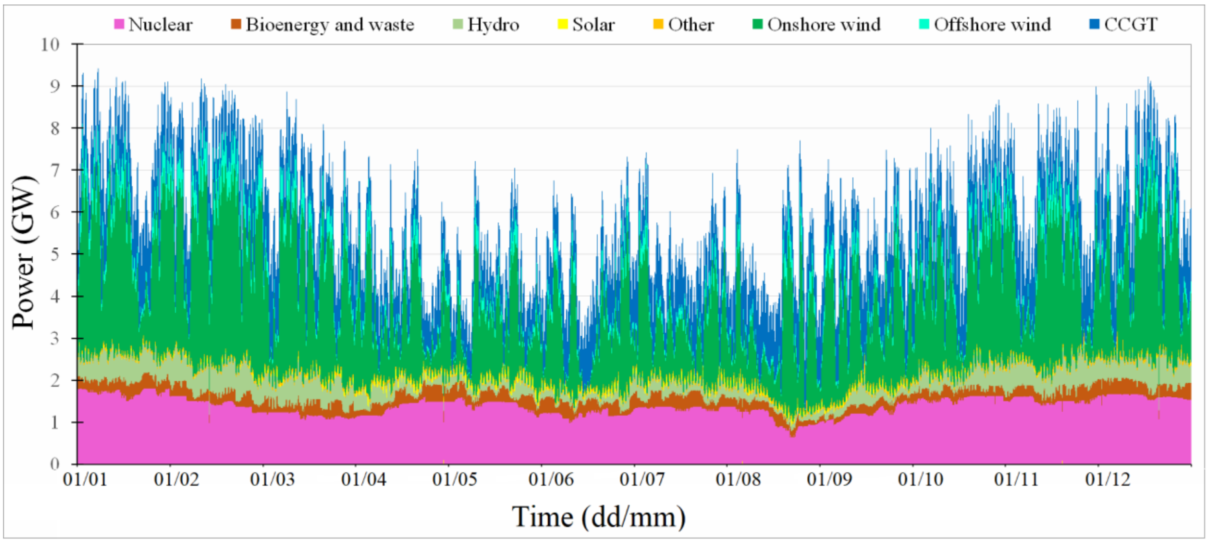


Fig. 4: Approximation of the electricity generation by generation type for Scotland in 2020.

The distribution of the CCGT looks to be inaccurate but this doesn’t feature in the future model. The important features to capture ae those related to renewable generation. This half hourly data was converted into daily data and forms the template for scaling the electricity generation from increased installed generation capacities in the future scenarios.

3.2.2. *2020 Scottish electricity supply profile*

To scale the electricity generation shown in Fig.4 the current installed capacity is required. As the electricity network continues to evolve along with the way generators and customers interact with and operate on the grid it is becoming harder to get an exact value for capacity with varying definitions between publications and differences between the inclusion of embedded generation and 'other' generators who produce power primarily for their own needs but also at times export to the grid. The values given by the Digest of UK Energy Statistics (DUKES) and SESH are given in Table 3. Significant variation between the two is clear, most notably solar. The higher value in each case was used. These installed capacity values will be used to scale the electricity supply data to the estimated future installed capacities.

Table 3: Installed electricity generation capacity by technology for Scotland with data from the Digest of UK Energy Statistics and the Scottish Energy Statistics Hub compared. (Sources: Digest of UK Energy Statistics & Scottish Energy Statistics Hub)[14], [37]

	Installed electricity generation capacity (MW)		
	DUKES	**SESH**	**Assumed**
Diesel/gas oil	138	-	138
CCGT	1,180	-	1,180
Nuclear	2,185	-	2,185
Biomass and waste	126	517	517
Solar	46	378	378
Onshore wind	685	898	898
Offshore wind	7,029	8,468	8,468
Shoreline wave/tidal	-	22	22
Hydro	1,325	1,651	1,651
Pumped hydro	740	-	740
Interconnectors	500	-	500

3.2.3. *Future installed electricity generation capacity*

The National Grid's Future Energy Scenarios give installed electricity generation capacities for its three net-zero future energy scenarios in 2050. These are presented in Table 4 along with the 2020 capacities and a calculated percentage of each future capacity in relation to its current capacity.

Table 4: Installed electricity generation capacity for Great Britain for 2020 and the National Grid's three net zero scenarios given as absolute values and as a percentage of 2020 levels. (Source: National Grid) [15]

	GB installed electricity capacity (GW)						
		2050					
	2020	**Consumer Transformation**		**System Transformation**		**Leading the Way**	
	(GW)	**(GW)**	**(%)**	**(GW)**	**(%)**	**(GW)**	**(%)**
Biomass	4.43	0.67	15.1	1.38	31.2	0.67	15.1
BECCS	0.00	12.00	-	11.40	-	5.40	-
Nuclear	7.07	17.14	242.4	14.94	211.3	5.45	77.1
Hydrogen	0.00	12.73	-	21.11	-	14.50	-
Fossil fuel	42.00	0.00	0.0	0.04	0.10	0.00	0.00
Gas CCUS	0.00	0.00	-	12.50	-	0.00	-
Solar	13.05	77.84	596.5	57.18	438.2	88.57	678.7
Offshore wind	10.45	113.17	1,083.0	94.91	908.2	86.98	832.3
Onshore wind	12.68	44.58	351.6	30.99	244.4	40.00	315.5
Other renewables	5.57	11.52	206.8	13.31	239.0	6.89	123.7
Interconnectors	4.75	26.95	567.4	19.55	411.6	28.15	592.6
Storage	3.53	40.70	1,153.0	27.88	789.8	43.00	1,218.1

The percentages given in Table 4 indicate the change in the installed capacity for each scenario. The installed capacities for Scotland from Table 3 were taken and increased by the indicated rate to estimate the installed capacity in Scotland in the net-zero 2050 futures. Biomass was combined with other renewables as it was not possible to isolate the renewable waste component from this figure, and hydro was removed from other renewables as it was assumed to remain consistent given the limited capacity for further development. The percentage change for other renewables with the inclusion of biomass and the removal of hydro was adjusted. BECCS, hydrogen powered generation and gas CCUS for which there is no current capacity were scaled by population. This is presented in Table 5.

Table 5: Estimated Scottish installed electricity capacities scaling the current capacities to the required increase in each of the National Gird's net-zero scenarios.

	GB installed electricity capacity (GW) – scaled to Scotland			
		2050		
	2020	**Consumer Transformation**	**System Transformation**	**Leading the Way**
BECCS	0.000	1.007	0.956	0.453
Nuclear	2.185	5.296	4.617	1.685
Hydrogen	0.000	1.068	1.771	1.217
Fossil fuels	1.318	-	0.001	-
Gas CCUS	0.000	-	1.049	-
Solar	0.378	2.255	1.656	2.565
Offshore wind	0.898	9.725	8.156	7.474
Onshore wind	8.468	29.773	20.696	26.717
Other renewables	0.539	0.685	1.288	0.667
Hydro	1.651	1.651	1.651	1.651
Interconnectors	0.500	2.837	2.058	2.963
Storage	0.764	8.809	6.034	9.306

Despite simply scaling up the current capacity in Scotland by the factor for which each generation type needs to change, the values produced are unlikely to approximate Scottish generation capacity in 2050, and a more regional approach is required. Table 5 implies Scotland will operate a significant nuclear capacity, but this is unlikely to be the case. Although governments and political opinions can change, given the current government's strong opposition to nuclear development, the next election being in 2026 and the long lead in time that can be over a decade, nuclear is modelled with no nuclear capacity. The estimated capacities for onshore look to be bigger than would be expected and offshore smaller than expected. This is caused by onshore wind being more developed in Scotland than the rest of the GB network given the UK Government's removal of subsidies and support from 2016 to 2020. [38] Therefore when scaled this doesn't account for this effect. The opposite effect is seen with offshore wind which has a large potential in Scotland but is less developed than the rest of Great Britain and so underestimated in Table 5. Solar in Scotland is also less developed than the rest of the GB network and underestimated. A better estimate can be found by considering the Scottish distribution network future scenarios, produced by Scottish and Southern Electricity Networks (SSEN) [39] Scottish Power Energy Networks (SPEN), [40] which are less in depth but give more regional specific values.

The SPEN future scenarios covering the south of Scotland are the same as those used by the National Grid and so can easily be compared. The SSEN scenario covering the north of Scotland use a different set of scenarios which makes comparison more difficult. They employ three scenarios. The Decelerated Transition which like the National Grid's Steady Progress scenario doesn't reach net zero by 2050 and so is not considered here. The Green Society (GS) is a largely electrified future with high levels of consumer engagement and so is comparable to the Consumer Transformation. The Green Economy (GE) makes use of higher levels of hydrogen and is most like the System Transformation. There is no equivalent to the Leading the Way scenario and so a mix of the installed generation capacities from the Green Society and the Green Economy was used dependent on which figure was deemed the better representation by considering the Leading the Way scenarios for the National Grid and SPEN and whether the capacity for that generation type is typically high or low compared to the other scenarios. This is presented in Table 6. and combined to give an estimate for Scotland as a whole.

Table 6: Installed electricity capacity in future net-zero scenarios published by SPEN and SSEN along with a combined total for the whole of Scotland. (Sources: Scottish Power Energy Networks & Scottish and Southern Electricity Networks)

	Installed electricity capacity (MW)								
	SPEN			**SSEN**			**Combined**		
	CT	**ST**	**LTW**	**GS**	**GE**		**CT**	**ST**	**LTW**
Hydrogen	568	453	869	-	-	-	568	453	869
Fossil fuels	0	0	0	0	0	0	0	0	0
BECCS	-	-	-	1,200	1,200	1,200	1,200	1,200	1,200
Solar (incl. btm)	2,770	1,940	2,155	1,700	1,600	1,700	4,470	3,540	3,855
Hydro	218	195	331	1,700	1,700	1,700	1,918	1,895	2,031
Onshore wind	6,256	3,058	7,405	13,000	11,900	13,000	19,256	14,958	20,405
Offshore wind	0	0	0	13,100	11,300	11,300	13,100	11,300	11,300
Biomass and waste	473	479	472	0	0	0	473	479	472
Tidal	0	0	0	300	260	260	300	260	260
Other	122	119	114	1,100	1,300	1,100	1,222	1,419	1,214
Pumped storage	0	0	0	2,240	2,240	2,240	2,240	2,240	2,240
Batteries (incl. btm)	2,873	2,204	2,810	910	1,000	1,000	3,783	3,204	3,810
Interconnectors	-	-	-	1,400	1,400	1,400	1,400	1,400	1,400

Comparing Table 5 and Table 6 there are major differences as was expected with those in Table 6 taken to be a better representation and these figures were used with some further adjustments. The hydrogen power generation is lower in Table 6 which may be a result of not being considered in the SSEN scenarios, therefore the Table 5 values were used. The SSEN has a high capacity of BECCS but given the potential for CCS in the north of Scotland this seemed reasonable. There is a small increase in hydro which is within the feasible development outlined previously. Biomass and waste, tidal and other were combined as they are relatively small but difficult to accurately model and so were combined and modelled as described below. One point to note is the ‘other’ from SSEN is significant but there is no indication of what this is. It may be making use of the definition whereby it generates electricity for its own use but does export at times. Therefore this is difficult to model and hence was combined with tidal and biomass and waste and will be modelled in a basic way.

The levels of interconnection and pumped storage are highly significant to the modelling process. The current 500MW Moyle HVDC is missing from Table 6 but is included in the total interconnector capacity which then equals 1,900MW, comprised of the 1,400MW NorthConnect to Norway, currently in development, and the Moyle HVDC to Northern Ireland. For this model pumped storage was assumed to be highly developed as outlined previously with a total capacity of 4.79GW / 55.9GWh. Whether pumped hydro is developed to this level is entirely up for debate and influenced by numerous factors. When combined this gives the installed capacities given in Table 7 which are given alongside a percentage indicating the relative increase. These results are represented in Fig.5.

Table 7: Assumed installed electricity generation capacities for Scotland in the National Grid’s three net zero scenarios in energy terms and as a percentage of 2020 values.

	Assumed installed electricity generation capacities						
		Consumer Transformation		**System Transformation**		**Leading the Way**	
	2020	**(MW)**	**(%)**	**(MW)**	**(%)**	**(MW)**	**(%)**
BECCS	0	1,200	-	1,200	-	1,200	-
Nuclear	2,185	0	0	0	0	0	0
Hydrogen	0	1,068	-	1,771	-	1,217	-
Fossil fuels	1,318	0	0	0	0	0	0
Gas CCUS	0	0	-	1,049	-	0	-
Solar (incl. btm)	378	4,470	1,182	3,540	937	3,855	1020
Onshore wind	8,468	19,256	227	14,958	177	20,405	241
Offshore wind	898	13,100	1,459	11,300	1,258	13,100	1,459
Hydro	1,651	1,918	116	1,895	115	2,031	123
Other	539	1,995	370	2,158	400	1,946	361
Pumped storage	740	4,790	647	4,790	647	4,790	647
Batteries (incl. btm)	24	3,783	15,763	3,204	13,350	3,810	15,875
Interconnectors	500	1,900	380	1,900	380	1,900	380

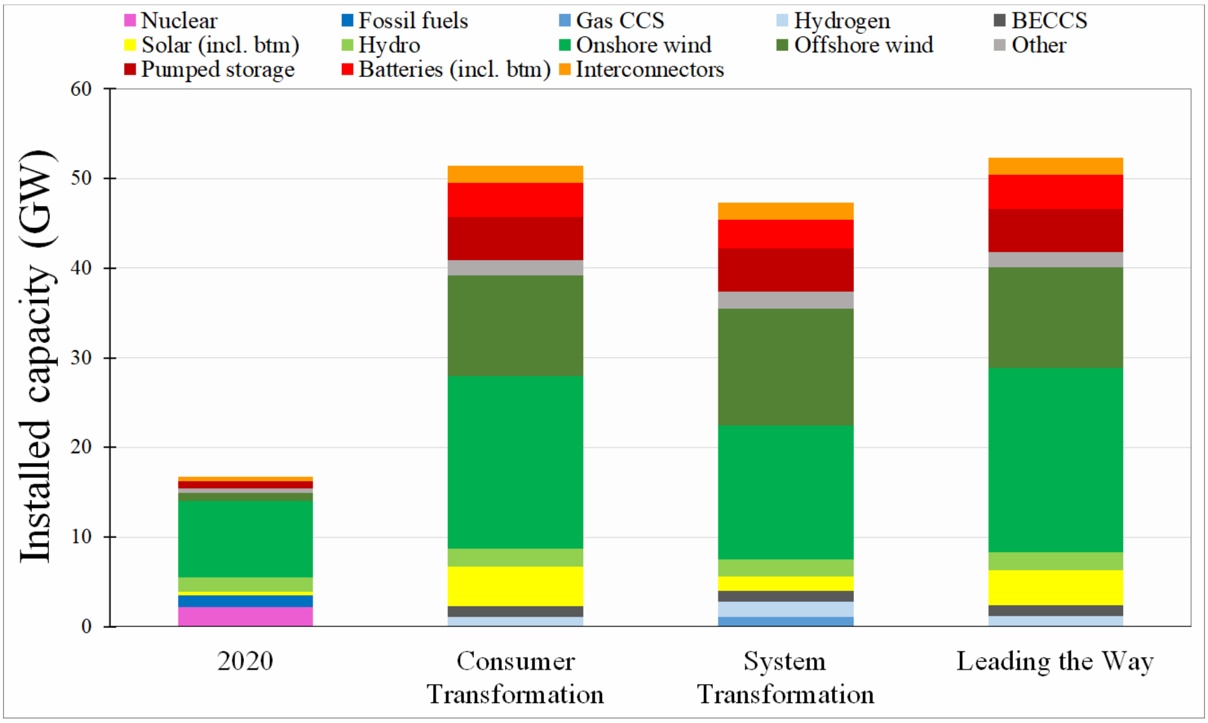


Fig. 5: Assumed installed electricity generation capacities for Scotland in the National Grid's three net zero scenarios compared with 2020 values.

3.2.4. *Capacity factor adjustment*

The future scenarios introduce the use of BECCS which cannot be scaled based on 2020 values, therefore a capacity factor is needed to understand the generation capacities. Table 8 is taken from the Future Energy Scenarios worksheet and gives the capacity factors for different technologies within the different models. Although BECCS may seem more suited as a means of dispatchable generation it is modelled as a baseload to maximise the negative emissions potential which is required to meet the country's net zero target. Therefore the BECCS energy generation is assumed to be the same each day with an output corresponding to the capacity factors given in Table 8.

Table 8: Capacity factor of selected technologies in the National Grid's Future Energy Scenarios (Source: National Grid) *[15]*

	Capacity factor (%)			
	2020	**Consumer Transformation**	**System Transformation**	**Leading the Way**
BECCS	0.0	50.8	44.2	75.8
Onshore wind	39.1	36.6	35.3	39.1
Offshore wind	49.9	50.9	50.3	51.1

Scotland's energy capacity in all scenarios is dominated by wind power. Therefore it is important to understand the characteristics of the wind that is being modelled. For onshore wind Table 8 gives a current value of 39.1% and remains between 35.4-39.1% in all scenarios. This seems erroneous as the current average onshore wind capacity factor is around 27%, [37] the published Future Energy Scenarios document even discusses a figure of 27%. The offshore figures are more what would be expected. Using the 2020 Scottish generation and capacity data considered earlier a capacity factor for the onshore and offshore wind for the dataset used was found to be 26.3% for onshore and 44.3%. The onshore wind capacity factor is slightly below the average but given the aim of this project it was deemed acceptable. The offshore wind capacity factor however was deemed to be too low. Whilst onshore capacity factor has largely settled around a long term 27% average, [41] the offshore wind capacity factor is still following an upward trend as turbines become more efficient, larger and make use of less accessible high wind resource areas. Therefore, for a 2050 scenario a 44.4% wind capacity was taken to be too low to represent a typical scenario and so the offshore generation data was adjusted by 12.9% allowing the data to represent a 50% capacity factor as given in Table 8.

For each scenario a second set of electricity generation data was created to simulate a very low wind year. The capacity factor of both the onshore and offshore wind capacity factors was reduced by 5%, from 26.3% to 21.3% and from 50% to 45%. This also influences the non-networked hydrogen electrolysis described in section 3.3.

The other generation given in Table 7 is largely unknown. The energy output was taken to be a constant across the year with a capacity factor of 15%. A better understanding of this generation would be valuable but seems to be a feature of the changing energy system with smaller generators and parties involves in the energy market. Fig.6 is a representation of the Leading the Way scenario with standard wind conditions.

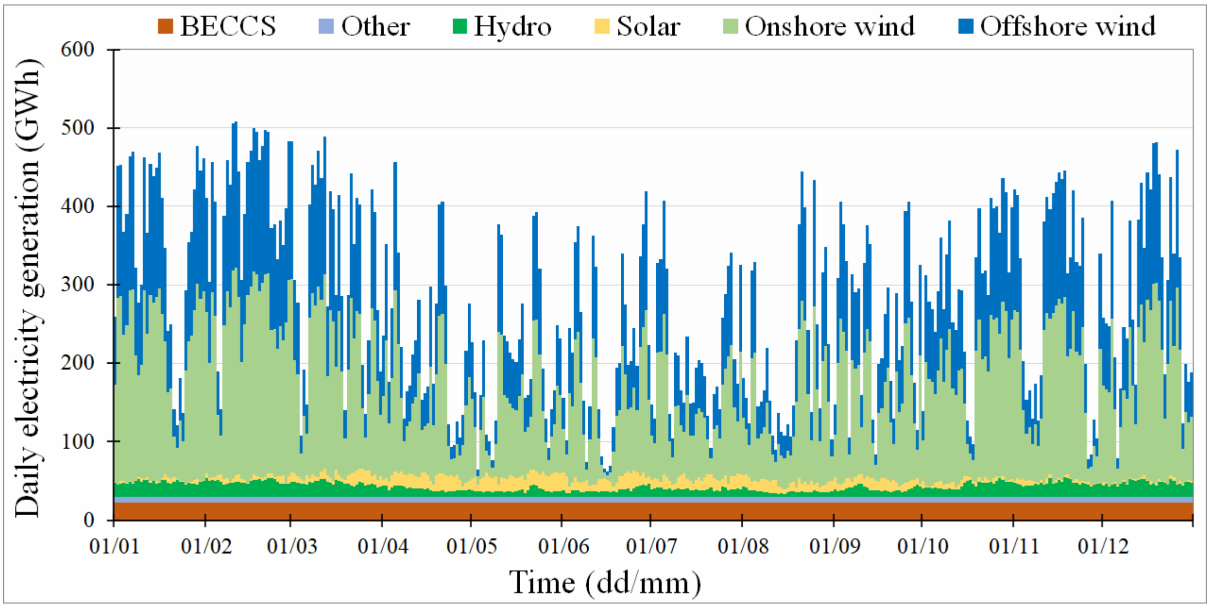


Fig. 6: Typical daily electricity generation by source over a year for the Leading the Way scenario in Scotland.

3.3. Hydrogen production capacities

The hydrogen production capacities of different methods for each scenario aren’t given but an estimate can be made. The total hydrogen production capacity is given for each scenario as well as the total hydrogen production for each method. The total capacity can then be divided accordingly based on the generation data. The Consumer Transformation and the System Transformation both have hydrogen production from nuclear electrolysis. Given that it has already been assumed that Scotland will have no nuclear generation this nuclear electrolysis capacity was replaced by an equal capacity of additional of green networked hydrogen.

Table 9: Assumed hydrogen production by method for Scotland in the three future energy scenarios.

	Hydrogen production capacity (GW)		
	Consumer Transformation	**System Transformation**	**Leading the Way**
BECCS	0.00	0.56	0.18
Methane reformation with CCS	0.69	4.35	0.00
Networked electrolysis	2.09	1.02	3.95
Non-networked electrolysis	0.00	0.00	1.53

3.4. Model processes

Using the daily electricity and hydrogen demand profiles, the electricity generation supply profiles, and the hydrogen production capacities, for each scenario an approximation of the minimum hydrogen storage requirement can be found. Four conditions were modelled for each scenario. Standard wind and low wind conditions were modelled alongside high interconnector use and no interconnector use. The wind conditions are varied by using the different energy supply profiles described previously. The high interconnector condition assumed 1.4GW was always available across the NorthConnect from Norway. The 'no interconnector' condition assumed no power was ever available across Scotland's interconnectors to Northern Ireland and Norway. The internal connection to the rest of the GB network was not considered as this will primarily be transmitting from north to south and at times when Scotland has the need to import energy the rest of the GB network would likely be in the same situation. The following steps were then carried out for each of the 12 simulations:

1. For each day the difference between electricity supply and demand was found.
2. If there is a shortage of electricity this is met using the following hierarchy:
    2.1. Shortages are first met by pumped storage, which was assumed to run at 90% efficiency in both directions for a round trip efficiency of 81%, with the pumped storage energy levels updated accordingly.
    2.2. If the energy within the pumped storage is depleted interconnectors are employed if they are being used in that case and can provide up to 33.6GWh pr day assuming 24-hour operation at 1.4GW.
    2.3. In the case of System Transformation which is modelled to have a 1.05GW of gas CCS installed, this can provide up to 25.2GWh, again assuming 24-hour operation at full output.

   2.4. Finally, if there is still a shortage of electricity this is met by hydrogen fuelled power stations. Assumed to run at 50% efficiency, a figure of double the electricity shortage is added to the hydrogen demand profile for that day.

3. If there is a surplus of electricity this also follows a hierarchy:

   3.1. Firstly the pumped storage sites are replenished, again 90% efficiency.

   3.2. Following this any remaining electricity is made available for electrolysis.

4. The difference between the maximum hydrogen production and demand, considering any additional demand and the electricity available for electrolysis assuming an efficiency of 75%, is then found with this value representing either the shortfall or the maximum excess possible each day.

5. The daily values found in 4. can then be used to find the hydrogen storage capacity for which hydrogen levels fall to zero only once. This represents the minimum hydrogen storage requirement for that scenario under those conditions.

This process was carried out using Excel 12 times coving the four combinations of standard and low wind conditions with high and no interconnector for the three future energy scenarios, Consumer Transformation, System Transformation and Leading the Way. The results are presented in section 4.

4. Results

The results of the model simulations for the three scenarios and the four conditions outlined in section 4 are presented in Table 10 which gives the minimum hydrogen storage capacity requirement in each case. The minimum storage requirement varies from 167.5GWh in the Consumer Transformation with favourable conditions to 1,847GWh for the System Transformation with unfavourable conditions. The results for each scenario are presented in more detail below.

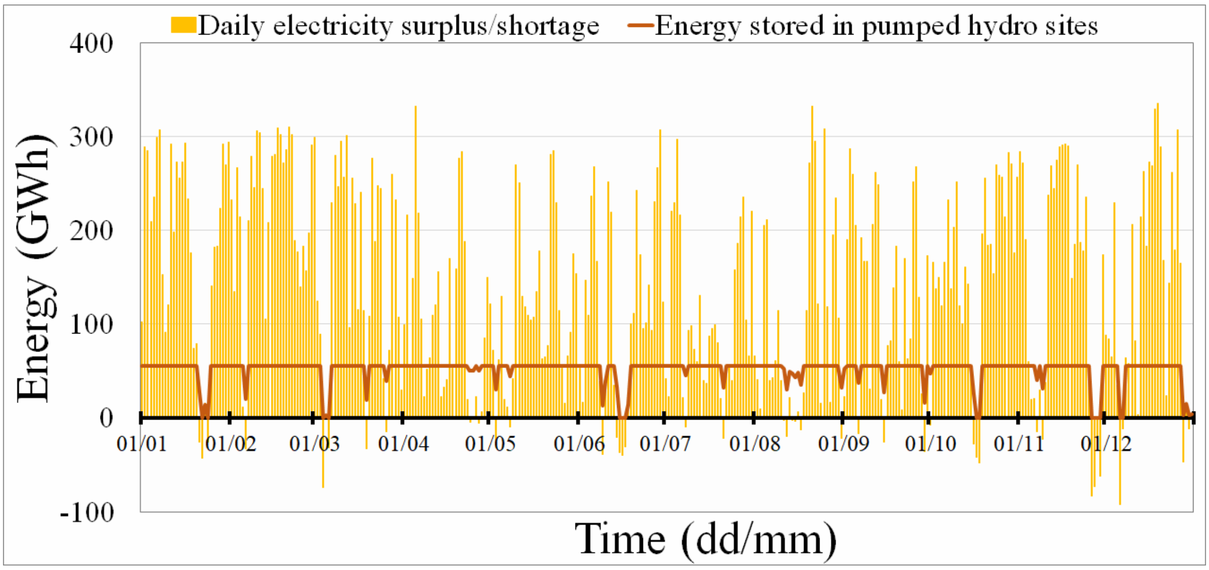
Table 10: Calculated minimum hydrogen storage requirements in Scotland for three net-zero future scenarios with varying wind conditions and interconnector use.

	Hydrogen storage requirement (GWh)	
	Standard wind	Low wind
	Consumer Transformation	
High interconnector use	167.5	225.9
No interconnector use	233.2	523.3
	System Transformation	
High interconnector use	1,675	1,764
No interconnector use	1,694	1,847
	Leading the Way	
High interconnector use	217.9	238.9
No interconnector use	341.6	442.9

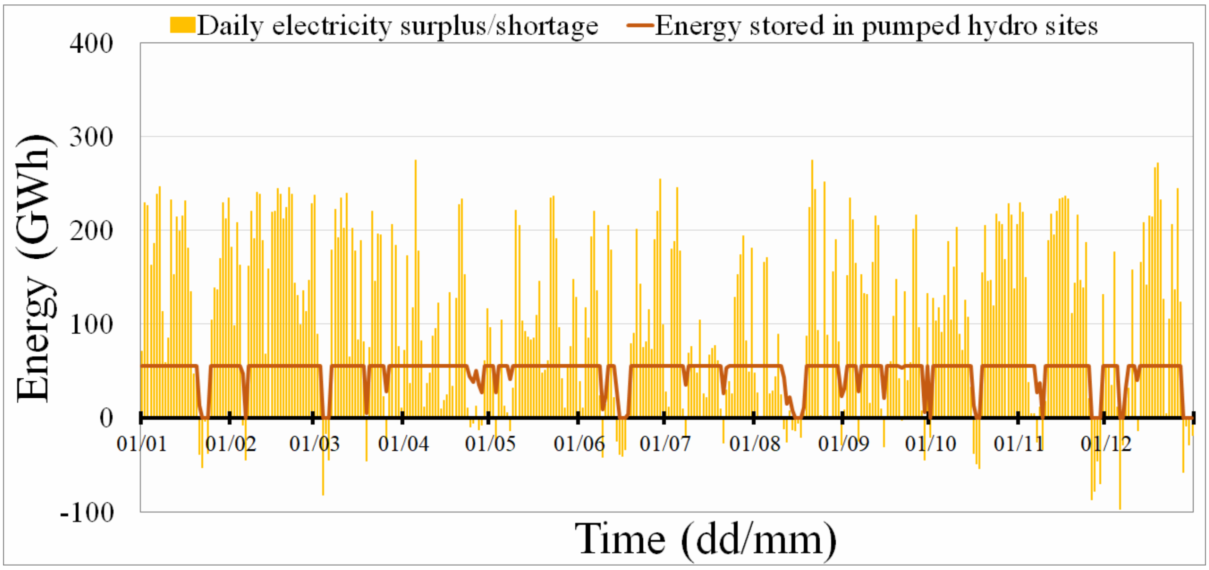
4.1. Consumer Transformation

With standard wind conditions and high interconnector use the Consumer Transformation has the lowest hydrogen storage requirement, 167.5GWh. However, it is the most sensitive to varying conditions both in absolute and percentage terms. Fig.7. shows the daily electricity surplus/shortage along with the state of the pumped storage for (a) the standard wind conditions and (b) low wind conditions.

An import feature not captured in any of the tables and figures presented is that in all four conditions the capacities for the Consumer Transformation are inadequate to meet demand. Following the hierarchy laid out in section 4, any shortage of electricity is met by pumped storage, interconnectors and then hydrogen fuelled power generation, in that order. Whereas the pumped storage has a limited capacity in the model and the interconnector has a daily limit, the last part of the electricity shortage, however, isn't considered to have a limit. This last section is assumed to be met by hydrogen no matter the size. In the high wind, high interconnector use case this last section has a maximum value of 39.2GWh and the low wind, no interconnector case has a maximum value of 78.4GWh. Table 11 shows hydrogen fuelled power generation to have been estimate at 1,068MW which would only be capable of generating 25.5GWh, less than the 39.2GWh and 78.4GWh values found in the model. This doesn't affect the modelled hydrogen storage requirement but is an important feature and will be discussed further in section 6.



(a) Standard wind conditions.



(a) Low wind conditions.

Fig. 7: Daily electricity surplus/shortage for a typical year along with the pumped hydro storage state for the Consumer Transformation scenario.

The daily hydrogen storage levels across the simulated year are shown in Fig.8. Hydrogen in this scenario is acting in a similar way to the pumped storage in that it generally discharges and recharges over relatively short periods. All four cases can be seen to follow similar behaviour and are sized by the same event at the end of November.

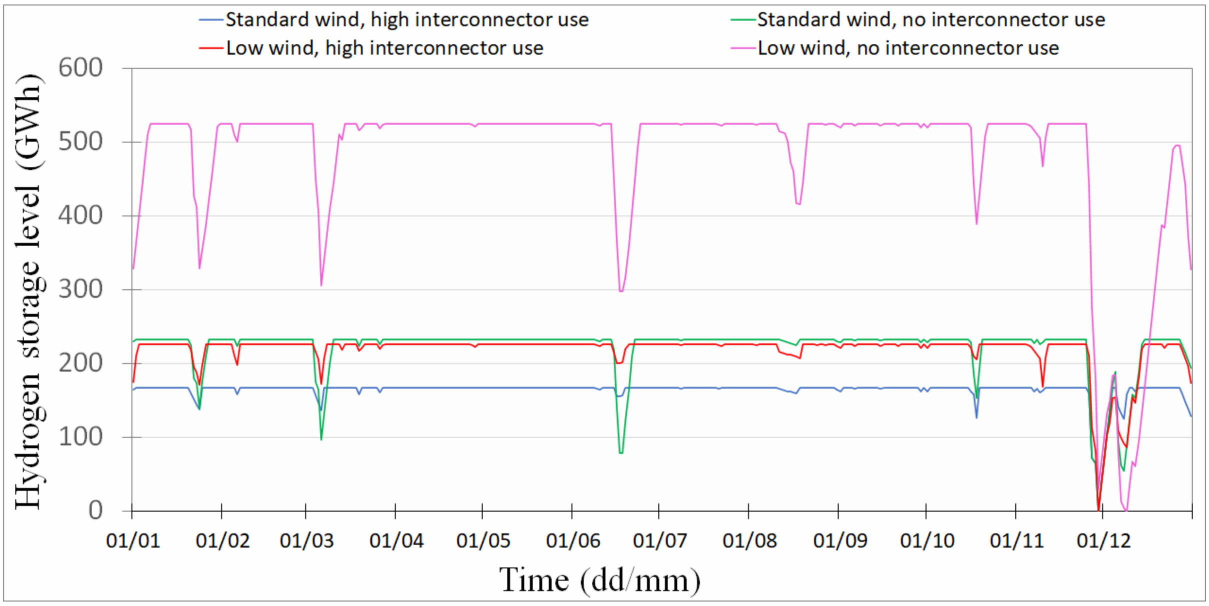
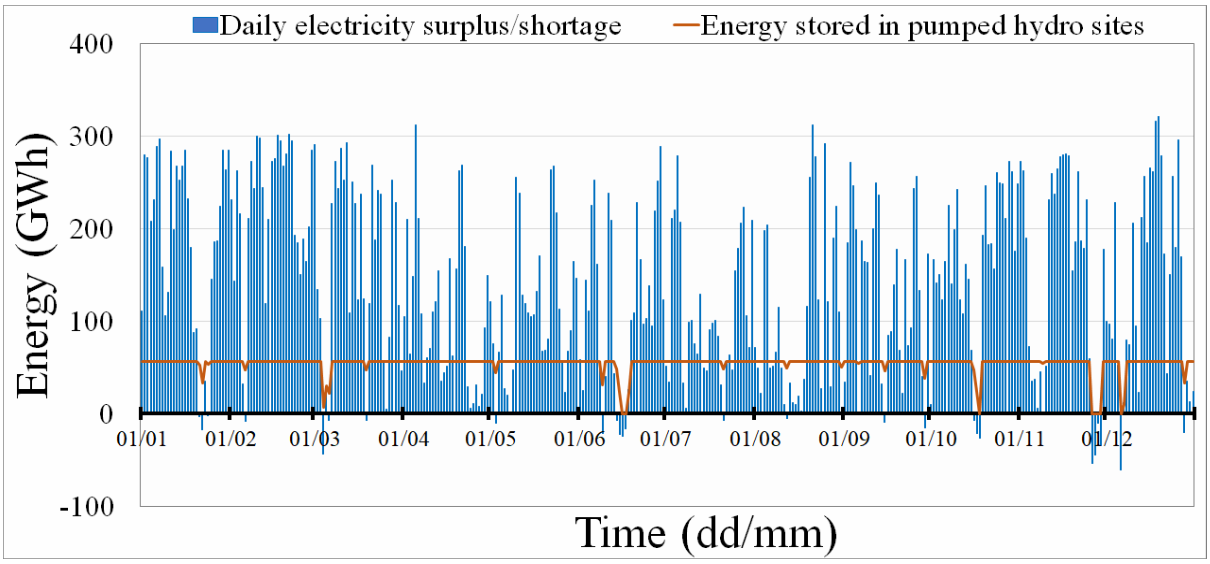


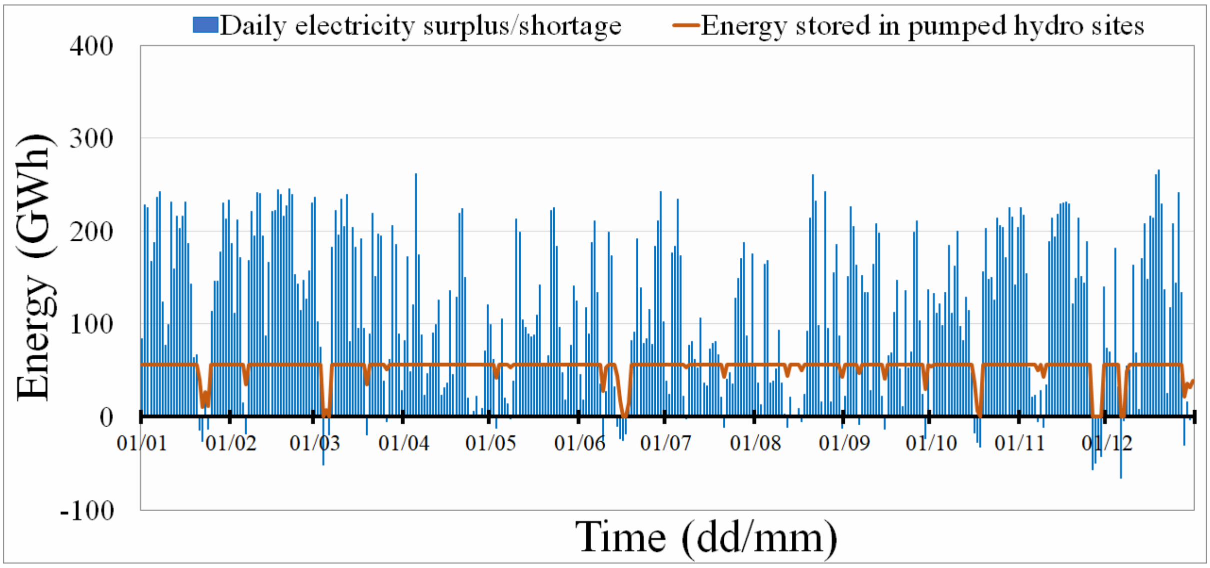
Fig. 8: Daily hydrogen storage level for a typical year for the Consumer Transformation scenario.

4.2. System Transformation

The System Transformation is less dependent on pumped storage than the Consumer Transformation. This is shown in Fig.9 which shows the daily electricity surplus/shortage and pumped storage levels across the year.



(a) Standard wind conditions.



(a) Low wind conditions.

Fig. 9: Daily electricity surplus/shortage for a typical year along with the pumped hydro storage state for the System *Transformation scenario.*

The role of hydrogen storage in the System Transformation is different to that in the Consumer Transformation. Fig.5.10 shows the hydrogen storage levels across the year and it can be seen through the winter months the hydrogen levels are gradually depleted before being replenished in the following months. These differing roles are discussed further in section 5. The variation found between the different conditions is small in relative terms. This is because with gas CCS used in the System Transformation there is less variation in the demand for hydrogen between the conditions owing to the limited hydrogen fuelled power generation.

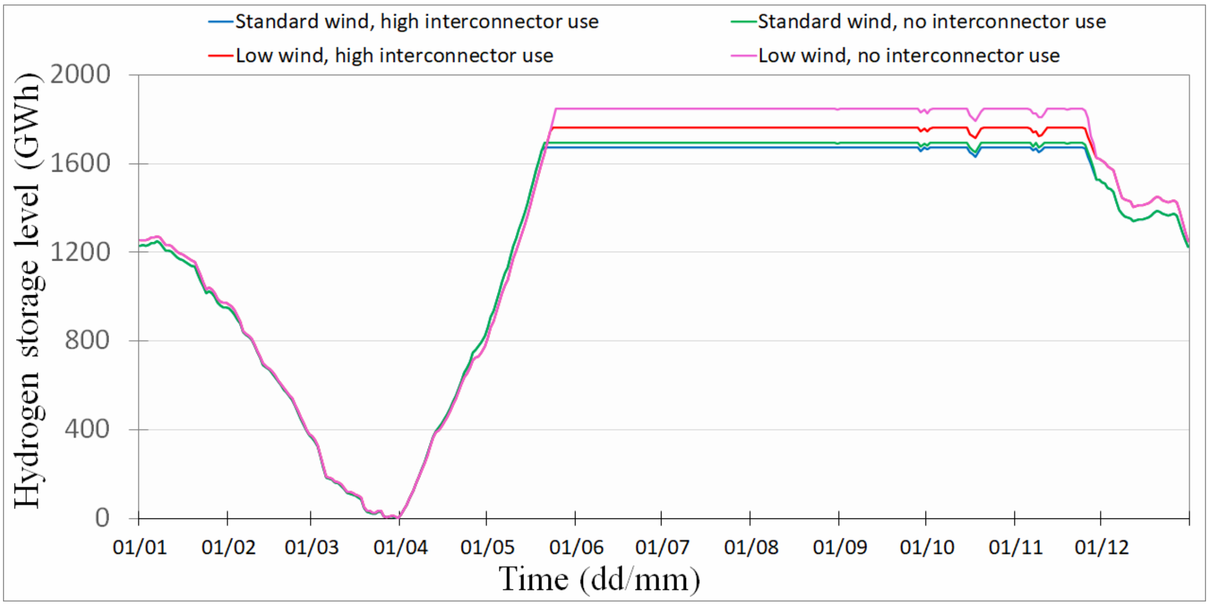


Fig. 10: Daily hydrogen storage level for a typical year for the System Transformation scenario.

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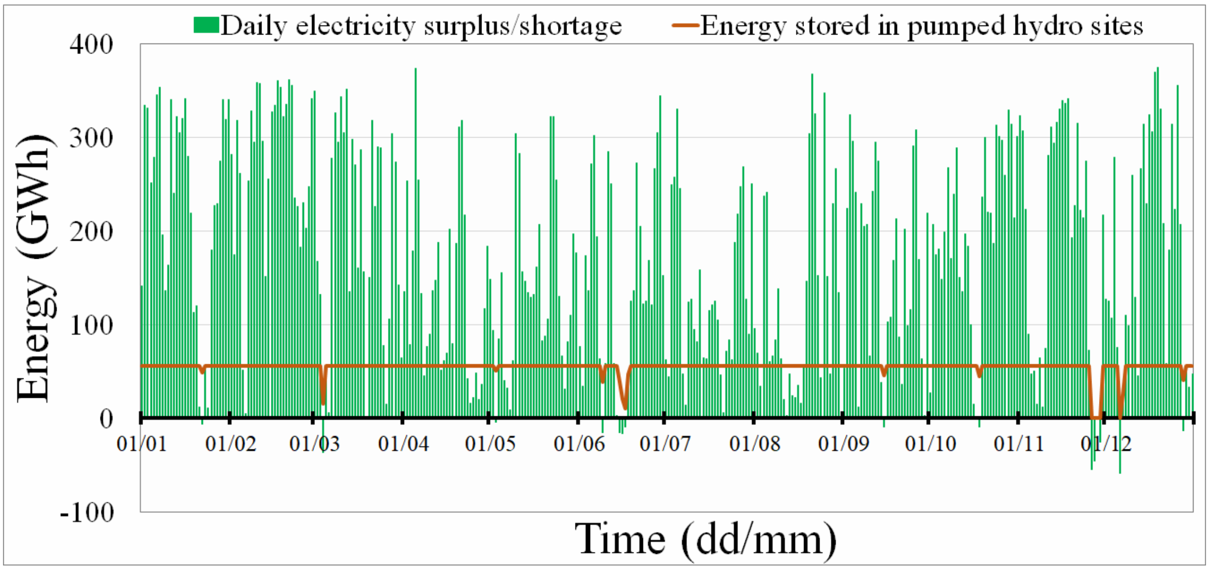
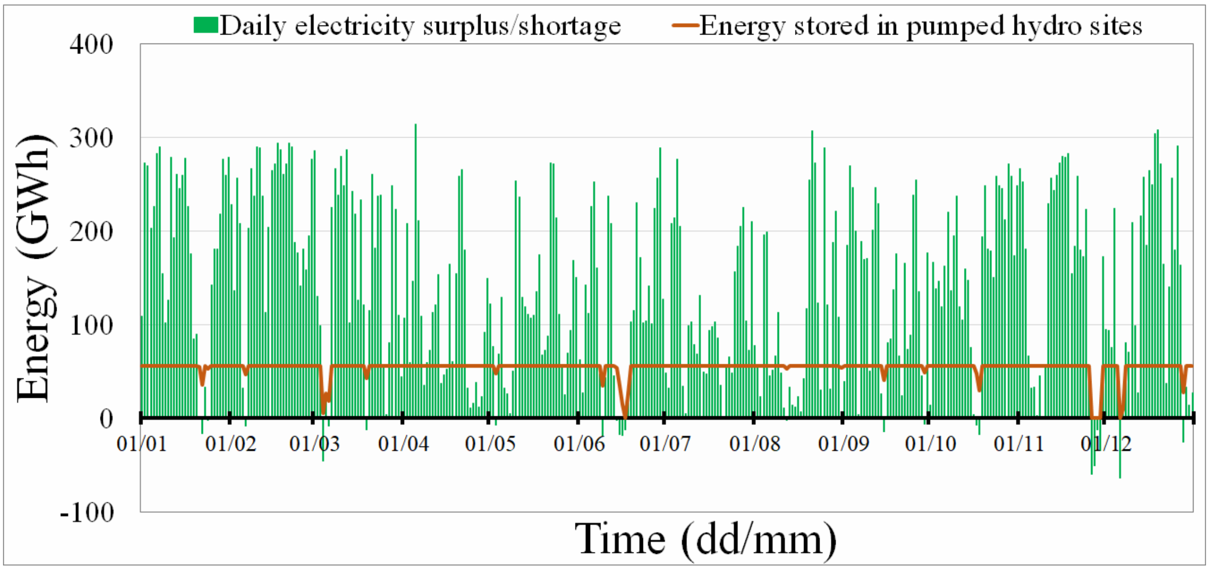
4.3. Leading the Way

The daily electricity surplus/shortage along with the energy levels of the pumped hydro is shown in Fig.11. The use of the pumped storage is lowest in this scenario.



(a) Standard wind conditions.



(a) Low wind conditions.

Fig. 11: Daily electricity surplus/shortage for a typical year along with the pumped hydro storage state for the Leading the Way scenario.

The hydrogen storage levels across the year are for the Leading the Way scenario are shown in Fig.12. This takes a similar role to the Consumer Transformation where the hydrogen storage is discharged and charged over short periods. However, the frequency of the use of the hydrogen storage in this scenario is greater than in the Consumer Transformation. This may in part explain the low use of pumped hydro storage, with the hydrogen storage providing more of the flexibility in this scenario. The required storage capacity is again dictated by the events at the end of November.

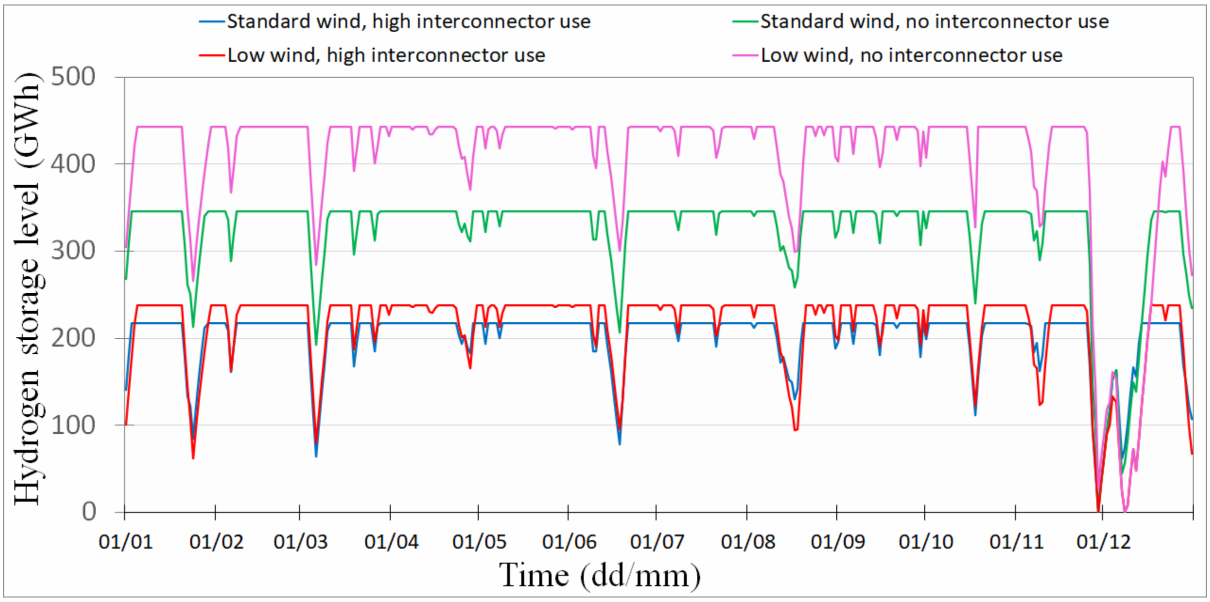


Fig. 12: Daily hydrogen storage level for a typical year for the Leading the Way scenario.

5. Discussion

The results presented in section 4 highlight the potential for significant variation in the required capacity as well as the tole of the hydrogen storage. The results are discussed further in this section along their potential implications.

5.1. Consumer Transformation

As mentioned in section 4 the Consumer Transformation does not have the required capacity to meet its needs as currently modelled. Table 11 gives the maximum daily energy shortfall that cannot be met by any of the modelled methods. The standard wind and high interconnector use conditions only requires capacity beyond what’s already modelled for 2 days across a 3-day period. Additionally the sizing of the energy storage is entirely dictated by this 3-day period. The hydrogen levels for these modelled conditions are shown in Fig.13. If a highly electrified energy system is developed these shortages of energy will need to be fully understood. The Customer Transformation is highly dependent on electricity whereas the other two scenarios are diversified to differing degrees with hydrogen use. Additionally this electricity is then heavily reliant on wind generation. This was also modelled with a highly developed pumped hydro sector. A large amount of generation and energy storage may be needed for events such as this, but if this takes the form of hydrogen which is then underutilised as it is a within a highly electrified system this may become unfeasible. The hydrogen storage in this scenario appears to play more as an emergency fuel from the limited results produced. If this is the case the sizing of any hydrogen storage becomes a question of how much resilience is desired and the cost industry or government is willing to pay for his resilience.

Table 11: Maximum daily energy demand that cannot be met by any means of modelled generation.

	Unmet demand (GWh)	
	Standard wind	**Low wind**
High interconnector use	13.6	19.2
No interconnector use	16.3	52.8

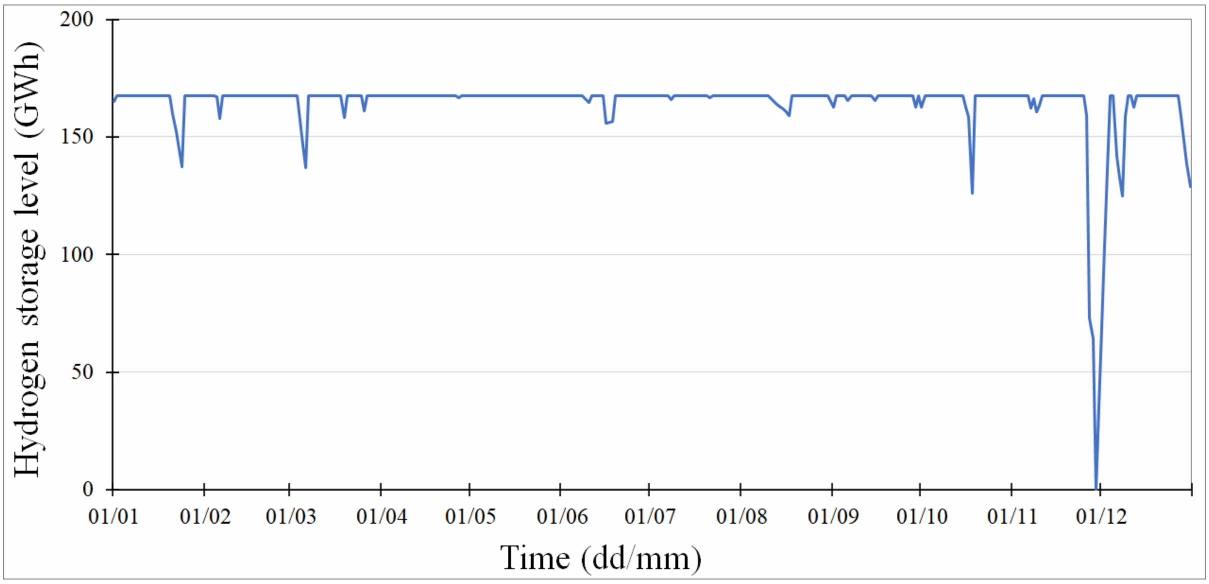


Fig. 13: Daily hydrogen storage levels across a year for the Consumer Transformation scenario with standard wind and high interconnector use.

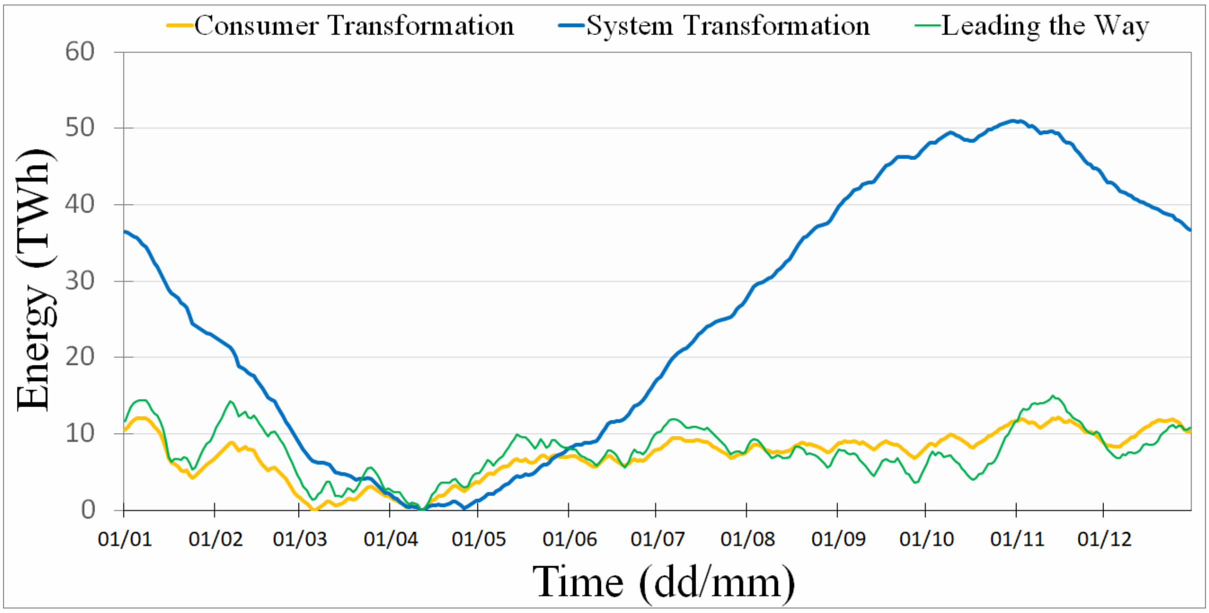
5.2. System Transformation

The System Transformation sees hydrogen used largely in heating increasing demand during winter causing the seasonal storage pattern shown in Fig.11. The energy storage required in this scenario, whilst influenced by the electricity generation, it is primarily a factor of the hydrogen production capacity. Even if electrolyser always has access to adequate electricity the System Transformation as modelled here will still require 1,227GWh of storage. This is just a feature of the System Transformation. Hydrogen demand in winter will outpace production and during the non-winter months production will outpace demand. The storage requirements are based on seasonal requirement rather than a single event as is the case with the Consumer Transformation and the Leading the Way scenarios.

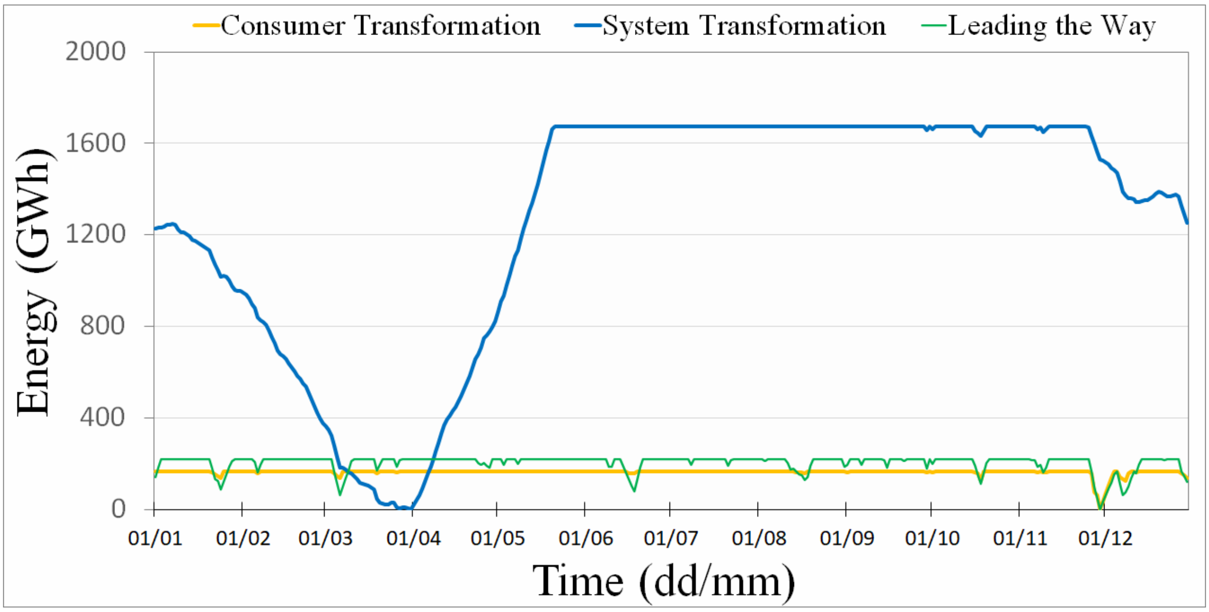
Gas CCS is modelled by the National Grid within the System Transformation; however a better option may be to increase the hydrogen fuelled power generation given the large amount of hydrogen infrastructure already in place in this future scenario. Work carried out by Jacobs into the UK’s long term energy storage strategy found a mix of 10GW of pumped hydro and 30GW of electrolysed hydrogen fuelled CCGT to be the best cost option. [42] The cost of the examined scenarios grew with increasing gas CCS installed. Although the System Transformation is largely comprised of ‘blue’ hydrogen there is no reason the production of ‘green’ hydrogen couldn’t be increased. The Future Energy Scenarios are simply indications of possible energy systems.

5.3. Estimated Scottish hydrogen storage comparison to the GB total

A comparison of the National Grid's hydrogen storage capacity across a year is shown in Fig.14. There are similarities, but equally noticeable differences. The trend for the System Transformation is very similar, the variation in the rate at which the hydrogen refills is likely because the Scottish model assumes 100% output. The National Grid model may slow down production following the winter as supply can comfortably meet supply and routine maintenance would be conducted. The Consumer Transformation and Leading the Way behave differently in the National Grid's model as the do not continually charge and discharge from a full capacity although the hydrogen levels do eb and flow, likely responding to weather events in similar manner to the Scottish model. The most significant difference between the two is the point at which the hydrogen level reaches zero. Whereas the sizing of the Scottish model was caused by an event around the end of November, the National Grid's has an element of seasonality, gradually depleting to reach the critical zero point in unison with the System Transformation.



(a) National Grid GB values.



(b) Modelled Scottish values.

Fig. 14: Comparison of National Grid hydrogen storage figures against the modelled Scottish values.

Fig.15 shows the hydrogen storage levels for the National Grid's scenarios published in 2020. These bare no resemblance to the patterns and behaviour shown in Fig.14. Exactly how much hydrogen storage Scotland and the UK will need in the future and what role this play still requires significant study as highlighted by this change between the 2020 and 2021 scenarios with the hydrogen storage requirement up to 3 times higher in the System Transformation scenario.

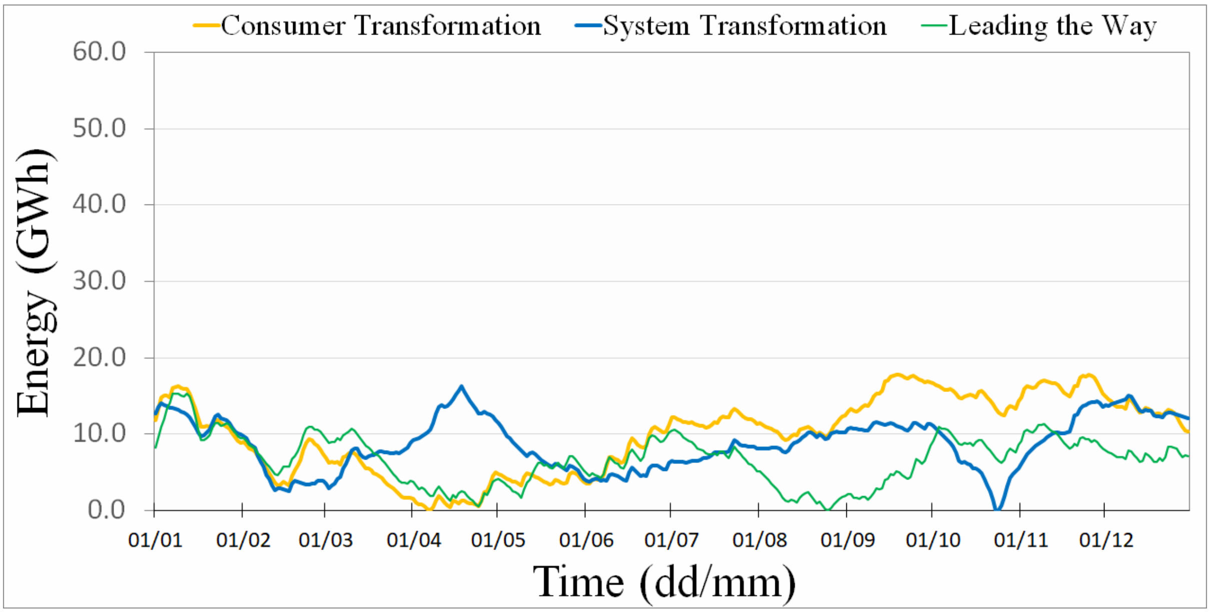


Fig. 15: Hydrogen storage levels for the National Grid's 2020 future energy scenarios. (Source: National Grid) [29]

6. Conclusion and further work

This project aimed to model potential future net zero scenarios to gain insight into the role and the required size of long-term deep storage. With batteries acting at the intraday time scale, a well-developed pumped hydro sector acting at the interday time scale, hydrogen was taken to be the energy storage mechanism that would be modelled and considered for this project. The requirements and even the role this storage performs was found to vary greatly between the three future energy scenarios.

Based on only a single data set, further work should be carried out using long term weather data. The work should also be expanded to consider not just the minimum storage requirement here, which was taken to be the storage required that resulted in hydrogen levels hitting zero only once, but energy security moving from the resolution of a day to an hour. This would then allow the loss of load expectation to be found under different scenarios and conditions and different levels of energy storage to be sized based on different level of certainty in meeting demand. This work would be similar to the that carried out following the closure of Longannet to assess Scotland’s ability to meet its peak energy needs. [43] This could be adjusted to assess whether Scotland could meet its peak day energy need, corresponding to the yearly event that was found to play a significant and deciding role in the sizing of the Consumer Transformation and Leading the Way scenarios.

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