Research Project: GW01

Has the operation and level of flexibility provided by pumped hydro energy storage been significantly impacted by the evolving energy sector in Great Britain?

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Abstract

Pumped hydro energy storage (PHES) is a crucial infrastructure of Great Britain's electrical network and is vital to ensure the targets and ambitions for net-zero future are met. It is a sustainable for of energy storage that functions through elevating water using excess electricity and then releasing it down through a turbine at times of higher demand.

This study was focused on identifying how and why the operation of PHES facilities have changed over the last decade or so and to highlight the importance of energy storage systems in the wider electrical industry. During this research, barriers to PHES operation such as legacy legislation, were identified and discussed. The implications of an unfavourable regulatory framework were highlighted and the benefits of lawmakers providing PHES operators with more suitable economic regulations was also provided.

To discover how PHES operation has changed in this evolving energy sector, the analysis of half-hourly generation data serving as the electrical demand for Great Britain was carried out using Python. During this analysis, it was discovered that PHES output had declined by nearly 50% despite a substantial rise in renewable energy output. The thinking behind energy storage is that it can now aid greater levels of intermittent generation, such as solar and wind, on the network. However, the opposite was found. This was linked to previously mentioned legislation and economic frameworks that these systems operated in.

Further analysis identified a gap in the research with regards to flexibility. Using a novel technique to determine how much a power output has varied over the course of a given time period, levels of flexibility were able to be determined for the major power types. Despite having a 50% decrease in generation and providing less than 1% of the overall generation in some years, the levels of flexibility that PHES provides to the grid have remained constant and well above what its generation percentage would suggest. The results from all of the analysis' mentioned were then discussed, and future work that would provide greater levels of evidence for the conclusions put forward was also supplied.

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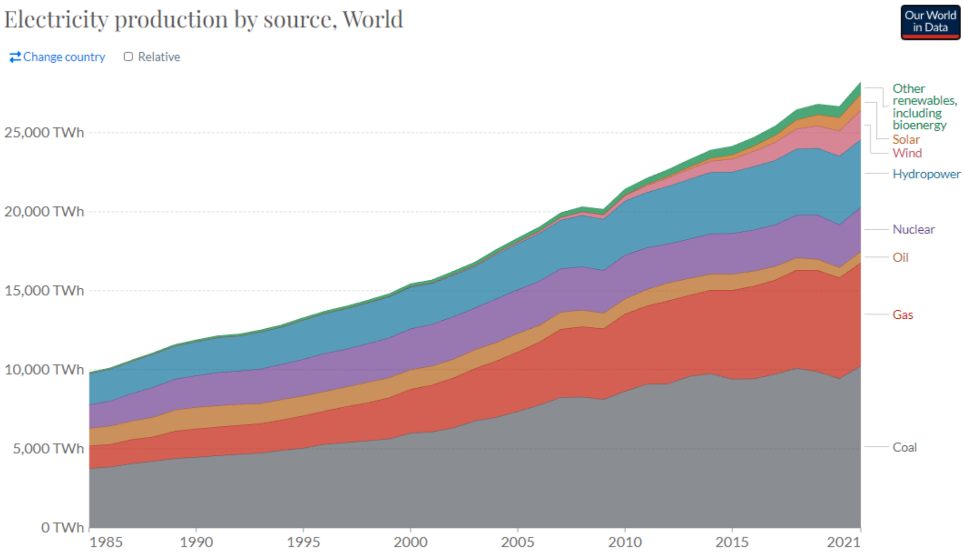
Contents

1. Introduction

Modern society has seen rapid growth of its electrical generation over recent years, with worldwide production rising from 21,400 TWh in 2010, to 28,200 TWh in 2021; a 32% increase in little over a decade (1).



[Figure 1 – World Electricity production by source] (1)

Alongside this vast surge in generation, there has been significant investment in renewable energy technologies to provide electricity due to a number of social, political and economic reasons; the most obvious, and perhaps most widely discussed, being the looming threat of climate change. The share of electricity production from wind and solar has increased by more than a factor of 5 in the last decade, from only 1.81% in 2010, to 10.31% last year (2). However, unlike traditional fossil fuel methods, the major renewable approaches are typically viewed as a form of non-dispatchable generation; they cannot be turned up or down to meet the fluctuating demand of the electrical network due to relying on primary energy sources out of human control, e.g., the weather (although curtailment does offer a small element of control). They also lack the intrinsic energy storage that comes with fuel-based sources, although it can be said that biomass fits this category but is unlikely to provide the amounts of power that wind and solar will (3). This gives rise to the need for a mix of energy storage system with a high capacities and power outputs that can be utilized quickly and efficiently to help balance the grid.

The most commonly used method globally for storing electrical energy is pumped hydro energy storage (PHES), accounting for more than 90% of installed capacity (4). PHES facilities use two reservoirs of water at different heights to store energy in the form of gravitational potential energy. Water from the lower reservoir is pumped to a higher elevation during off-peak times and is then run back through a turbine to generate electricity at times of higher demand and higher prices, allowing the operators to generate a revenue stream (5).

Great Britain currently has four PHES schemes with a combined capacity of 26.7 GWh and power of 2,828 MW (6). The oldest facility became operational in 1963 and the most recent was commissioned nearly 40 years ago in 1984, and there are plans for several new constructions and upgrades to existing facilities which would drastically boost Great Britain's capacity for energy storage (7). These major increases may well be as a direct result of increased renewable generation in Great Britain and beneficial changes to the market in which these systems operate (8) (9). Greater variability in electricity generation must be coupled with increased storage capacity and power to ensure the electrical grid remains balanced at all times. Moreover, the way these systems are operated, in particular their cycle rate, may have also changed due to increased variability of the generation. Whereas in the past, PHES systems may charge and discharge daily, data is now showing some cycling over 50 times a day (6).

Status	Name	Location	Power (MW)	Capacity (GWh)
Operational	Dinorwig	Snowdonia, Wales	1,728	9.1
	Cruachan	Argyll & Bute, Scotland	440	10.0
	Ffestiniog	Snowdonia, Wales	360	1.3
	Foyers	Inverness, Scotland	300	6.3
Planning	Cloire Glas	Loch Lochy, Scotland	1500	30 - 40
	Sloy	Loch Lomond, Scotland	60	20 - 40
	Glenmuckloch	Kirkconnel, Scotland	400	1.6
	Muiatheabhal	Isle of Lewis, Scotland	150	TBD
Proposed	Glyn Rhonwy	Llanberis, Wales	100	1.2
	Balmacaan	Balmacaan, Scotland	300 - 600	30 - 40
	Cruachan	Argyll & Bute, Scotland	+440 - 600	+7.2

[Table 1 – Operational PHES schemes in Great Britain] (6)

The motivation behind this paper is to highlight the changing trends in operation of PHES facilities in Great Britain and discuss the factors that may be influencing them. Using data analysis techniques, it aims to highlight the importance of these large-scale energy storage technologies, that provide a strong level of flexibility to the grid, and to consider the requirements for greater flexibility in a renewable-dominated electrical network. Moreover, throughout the literature review, certain barriers to PHES uptake and operation were discovered and examined.

2. Literature Review

The following literature review was carried out to provide an understanding of the current state of knowledge and discourse on PHES and wider energy storage technology, the barriers and incentives to the uptake of facilities, and how the requirements for flexibility in a renewable-dominated generation mix will affect their operation.

a. Energy Storage Technology

PHES currently has an overwhelmingly large market share of the energy storage sector. Accounting for more than 90% of installed capacity worldwide (4). This is mainly due to the maturity of the technology and its economic feasibility. Additional benefits include minimal operational costs, a lifetime of 50+ years and black start capabilities, which aid the electrical network during major outages, as they can self-start without external electrical input from the wider network (10) (11). However, PHES systems require both a high capital investment and a suitable topography that allows them to exploit the difference in gravitational potential energy of two reservoirs (10). Therefore, despite the planned construction of new sites, net-zero scenarios for Great Britain include a range of energy storage technologies.

Despite only accounting for a tiny percentage of current storage capacity, stationary battery storage is likely to make up the 2nd largest portion of Great Britain's storage capacity by 2050 and by far the largest in terms of power output. Estimates vary but the National Grid predict a stationary battery storage capacity of anywhere from 30 to 40 GWh and an output of 16 to 26 GW (excluding vehicle to grid technology), around 4 times more than the power output of PHES by 2050 (12). A major driving force behind this is a substantial drop in costs. MIT has found a 97% decrease in cost for lithium-ion batteries since commercial introduction in 1991, and a 17 to 24% reduction in price per year, of which this trend is expected to continue as market size increases (13). Imperial College have also predicted similar trends for the price of energy storage technologies in the future, with lithium-ion systems likely to be the most cost efficient for stationary applications (14). The other technologies likely to play a major role in energy storage are compressed air energy storage and liquid air energy storage (3). However, CAES faces similar barriers to PHES, in that their installation can be strongly dictated by geographical requirements, although underground salt caverns may provide a storage option (15) . They also have substantially lower cycle efficiencies; 45% compared to 80% and 90% for PHES and lithium-ion batteries, respectively (11) (16).

b. Barriers to PHES Systems

Throughout this research, a handful of barriers to PHES and wider energy storage operations and uptake were discovered. These are thought to have significant effects on the way these facilities function and why there have been no new PHES sites since 1984. Firstly, PHES schemes incur very long payback times. A hypothetical 300MW, 1800MWh facility with 75% efficiency, was found to have a payback time of 40 years (17). This presents an obvious deterrent to investors and could be attributed as a reason behind the lack of significant investment PHES systems have seen over the late 20th and early 21st century. In order to increase the competitiveness of these sites, incentives such as government subsidies for PHES operation and reduced tariffs on imported hydro equipment should be implemented (18).

Secondly, legislation from the UK Government has resulted in the creation of a double charging mechanism within PHES operation. Since storage facilities were defined as being an end-user, they were charged for both storing energy and releasing it to the grid (19). The lack of clarity with regards to the legal and commercial status for energy storage systems has resulted in an unclear framework within which these facilities have to operate. However, the double charging hurdle was resolved in 2020 after Ofgem made changes to the Connection and Use of System Code, redefining energy storage in such a way that charges would only be levied on the generation or discharge side (20).

In recent years there have been further positive improvements relating to clarity on energy storage definition and ownership. The European Parliament has adopted a motion that would place storage in its own asset class, alongside interconnectors, supply, distribution, transmission, and generation (21). There are also calls for the UK government to adopt the same approach (22).

c. Flexibility in a Renewable Network

Flexibility can be defined as the ability of an energy system to adjust both supply and demand in real time to ensure they are balanced (23). As Britain progresses towards a decarbonisation of the electrical grid, increased amounts of variable renewable generation will be added onto the network. This will be coupled with a major decrease in conventional sources of flexibility, namely, coal and gas-powered generation (23) (24). There is also likely to be major electrification in heating and transport sectors, further growing the need for system flexibility to ensure overall stability (24).

Current flexibility is provided primarily through the gas network due to its ease of storage and ability to store large volumes over different timescales. The start of 2022 saw 16,000 GWh of gas in storage and 4,500 GWh in the form of linepack, which refers to the volume of gas stored in a given pipeline (23). To put this in perspective, PHES had just under 26 GWh of storage at the beginning of this year. Gas provides fantastic flexibility for seasonal changes in heating demand, resulting in a much larger storage capacity. However, as the heating sector becomes more reliant on electricity for technology such as heat pumps, a greater portion of flexibility must come from the electrical network (25). It is very likely that this will take the form of several technologies and new ways of dealing with demand. Interconnectors are expected to provide a significant portion of this flexibility, alongside demand side response management, where consumers alter their usage to match supply at a given time, and storage facilities such as PHES, battery storage and compressed air energy storage (26) (27).

Despite the relatively understandable concept of flexibility in energy systems, there is no clear definition of the characteristics and indicators that describe this quality. For example, the German Federal Network Agency lists duration and response time as two parameters in its flexibility definition. However, the differentiation between flexibility and capacity is unclear (28). This introduces barriers to assessing the effectiveness and quality of flexibility that certain technologies offer (29). Ensuring flexibility parameters are clearly understood and definable will help to prevent regulatory barriers to flexibility incentives and allow for widespread collaborative efforts amongst industry, research partners, government and stakeholders (30).

During this research, a gap has been identified with regards to flexibility parameters. The most common indicators tend to be defined as response time, duration and location of flexibility. One that is not mentioned is the power output delta (change in output over a given time period). This seems a rather intuitive way of measuring and comparing the flexibility levels of different technologies and discussing how they have changed over time. Therefore, as part of this project, the power output deltas of a Great Britain's electrical power sources will be determined and compared.

3. Methodology

Alongside the literature review, an analysis of a dataset was carried out to find evidence on PHES operation that would support the conclusions. The following methodology section will discuss the origins of the dataset, and the key analysis tasks involved.

a. ESPENI Dataset

Great Britain's electrical market is operated in half hour chunks known as settlement periods, although the flow of generation, transmission and supply is obviously continuous (31). This provides Elexon, a subsidiary of National Grid, an orderly way of managing the distributing the financial costs to parties that have either caused an imbalance or aided in balancing the electrical system. Elexon publish some of this half-hourly data on their portal, making it publicly available (32). The data is aggregated into fuel types but doesn't contain values for solar or embedded wind generation, moreover, there are no negative values for pumped storage charging (taking energy away from grid). Therefore, the ESPENI (Elexon Sum Plus Embedded Net Imports) dataset was used (33). Put together by members from the Energy Informatics Group and The University of Birmingham, it addresses the issues mentioned above and provided cleaned half-hourly generation, storage and import/export data for Great Britain.

b. PHES Operation Analysis

For all of the analysis tasks, the Python programming language was used in Google Colab, a cloud-based notebook environment that can be used to write and execute Python code. The first set of tasks focused on the operation of PHES facilities and how it may have changed over recent years. This covered a year-by-year analysis for PHES generation to see how if it had been affected by the growing renewable generation. This required aggregating the half-hourly MW data in the ESPENI set into yearly MW data for each power type, and then converting it into TWh values. Python libraries Pandas and Matplotlib were both used to sort and visualise the data.

The 2nd operational analysis was centered on daily generation data, in particular, comparing the same month from various years to see how the output cycles had changed. The coding for this analysis was slightly more complex than the previous yearly assessment. In order to plot the same month from different years on one axis, the data had to be indexed by both the year and the day of the year. This however, made it challenging when attempting to locate the index of a specific date period (e.g., 01.01.2009 to 31.01.2009) in a multi-index dataframe. After trying different methods, eventually separate dataframes, displaying PHES daily generation, were created for the various time periods that were going to be compared, such as January 2009, 2013, 2017 and 2021. These four dataframes were then plotted on a single chart to show the comparison of daily generation output for PHES.

c. PHES Flexibility Analysis

The last part of the data analysis aimed to discover trends in the flexibility that PHES and other power types provide to the grid. During the research for this project, no method representing the method explained here was found. Hopefully this novel technique will provide value to determining the level of flexibility that a power type supplies and for comparing different systems.

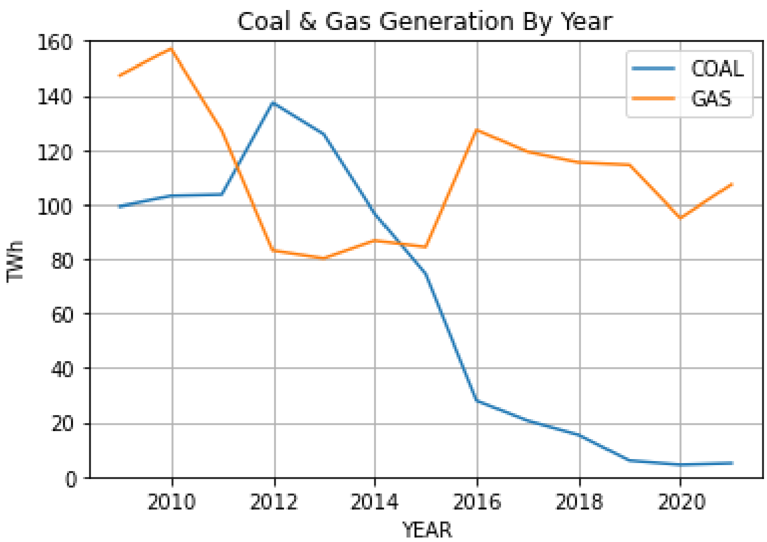
If data points were taken at set time intervals across a wave that represented the generation (and charging as well for PHES), then it is possible to calculate the difference between each time interval and total them up to get a value for how much that power type has changed over a certain period. If this was done for all systems supplying and removing electricity from the grid, then a percentage representing the level of flexibility a certain power type provides can be determined.

4. Results and Discussion

All graphs and figures shown in the results section were created using the Python programming language. The analysis focuses on data over a variety of timescales to identify trends and patterns in the operation of PHES and the wider electrical sector in Great Britain.

a. Yearly Trends in Great Britain’s Electrical Sector

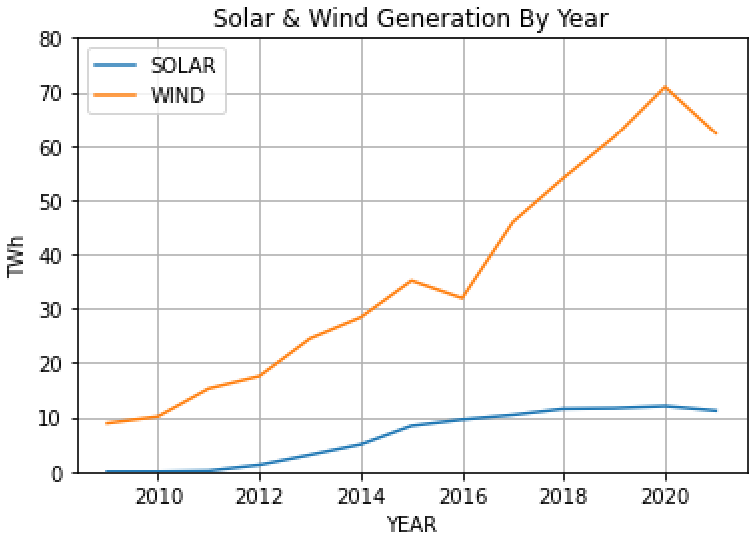
The first analysis focused on yearly generation data for the major power types. This includes fossil fuels, renewables and of course PHES. Clear trends in the output for these generation methods were identified. For example, figure 2 shows a substantial decline in the power output from coal over the last decade; having dropped from 140 TWh in 2012, to less than 10 TWh in 2020, a 93% decrease in only 8 years. Although it is not shown in the graph, oil also contributes a near negligible amount to electricity generation, producing only 1.54 TWh of electricity in 2021 (34). This major shift away from fossil fuel generation is mainly driven by the UK Government's commitment to carbon neutral by 2050 and to decarbonise electricity generation by 2035 (35).



[Figure 2 – Yearly generation data for coal & gas in Great Britain]

An interesting observation from figure 1 that is in stark contrast to the decline of coal and oil, is that the generation output from gas has remained relatively constant over the last 10 years. This fact contradicts the UK's goals of reducing fossil fuel usage for electricity production and therefore, gas must have been kept on the system in high amounts for a specific reason, in particular to manage the flexibility of the electrical network (this will be discussed in section 4c).

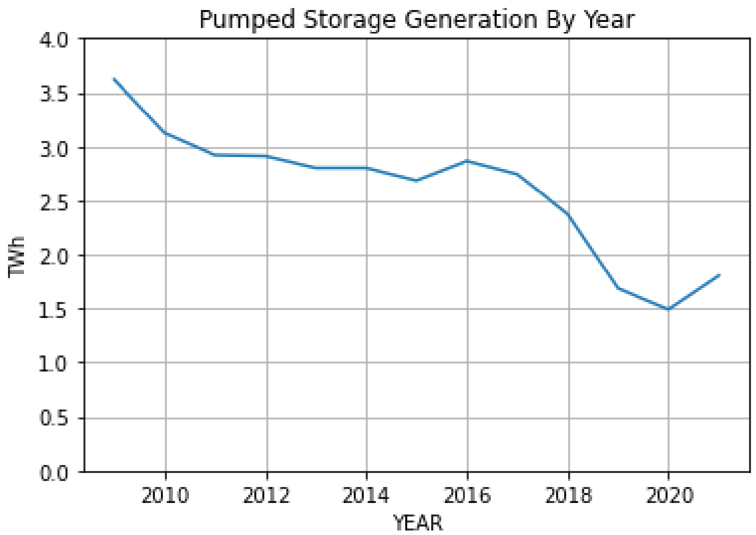
Despite the large reduction in fossil fuel output, the overall electrical generation for the UK has not seen the same decline. In the last 10 years the UK's electrical output has decreased by only 54 TWh (34). (This reduction can be attributed to factors such as more efficient technologies and a decline in the heavy industry sector (36)). Therefore, the electrical shortfall must have been made up for by other sources. Figure 3 shows that since 2010 there has been a significant increase in the generation from renewable energy sources. Wind has increased by 85% to 70 TWh and solar by 90% to 11 TWh from 2010 to 2020. This rise in renewable generation is the type of change that can be expected to be seen from the implementation of the UK Government's climate and energy targets.



[Figure 3 – Yearly generation data for solar & wind in Great Britain]

Given the rising growth of renewable generation in Great Britain, it would be expected that energy storage systems would play a larger role in balancing the grid due to the intermittent nature of sources like the wind and the sun. A more variable generation network means energy must be stored at times of high supply and low demand in order to provide short-term support to the grid if supply cannot meet the demand. Thus, the usage and therefore output from PHES facilities would increase. However, this is not what is seen in the data, in fact the exact opposite can be seen in figure 4. PHES output has declined steadily since 2009 from a high of 3.6 TWh down to 1.5 TWh in 2020, more than a 50% decrease. The cause for this counterintuitive finding was therefore investigated.

Firstly, alternate energy storage technologies were analysed. As discussed previously in the literature review, PHES is one of, if not the most, mature energy storage technology in current use. Stationary battery storage and CAES, whilst still prevalent around the world, do not compare to the current capacity or power output from PHES facilities. Therefore, it is not possible that this reduction in PHES usage was due to the uptake of other energy storage technologies. Secondly, the legislation and regulation that govern energy storage operation in Great Britain was looked at. During the literature review, a double-charging mechanism in the operation of PHES sites was identified (19). Due to the lack of clarity on the legal and commercial status of these facilities, these energy storage operators would have charges levied against them for both storing and discharging energy to and from the grid, negatively impacting their finances. This factor could be attributed to the steady decline in PHES output displayed in figure 4. Moreover, there appears to be evidence that the removal of the double-charging mechanism by Ofgem in 2020 has had a positive effect on PHES output. 2021 saw the first rise in generation output since 2016, a 20% increase in generation output. Including data from 2022, when made available, could provide more evidence to this hypothesis if a similar trend was seen. Although in the coming years, positive changes to the market in which energy storage systems operate will also have a large impact on the uptake of sites and overall generation and must therefore be at least partly attributed to the rise in energy storage generation. For example, the Department for Business, Energy and Industrial Strategy has published a report detailing how new market structures, such as a cap and floor regime, may be the best solution to providing better investment opportunity for long-term energy storage projects (8) (37). This economic model would also encourage energy storage operators to respond to network needs, helping National Grid ESO to maintain system stability (38).



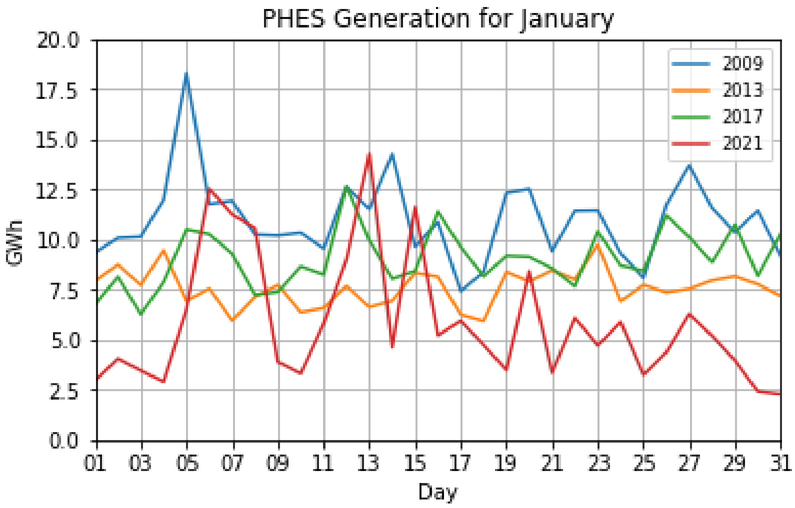
[Figure 4 – Yearly generation data for PHES in Great Britain]

b. Changes to the Daily Output from PHES Facilities

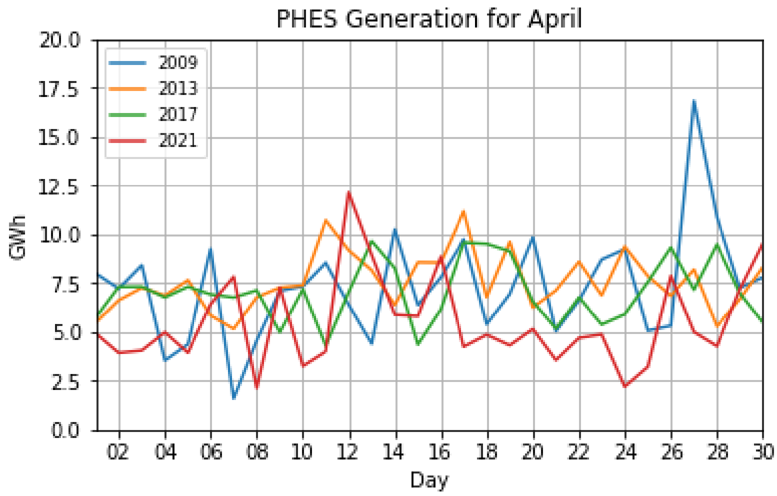
After analysing the yearly trends in PHES output, the resolution of the timeseries data to be analysed was increased. Aggregating the half-hourly generation data from the dataset into daily amounts would provide a method for comparing time periods from different years for PHES output to determine if there have been any changes in the discharge rates.

Python scripts were written to compare the same month from various years across the dataset, in particular 2009, 2013, 2017 and 2021. This spread of years provides a strong range to identify changes or patterns in how PHES facilities discharge their energy on a daily basis.

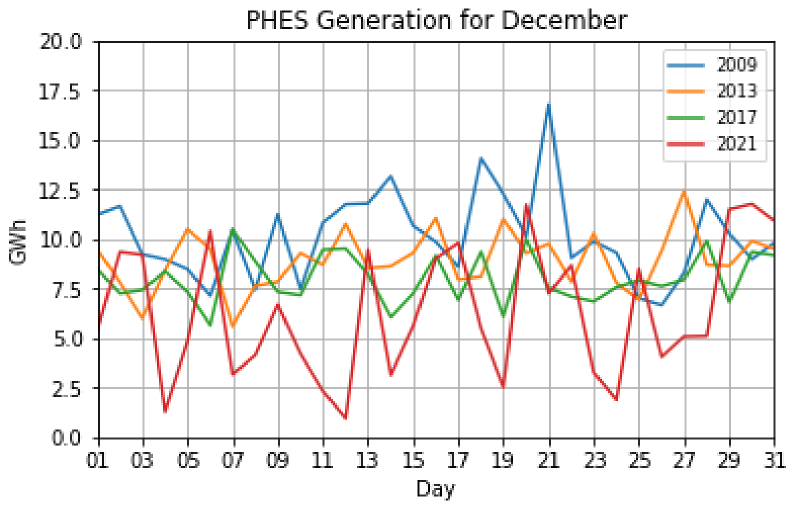
Figures 5, 6 and 7 show the comparisons for the years mentioned above for the months of January, April and December respectively. There are a few notable characteristics that can be seen in each of these figures. Firstly, as the years progress, the overall generation decreases, as shown in figure 4. However, the more interesting point occurs in the final year, 2021. Not only is there a spike in generation, possibly due to the removal of the double-charging mechanism, but the discharge cycles are far more erratic than previous years. When compared to the somewhat smooth outputs for 2009, 2013 and 2017, 2021 appears to be more unpredictable in its discharge pattern. While not all months represented this erratic characteristic for 2021 generation data, all displayed a spike in overall generation.



[Figure 5 – January generation data for PHES in Great Britain]



[Figure 6 – April generation data for PHES in Great Britain]



[Figure 7 – December generation data for PHES in Great Britain]

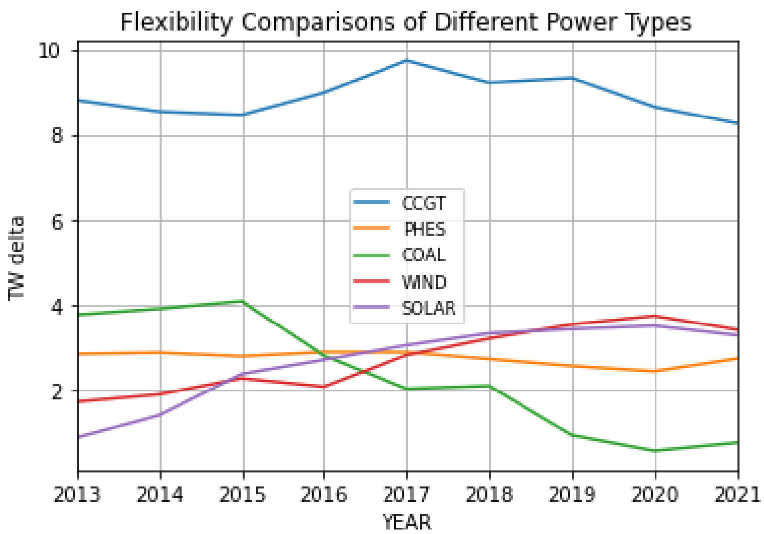
The cause for this increase in a more unpredictable generation pattern was first thought to be due to the increased amount of renewable electricity generation on the network since greater variability could cause a more irregular output for PHES. However, figure 3 and other data sources show 2021 as having a slight decline in renewable output (2). This counteracts the statement that greater amounts of renewables have caused a more unpredictable output pattern for PHES systems. Therefore, another hypothesis was put forward.

Since PHES generation prior to 2021 is under the influence of the double-charging mechanism, it may be that the removal of this finance structure by Ofgem, has itself allowed PHES facilities to operate at greater levels of variability. It makes sense that the elimination of an economic hamstring in the operation of energy storage systems will allow them to provide higher levels of flexibility to the grid, and that this is manifested through a more erratic generation output as they deal more balancing acts. In order to evaluate this hypothesis, when made available, generation data for 2022 should be analysed to see if this trend continues. If found to continue, this trend would signify not only the importance and capability of energy storage schemes, but that ensuring they operate within favourable legislation and market conditions can have significantly positive benefits.

c. Flexibility Analysis of Various Power Types

The final analysis was centered on the flexibility levels provided to the electrical network by different power types. As mentioned in the literature review and methodology, this analysis uses a novel method not found in research. The principle behind the method is that taking values for how much a power type's output has changed (increased or decreased) over a set time period, will provide an approach for determining the level of flexibility it provides to the grid. Using the half-hourly generation data, the absolute difference between each value for the major power types was taken and then totalled for the year. Figure 8 shows these results plotted for 2013 to 2021; charging data for PHES systems was only available for 2013 onwards.

The first point of interest is that around 40% of the electrical network's flexibility is provided by closed cycle gas turbines. This is the main reason why gas has remained at such at high output when compared to other fossil fuels such as coal and oil for electricity production. The natural gas system is particularly effective at altering the supply of energy over short timescales due to its linepack characteristic (39). Furthermore, the seasonal swing in demand, mainly due to heating requirements, can also be controlled due to long term seasonal gas storage and interconnector pipelines. These factors make gas an ideal candidate in terms of the level of flexibility and control it can provide.



[Figure 8 – Flexibility comparisons of different Power Types]

However, it is clear that other technologies will eventually have to take the reins once natural gas systems are phased out. Notably, wind and solar have both risen substantially in terms of the level of flexibility they provide to the grid, although it is debatable over how much this is due to the overall increase in wind and solar output, and the increased flexibility being a by-product of a, expanded generation network. Furthermore, it is not possible to solely rely on renewables for system flexibility in the future due to their variable nature. Although, it is predicted that there will be considerable levels of curtailment as part of a net-zero scenario for Great Britain which will introduce an element of control over renewable generation. However, curtailment should be seen as a last resort and only used once all other flexibility options have been utilised. One solution to reducing curtailment is electrolysis of water for hydrogen production. Hydrogen is far easier to store than electricity and offers solutions for long-term and seasonal energy storage (23) (37).

The final takeaway from figure 8 is the level of flexibility provided by PHES facilities. Shown in yellow, this level has remained relatively constant over the last 9 years. This is interesting since the generation output from PHES has decreased by 40-50% over the same time period. In fact, in 2013, PHES provided just 0.87% of Great Britan's electrical generation, but 13.2% of its network flexibility. This ratio is a constant characteristic of PHES operation throughout the last decade and signifies the importance of energy storage systems for maintaining network stability. Another important note is the increase of PHES flexibility in 2021. As discussed previously, with the removal of the double-charging mechanism, PHES sites are able to operate under more economically favourable conditions, thus provide greater balancing to the grid. This is also seen in figures 5, 6 and 7, where the differences between each day are far greater than earlier years. It could therefore be expected that this trend of increasing generation and flexibility will continue for 2022 as market conditions become more favourable for energy storage systems and as they play a larger role in helping Great Britain to achieve a net-zero electrical network.

5. Uncertainty

The main source of uncertainty for this project came from the Elexon and National Grid data used to create the ESPENI dataset used for analysis, in particular with data errors. Fortunately, in the production of the ESPENI dataset a methodology for error detection was used. Any values found to be incorrect were removed and new ones were entered using linear interpolation (33). Although this process does have limitations such as scalability and the reliance on an individual's assessment of the data, it is thought to provide an accurate representation of Great Britain's electrical demand.

6. Future Work

For the next few decades there are many trends in the energy sector that are expected to continue. Increased development of renewable energy generation and a reduction in fossil fuel usage are right at the centre of the changing energy industry. Alongside this however, it is very likely that a change in energy storage usage will occur.

As mentioned in the literature review, energy storage capacity and power output are both expected to increase if Great Britain is to transition to a net-zero scenario. Therefore, it would be beneficial if the timeseries data analysed in this project were extended to 2023 and beyond. This would provide greater evidence for the changing operation of PHES systems due to increased renewables and decreased fossil fuel usage. Moreover, with improvements to market conditions and the removal of the double-charging mechanism, having a longer time period to analyse the effects that these changes are having on PHES operation and uptake will ensure that any conclusions will be backed by a more representative dataset.

PHES operation is also likely to change due to increased amounts of alternative energy storage systems, such as stationary battery storage, compressed air energy storage and vehicle-to-grid energy storage. Since PHES overwhelmingly makes up the largest portion of energy storage capacity, it is currently not easy to see what effect, if any, alternative energy storage technologies are having on its operation. However, in the following years, due to the PHES drawbacks mentioned in this paper (geographical restrictions, high investment cost etc), other technologies will gradually make up a greater share of the energy storage market. Therefore, once the data becomes available, it would be beneficial to analyse how PHES operation changes when these other energy storage methods play a larger role in Great Britain's energy industry.

7. Conclusion

As Great Britain, and the world, progresses towards a sustainable and renewable energy industry, it is clear that, for the electricity sector, energy storage technologies such as PHES systems will be key to ensuring those ambitions are achieved. Therefore, it is necessary to understand how this evolving energy sector is changing and the effects this is having and will have on future PHES usage and operation.

Data clearly shows trends of increased renewable electricity generation and a decrease in fossil fuel usage, although natural gas is an outlier in this regard. Mainly due to the fantastic flexibility characteristics it provides the electrical network with. With these rising renewables, the expected increased usage of PHES facilities has not been seen. Instead, a decrease in generation output from all four sites across Great Britain is what the data shows. Research in the literature review has identified legacy legislation as a possible cause for this. Poor regulatory frameworks such as the double-charging mechanism have resulted in creating a system where energy storage schemes are unfairly charged for storing and releasing energy to the grid. Fortunately, this was remedied by Ofgem in 2020 and could be noted as the cause for the rise in PHES output the following year, although using 2022 generation data, when made available, would provide better evidence for this statement.

PHES usage on a daily basis has had the opportunity to deal with greater balancing loads in 2021 than when compared with previous years. This is shown in the more erratic daily output patterns seen in figures 5, 6 and 7. Again, this may be due to these facilities now operating in a more favourable economic framework.

With regards to the flexibility of PHES, it has remained at a near constant level across the last 10 years, despite having a 50% drop in generation up to 2020. This highlights not only the great importance of energy storage systems in ensuring the network remains stable, but also their ability to provide a constant level of flexibility year on year. As with the generation increasing in 2021, so to did the level of flexibility that PHES provided. It is likely then that with the introduction of greater incentives for PHES construction and a promising outlook on market scenarios such as the cap and floor system, that PHES uptake will increase along with the generation output and flexibility it delivers.

The findings of this paper reinforce the justification and requirements for PHES and wider energy storage technologies in Great Britain's electrical and energy sector. Research into legislation and economic conditions has highlighted the importance of ensuring lawmakers and regulators provide these system operators with a framework that allows them to best serve the country's network needs, since they have already displayed their strong ability to do so.

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9. Appendix

a. Code for yearly generation figures

```
# import libraries & espeni v2 dataset
from google.colab import files
upload = files.upload()

import pandas as pd
import matplotlib.pyplot as plt

# select dataframe and set YEAR as indexed column
df = pd.read_csv('espeni v2.csv', index_col=26)

# aggregate data by year
df_yearly = df.groupby('YEAR').sum()

# remove data for 2008 and 2022 as both sets are incomplete
df_yearly.drop(index=[2008, 2022], axis=0, inplace=True)

# convert yearly MW data to TWh for PHES, SOLAR, WIND, COAL and GAS
df_yearly['ENERGY_ELEXM_PHES_TWh']=(df_yearly['POWER_ELEXM_PS_MW']*0.5*/1000000
df_yearly['ENERGY_NGEM_SOLAR_TWh']=(df_yearly['POWER_NGEM_EMBEDDED_SOLAR_GENERATION
_MW']*0.5*/1000000
df_yearly['ENERGY_ELEXM_WIND_TWh']=(df_yearly['POWER_ELEXM_WIND_MW']+(df_yearly['PO
WER_NGEM_EMBEDDED_WIND_GENERATION_MW']))*0.5*/1000000
df_yearly['ENERGY_ELEXM_COAL_TWh']=(df_yearly['POWER_ELEXM_COAL_MW']*0.5*/1000000
df_yearly['ENERGY_ELEXM_CCGT_TWh']=(df_yearly['POWER_ELEXM_CCGT_MW']*0.5*/1000000

# plot yearly TWh data for PHES generation
plt.plot(df_yearly['ENERGY_ELEXM_PHES_TWh'])
plt.xlabel('YEAR')
plt.ylabel('TWh')
plt.ylim(0, 4, 0.5)
plt.title('Pumped Storage Generation By Year')
plt.grid()
plt.show

# plot yearly TWh data for WIND & SOLAR generation
plt.plot(df_yearly['ENERGY_NGEM_SOLAR_TWh'])
plt.plot(df_yearly['ENERGY_ELEM_WIND_TWh'])
plt.xlabel('YEAR')
plt.ylabel('TWh')
plt.ylim(0, 80, 10)
plt.title('Solar & Wind Generation By Year')
plt.grid()
plt.legend(['SOLAR', 'WIND'])
plt.show

# plot yearly TWh data for COAL & GAS generation
plt.plot(df_yearly['ENERGY_ELEXM_COAL_TWh'])
plt.plot(df_yearly['ENERGY_ELEM_CCGT_TWh'])
plt.xlabel('YEAR')
plt.ylabel('TWh')
plt.ylim(0, 160, 20)
plt.title('Coal & Gas Generation By Year')
plt.grid()
plt.legend(['Coal', 'Gas'])
plt.show
```

b. Code for PHES monthly comparison figures

```
# import libraries & espeni v2 dataset
from google.colab import files
upload = files.upload()

import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.dates as mdates

# select dataframe
df = pd.read_csv('espeni v2.csv')

# set ELEXM_utc as datetime column
df['ELEXM_utc'] = pd.to_datetime(df['ELEXM_utc'], utc=True)

# create column for YEAR & DAY OF YEAR
df['YEAR'] = df['ELEXM_utc'].dt.year
df['DAY'] = df['ELEXM_utc'].dt.dayofyear

# aggregate data by YEAR & DAY OF YEAR
df_daily = df.groupby(['YEAR', 'DAY']).sum()

# create new column for PHES GWh
df_daily['ENERGY_ELEXM_PHES_GWh'] = (df_daily['POWER_ELEXM_PS_MW']*0.5/1000

# select years that will be compared for January (DAY <= 31), & plot
ax = df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2009)&(df_daily.index.get_level_values('DAY')<=31)].unstack(level=0).plot(kind='l
ine')
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR') ==
2013) & (df_daily.index.get_level_values('DAY')<=31)].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR') ==
2017) & (df_daily.index.get_level_values('DAY')<=31)].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR') ==
2021) & (df_daily.index.get_level_values('DAY')<=31)].unstack(level=0).plot(ax=ax)

# format plot limits, margins, title etc
plt.ylim(0, 20, 2)
plt.grid()
plt.title('PHES Generation for January')
plt.ylabel('GWh')
plt.margins(x=0)
plt.legend(fontsize='small')
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%d'))
plt.gca().xaxis.set_major_locator(mdates.DayLocator())
plt.gca().xaxis.set_major_locator(mdates.DayLocator(interval=2))
plt.gcf().autofmt_xdate()
plt.xticks(rotation=0, ha='center')

# select years that will be compared for April (91 <= DAY <= 120), & plot
ax = df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2009)&((df_daily.index.get_level_values('DAY')<=120)&(df_daily.index.get_level_va
lues('DAY')=>91))].unstack(level=0).plot(kind='line')
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2013)&((df_daily.index.get_level_values('DAY')<=120)&(df_daily.index.get_level_va
lues('DAY')=>91))].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2017)&((df_daily.index.get_level_values('DAY')<=120)&(df_daily.index.get_level_va
lues('DAY')=>91))].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2021)&((df_daily.index.get_level_values('DAY')<=120)&(df_daily.index.get_level_va
lues('DAY')=>91))].unstack(level=0).plot(ax=ax)
```

```
# format plot limits, margins, title etc
plt.ylim(0, 20, 2)
plt.grid()
plt.title('PHES Generation for April')
plt.ylabel('GWh')
plt.margins(x=0)
plt.legend(fontsize='small')
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%d'))
plt.gca().xaxis.set_major_locator(mdates.DayLocator())
plt.gca().xaxis.set_major_locator(mdates.DayLocator(interval=2))
plt.gcf().autofmt_xdate()
plt.xticks(rotation=0, ha='center')

# select years that will be compared for December (335 <= DAY <= 365), & plot
ax = df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2009)&((df_daily.index.get_level_values('DAY')<=365)&(df_daily.index.get_level_va
lues('DAY')=>335))].unstack(level=0).plot(kind='line')
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2013)&((df_daily.index.get_level_values('DAY')<=365)&(df_daily.index.get_level_va
lues('DAY')=>335))].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2017)&((df_daily.index.get_level_values('DAY')<=365)&(df_daily.index.get_level_va
lues('DAY')=>335))].unstack(level=0).plot(ax=ax)
df_daily['ENERGY_ELEXM_PHES_GWh'].loc[(df_daily.index.get_level_values('YEAR')
==2021)&((df_daily.index.get_level_values('DAY')<=365)&(df_daily.index.get_level_va
lues('DAY')=>335))].unstack(level=0).plot(ax=ax)

# format plot limits, margins, title etc
plt.ylim(0, 20, 2)
plt.grid()
plt.title('PHES Generation for December')
plt.ylabel('GWh')
plt.margins(x=0)
plt.legend(fontsize='small')
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%d'))
plt.gca().xaxis.set_major_locator(mdates.DayLocator())
plt.gca().xaxis.set_major_locator(mdates.DayLocator(interval=2))
plt.gcf().autofmt_xdate()
plt.xticks(rotation=0, ha='center')
```

c. Code for flexibility comparison figures

```
# import libraries & espeni v2 dataset
from google.colab import files
upload = files.upload()

import pandas as pd
import matplotlib.pyplot as plt

# select dataframe & set ELEXM_SETTLEMENT_DATE as datetime column
df = pd.read_parquet('espeniWithNegPSvalues.ztsd.parquet')
df['ELEXM_SETTLEMENT_DATE'] = pd.to_datetime(df['ELEXM_SETTLEMENT_DATE'], utc=True)

# create new column for YEAR & set YEAR as indexed column
df['YEAR'] = df['ELEXM_SETTLEMENT_DATE'].dt.year
df.set_index('YEAR', inplace=True)

# take absolute values for POWER_ELEXM_PS_MW column
df['POWER_ELEXM_PS_MW_abs'] = abs(df(['POWER_ELEXM_PS_MW'])

# combine wind & embedded wind generation columns
df['POWER_ELEXM_WIND_MW_TOTAL']=df['POWER_ELEXM_WIND_MW']+df['POWER_NGEM_EMBEDDED_W
IND_GENERATION_MW']
```

```
# remove unnecessary columns
df.drop(['ELEXM_utc', 'ELEXM_SETTLEMENT_DATE', 'ELEXM_SETTLEMENT_PERIOD',
'ELEXM_localtime', 'ELEXM_ROWFLAG', 'NGEM_ROWFLAG', 'POWER_ESPENI__MW',
'POWER_ELEXM_PS_MW', 'POWER_ELEXM_WIND_MW',
'POWER_NGEM_EMBEDDED_WIND_GENERATION_MW'], axis=1, inplace=True)

# apply delta function to all columns
df_delta = df.apply(lambda x : (abs(x.diff().shift(-1)))/1000000)

# aggregate data by YEAR (new column headings should be in TW but remained in MW)
df_delta_sum = df_delta.groupby(['YEAR']).sum()

# plot major delta values from 2013 to 2021
plt.plot(df_delta_sum['POWER_ELEXM_CCGT_MW'].iloc[5:14])
plt.plot(df_delta_sum['POWER_ELEXM_COAL_MW'].iloc[5:14])
plt.plot(df_delta_sum['POWER_ELEXM_WIND_MW'].iloc[5:14])
plt.plot(df_delta_sum['POWER_ELEXM_PS_MW_abs'].iloc[5:14])
plt.plot(df_delta_sum['POWER_ELEXM_CCGT_MW'].iloc[5:14])
plt.plot(df_delta_sum['POWER_NGEM_EMBEDDED_SOLAR_GENERATION_MW'].iloc[5:14])
plt.legend(['CCGT', 'COAL', 'SOLAR', 'WIND', 'PHES'], fontsize='small',
loc='center')
plt.xlabel('YEAR')
plt.ylabel('TW delta')
plt.ylim(0, 10, 2)
plt.title('Flexibility Comparisons of Different Power Types')
plt.grid()
plt.xmargins(x=0)
```