applied sciences

MDPI

Article

Salt Cavern Exergy Storage Capacity Potential of UK Massively Bedded Halites, Using Compressed Air Energy Storage (CAES)

David Evans [1,*], Daniel Parkes [1], Mark Dooner [2], Paul Williamson [1], John Williams [1], Jonathan Busby [1], Wei He [2], Jihong Wang [2] and Seamus Garvey [3]

[1] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK; dparkes64@gmail.com (D.P.); jpw@bgs.ac.uk (P.W.); jdow@bgs.ac.uk (J.W.); jpbu@bgs.ac.uk (J.B.)
[2] School of Engineering, University of Warwick, Coventry CV4 7AL, UK; m.dooner.1@warwick.ac.uk (M.D.); wei.he.2@warwick.ac.uk (W.H.); jihong.wang@warwick.ac.uk (J.W.)
[3] Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK; seamus.garvey@nottingham.ac.uk
* Correspondence: devans50.de@gmail.com

Featured Application: The work provides important data and information relating to future energy storage options and in particular the role CAES might play in load balancing and the integration of renewable energy technologies into electricity grids.

Abstract: The increasing integration of large-scale electricity generation from renewable energy sources in the grid requires support through cheap, reliable, and accessible bulk energy storage technologies, delivering large amounts of electricity both quickly and over extended periods. Compressed air energy storage (CAES) represents such a storage option, with three commercial facilities using salt caverns for storage operational in Germany, the US, and Canada, with CAES now being actively considered in many countries. Massively bedded halite deposits exist in the UK and already host, or are considered for, solution-mined underground gas storage (UGS) caverns. We have assessed those with proven UGS potential for CAES purposes, using a tool developed during the EPSRC-funded IMAGES project, equations for which were validated using operational data from the Huntorf CAES plant. From a calculated total theoretical 'static' (one-fill) storage capacity exceeding that of UK electricity demand of ≈300 TWh in 2018, filtering of results suggests a minimum of several tens of TWh exergy storage in salt caverns, which when co-located with renewable energy sources, or connected to the grid for off-peak electricity, offers significant storage contributions to support the UK electricity grid and decarbonisation efforts.

Keywords: energy storage; exergy; CAES; salt caverns

Citation: Evans, D.; Parkes, D.; Dooner, M.; Williamson, P.; Williams, J.; Busby, J.; He, W.; Wang, J.; Garvey, S. Salt Cavern Exergy Storage Capacity Potential of UK Massively Bedded Halites, Using Compressed Air Energy Storage (CAES). *Appl. Sci.* **2021**, *11*, 4728. https://doi.org/10.3390/app11114728

Academic Editors: Jorge Loredo and Javier Menéndez

Received: 31 March 2021
Accepted: 14 May 2021
Published: 21 May 2021
Corrected: 25 March 2022

1. Introduction

Current energy systems, relying primarily on fossil fuels (coal, oil, natural gas), produce carbon and greenhouse gases (C&GHG), contributing to the problem of global climate change. There is therefore, an increasing need to reduce C&GHG emissions. From initial targets of 80% reductions by 2050, in June 2019, the UK Government set a revised target of net zero emissions by 2050 [1], which was followed by the launch of the EU's 'European Green Deal' in December 2019 [2]. These aims will require significant effort across many industrial sectors that represent large emission sources, including electrical power generation.

Worldwide, transitioning from fossil fuel to cleaner, but intermittent, unpredictable, and inherently more variable mixed renewable energy sources (wind-power and solar photovoltaic [PV] plants) for electricity generation is enabling GHG emission reductions. However, if naturally variable renewable electricity sources comprise high percentages

(>80%) of the generated supply, the daily and seasonal variations in generation and capacity places greater challenges on power networks to meet transmission and distribution demands [3]. Alongside seasonal variation in electricity demand, issues then arise over security of supply, as power systems require balancing at various scales, ranging from second and minute reserves, to hourly, daily, weekly, and inter-seasonal (monthly) storage to meet and offset variability [3,4]. Therefore, patterns of demand not following such variations in electricity generation from renewable sources require fast-ramping, back-up generation, supported by reliable forecasting and, importantly, increased bulk, grid-scale storage capacity [3,4].

Electrical energy storage (EES) technologies are recognised as underpinning technologies to meeting these challenges, but they vary greatly in capacity, role, and costs. Some technologies provide short-term, small-scale energy storage options (e.g., batteries), whereas others represent load-levelling and longer-term utility scale and grid support through chemical and mechanical bulk energy storage technologies. The two largest and only current commercial, grid-scale, mechanical bulk energy storage technologies capable of providing fast ramp rates, good part load, and long duration are pumped hydroelectric storage (PHS) and compressed air energy storage (CAES) [5]. They are less economic or suitable as inter-seasonal storage options to balance longer term, seasonal fluctuations, or long-lasting wind shortages due to low volumetric energy storage densities (≈0.7 and 2.40 kWh/m^3, respectively; see below) [6].

Despite extensive investigation and research into CAES technology from the 1960s [7,8], worldwide, commercially operational grid-scale CAES capacity is provided by just three salt cavern-hosted facilities: the conventional (diabatic) Huntorf, Germany (1978, 321-MW) [9], and McIntosh, USA (1991, 110-MW) CAES plants [7,8,10], and in November 2019, the small (1.75MW/7MWh+) plant at Goderich, Canada, which became the world's first commercial adiabatic CAES plant [11]. Sustained rapid growth in wind power and making it dispatchable has renewed interest in CAES [5,12]. Despite significant research and some extended tests [13,14], no porous rock CAES plants exist, which is due mainly to economic and geological factors that, prior to development as a realistic storage option at scale, must be overcome [3,12]. Nevertheless, offshore porous rock storage is advocated as having inter-seasonal potential for the UK [15].

Particularly pertinent, following the UK Government's October 2020 announced intention of becoming the world leader in green energy involving mainly increased offshore wind farm generation [16], we explore the prospects and possible capacity of salt caverns for UK CAES exergy storage in selected onshore and offshore massively bedded halite deposits (Figure 1). These offer large energy storage volumes to underpin affordable and energy-secured decarbonisation and the development of low-carbon energy system design, policy, and regulations. The method proposed here will also be applicable to other countries with storage potential identified in salt caverns, particularly in Eurasia, North and South America, and Sub-Saharan Africa [17].

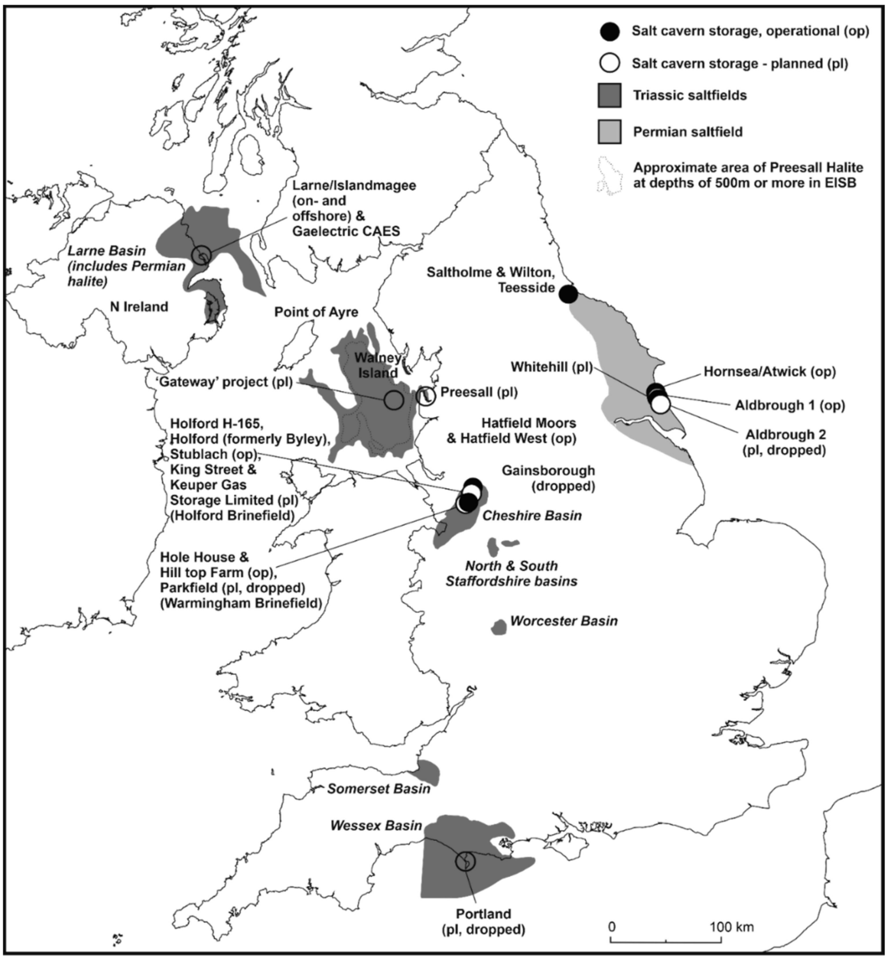

Figure 1. General outcrop map of the main halite basins studied onshore England and offshore East Irish Sea. Note area indicated in the East Irish Sea is that of the Triassic Preesall Halite at depths investigated (500–1500 m). Refer also S2, Table S1 for details on UGS facilities.

2. Mechanical, Bulk Electrical Energy Storage (EES), and the Potential of CAES

PHS is the most mature, proven bulk energy storage technology, whereby energy is stored in the form of the gravitational potential energy of water pumped from a lower to a higher elevation reservoir. Pumps are typically run by low-cost surplus, off-peak electrical power, and during periods of high/peak electrical demand, release of the stored water through turbines generates electric power. Used by electric power systems for load balancing, it reliably provides a large-scale and fast-responding storage option, with a current worldwide grid-connected capacity of ≈188 GW and representing ≈96% of the total global energy storage capability [18]. Significant potential for hydro-storage capacity may still exist in many other areas around the world [19]; however, ultimate development and capacity for PHS in most developed countries, including the UK, is considered limited and constrained by social, environmental, availability, and geographical considerations [5,20,21].

CAES, with a modest surface footprint and greater siting flexibility relative to PHS, represents a low-cost technology that is capable of a power output of over 100 MW. CAES is based on large quantities of electrical energy stored as high-pressure, compressed air in an underground storage 'reservoir' (currently salt caverns). During peak demand, air is withdrawn and used in the generation of electricity, and as with PHS, the release of power can be very quick. Worldwide, CAES capacity is currently around 431 MW [18], and CAES is viewed increasingly as offering bulk storage potential and a solution to levelling intermittent renewables generation (wind-power and solar photovoltaic [PV] plants), and capable of maintaining system balance (S1, Tables S1–S6) [3,5]. CAES technology has advantages over PHS, including a lower visible impact on the landscape and a greater scope for building CAES facilities nearer the centres of wind-power production, especially in parts of Europe and regions of the USA. CAES facilities in salt caverns already successfully provide minutes to hours reserve at Huntorf (Germany) and balancing out grid loads over a weekly cycle at McIntosh in the USA [4,9]. However, significant barriers to implementing large-scale CAES plants lie in identifying appropriate geological storage options and thus geographical locations, low round-trip efficiencies of CAES and the low volumetric energy density of compressed air (2.4 kWh/m^3) [6,22,23].

Energy in compressed air caverns is stored in the form of physical (mechanical) potential energy, whereas energy in compressed gases is chemical storage (chemical energy bonds). Consequently, the volumetric energy density of air is several orders of magnitude lower than that of gases such as hydrogen (≈170 kWh/m^3) or natural gas (≈1100 kWh/m^3) [4]. Accordingly, to make CAES economically viable requires very large volumes of air, which can only be achieved through high pressures and large volume storages. Geological storages at depth offer such storage conditions, with typical gas storage salt caverns, in particular, offering rapid cycling and high flow rates to provide ideal storage options. However, the lower volumetric energy density of air means that CAES plants are less suitable for long-term applications and storage because greater storage volume (increased cavern numbers) is required, increasing costs compared to gases with higher value.

Whilst geometrical volumes of compressed air caverns are comparable to those of conventional natural gas storage caverns, CAES operational pressure ranges (and thus storage volumes) will be considerably lower than for gas storage. This is because of the much higher cyclic pressure frequency rate together the with current technological development of compressors, heat storages, and turbines, meaning the operational pressures are also lower, being well below 100 bar [4]. Thus, commercial, central, grid-scale CAES plants will require deep underground (geological) storages such as those already used for natural gas, hydrogen, and the rare examples of already operational CAES plants.

Conventional (diabatic) CAES technology is based upon traditional gas-turbine plants requiring fossil fuel combustion and thus associated emissions during electricity generation, making it less attractive when compared with other EES technologies [24]. Nevertheless, the fitting of recuperators and advances in CAES technologies, particularly if advanced adiabatic or isothermal CAES technologies requiring no external source of energy to heat the withdrawn air eventually prove feasible, together with linking to renewables generation (including offshore wind), all offer the future prospect of improved cycle efficiencies, with the reduction and possibly elimination of emissions.

3. CAES-Geological Storage Options, Developments, and Restrictions

Bulk geological storage options and the technologies behind current and future electrical energy storages for compressed air are derived largely from tried and tested storage technologies developed for the underground storage of large volumes of high-pressure natural gas [4]. Most common geological options are porous rock formations (depleted gas fields and aquifers), or man-made (solution-mined) salt caverns. Where such options are not available conventionally mined, non-salt rock caverns and lined rock caverns represent alternatives, but they are significantly more expensive. These same options apply to potential CAES development (S1 and S1, Tables S1–S6).

As alluded to above, CAES has been considered for many decades [7,8] but to date, only three commercially operational CAES plants exist, at Huntorf [9], McIntosh [10], and most recently at Goderich [11]. Between 2012 and 2016, a small 2 MW isothermal CAES demonstration plant using a reconditioned former liquid hydrocarbon storage salt cavern and linked to wind generation, operated at Gaines, Texas, although it is not believed to be currently operating [25,26]. Salt caverns provide important high flexibility with respect to turnover frequency, as the open cavity enables very high flow rates permitting high injection/withdrawal rates required for rapid cycle storages. They also offer ideal conditions for compressed air storages because unlike porous reservoirs, the rock salt is inert to oxygen [4]. Thus solution-mined salt caverns are a likely first choice for CAES in the UK, and for CAES proposals linked with renewables, they are the overwhelming majority (S1, Table S1).

Many regions of the world lack suitable salt deposits, and so, the suitability of porous rock storage has long been and remains under investigation [12–14]. However, serious doubts exist over the likely development of porous rock storage (principally aquifers), with no CAES plants having operated commercially and only a few small test facilities having been constructed, with variable results (S1, Tables S2 and S3). The King Island project in California demonstrated the technical feasibility of using an abandoned natural gas reservoir for a 300 MW, 10 h CAES facility, with the reservoir capable of accommodating the flow rates and pressures necessary for the operation of the facility. Originally planned for opening around 2020, its progress appears stalled due to the high cost of a CAES facility relative to alternative energy storage technologies [27]. All test facilities encountered problems with one of more of the following: wells and economics, pressure anomalies, variations in reservoir quality and performance, formation of the 'air bubble' in the storage reservoir, and reaction between the oxygen of the injected air and minerals in the reservoir rock leading to oxygen depletion and/or potential for bacterial/micro-organism growth and porosity reduction. Proposed aquifer storage potential for the UK would be offshore [15], thereby increasing costs, which currently thus seems less likely than salt cavern storage.

Depleted field storages appear even more unlikely with a potential hazard posed by residual hydrocarbons in the depleted gas formation. Introducing compressed air presents the risk of ignition and explosion, both underground and during discharge [28].

Additionally, and although more expensive options, gas storages have and still operate in abandoned mines and unlined or lined, conventionally mined rock storages. Similar constructions could host CAES in regions lacking cheaper geological alternatives [7,8] and have been considered (S1, Tables S4–S6). Various CAES test facilities have operated briefly in Japan and Korea, and long-standing plans for CAES in a former limestone mine at Norton, Ohio were finally shelved in 2013 [29]. Small tests for adiabatic CAES are currently ongoing in an unlined Swiss tunnel [30] and a lined old mine working in Austria [31]. Whilst under consideration in, for example, USA, Mongolia, and Australia, such storages may be considered unlikely in the UK.

Non-geological CAES schemes offering storages of small volume. Though not considered here they include aboveground, or shallowly buried steel vessels or pipes [32,33], energy bags secured to the seabed [34], wind turbines linked with energy storage in supporting legs [35], or those in which power is converted directly from the rotor by means of gas/air compression within the rotor blades [36].

4. Materials, Exergy Storage Tool, and Methodology

This section outlines briefly the UK bedded halites, UGS sites together with the development of the model and the derivation of estimates for exergy storage (refer Figure 2), further details of which are provided in S1–S3.

4.1. Massively Bedded UK Halite Deposits Available

Important massively bedded halite deposits are developed in the UK and have been associated with, or identified as potential hosts for, large solution-mined natural gas storage caverns (Figure 1; S2, Table S1). The halite deposits considered extensive and thick enough for cavern construction occur in four main basins (with ages) [37]:

- The Northwich Halite Member of Cheshire Basin, onshore north-central England (Triassic)
- The Preesall Halite Member of the offshore East Irish Sea (EIS) (Triassic)
- The Dorset Halite Member of Wessex Basin, on- and extending offshore southern England (Triassic)

- The Fordon Evaporite Formation, on- and extending offshore Eastern England (Upper Permian, Zechstein [Z2]).

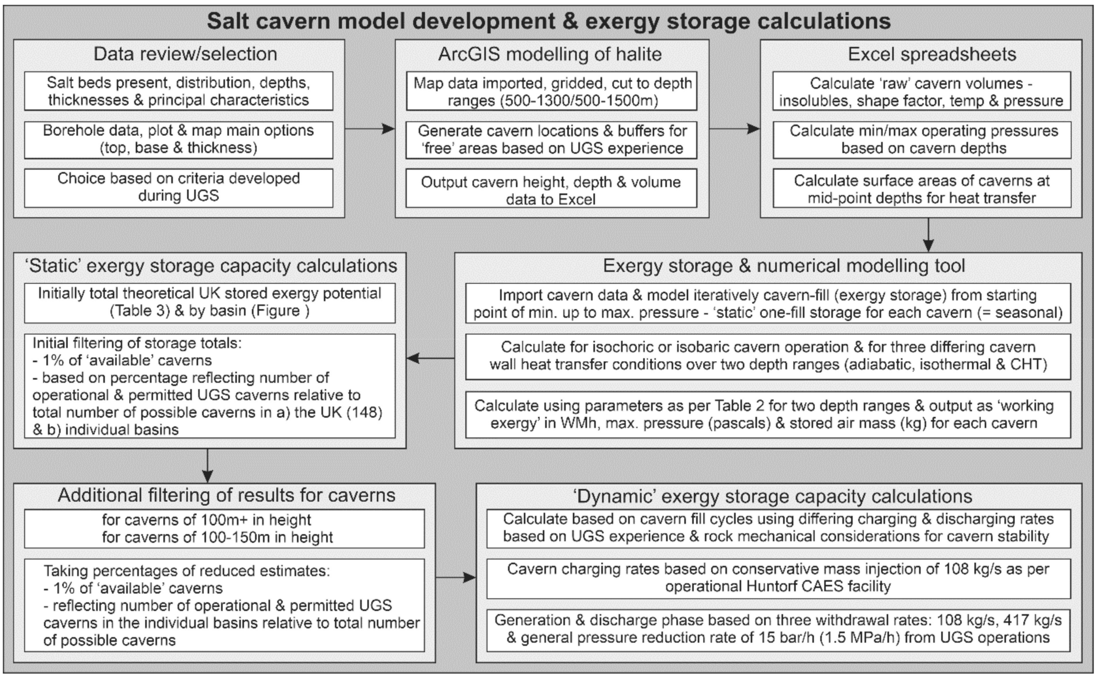

Figure 2. Workflow for the estimation of exergy storage provided by solution-mined salt caverns in the main halite-bearing basins of the UK.

These deposits offer important alternative energy storage capacity, and this study has assessed their potential for large-scale exergy storage through CAES. Differing from energy that is always conserved, exergy which takes its basis from the second law of thermodynamics, measures the loss of energy quality in every energy transformation process. Exergy tends to be destroyed during any conversion or storage processes, and therefore, exergy storage capacity quantifies the maximum useful work of the stored air that could be used in subsequent power generation. Exergy analysis is employed in applications with electricity output and power generation processes, and an exergy analysis tool was developed to estimate the exergy losses in energy conversions associated with a salt cavern-based CAES system. This permitted an estimate of the exergy storage capacity of the compressed air stored in a salt cavern for generating electricity during the discharging period [38]. Compared to conventional static thermodynamic exergy analysis, our developed tool also considers time-dependent factors that affect the overall electrical efficiency of a CAES system, such as dynamic internal air responses in the cavern and the coupled thermal effects of surrounding rocks [S3].

The Triassic and Permian bedded halite deposits in Northern Ireland have not been included here, as they are poorly defined and largely identified for UGS purposes [37]. Equally, the available Preesall Halite in NW England has also been identified for UGS and is not included here [37,39]. The Zechstein halite beds extend offshore from eastern England into the Southern North Sea, where due to halokinesis, they may attain great thicknesses. For various reasons, they have not been included in this study: they occur often far offshore and show significant changes in thickness over short distances, with some salt structures rising to shallow depths, even approaching close to sea bed, and are often in association with existing producing gasfields [40]. However, they should not be ruled out as CAES hosts, perhaps linked to the growing number of offshore windfarms. If existing hydrocarbon infrastructure (platforms, pipeline and cable routes, etc.) could be re-purposed, development costs, which are high for proposed gas storage caverns (A. Stacey, pers comm.), might be reduced significantly.

4.2. Exergy Storage Terminology—The Gas Storage Experience

The technology behind current and future storages for electrical energy based on compressed air, H_2, or SNG storages is derived largely from tried and tested storage technologies developed for the storage of natural gas [4]. A terminology has emerged to define operations and refer to the volumes of gas in an underground gas storage facility, which we adopt here when defining the exergy stored and explain below.

Underground gas storages generally operate by compressing the storage gas during injection and decompressing the gas again during withdrawal. The total gas storage capacity or volume is the maximum volume of natural gas that can be stored at the storage facility. This is governed by several physical factors such as the reservoir volume, engineering, and operational procedures including minimum and maximum pressure ranges and injection rates, which are determined from rock mechanical studies. The total storage volume comprises two elements:

- Working gas' volume, which represents the available gas that can be used between the maximum and the minimum operating storage pressures
- Cushion gas' volume, representing that below minimum operating pressure that is not available and which must remain permanently in the storage to provide the required minimum pressure to maintain the geomechanical stability of the storage. In the case of porous rock storage, it also provides some of the drive, but it is irretrievable, being effectively lost in the porosity.

The working gas volume represents the 'static', one-fill gas capacity and does not reflect multiple filling cycles. Thus, it is representative of a seasonal storage, similar to most traditional aquifer and depleted field storages. Of course, gas storages may be cycled many times during a year, which gives rise to what is described as a 'dynamic working gas volume' [39], which is greater than the static one-fill working gas volume.

Thus, exergy storage estimates are here referred to as the 'working exergy' (that available for work) and the 'cushion exergy' (that portion that must remain in the salt cavern/storage). The exergy tool was set up to calculate the static 'working exergy' (available) volume (see below). After introducing the static one fill 'working exergy' storage, we describe how, through a series of filters, attempts are made to derive realistic static 'working exergy' storage estimates from the total theoretical storage calculated (Figures 2 and 3a,b). These are based on cavern sizes and percentages of the total number of caverns, including that based upon the number of gas storage caverns in any particular basin (Figures 4–8).

However, as with gas storage caverns, the static 'working exergy' storage capacity is increased by multiple cavern-filling cycles. Therefore, also described and calculated are 'dynamic working exergy storage' capacity estimates, which are based upon multiple cavern cycles per year. The yearly cycle numbers are derived from different injection and withdrawal rates, which are informed by both CAES and UGS experience (S2, S3).

4.3. Exergy Storage Tool

The exergy storage system is represented by a thermal modelling tool developed during the EPSRC-funded IMAGES project [38] and augmented during this study (S3) to calculate stored exergy for individual caverns of known depths and size/volume, in two operational modes: constant volume, variable pressure (isochoric), and constant pressure, variable volume (isobaric) modes. The tool, equations for which were validated using operational data from the Huntorf CAES facility [38], considers three wall conditions to approximate and model the unsteady heat transfer (flux) between the injected air and cavern walls and models. Two cavern wall conditions represent idealistic and somewhat unrealistic, end-member models:

- Adiabatic boundary conditions in which heat flux into the surrounding rock mass is zero
- Isothermal boundary conditions in which heat flux is infinite with perfect conduction into and through the surrounding rock mass

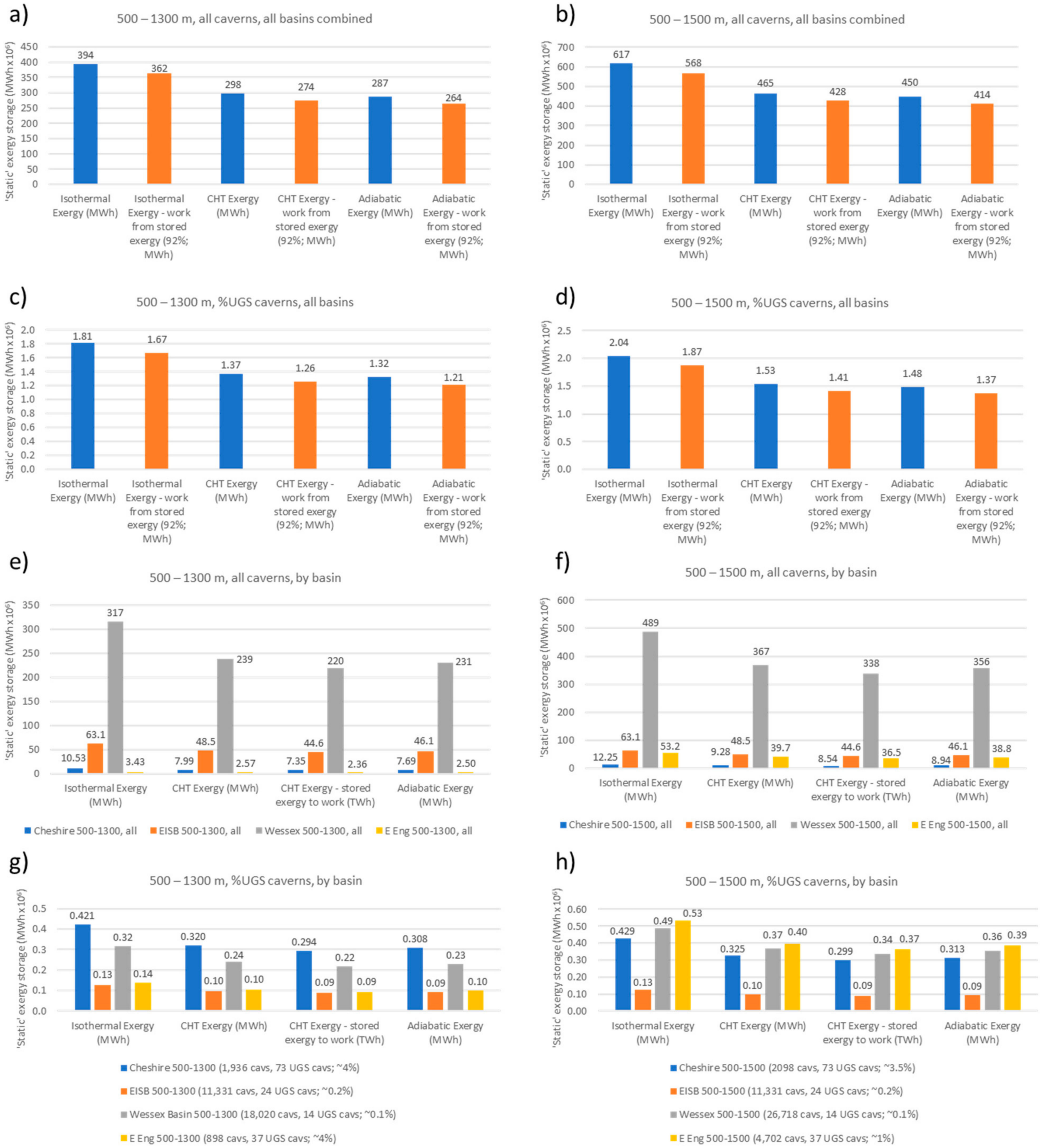

Figure 3. Plots of theoretical 'static' (one-fill) exergy storage estimates for the three thermal models for all potentially available caverns over the two depth ranges for all caverns with the basins studied. Parts (**a**,**b**) show graphs for combined totals from each basin for the two depth ranges, together with the estimated stored exergy to work for each thermal model. Parts (**c**,**d**) show graphs for the estimated stored exergy to work for each thermal model based upon percentages related to UGS numbers of the combined totals from each basin for the two depth ranges. Parts (**e**,**f**) show graphs breaking storage down by basin for the three thermal models, including stored exergy to work estimate for the CHT model also shown, with outlines data ranges being those pertinent to CHT model storage data presented in Figure 4. Parts (**g**,**h**) show graphs for estimates based upon a percentage related to the number of operation and/or planned UGS caverns in the basins.

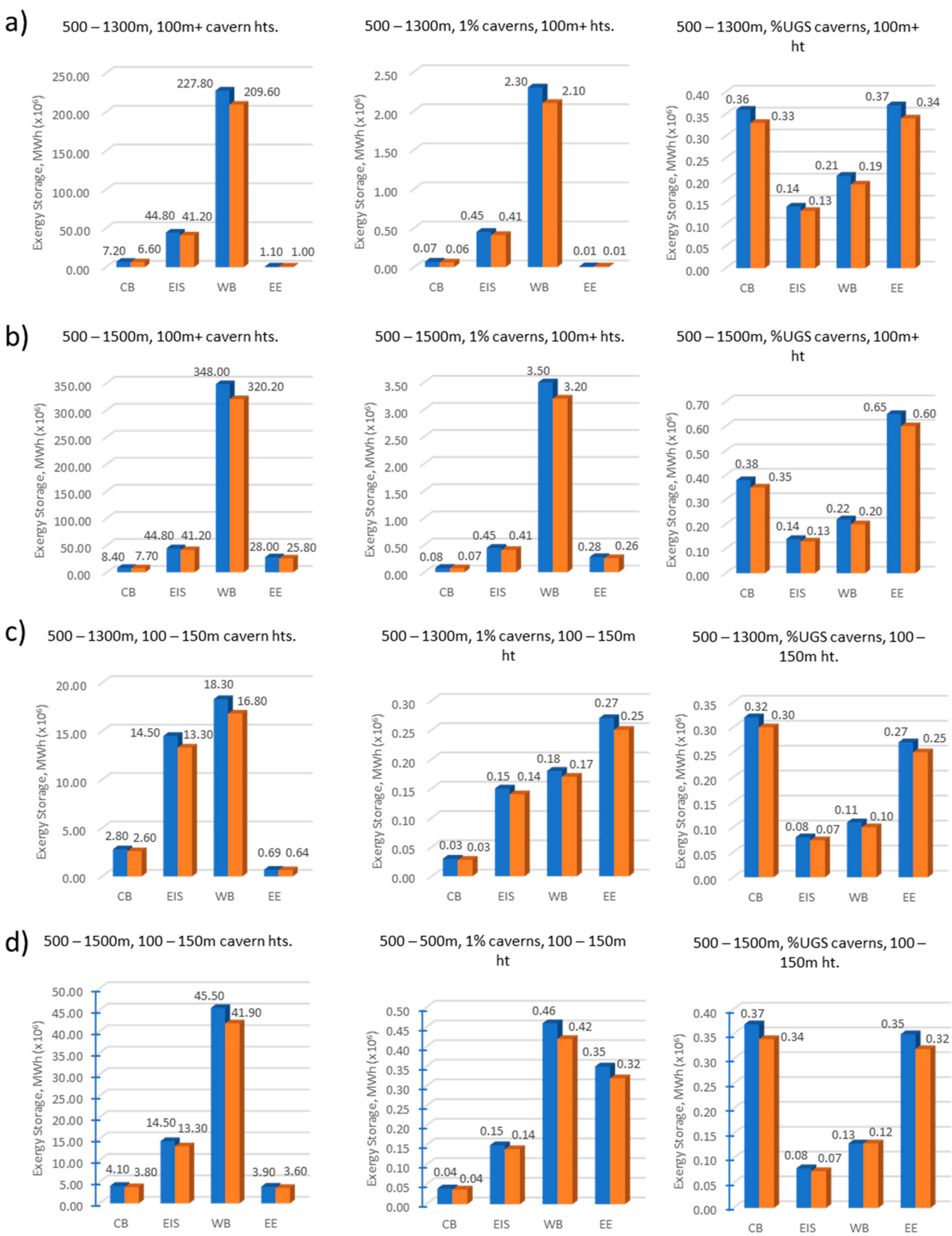

Figure 4. Plots of 'static' (one-fill) exergy storage estimates for the preferred CHT model, over the two depth ranges and cavern sizes (100 m+ and 100–150 m height) considered for CAES. Graphs for all potentially available caverns, 1% of available caverns and estimates based upon a percentage related to the number of UGS caverns in the basin. Parts (**a**,**c**) show data for the 500–1300 m depth range and parts (**b**,**d**) those data for the 500–1500 m depth range. Key common to all: blue = stored exergy, brown = stored exergy to work.

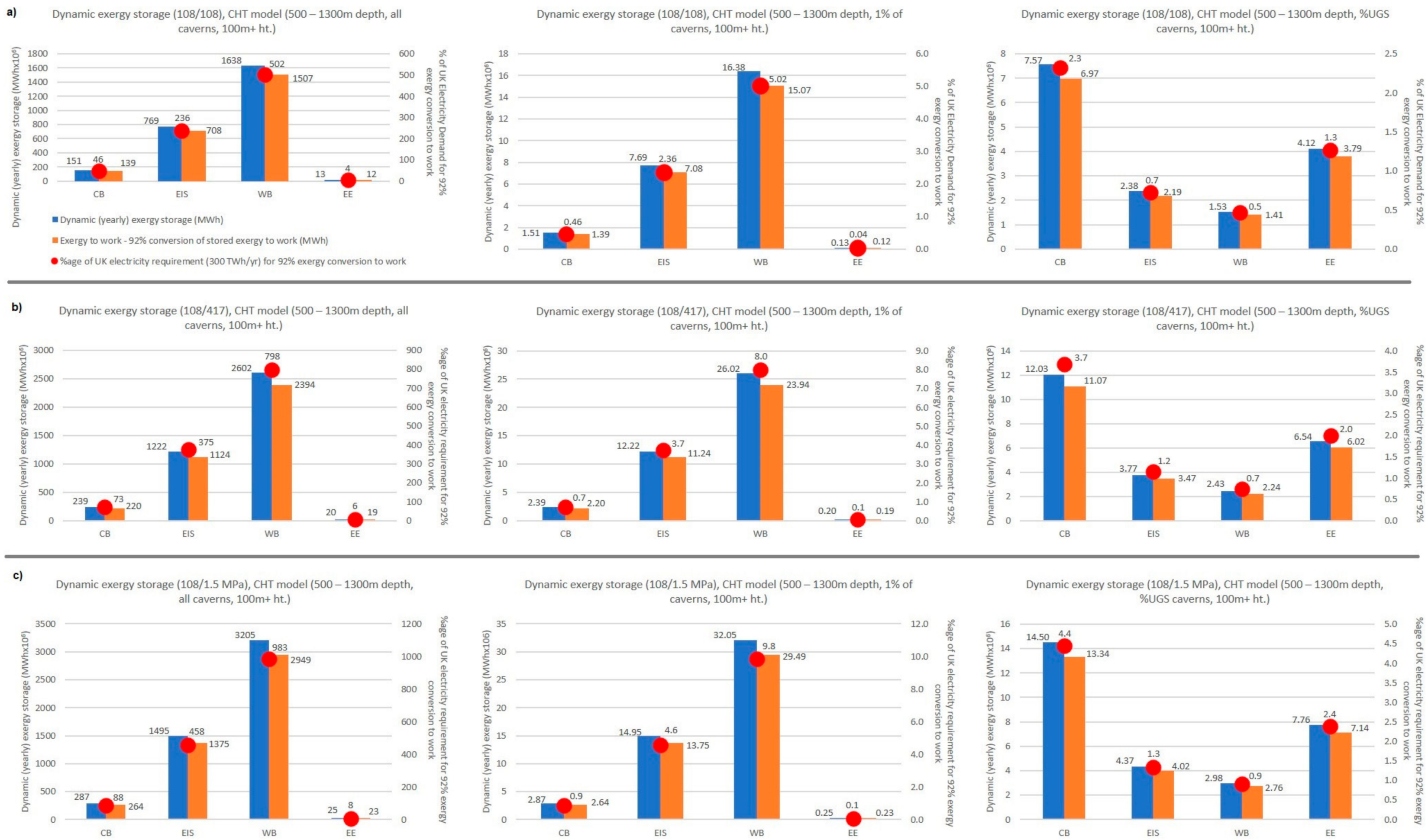

Figure 5. Plots of dynamic exergy storage and exergy to work estimates for the preferred CHT model, over the depth range 500–1300 m and cavern heights 100 m+ considered for CAES. Parts (**a**–**c**) show graphs for differing injection/withdrawal rates (108/108 kg/s and 108/417 kg/s) or fill and pressure reduction rates (108 kg/s/1.5 MPa/h) for all potentially available caverns, 1% of available caverns and estimates based upon the number of UGS caverns in the basins. Additionally shown, by basin, the percentage of UK electricity demand for 92% of stored exergy to work. Key common to all, see Figure 3.

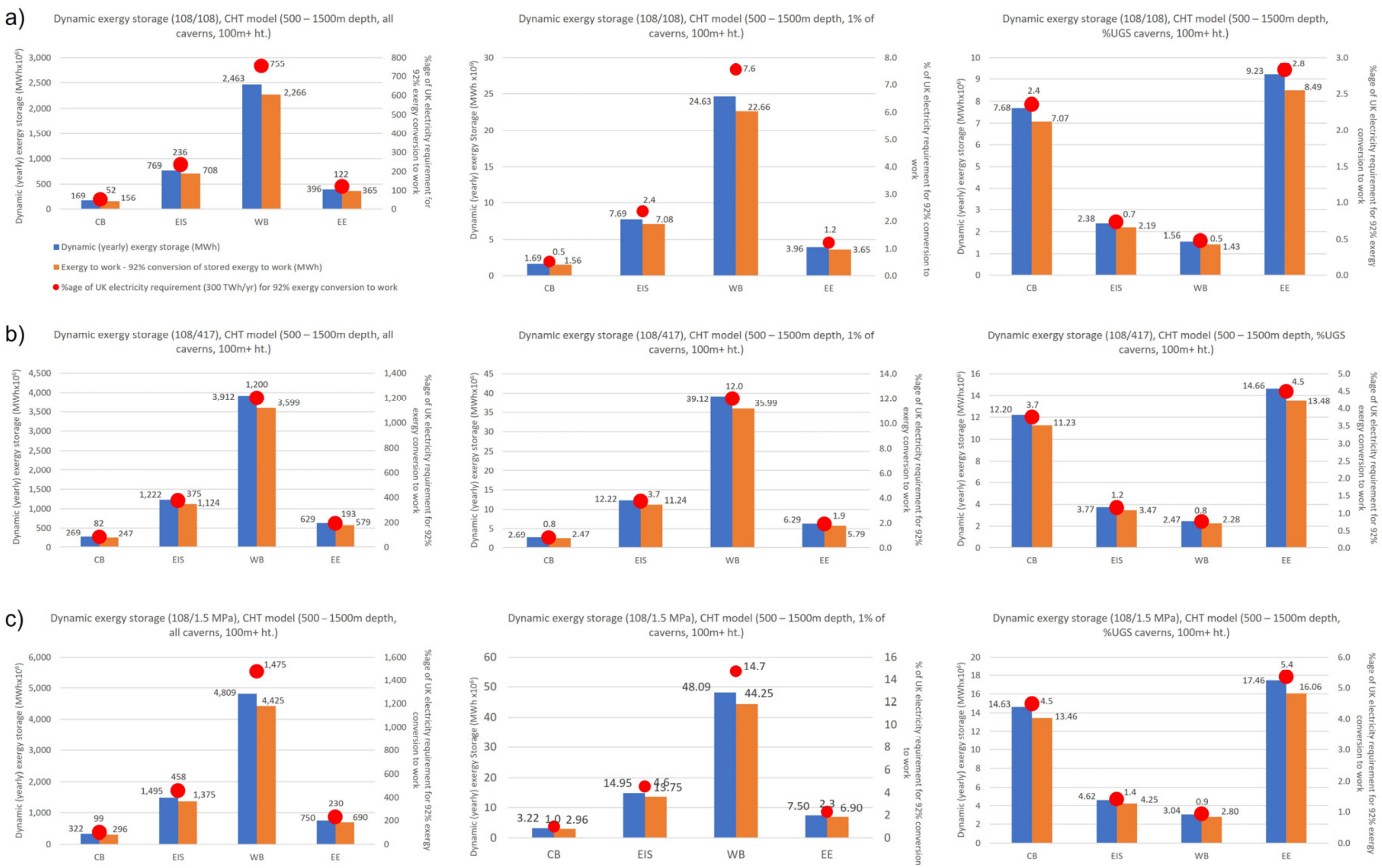

Figure 6. Plots of dynamic exergy storage and exergy to work estimates for the preferred CHT model over the depth range 500–1500 m and cavern heights 100 m+ considered for CAES. Parts (**a**–**c**) show graphs for differing injection/withdrawal rates (108/108 kg/s and 108/417 kg/s) or fill and pressure reduction rates (108 kg/s/1.5 MPa/h) for all potentially available caverns, 1% of available caverns, and estimates based upon the number of UGS caverns in the basins. Additionally shown, by basin, the percentage of UK electricity demand for 92% of stored exergy to work. Key common to all, see Figure 3.

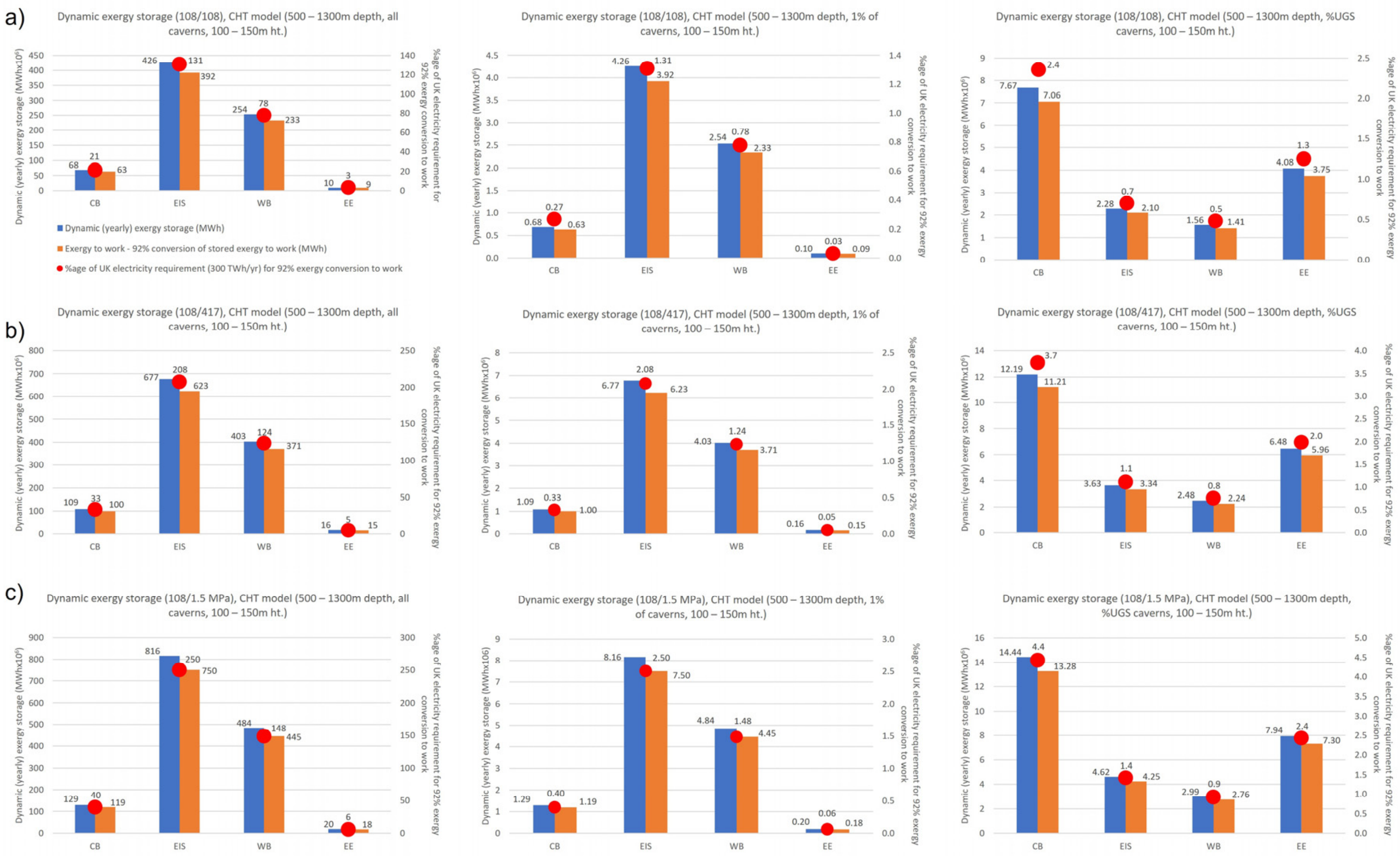

Figure 7. Plots of dynamic exergy storage and exergy to work estimates for the preferred CHT model, over the depth range 500–1300 m and cavern heights 100–150 m considered for CAES. Parts (**a**–**c**) show graphs for differing injection/withdrawal rates (108/108 kg/s and 108/417 kg/s) or fill and pressure reduction rates (108 kg/s/1.5 MPa/h) for all potentially available caverns, 1% of available caverns and estimates based upon the number of UGS caverns in the basins. Additionally shown, by basin, the percentage of UK electricity demand for 92% of stored exergy to work. Key common to all, see Figure 3.

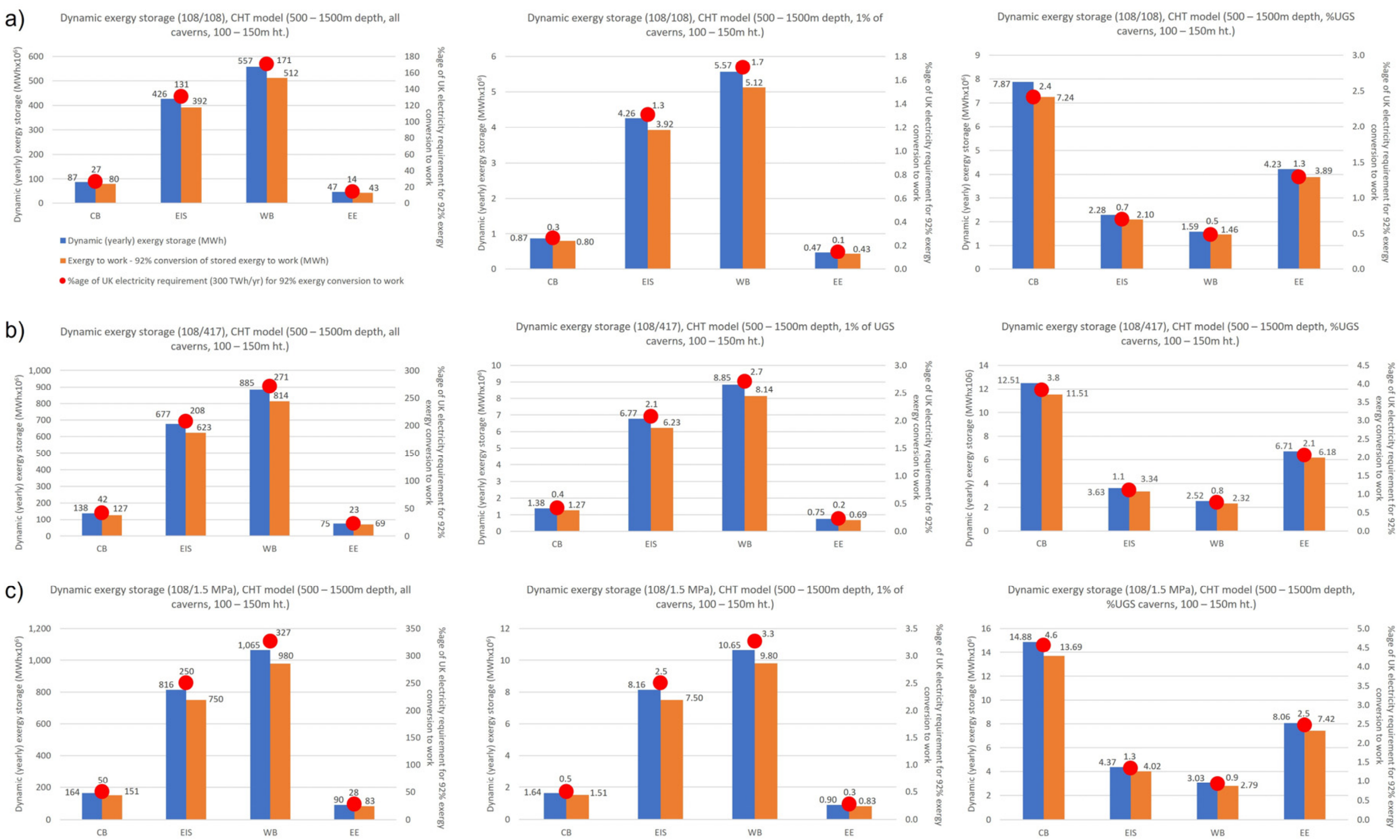

Figure 8. Plots of dynamic exergy storage and exergy to work estimates for the preferred CHT model, over the depth range 500–1500 m and cavern heights 100–150 m considered for CAES. Parts (**a**–**c**) show graphs for differing injection/withdrawal rates (108/108 kg/s and 108/417 kg/s) or fill and pressure reduction rates (108 kg/s/1.5 MPa/h) for all potentially available caverns, 1% of available caverns and estimates based upon the number of UGS caverns in the basins. Additionally shown, by basin, the percentage of UK electricity demand for 92% of stored exergy to work. Key common to all, see Figure 3.

In practice, realistic CAES cavern operation lies somewhere between the two end-member cases, and the convective heat transfer (CHT) wall condition for a practical (diabatic) cavern operational scenario was developed and is thought to more accurately represent actual storage conditions: during the cavern charging period, thermal energy of the air stored in the cavern is lost to the immediate surrounding rock mass, whilst the air temperature still increases due to the internal compression [38]. The two-end member scenarios produce slightly greater (isothermal) and smaller (adiabatic) exergy values, bracketing the CHT model (see Figure 3 and S2, Tables S3 and S4). Consequently, we have further refined the modelling tool for CHT conditions to implement their equations and predict the exergy stored when charging an uncompensated isochoric (constant volume, variable pressure) cavern or set of caverns. Results of this scenario are presented and discussed here.

Input parameters to the exergy modelling tool are summarised in S2, Table S2. Cavern surface areas and the calculation of heat transfer from the cavern void into the walls are necessary for CAES, estimates of which were derived relative to each cavern mid-point depth. They were calculated using the geothermal gradient for each specific basin, with an average annual surface temperature of 9.5 °C and pressure of 1 bar (14.5 psi). The tool imports the depths, volumes, temperatures, and min/max storage pressures calculated for each cavern and models iteratively, as well as the cavern-fill (exergy storage) from the starting point of the minimum to maximum permissible storage pressures. Results for the three differing cavern wall heat transfer models for each cavern over the two cavern depth ranges are output to a spreadsheet as the 'working exergy' storage in megawatt hours (MWh), together with the maximum pressure (pascals) and stored air mass (kg).

However, energy losses occur during generation, most notably through heat exchangers and in the turbines. From an energy and exergy analysis for 10 salt caverns of 100 m plus height in the Cheshire Basin, it was calculated that a full charge of all 10 caverns could store a net exergy of 25.32 GWh, of which ≈92% (23.19 GWh) could be converted to work via the turbines [41]. Therefore, alongside stored exergy estimates in Figures 3–8, we also present estimates of the stored exergy to work available, data behind which are provided in S2, Tables S3–S8.

4.4. Exergy Storage Assessment—Methodology

Figure 2 summarises the exergy storage assessment process. From borehole log data and map information in the public domain and held by the British Geological Survey, the tops, bases, and thicknesses of the halite deposits and major faults were mapped within each basin. These data were input to ArcGIS, which was used to obtain potential cavern locations, depths, and basic cavern parameters such as heights, diameters, available volumes, spacing and casing shoe depths based upon criteria applied to the design, development, and construction of gas storage caverns in the same strata [42]. The halite beds were evaluated over the depth ranges under consideration for CAES operations, with casing shoe depths (and thus pressures) in general between 500 and 1300 m [23] as well as up to 1500 m depth as at the proposed CAES plant at Larne, Northern Ireland [43]. Then, these basic cavern data were input to a modelling tool and used to estimate the exergy storage potential of prospective UK onshore and offshore East Irish Sea areas, using pressure and temperature ranges derived from gas storage investigations in these areas. Basic theoretical storage estimates are derived (Figure 3) that are only that and which, for various reasons, are clearly unrealistic totals. Most obviously, not all cavern locations will ultimately be available or suitable for cavern creation due to geological constraints, salt quality across the basin, together with economically and operationally viable cavern sizes. Therefore, a series of filters, based upon likely cavern height ranges, sizes, and differing storage operations, have been applied to derive more realistic CHT storage estimates for each basin. These can be compared to the annual UK electricity demand of 300 TWh [44].

In an attempt to obtain realistic assessments of the potential provided by the bedded halite resource, the total exergy storage estimates from each basin were filtered in a variety of ways:

- Taking 1% of the estimated exergy storage for the 'available' UK caverns
- Calculating the cavern storage estimates based on a percentage reflecting the number of operational or permitted UGS caverns in the UK (148) relative to the total number of possible caverns
- Filtering the caverns to include only those of greater than 100 m height
- Filtering the caverns to include only those of 100–150 m in height
- For the two filtered cavern height datasets, applying filters taking 1% of caverns and a percentage of the storage, using UGS cavern numbers relative to the total number of possible caverns in individual basins.

The figure of 1% is not based on industrial experience or previous studies. However, it provides a first pass understanding of the potential cavern numbers and storage capacities over the differing depth ranges, against which estimates set against the constructed or planned UGS cavern numbers in the two most developed basins can be evaluated (S2, Table S1): Cheshire Basin (73 caverns = 3.5–4%, for 500–1300 and 500–1500 m depths, respectively), Eastern England (37 caverns = 2–4%, respectively). Therefore, the figure of 1% is lower than these percentages and thus appears a reasonable gauge against which exergy storage estimates might be assessed initially (Figures 3 and 4). However, Figure 3 reveals very high storage estimates for the Wessex Basin, which is a potentially large region, but one in which the halite beds are less well characterised; halite beds were unknown in the area until oil and gas exploration began in the 1970s [37]. Consequently, further refinement of the estimates was attempted, reflecting more the degree of exploration and the proven potential and capabilities of the halite beds in each of the main halite basins. The greater numbers of storage caverns in the Cheshire Basin (73) and Eastern England (37) mean that these basins represent the most mature areas in terms of exploration and development of the halite beds. Thus, they potentially provide the more accurate and greater storage estimates when compared to using only the planned or permitted 24 and 14 cavern numbers for the lesser exploited EISB [45] and Wessex [46] basins, respectively. The latter two basins currently represent higher-risk target storage horizons, where in the case of the EIS, remoteness and its offshore location also increase CAPEX and OPEX costs of storage projects [45].

Additional efforts to derive realistic exergy storage estimates were also undertaken through filtering the storage outputs based upon cavern heights, with two sets of caverns assessed based on the experience of the maximum heights of gas storage caverns in the same salt beds, or those of proposed storage caverns in the Wessex Basin and the EIS. Firstly, caverns of 100 m and greater were selected, arising from the general sizes of UGS caverns developed or proposed in the same halite beds (refer S2, Table S1). Caverns smaller than ≈90 m in height are less economic to operate for gas storage purposes and are likely even more so for CAES due to the lower volumetric energy density (≈2.4 kWh/m^3) of air in comparison to natural gas (1100 kWh/m^3) [23]. Importantly, those caverns in which diameters are much larger than cavern heights of a few tens of metres could be geomechanically less stable, with caverns thus requiring smaller diameters and thereby likely to also result in uneconomically small cavern volumes [47]. Secondly, very large (tall) caverns carry stability issues and operational limits for rapid cycle storage, and therefore, cavern heights were limited to 100–150 m. This is in part based upon the nature of halite beds in the Wessex Basin, where geophysical logs reveal that the insoluble content can comprise significant percentages of the Dorset Halite Member (DHM) [37] and are likely to significantly impact cavern volumes, stability, and location. This will likely limit areas of development to those with suitably clean halite for cavern construction. However, salt exploration boreholes for the construction of 14 gas storage caverns have proved a saliferous sequence 470 m thick in areas of the basin, with the main halite unit (referred to as 'S7') up to 140 m thick with a low insoluble content of ≈16.5% and in which it was assessed that caverns of 100 m in height could be constructed for the purposes of gas storage [46]. Elsewhere, the Winterborne Kingston Borehole in the NE of the basin proved halite beds to be 190 m thick [37,48]. Thus, constraining cavern heights to between 100 and 150 m was thought to be realistic for the UK in general and the Wessex Basin in particular. As previously, a percentage of potentially available caverns and volumes, based upon filtering for 1% and the percentage of UGS caverns relative to the UGS cavern numbers, was also extracted for the two cavern height ranges.

5. UK Salt Cavern Exergy Storage Capacity Estimates—Results and Commentary

We now summarise and present the exergy storage estimates and storage capacities (Figures 3–6) for salt caverns in four of the main UK halite-bearing sedimentary basins: onshore Cheshire, Wessex, eastern England, and the offshore East Irish Sea (Figure 1; S2, Tables S3–S8). Figure 3a,b illustrate the total theoretical UK 'static' (one-fill) exergy storage and work from stored exergy for the three models and two depth ranges considered. For the preferred CHT model conditions, the stored exergy to work available in caverns for the 500–1300 m depth range (274 MWh) would almost meet the annual UK electricity requirement of ≈300 TWh (Figure 3a), whilst for the depth range 500–1500 m, the stored exergy to work available from all three models would prove sufficient to meet UK electricity needs (Figure 3b). Taking just 1% of the potential caverns provides a 'static' exergy storage for the CHT scenario of between ≈3 and 4.7 TWh in the 500–1300 and 500–1500 m cavern depth ranges, respectively (Figure 3a,b, S2, Table S3). Cycled once a month, this could generate between 36 and 56.5 TWh of storage, or up to one-fifth of the UK electricity demand, illustrating the importance of this technology in providing a significant contribution to the UK's energy storage capacity and electricity supply. It should be noted that cavern numbers in eastern England are influenced strongly by depth, with much of the available halite and thus cavern volume being below 1300 m depth.

Taking a percentage of the 'static' exergy storage estimates derived from the numbers of operating or permitted UGS caverns (148) relative to the number of potential storage caverns (32,185 and 44,849), for the CHT scenario, exergy storage ranges from ≈1.37 TWh (500–1300 m depth range) to 1.53 TWh (500–1500 m) for the UK as a whole (Figure 3c,d, S2, Table S3). Figure 3e,f shows the influence of the less explored and characterised Wessex Basin halite beds on storage estimates, being significantly greater than other basins, suggesting perhaps 239–367 TWh of storage available and far greater than in the Cheshire Basin (8–9.3 TWh) or eastern England (2.6–39.7 TWh). Figure 3g,h show the effects on 'static' storage of applying a filter based upon the number of operational or planned UGS caverns in a basin, with the Wessex Basin storage reducing markedly to 0.24–0.37 TWh, similar to the Cheshire Basin (0.32 TWh) and eastern England (0.1–0.4 TWh).

To refine the estimates, the data were filtered to extract those caverns with heights of 100 m and greater and those caverns of 100–150 m in height, as described above. For caverns of 100 m and greater (Figure 4a,b, S2, Table S4), CHT 'static' exergy to work storage estimates for the basins range from between 6.6 (500–1300m) and 7.7 (500–1500 m) TWh in Cheshire to ≈210 to 348 TWh in the Wessex Basin, the latter skewing the estimates. Cycled once a month, this could generate between ≈79 and 95 TWh of storage in Cheshire and 12–300 TWh in eastern England. For caverns of 100–150 m in height, the results range from 2.6 and 3.8 TWh in the Cheshire Basin, to between 18.3 and 45.5 TWh in the Wessex Basin, the latter again being highest, although estimates appear more realistic than simply taking caverns of 100 m and greater, which takes much of the thick DHM interval as available. For reasons discussed above, cavern construction may not be feasible over much of the upper DHM across the basin. Cycled once a month, this could generate between ≈79 and 95 TWh of storage in Cheshire and 12–300 TWh in eastern England.

When the 'static' stored exergy to work estimates for each basin are assessed in relation to the numbers of operational or permitted gas storage cavern numbers in the basins over the two depth ranges (Figure 4c,d, S2, Table S4), then the potential exergy storage offered is highest in the Cheshire Basin (up to 0.30 TWh) and eastern England (0.25 to 0.32 TWh) areas, with much less estimated for the EIS (<0.1) and Wessex Basin (0.1 to 0.12 TWh). Cycled once a month this could generate between ≈3.6 TWh of storage in Cheshire and 3–3.84 TWh in eastern England.

Gas storage caverns are cycled more than once a year, and CAES caverns more than gas storage caverns, effectively increasing the 'static' working gas storage capacity and giving rise to a larger 'dynamic' working gas volume [39], or 'dynamic exergy storage', as considered here. At this stage, it is impossible to determine precise cavern depths, sizes, and temperatures and thus undertake detailed geomechanical and thermodynamic modelling for all potential cavern locations, volumes, storage pressures, operating scenarios, and cycle times. Therefore, we outline the processes behind an attempt to calculate the general 'dynamic exergy storage' potential for both the 100 m and greater, and the 100–150 m cavern sets. This was undertaken by estimating the number of cycles per year, which is based upon flow rates calculated from cavern fill and withdrawal rates in UGS and CAES operations and taking the average values for the outputs of maximum cavern pressure, exergy stored and air mass in caverns for CHT conditions from the exergy modelling tool (see S3 and S2, Table S5).

Thus, cavern emptying or withdrawal times were calculated for three scenarios based upon an injection phase (cavern charging), involving a conservative mass injection rate of 108 kg/s, as reported from the Huntorf CAES facility [9] and three differing withdrawal rates (generation or cavern discharge phase): 108 kg/s (equivalent to injection rate), 417 kg/s (from Huntorf [9]), and a general maximum pressure rate reduction of 15 bar/h (1.5 MPa/h) for gas storage operations [9,49]. For the latter, an approximate equivalent air mass withdrawal rate in kg/s was calculated to assess how realistic the rate might be for any particular scenario. For the higher flow rates, it may be that caverns would require more than one withdrawal well to achieve the air mass withdrawal rates. Then, the calculated injection and withdrawal rates were used to derive an estimate of the number of cycles per year and thus determine the 'dynamic' exergy capacity available for the different model categories (Figures 5–8, S2, Tables S6–S8).

Figures 5–8 illustrate the 'dynamic' exergy storage (and stored exergy to work) increases of the 100 m plus and 100–150 m cavern height subsets over the 'static' storage estimates presented in Figures 3 and 4. Dynamic exergy storage estimates based upon the Huntorf operational parameters (Figure 5a, Figure 6a, Figure 7a and Figure 8a, S2, Table S6) are lower than those using faster withdrawal rates, which increase the number of storage cycles possible (Figure 5b,c, Figure 6b,c, Figure 7b,c and Figure 8b,c, S2, Tables S7 and S8). The 'dynamic' exergy storage results illustrate more markedly the potentially significant contribution of exergy storage through CAES in salt caverns to the UK's energy storage capacity and electricity supply. This is highlighted by taking the Cheshire Basin as an example. Here, exergy storage estimates from the operational cycle based on 108 kg/s fill rates and 108 kg/s withdrawal rates suggest that caverns of 100 m and greater or 100–150 m in height over the two depth ranges have the potential to provide between ≈139–156 TWh (Figures 5a and 6a) and 63–80 TWh (Figures 7a and 8a) stored exergy to work respectively, meeting between ≈46–52% and 21–27% of the UK electricity demand respectively. For the operational cycle based on 108 kg/s fill rates and maximum withdrawal rates of 1.5 MPa/hr, stored exergy to work estimates range between ≈264–296 TWh (Figures 5c and 6c) and 119–151 TWh (Figures 7c and 8c) respectively, meeting between ≈88–98% and 40–50% of the UK electricity demand, respectively. Taking the estimates based on UGS cavern numbers for the two depth ranges and cavern sizes, stored exergy to work estimates could, using the most cycled operational mode (Figures 5c and 8c), provide between 13.3 and 13.7 TWh, respectively, meeting ≈4.5% of the UK electricity demand.

The other halite basins provide similarly important additional exergy storage and exergy to work support, with for example, just 1% of all caverns of 100 m and greater in the 500–1500 m depth range in the basins providing a further ≈34–65 TWh of work and meeting ≈12–22% of the UK electricity requirements, depending on the mode of operation and cycle numbers (Figure 6a–c, S2, Tables S6–S8). Whilst 1% of caverns 100–150 m height in the same depth range might provide a further ≈9.53–18.1 TWh of work, meeting ≈3.2–6.0% of the UK electricity requirements (Figure 8a–c, S2, Tables S6–S8). Relative to UGS cavern numbers in the basins, the figures for 100 m plus caverns in the depth range 500–1500 m might provide an additional ≈12.1–23.2 TWh of work, meeting ≈4–7.7% of the UK electricity requirements (Figure 6a–c, S2, Tables S6–S8), whilst 100–150 m height caverns might provide ≈7.5–14.2 TWh of work, meeting ≈1.5–4.7% of UK electricity requirements (Figure 8a–c, S2, Tables S6–S8). These data illustrate the potential importance of CAES and salt cavern storage to UK electricity demand and supply.

6. General Discussion

This study has attempted an estimate of the exergy storage (and stored exergy to work) potential of major bedded halite deposits of the UK onshore and offshore East Irish Sea areas. Storage would be using salt caverns constructed in the massively bedded halites and storage estimates are based on three thermodynamic models for the temperature and pressure variations within CAES caverns developed by ref [38]. Clearly, a number of significant assumptions and generalisations have been necessary when assessing entire sedimentary basins. However, current salt cavern hosted gas storage facilities prove that the UK halite beds studied are capable of hosting large, stable caverns for high-pressure gas storage. 'Static' theoretical storage volume is enough to meet the UK electricity demand of 300 TWh, although this is unrealistic. Various filters applied to the cavern storage data together with cycle numbers based upon gas storage operational parameters provide more realistic dynamic exergy storage and stored exergy to work estimates of at least 36 MWh, illustrating that salt caverns onshore and in the EIS could deliver significant EES and grid-scale support.

Estimates for future UK electrical energy storage capacity needs for a net-zero system in 2050 range from about 1 TWh in total [50] to the latest National Grid Future Energy Scenario (NGFES) estimates of about 200 GWh [51]. In both cases, the majority of capacity requirement will be for large-scale, long-duration energy storage, with CAES in all three NGFES net-zero scenarios contributing about 20–40 GWh. Currently, PHS accounts for the majority of the UK energy storage capacity, which has 2.8 GW power capacity and 27.6 GWh storage capacity. In 2019, the total energy discharged by PHS in the UK was 1.7 TWh, which is only about 1/70 of the total gas power generation. Due to the potential site-specific negative environmental and ecological impacts of PHS and the limited availability of favourable sites, further expansion of PHS capacity in the UK will be difficult. Lithium-ion battery storage and hydrogen are two promising technologies that may fulfil this required capacity. Lithium-ion batteries have attracted attention and undergone significant development in the last 5 years. However, the cost structure (high CAPEX of energy in $/kWh) renders it suitable only for mainly daily cycling applications, instead of energy storage operations at timescales greater than 10 h, even with a significantly reduced cost in future (e.g., $150/kWh) [52]. The design space for large-scale, long-duration electrical energy storage is plausibly set to be up to $20–40/kWh for balancing a grid with high-penetration (>90%) variable renewable energy generation [53,54]. Alternatively, hydrogen energy storage is at the other end of the storage spectrum, being particularly suitable for long-duration energy storage. Compared to technologies such as PHS, batteries, and CAES, hydrogen is still in the development phase of prototype or demonstration in order to validate its technical performance. Its cost reduction may require massive infrastructure construction (e.g., centralised electrolysis) that enables convenient transmission and distribution of hydrogen [54,55] and further research on currently less mature technologies such as high-temperature solid oxide or molten carbonate fuel cells that may enable low-cost scalable hydrogen production [56]. Either of these will add to the uncertainty in timescale and system-scale of the technology in decarbonising the power system. Although a diverse range of large-scale long-duration energy storage technologies are needed to deeply decarbonise electrical systems, technologies with relative high technology maturity and resource availability will help mitigate the risk and ensure an early and steady decarbonisation progress in the next decade, which may also help reduce the cost required for meeting the net-zero goal [57].

Amongst all the EES technologies, CAES is a relatively mature technology with large-scale conventional (diabatic) CAES having been commercially operational since 1978 at Huntorf, in systems of over 100 MW capacity and employing salt cavern storages. In this time, pilot ACAES plants have been considered, with a small (2 MW) pilot plant having operated between 2012 and 2016 in Texas [25,26], and the commissioning in 2019 of the world's first ACAES plant in Canada [11], also using salt caverns. Demonstration plants on the scale of 1–10 MW have been under appraisal (S1, Tables S1–S6) in Europe [30] and China, where there has also been a successful integration test of the world's first 100 MW CAES expander [58]. In comparison with other EES technologies, CAES has very low energy-storage costs ($3–6/kWh) [59], which makes it a cost-effective solution for long-duration grid-scale energy storage. The cost of CAES is described as low compared to all other energy storage technologies, which is evidenced by [59,60]. This includes the cost of hydrogen energy storage, amongst other energy storage technologies. The works are considered by the authors to be suitable resources for comparing the costs and other important performance methods of energy storage technologies as opposed to providing too much detail in this manuscript. Therefore, there exists the real possibility for the deployment of CAES to offer flexibility at a scale currently provided by fossil fuels in the system balance on various timescales from short duration (minute to hourly) to long duration (days/weeks). In contrast to the alternative large-scale storage technology, PHS, recent studies, and our analysis indicate that substantial exergy storage potential exists for CAES in the UK area. It is suggested that saline porous rocks (aquifers) in sedimentary basins of the UKCS area could provide inter-seasonal electricity storage amounting to approximately 160% of the UK's electricity consumption for January and February of 2017 [15]. However, this storage is offshore and distant to demand centres onshore. Additionally, whilst there has long been interest in the potential for CAES in porous rock formations [13,14], serious doubts exist over the likely development of porous rock CAES, with no plants having operated commercially and only a few, mostly small, test facilities having been constructed: a small 25 MW R&D CAES demonstration facility operated between 1987 and 1991 at Sesta, Italy [61], while an aquifer field test facility was built at Pittsfield, Illinois, USA and ran from 1982 through to mid-1984 [14,62]. Following eight years of investigations and research (2003–2011) funded by the US DOE at the Dallas Centre, Iowa USA, the Iowa Energy Storage Project, which aimed to develop a utility-scale, bulk energy storage facility linked to renewable wind energy, was shelved [12]. All of the above porous rock projects encountered problems with one of more of the following: pressure anomalies, variations in reservoir quality and performance, 'air bubble' formation in the reservoir, reaction between the oxygen of the injected air and minerals in the reservoir rock leading to oxygen depletion and/or potential for bacterial/micro-organism growth and porosity reduction. Aquifer storage for the UK, which would be remote offshore, thereby increasing costs, thus seems less likely than salt cavern storage, at least in the short term.

By contrast, our results illustrate the main halite-bearing strata of the UK onshore and East Irish Sea areas offer very significant CAES exergy storage possibilities and capacity, which being closer to demand could play a major role in grid support, load-levelling, and helping to meet the UK's annual electricity demand, which is currently at a level of ≈300 TWh [44]. Such resources in combination with renewable energy generation, particularly solar and wind, could replace the current flexible power generation at a national scale. Open-source data [63] illustrate that although the UK has achieved substantial carbon emission reductions in its power sector in the last decades by reducing the coal-based generation by almost 95%, from about 100 TWh in 2009 to 6 TWh in 2019, gas power is still an essential source in offering flexibility to maintain the second-by-second balance between the power supply (including intermittent renewable power) and varying demand. In 2019, gas power provided 114 TWh electricity that is 42% of all the electricity generated.

To decarbonise the gas power and provide the flexibility sacrificed, energy storage will play a significant role and the use of salt cavern-hosted CAES could underpin decarbonisation of the UK power system by offering large-scale flexibility over multiple timescales.

7. Conclusions

A study of the main halite-bearing strata of the UK onshore and East Irish Sea areas in which UGS caverns have been constructed or planned has been undertaken to assess their potential for the construction of salt caverns for CAES purposes and their exergy storage potential. Storage depths investigated are between 500 and 1500 m. Revisions to an earlier exergy modelling tool, equations for which were validated by operational data from the Huntorf CAES plant, have led to a series of exergy storage capacity estimates for three differing heat models. Both the 'static' one-fill exergy storage capacity and a series of 'dynamic' exergy storage capacities based on various fill and empty rates are derived. From a theoretical storage of over 300 TWh, more realistic storage estimates of many tens of TWh are achieved by way of filtering the estimates based on cavern dimensions and different storage cycles considering UGS projects and operational modes. Significant exergy storage capacity exists for CAES in salt caverns, which could provide important support to the UK electricity grid, requiring 300 TWh per year. As the contribution of intermittent renewables generation to the grid rises, it is suggested that salt cavern storages constructed onshore, rather than porous rock storages located offshore, are likely to be the main CAES storage technology available in the UK at least in the short term.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app11114728/s1, S1, Tables S1–S6, S2, Tables S1–S8 and S3.

Author Contributions: Conceptualisation, D.E., J.B., J.W. (Jihong Wang) and S.G.; Formal analysis, D.E., D.P., M.D., P.W. and J.W. (John Williams); Funding acquisition, D.E., J.B., J.W. (Jihong Wang) and S.G.; Investigation, D.E., D.P., M.D., P.W. and J.W. (John Williams); Methodology, D.E., D.P., M.D., P.W., J.W. (John Williams) and W.H.; Project administration, D.E., J.W. (Jihong Wang) and S.G.; Software, D.P., M.D., P.W. and W.H.; Writing—original draft, D.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded from the UK Government's Engineering and Physical Science Research Council (EPSRC), UK grants EP/L014211/1 and EP/K002228/1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank three anonymous referees for comments on the manuscript all of which improved the final version. Financial support from the Engineering and Physical Science Research Council (EPSRC) funded Grand Challenge [Energy Storage] IMAGES project (EP/K002228) is gratefully acknowledged. This paper is published with permission of the Executive Director of the British Geological Survey (NERC).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. BEIS. *UK Becomes First Major Economy to Pass NET Zero emissions Law New Target Will Require the UK to Bring all Greenhouse Gas Emissions to Net Zero by 2050*; Department for Business, Energy and Industrial Strategy (BEIS): London, UK, 2019.
2. EU. Climate Action and the European Green Deal. Available online: https://ec.europa.eu/clima/policies/eu-climate-action_en (accessed on 31 March 2021).
3. Elliott, D. A balancing act for renewables. *Nat. Energy* **2016**, *1*, 1–3. [CrossRef]
4. Crotogino, F.; Schneider, G.-S.; Evans, D.J. Renewable energy storage in geological formations. *Proc. IME Part A J. Power Energy* **2017**, *232*, 100–114. [CrossRef]

5. Succar, S.; Williams, R.H. Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power. Report Prepared by Princeton Environmental Institute, Princeton University, 8 April 2008. Available online: https://acee.princeton.edu/wp-content/uploads/2016/10/SuccarWilliams_PEI_CAES_2008April8.pdf (accessed on 17 May 2021).
6. Crotogino, F.; Donadei, S. Grid-scale energy storage in salt caverns. In Proceedings of the 8th International Workshop on Large-Scale Integration of Wind-Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, Bremen, Germany, 14–15 October 2009.
7. Budt, M.; Wolf, D.; Span, R.; Yan, J. A review on compressed air energy storage: Basic principles, past milestones and recent developments. *Appl. Energy* **2016**, *170*, 250–268. [CrossRef]
8. Evans, D.J.; Carpenter, G.; Farr, G. Mechanical Systems for Energy Storage—Scale and Environmental Issues. Pumped Hydroelectric and Compressed Air Energy Storage. In *Issues in Environmental Science and Technology No. 46 Energy Storage Options and Their Environmental Impact*; Hester, R.E., Harrison, R.M., Eds.; The Royal Society of Chemistry: London, UK, 2018; pp. 42–114.
9. Crotogino, F.; Mohmeyer, K.U.; Scharf, D.R. Huntorf CAES: More than 20 years of successful operation. In Proceedings of the Spring 2001 Meeting, Orlando, FL, USA, 15–18 April 2001.
10. PowerSouth. Compressed Air Energy Storage. *McIntosh Powerplant, McIntosh, Alabama. PowerSouth Energy Cooperative Brochure.* 2017. Available online: http://www.powersouth.com/wp-content/%20uploads/2017/07/CAES-Brochure-FINAL.pdf (accessed on 2 April 2018).
11. Peretick, K. Energy Storage in the Real World: Practical Applications and Considerations. Michigan Agency for Energy "Plugging Into Storage—Energy Storage Symposium", Held 25 March 2019. Available online: https://www.michigan.gov/documents/energy/Energy_Storage_Session_4-Energy_Storage_in_the_Real_World_Peretick_652341_7.pdf (accessed on 17 May 2021).
12. Schulte, R.H.; Critelli, N., Jr.; Holst, N.; Huff, G. *Lessons from Iowa: Development of a 270 Megawatt Compressed Air Energy Storage Project in Midwest Independent System Operator: A Study for the DOE Energy Storage Systems Program*; Sandia National Laboratories: Albuquerque, NM, USA, 2012. Available online: https://www.sandia.gov/ess-ssl/publications/120388.pdf (accessed on 17 May 2021).
13. General Electric. Economic & Technical Feasibility of CAES. General Electric Co. Final Report Prepared for the United States Energy Research and Development Administration Office of Conservation, Contract E (11-1)-2559. 1976. Available online: http://www.osti.gov/scitech/servlets/purl/7195898/ (accessed on 17 May 2021).
14. Allen, R.D.; Doherty, T.J.; Kannberg, L.D. *Summary of Selected Compressed Air Energy Storage Sites*; Report prepared for the U.S. Department of Energy; Pacific Northwest Laboratory for Battelle: Richland, WA, USA, 1985.
15. Mouli-Castillo, J.; Wilkinson, M.; Mignard, D.; McDermott, C.; Haszeldine, S.R.; Shipton, Z.K. Inter-seasonal compressed air energy storage using saline aquifers. *Nat. Energy* **2019**, *4*, 131–139. [CrossRef]
16. UK Gov. New Plans to Make UK World Leader in Green Energy—The Announcement Is Part of the Government's Commitment towards Net Zero Emissions by 2050 and Will Support 60,000 Jobs; Johnson, B.H., Sharma, H.A., Eds.; UK Government Press Release. 2020. Available online: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy (accessed on 17 May 2021).
17. Aghahosseini, A.; Breyer, C. Assessment of geological resource potential for compressed air energy storage in global electricity supply. *Energy Convers. Manag.* **2018**, *169*, 161–173. [CrossRef]
18. United States Department of Energy Global Energy Storage Database. Available online: http://www.energystorageexchange.org/ (accessed on 5 December 2019).
19. Díaz-González, F.; Sumper, A.; Gomis-Bellmunt, O.; Villafáfila-Robles, R. A review of energy storage technologies for wind power applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2154–2171. [CrossRef]
20. Rosenberg, D.M.; Bodaly, R.A.; Usher, P.J. Environmental and social impacts of large scale hydro-electric development: Who is listening? *Glob. Environ. Chang.* **1995**, *5*, 127–148. [CrossRef]
21. Renewables, S. *The Benefits of Pumped Storage Hydro to the UK, Scottish Renewables*; DNV GL: Glasgow, UK, 2016.
22. Crotogino, F.; Huebner, S. Energy storage in salt caverns-developments & concrete projects for adiabatic compressed air and for hydrogen storage. In Proceedings of the SMRI Spring Meeting, Porto, Portugal, 27–30 April 2008; p. 179.
23. Kepplinger, J.; Crotogino, F.; Donadei, S.; Wohlers, M. Present Trends in Compressed Air Energy and Hydrogen Storage in Germany. In Proceedings of the Solution Mining Research Institute (SMRI) Fall 2011 Technical Conference, York, UK, 3–4 October 2011; p. 13.
24. Denholm, P.; Kulcinski, G.L. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Convers. Manag.* **2004**, *45*, 2153–2172. [CrossRef]
25. General Compression. Texas Dispatachable Wind 1, LLC. 2014. Available online: http://www.generalcompression.com/index.php/tdw1 (accessed on 8 November 2017).
26. Wilson, T.; Turaga, U. Oil Majors Pursue Energy Storage. 2016, Online Article by ADI Analytics, 29 July 2016. Available online: http://adi-analytics.com/2016/07/29/oil-majors-pursue-energy-storage-technology/ (accessed on 26 November 2016).
27. Medeiros, M.; Booth, R.; Fairchild, J.; Imperato, D.; Stinson, C.; Ausburn, M.; Tietze, M.; Irani, S.; Burzlaff, A.; Moore, H.; et al. *Technical Feasibility of Compressed Air Energy Storage (CAES) Utilizing a Porous Rock Reservoir*; Final Report; DOE-PGE-00198-1; Pacific Gas & Electric Company: San Francisco, CA, USA, 2018. Available online: https://www.osti.gov/servlets/purl/1434251 (accessed on 17 May 2021).

28. Grubelich, M.C.; Bauer, S.J.; Cooper, P.W. *Potential Hazards of Compressed Air Energy Storage in Depleted Natural Gas Reservoirs*; Sandia National Laboratories: Albuquerque, NM, USA, 2011.
29. Funk, J. First Energy Postpones Project to Generate Electricity with Compressed Air. Online Article, Posted 5 July 2013 at 1:44 PM. Available online: https://www.cleveland.com/business/index.ssf/2013/07/firstenergy_postpones_project.html (accessed on 17 May 2021).
30. Zanganeh, G.; Calisesi, Y.; Brüniger, R. *Demonstration of the Ability of Caverns for Compressed Air Storage with Thermal Energy Recuperation*; ALACAES SA Via Industria 10 CH-6710 Biasca; ALACAES: Lugano, Switzerland, 2016; 98p. Available online: https://www.aramis.admin.ch/Default?DocumentID=35281&Load=true (accessed on 17 May 2021).
31. Perillo, G. Report on Material Qualification Including Guidelines for Material Selection/Development. Design Study for European Underground Infrastructure Related to Advanced Adiabatic Compressed Air Energy Storage. RICAS2020 Deliverable D6.1 Report, 2016, 67p. Available online: http://www.ricas2020.eu/media/deliverable-d4-1-numerical-simulations/ (accessed on 17 May 2021).
32. EPRI. *Compressed Air Energy Storage Newsletter*; Electric Power Research Institute (EPRI): Palo Alto, CA, USA, 2010; p. 7.
33. EPRI. *Compressed Air Energy Storage Newsletter*; Electric Power Research Institute (EPRI): Palo Alto, CA, USA, 2012; p. 8.
34. Pimm, A.; Garvey, S.D.; de Jong, M. Design and testing of Energy Bags for underwater compressed air energy storage. *Energy* **2011**, *66*, 496–508. [CrossRef]
35. Li, P.Y.; Loth, E.; Simon, T.W.; Van de Ven, J.D.; Crane, S.E. Compressed Air Energy Storage for Offshore Wind Turbines. In Proceedings of the International Fluid Power Exhibition (IFPE), Las Vegas, NV, USA, 22–26 March 2011; p. 7.
36. Garvey, S.D. Integrating Energy Storage with Renewable Energy Generation. *Wind Eng.* **2015**, *39*, 129–140. [CrossRef]
37. Evans, D.J.; Holloway, S. A review of onshore UK salt deposits and their potential for underground gas storage. In *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe*; Evans, D.J., Chadwick, R.A., Eds.; The Geological Society: London, UK, 2009; pp. 39–80.
38. He, W.; Luo, X.; Evans, D.; Busby, J.; Garvey, S.; Parkes, D.; Wang, J. Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale compressed air energy storage system. *Appl. Energy* **2017**, *208*, 745–757. [CrossRef]
39. Mott MacDonald. *Preesall Underground Gas Storage Facility: Geological Summary Report, 2014*; Mott MacDonald for Halite Energy Group: Altrincham, UK, 2014; p. 169.
40. Cameron, T.D.J.; Crosby, A.; Balson, P.S.; Jeffrey, D.H.; Lott, G.K.; Bulat, J.; Harrison, D.J. *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea*; HMSO: London, UK, 1992.
41. Dooner, M.; Wang, J. Potential Exergy Storage Capacity of Salt Caverns in the Cheshire Basin Using Adiabatic Compressed Air Energy Storage. *Entropy* **2019**, *21*, 1065. [CrossRef]
42. Parkes, D.; Evans, D.J.; Williamson, P.; Williams, J.D.O. Estimating available salt volume for potential CAES development: A case study using the Northwich Halite of the Cheshire Basin. *J. Energy Storage* **2018**, *18*, 50–61. [CrossRef]
43. Haughey, C. Larne CAES: A Project Update In Gaelectric Energy Storage: The Missing Link. Gaelectric. 2015. Available online: http://www.gaelectric.ie/wpx/wp-content/uploads/2015/09/Gaelectric-Supplement-June-2015.pdf (accessed on 17 May 2021).
44. Dukes. Digest of United Kingdom Energy Statistics 2019: Chapter Five-Electricity. Digest of UK Energy Statistics (DUKES), Department for Business, Energy & Industrial Strategy (BEIS), Published 25 July 2019, p. 182. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820708/Chapter_5.pdf (accessed on 25 July 2019).
45. Gateway. *Gateway Gas Storage Project Offshore Environmental Statement: Non-Technical Summary*; Gateway Gas Storage: Edinburgh, UK, 2007; p. 282.
46. Wilke, F.H.; Wippich, M.G.E.; Zündel, F. *Outline Design of the Proposed Gas Storage Project at 'Upper Osprey' on the Isle of Portland, Dorset*; DEEP: Bad Zwischenahn, Germany, 2007; p. 67.
47. Charnavel, Y.; Durup, G. First Gaz de France Horizontal Salt Cavern Experiment. In Proceedings of the Spring 1998 Meeting, New Orleans, LA, USA, 19–22 April 1998; p. 14.
48. Rhys, G.H.; Lott, G.K.; Calver, M.A. *The Winterborne Kingston Borehole, Dorset, England*; Report of the Institute of Geological Sciences, Report Number CF/81-03; HMSO: London, UK, 1982.
49. Bérest, P.; Brouard, B.; Karimi-Jafari, M.; Pellizzaro, C. Thermomechanical aspects of high frequency cycling in salt storage caverns. In Proceedings of the International Gas Union Research Conference 2011, Seoul, Korea, 19–21 October 2011.
50. ETI. Catapult Energy Systems—Balancing Supply and Demand. Report funded by the Energy Technologies Institute (ETI), Published September 2019, p. 7. Available online: https://es.catapult.org.uk/reports/balancing-supply-and-demand/?download=true (accessed on 30 September 2019).
51. National Grid. Future Energy Scenarios. 2020, p. 124. Available online: https://www.nationalgrideso.com/document/173821/download (accessed on 17 May 2021).
52. Holladay, J.D.; Hu, H.; Kinf, D.L.; Wang, Y. An overview of hydrogen production technologies. *Catal. Today* **2009**, *139*, 244–260. [CrossRef]
53. Ziegler, M.S.; Mueller, J.M.; Pereira, G.D.; Song, J.; Ferrara, M.; Chiang, Y.M.; Trancik, J.E. Storage requirements and costs of shaping renewable energy toward grid decarbonization. *Joule* **2019**, *3*, 2134–2153. [CrossRef]
54. Albertus, P.; Manser, J.S.; Litzelman, S. Long-duration electricity storage applications, economics, and technologies. *Joule* **2020**, *4*, 21–32. [CrossRef]

55. Schmidt, O.; Gambhir, A.; Staffell, I.; Hawkes, A.; Nelson, J.; Few, S. Future cost and performance of water electrolysis: An expert elicitation study. *Int. J. Hydrog. Energy* **2017**, *42*, 30470–30492. [CrossRef]
56. Davis, S.J.; Lewis, N.S.; Shaner, M.; Aggarwal, S.; Arent, D.; Azevedo, I.L.; Benson, S.M.; Bradley, T.; Brouwer, J.; Chiang, Y.-T.; et al. Net-zero emissions energy systems. *Science* **2018**, *360*, 6396. [CrossRef]
57. Victoria, M.; Zhu, K.; Brown, T.; Andresen, G.B.; Greiner, M. Early decarbonisation of the European energy system pays off. *Nat. Commun.* **2020**, *11*, 1–9. [CrossRef]
58. Beijing Science and Technology Plan Project "Development and Demonstration of Large-Scale Advanced Compressed Air Energy Storage System" Passed the Acceptance Test. Available online: http://www.iet.cas.cn/xwdt/zhxw/201902/t20190211_5240114.html (accessed on 17 May 2021).
59. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
60. Mongird, K.; Viswanathan, V.; Balducci, P.; Alam, J.; Fotedar, V.; Koritarov, V.; Hadjerioua, B. An Evaluation of Energy Storage Cost and Performance Characteristics. *Energies* **2020**, *13*, 3307. [CrossRef]
61. Ter-Gazarian, A. Compressed air energy storage. In *Energy Storage for Power Systems*; Peter Peregrinus Ltd., on behalf of the Institution of Electrical Engineers: London, UK, 1994; p. 197.
62. EPRI. *Compressed Air Energy Storage Newsletter*; Electric Power Research Institute (EPRI): Palo Alto, CA, USA, 2011; p. 10.
63. Available online: http://www.gridwatch.templar.co.uk/download.php (accessed on 17 May 2021).