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Techno-economic analysis of deploying a short or mixed energy storage strategy in a 100 % green power grid

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ABSTRACT

A fully decarbonised electricity grid with extensively deployed renewable systems is a fundamental step in transitioning to a net-zero world. Unlike fossil energy, renewable energy systems are subject to meteorological intermittency. However, few studies have investigated the techno-economic performance of integrating short- and promising long-duration energy storage into a 100 % renewable energy grid to balance short-term and inter-seasonal demand.

This research developed an economic model to investigate the techno-economic performance of standalone and combined energy storage solutions for a fully green grid in three defined scenarios. Lithium-ion batteries (Li-ion), hydrogen, and electrical thermal energy storage (ETES) were selected as promising storage technologies due to their maturity, commercial availability, and scalability. The three examined scenarios are: 1) Li-ion battery only, 2) Li-ion battery with ETES, and 3) Li-ion battery with hydrogen. The research aims to determine whether combining long-duration energy storage (e.g., ETES and hydrogen) with Li-ion batteries offers greater economic and technical benefits, resulting in a more affordable, resilient, and secure power supply.

The results show that the Li-ion battery only scenario (Scenario 1) requires a capacity of 234,956 MWh. Adding ETES and hydrogen reduces this capacity to 53,304 MWh (Scenario 2) and 7020 MWh (Scenario 3). The addition of ETES and hydrogen improves power supply flexibility, increasing the proportion of generated electricity used to meet demand from 32.7 % in Scenario 1 to 41.2 % and 52.3 % in Scenarios 2 and 3, respectively. These technologies also help avoid electricity deficits, reduce the loss of power probability (LOPP), and lower the cost of electricity supply losses from $8365 million in Scenario 1 to $1793 million in Scenario 2 and only $4 million in Scenario 3. Power delivery costs decrease from $99.5/MWh in Scenario 1 to $77.6/MWh and $76.6/MWh in Scenarios 2 and 3, respectively. The research concludes with four policy recommendations to advance long-duration energy storage and transition to a fully green power supply system.

1. Introduction

In 2022, global electricity consumption was >25,000 TWh, which has more than tripled that of about 7000 TWh in 1980, and it contributes to >20 % of final energy consumption [1,2]. However, fossil fuels, like coal and natural gas, are still the main resources in electricity production, which contribute 58 % of overall worldwide electricity generation [3]. With the climate change agenda agreed by member countries in the Paris Agreement and COPs, all member countries set a clear climate change target either by 2050 (e.g., UK, EU countries, U.S.) or 2060 (e.g., China), shifting from fossil fuels to green energy resources (e.g., solar and wind).

Solar PV and wind turbines have become competitive green energy solutions to take over fossil energy sources in the power supply sector. The reason is that the capital cost of such technologies has significantly decreased in the last decade. For example, the global cost of solar PV has dropped by about 80–90 % between 2010 and 2019, benefiting from the implemented number of energy incentive schemes and technological innovations [4]. Unlike fossil energy sources, renewable energy systems

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Nomenclature

Acronym and equation characters

CAPEX	Capital Expenditure
CCUS	Carbon Capture, utilisation, and storage
COPs	Conference of the Parties
EAC	Equivalent Annual Cost
ETES	Electric Thermal Energy Storage
EU	European Union
EVs	Electric Vehicles
G20	The Group of Twenty
GA	Generic Algorithm
GHG	Greenhouse Gas
LOPP	Loss of Power Probability
MATLAB	Matrix Laboratory
OPEX	Operational Expenditure
PEM	Polymer Electrolyte Membrane
PHS	Pumped Hydrogen System
PJM	Pennsylvania-New Jersey-Maryland Interconnection
RTE	Round Trip Efficiency
Solar PV	Solar Photovoltaic
VAT	Value Added Tax
VOLL	Value of Lost Load
$C_{BES\_revenue}$	The received revenue using lithium-ion battery in the ancillary market
C_e	Equivalent Annual Cost
C_{ES}	The CAPEX of lithium-ion batteries (\$/MWh$_e$)
$C_{ETES/Hydrogen}$	The CAPEX of ETES and the CAPEX of hydrogen as the storage (\$/MWh$_{th}$)
$C_{installation}$	The associated installation capacity
C_p	The CAPEX of solar PV (\$/MW)
C_{VOLL}	The value of lost load (\$/MWh)
C_w	The CAPEX of wind turbine (\$/MW)
CI_e	The CAPEX of renewable energy systems and energy storage (\$/MWh)
L_D	The required electricity demand (MWh)
$L_{ES,t}$	The charging or discharging condition at time ‘t’
$L_{H,t}$	The volume-changing condition of the hydrogen tank at time ‘t’
L_{RE}	The total generated electricity from solar PV and WT (MWh)
$minC_T$	The most economically viable energy supply solution
P_e	The unit product cost of renewable energy system or energy storage
P_H	The produced hydrogen and η is the efficiency for the conversion from hydrogen to electricity
Pow_{ES}	The capacity of the added energy storage.
$Sto_{t,H}$	The stored hydrogen at the time ‘t’
$\overline{Sto}$	The maximum storage limit
\$/ kWh$_{cap}$	Cost per installed capacity of the lithium-ion battery
n	The lifespan of each renewable energy system or energy storage
SG_t	The loss of electricity at a specific time ‘t’.
Sto_t	The stored energy at ‘t’ time
ε	The charging efficiency
μ	The cost of electricity loss per unit of time
ρ	The discounted rate

are subjected to meteorological intermittency. Energy storage is therefore needed with renewable energy systems to enable a secure and stable power supply.

The existing studies started exploring the techno-economic performance of using Li-ion batteries and pumped hydro storage (PHS) with a mixed energy supply strategy (fossil + renewable + nuclear power) in the national power supply system [5,6]. To enable the net-zero transition, it is imperative to consider the feasibility of a power system that operates solely on renewable energy sources. However, few studies explored the power supply stability of implementing a fully green renewable energy system in a national power grid across different seasons. In addition, the short-duration energy storage like Li-ion battery can only continuously discharge electricity for a short-period (most commercially available batteries have duration up to 8 h) [7].

Existing studies have not demonstrated whether building up the over-deployed capacity of Li-ion batteries to manage the seasonal demand-supply balance is an economically and practically viable solution. In addition, existing studies have not yet examined the techno-economic performance of combining the existing commercially available short-term energy storage (e.g., a Li-ion battery) with inter-seasonal energy storage that has the potential to be scaled up to the utility level into a fully green grid. The findings, however, are beneficial in supporting future energy policy to shape a fully green national power supply strategy.

This research, therefore, developed an economic model to evaluate the techno-economic performance of short-term and mixed energy storage to incorporate a fully green power grid. Mixed energy storage refers to the combination of short-term and inter-seasonal energy storage. The findings address the knowledge gap identified in existing studies and could help policymakers reevaluate and shape future energy policies for long-duration energy storage. This would support the development of practical and affordable storage solutions for stabilising a 100 % green electricity system.

The rest of this research is structured as follows: Section 2 explains the review method and criteria for shortlisting the potential short-duration and inter-seasonal energy storage options to study in this research. This section also presents detailed techno-economic findings for the shortlisted energy storage technologies based on the reviewed relevant articles. Section 3 explains the methods used in developing the numerical model to evaluate the techno-economic performance of the short-duration and the mixed energy storage from the shortlisted energy storage options. Section 4 presents the techno-economic performance results, and section 5 discusses the potential impact of combining short and long-duration energy storage in a fully green power grid.

2. Literature review

This section defines the selection criteria for shortlisting storage options. The shortlisted storage options are then used as inputs to explore the economic performance of a fully green national power supply system. The defined selection criteria are shown in Table 1.

This research reviewed an extensive range of power storage options from the current and future storage market trends [8]. The reviewed storage options include compressed/liquid air energy storage, Li-ion battery, flywheel, hydrogen, pumped hydro, and electric thermal

Table 1
Defined criteria for energy storage option selection.

Criteria	Explanation
C1	Storage systems can manage both short-term and long-term power balance, with their primary functions being energy balancing and managing demand peaks.
C2	The storage option is not limited to any specific geographical location. In addition, the storage can be scaled up to the required size without any restrictions.
C3	The system is a mature technology with the potential to scale up quickly.

energy storage (ETES) [5,9–18]. Table 2 presents technical information of the reviewed energy storage technologies. It also presents the selected three energy storage technologies, including Li-ion batteries, ETES, and hydrogen, as well as the reasons for excluding other energy storage technologies.

2.1. Lithium-ion battery

Li-ion batteries are rechargeable batteries and are broadly used in cell phones, laptops, drones, robotic equipment and EVs. Li-ion batteries contain a lithium salt and an electrolyte solution that is a mixture of organic carbonates and additives [7]. Compared to a lead-acid battery, a Li-ion battery is more likely to have a safety issue [7]. This is due to Li-ion battery cells contain flammable electrolyte and significantly higher stored energy. The volumetric energy density of Li-ion batteries has increased from 55 Wh/L in 2008 to 450 Wh/L in 2020 [19]. If a Li-ion battery cell generates more heat than can be effectively dissipated, the excess heat may cause the separator to melt and shrink, leading to a short circuit [20]. The short circuit can lead to a rapid, uncontrolled release of heat energy, known as thermal runaway, which would result in a fire or explosion [21].

From the whole life-cycle environmental perspective, Li-ion battery is not entirely carbon free, as mining of the cathodic metals and anodic graphite is resource intensive. In addition, the lithium accounts for 11 % energy consumption in the manufacturing of Li-ion batteries [22]. Other components like aluminium and copper current collectors also present a significant environmental concern. However, the recycling industry of Li-ion batteries is growing helping to shape the Li-ion battery market to be more competitive than the lead-acid battery [7].

The lifespan of Li-ion batteries on average is between 9 and 15 years [7] or about 1500 cycles [23] within its lifespan. Moreover, the lifespan of Li-ion batteries is approximately 10 times longer than that of a standard lead-acid battery [24]. Tesla, in recent years, claimed that Powerwall 3.0 has an expected lifespan of >15 years [25]. In general, the continuous discharging of Li-ion battery at the utility level is about 2 h and can last up to 8 h at maximum [26].

The accurate estimation of the remaining functional capacity improves the security of the power supply using Li-ion batteries. Some existing studies have demonstrated that using improved dynamic mathematical models can accurately estimate the remaining functional capacity of Li-ion batteries [27,28]. The findings laid a concrete theoretical foundation for accurately estimating the remaining capacity of the Li-ion batteries from the whole-life-cycle perspectives, prompting the industrial application of Li-ion batteries.

Whilst Li-ion batteries have a short continuous discharging duration (up to 8 h), they play a pivotal role in managing the inter-day power supply-demand balance. They can respond to the discharge quickly (in seconds) and has a higher round trip efficiency at 95 % [29]; those factors are important to maintain the required frequency of the power supply.

The capital cost of Li-ion batteries slightly increased in 2022 due to the high inflation rate, expensive raw materials, and battery component costs. It was the first time that the capital cost of Li-ion batteries increased after a long period of cost reduction since 2010 [30]. The capital cost increased to \$151/kWh$_{cap}$ on average in 2022, with a 7 % rise from \$140/kWh$_{cap}$ in 2021 [30]. The cheapest Li-ion battery was

Table 2
List of energy storage technologies.

Storage technology	Type	Response time	Duration coverage	Commercial readiness	Power management function	Selection	Note
Compressed air energy storage (CAES)	Mechanical	minutes	Medium and Long	The diabatic CAES projects already exist, ongoing research on adiabatic CAES.	Energy balancing, demand peaks, weather variation and seasonal demand	N	Some storage options (salt cavern) might be restricted to geographical location (C2).
Compressed liquid energy storage	Mechanical	minutes	Medium	Pre-commercial stage	Energy balancing, demand peaks and weather variation	N	The system has not been used for either short or inter-seasonal power management (C1). The system is yet a mature technology (C3).
Electric Thermal Energy Storage	Thermal	minutes	Medium and Long	Mature technology	Energy balancing, demand peaks, weather variation and seasonal demand	Y	
Flow Batteries	Electrochemical	milliseconds	Medium	Increasingly commercialised, many deployed projects are located in Europe.	Energy balancing, demand peaks and weather variation	N	The system has not been used for either short or inter-seasonal power management (C1). The system is yet a mature technology (C3).
Flywheel	Mechanical	seconds	Short	Commercialised	Frequency response	N	The system has not been used in maintaining energy balancing or managing demand peak (C1). The system is also subjected to specific geographical locations (C2).
Li-ion Batteries	Electrochemical	milliseconds	Short and Medium (up to 6–8 h)	Mature technology, widely deployed across the world in both distributed and transmission level.	Frequency response, energy balancing, demand peaks and partial weather variations	Y	
Power to Gas (Hydrogen)	Hydrogen based storage	seconds	Medium and Long	Increasingly commercialised	Frequency response, energy balancing, demand peaks, weather variations and seasonal demand	Y	
Pumped Hydro	Mechanical	few seconds	Medium and Long	Mature technology, it has long history of deployment across the world	Energy balancing, demand peaks, weather variation and seasonal demand	N	The system is subjected to specific geographical locations (C2)

manufactured in China with a capital cost of \$127/kWh$_{cap}$; the capital cost of Li-ion batteries manufactured in Europe and the U.S. were about 33 % and 24 % higher than Chinese batteries in 2022. The higher capital cost of batteries indicates the relative immaturity of battery market in the Europe and the U.S, the higher production cost, the diverse range of applications and battery imports [30]. In 2023, Bloomberg NEF updated its annual Li-ion battery price survey, indicating that the global price dropped by 14 % to a record low of \$139/kWh between 2022 and 2023. The decreased price was driven by raw material and component prices failing due to the production capacity increase across the whole battery value chain [31]. The capital cost was expected to fall again from 2024 onwards due to recycling of the materials, expanding extractions, and refining capacity [31,32].

2.2. Hydrogen

Hydrogen has become a potential energy storage option because of its higher energy density per unit weight (e.g., 3 times higher than oil and 4.5 times higher than coal) [33]. Since 2018, many G20 countries like Australia, China, the EU, India, Japan, the UK, and the U.S., released detailed plans to strategically use hydrogen as energy storage in the power supply at either centralised or decentralised level ([34,35]; BEIS, 2021; [33]; The U.S. [36]; [74]).

Hydrogen can be produced via methane steam reforming or gasification and electrolysis [37,38]. The reforming method uses fossil energy sources like methane, natural gas, or the gasification of coal through a steaming process to produce hydrogen. GHG emission is generated in the hydrogen production process but is collected through a CCUS system; the produced hydrogen is then named blue hydrogen. If the GHG emission and the hydrogen production process have not been collected through a CCUS, then the produced hydrogen is termed grey hydrogen. When hydrogen is produced through an electrolyser system without any GHG emission, the produced hydrogen is termed green hydrogen. The reforming or gasification method accounts for 96 % (47 % from natural gas, 27 % from coal and 22 % from oil) of hydrogen production in 2021 [39,40].

The electrolyser produces hydrogen through the electrolysis process, which splits water molecules into hydrogen and oxygen using electricity [41]. Along with the increasing deployment of renewable systems and the progress to fully decarbonise the electricity grid, electrolysis is considered the main approach to achieving green hydrogen. Green hydrogen means that no GHG emission would be generated in hydrogen production. The PEM, alkaline and solid oxide are the three main electrolysers that are used to produce hydrogen [42]. The PEM and alkaline electrolysers have been broadly used at the commercial level, the solid oxide electrolyser is still at the demonstration level and has yet to be extensively used in the commercial market [43].

The alkaline and PEM approaches for producing hydrogen were established for different purposes. The alkaline electrolyser was invented to supply the needs of oxygen and hydrogen in the relevant chemical industries. However, PEM electrolysers were invented to achieve the climate change target and energy demand through the production of hydrogen. In the current electrolyser market, PEM is more expensive than the alkaline electrolyser; but PEM has a higher efficiency (80–85 %) than alkaline electrolyser (about 70 %) in hydrogen production [44].

2.3. Electric thermal energy storage (ETES)

Like hydrogen, ETES is also considered one of the promising inter-seasonal energy storage options, working with a fully renewable power supply system [45]. In the charging process, the excess electricity will be converted to heat and stored in a thermal storage tank. In the discharging process, the stored heat is used to re-generate electricity [46]. Three mechanisms are used to store heat in ETES, namely, sensible, latent, and thermochemical. The sensible and latent approaches face high energy loss in a longer storage period, resulting in their difficulty serving as long-term storage. Different from the sensible and latent approaches, the thermochemical approach is an ideal approach to storing heat for a longer period.

For an ETES using the thermochemical mechanism to store heat, the excess electricity is first converted to heat and then stored through reversible chemical reactions. In the discharging process, the stored heat is released to turn the turbines to generate electricity [47].

In general, ETES is flexible enough to incorporate with any renewable power generation system to store excess generated electricity to avoid the curtailed electricity. The RTE of ETES is between 50 and 60 % [48], and it has a good lifespan of up to 20 years on average [49], which allows payback of the capital cost within the lifespan. Thus, ETES is more economically competitive than Li-ion batteries due to the lower capital cost and the expected economic payback within the lifespan [50]. Tetteh et al. [48] carried out a cost calculation of an ETES based on a system-rated capacity of 88kWh. The calculation includes the cost of a metal tank, insulators and Stirling engine generator (in some ETES) and results in an estimated cost of \$69/kWh$_{cap}$.

3. Methodology

The economic model is developed to evaluate the techno-economic performance of the shortlisted short and mixed energy storage in a fully green power grid. This section explains the methods used to develop the numerical model. Section 3.1 describes the method used to develop an energy demand case that is then used to feed into the numerical model. Section 3.2 describes the development of three energy storage application scenarios. Those developed scenarios are tested in the numerical model to demonstrate the techno-economic performance of the short and mixed energy storage in a fully green power grid. Section 3.3 explains the method used to collect the economic data of renewable systems and the shortlisted energy storage technologies. Section 3.4 explains the development of the numerical model in detail.

3.1. Demand estimation

This research uses the Pennsylvania-New Jersey-Maryland Interconnection (PJM) sub-hourly electricity consumption data as an electricity consumption case profile. The reason for adopting the dataset is that it is a reliable resource to provide free historical sub-hourly electricity consumption data. Although the data reflects U.S. energy consumption, the research findings can still be extensively used in any countries that plan to use a fully green national power supply systems with different storage options. The two main reasons for adopting sub-hourly energy consumption data in this research are summarised as follows.

- Sub-hourly energy consumption data helps to identify the reliable and accurate size of renewable systems and the selected energy storage options in the defined Scenarios.
- The selected energy storage options can manage sub-hourly supply-demand balance.

3.2. Scenario development

This research creates three Scenarios to investigate the economic performance of the selected renewable systems and storage options to maintain the demand-supply balance at the national level. From the generation side, it assumes nuclear and hydro power capacity remains the same; renewable energy systems, including solar PV and wind turbines, will cover the exceeded demand. The selected energy storage options like Li-ion batteries, hydrogen and ETES are added to minimise the loss of electricity supply caused by the inflexibility of using renewable energy systems to generate electricity. The main difference in the function of the selected storage options is that the Li-ion battery manages the demand-supply balance in a short period (up to several hours), while ETES manages long-term (inter-seasonal) demand-supply balance [51]. Unlike Li-ion batteries and ETES, hydrogen is designed mainly to manage inter-seasonal demands but also assists with balancing where the optimised size of Li-ion batteries cannot cope with short-term demand-supply management. Table 3 presents the information of the developed three Scenarios.

3.3. Economic data collection

This research collects the CAPEX of the selected renewable systems, including solar PV, on/offshore wind and hydropower, from the report published by IRENA [52]. The report collected the global historical cost of different renewable systems based on real operating projects between 2010 and 2020. The collected CAPEX ($/kW) of solar PV, on/offshore wind and hydropower at the utility level is derived from the published weighted average total installation cost database in the report.

Those collected costs are excluded VAT (Value Added Tax) as VAT on renewable systems are different in countries. Table 4 presents the collected CAPEX of the selected renewable systems.

This research also collects the relevant costs of the shortlisted energy storage technologies. The CAPEX of Li-ion batteries is based on the report published by [31] with the global average cost of $139/kWh ($ per energy capacity) in 2022.

This research only considers the use of green hydrogen to store and balance the security of the power supply. Grey hydrogen releases a significant amount of greenhouse gas emissions. Although it is currently the primary approach for hydrogen production, it is expected to be replaced by low-carbon hydrogen in a net-zero scenario. Carbon capture technology (e.g., CCUS) can eliminate the negative impacts of the reforming or gasification process, resulting in low-carbon hydrogen production. However, the carbon capture efficiency might be overestimated, leading to an underestimated residual carbon and thereby decreasing the carbon reduction capability [53]. Only green hydrogen is a carbon-free energy fuel and is therefore considered as a viable storage option in the developed economic model.

Chrometzka et al. [54] found that CAPEX and OPEX are the two main parts of estimating hydrogen production costs. The CAPEX includes the cost of primary hydrogen production equipment. The operational cost includes the water and water purification cost, electricity charge and equipment maintenance cost. In addition, Chrometzka et al. [54] suggested considering factors like hydrogen production rate (kg/h) and lifespan that can improve the accuracy in estimating the cost.

This research follows the method Chrometzka et al. [54] developed with the adoptive changes to estimate hydrogen production cost. Such changes enable the calculation is more representative and fit for this research. In the CAPEX calculation, the average cost of an electrolyser is $1213/kW based on the published global average price of the PEM and alkaline electrolyser by IEA [43]. Except for the economic data, the calculation also adopted the following technical data from a 3 kW commercial PEM electrolyser [55], 1) the average hydrogen production rate of an electrolyser is 0.045 kg/h, and 2) The average lifespan is about 30,000 h and it can generate 1348 kg of hydrogen throughout the defined lifespan. Adding such technical data can enhance the accuracy of the estimated green hydrogen production cost.

For the OPEX part, this research uses the average UK business water rates between 2023 and 2024 published by AquaSwitch [56]. The water purification cost is collected from GrippaTank [57]. The electricity charge in hydrogen production is not considered in this research, as it assumes using the curtailed electricity from renewable systems is used to produce hydrogen; therefore, the electricity cost is zero. The maintenance cost of an electrolyser is $45/kW per year [54].

Table 3
The developed three scenarios.

Scenario number	Power system	Energy storage
1	Solar PV + WT	Lithium-ion Battery
2		Li-ion Battery + Thermal Energy Storage
3		Li-ion Battery + Hydrogen

Table 4
Collected installation cost of solar PV, on/offshore wind turbine, and hydropower at utility-scale.

Renewable technology	The weighted average CAPEX in $/kW
Solar PV	857
Onshore wind turbine	1325
Offshore wind turbine	2858
Hydropower	2135

The model developed by Chrometzka et al. [54] does not include the cost of the hydrogen storage tank due to the following two reasons. First, the hydrogen storage tank cost is expensive in the present market [58]; adding the hydrogen storage tank can significantly increase hydrogen production cost. Secondly, the hydrogen storage tank is still at an early market stage, with limited publicly accessible commercial price data in the market. A compressed 700 bar Type - 4 hydrogen storage tank from the research of Houchins & James [59], is then used as a representative example in this research to calculate the total hydrogen production cost.

Using the collected data, the estimated cost of producing 1 kg of hydrogen based on the selected system and a hydrogen storage tank in a lifespan of 10 years is $418. It is then assumed 1 kg of hydrogen can generate 23 kWh of electricity [60]. Given the calculation explained above, using the produced and stored 1 kg of hydrogen to produce electricity is about $18/kWh.

This research uses the cost of ETES from the study investigated by Tetteh et al. [48], who calculated the cost of ETES based on an ETES case study. The study calculated the total cost of **$69/kWh** using ETES to deliver electricity back to the grid. The calculation considered using sand in the thermal storage tank, a Stirling engine generator and the round-trip efficiency of 85 %.

3.4. Economic model development

The economic evaluation model is developed in MATLAB to assess the defined three Scenarios (section 3.2). This model aims to find the optimal size of each system in the defined scenarios to achieve the minimum electricity delivery cost using the Generic Algorithm (GA). Once the optimal size of each system in the defined scenarios is found, it then continues to discuss and compare the techno-economic performance of the optimised system in each defined scenario.

Eq.(1) presents the used optimisation equation to find the optimal size of each system in the defined scenarios.

$$minC_T = C_p + C_w + C_{ES} + C_{ETES/Hydrogen} + C_{VOLL} - C_{BES\_revenue} \tag{1}$$

Where, C_p represent the total cost solar PV, C_w represents the total cost of wind turbines, C_{ES} represents the total cost of Li-ion battery, and $C_{ETES/Hydrogen}$ represents the total cost of ETES or hydrogen. C_{VOLL} represents the cost of the generated load cannot meet the demand. In the Li-ion battery and hydrogen scenario, hydrogen can manage the long-term (monthly and seasonally) power supply-demand balance and assist Li-ion battery in managing the short-term (daily and weekly) supply-demand balance. Given that response time of Li-ion batteries and hydrogen being similar, the added $C_{BES\_revenue}$ helps to identify the exact amount of electricity from the Li-ion battery used to manage the supply-demand balance. Balance. This research used a unit revenue of $10,000/MW for Li-ion batteries ($C_{BES_revenue} = \$10,000/MW$) from the California ISO ancillary market as an indicative figure to distinguish the contribution to the short-term demand balance from Li-ion batteries and hydrogen [61]. In the Li-ion battery and ETES scenario, the ETES, however, is not characterised by a fast power response, it is only used to maintain the long-term power supply-demand.

The total generated or stored electricity (CI_e) of solar PV, wind turbine, Li-ion batteries, ETES and hydrogen is calculated through Eq. (2).

$$CI_e = P_e \times C_{installation} \tag{2}$$

Where, P_e is the unit generation load of renewable systems or the unit stored electricity load of energy storage technologies. $C_{installation}$ stands for the optimised size of each system.

The equivalent annual cost (EAC) (C_e) in Eq. (3) is used to represent the total cost of solar PV (C_p) and wind turbines (C_w), Li-ion Batteries (C_{ES}) and ETES or hydrogen storage ($C_{ETES/Hydrogen}$) in the associated lifespan. ρ is the discounted rate, which is 3.5 % in this research. n is the lifespan of the system.

$$C_e = CI_e \times \frac{\left[1 - {}^{1}/(1+\rho)\right]}{\left[1 - {}^{1}/(1+\rho)^{n}\right]} \times (1+\rho)^{0.5} \tag{3}$$

The SG_t represents the yearly overall unmet electricity demand by the optimised renewable systems and energy storage technologies in each scenario. The associated cost is calculated through Eq. (4).

$$C_{VOLL} = \mu \sum_{t=1}^{8760} SG_t \tag{4}$$

Where, the unit cost of VOLL (μ) is \$1409/MWh, and the value is derived from the historical average value used in the residential and industry sector reported by Fairbairn [62].

Once Li-ion batteries are added to the power supply strategy, the charging and discharging process is calculated through the following equations.

The net electricity load (l_{NNS}) represents the differences between the total generated electricity (L_{RE}) by solar PV and wind turbines and the estimated energy demand (L_D). L_{NNS} is calculated through Eq. (5).

$$l_{NNS} = L_{RE} - L_D \tag{5}$$

If $L_{NNS} > 0$ (generation is higher than the demand), Li-ion batteries will be in charging mode; while $L_{NNS} < 0$ (demand is higher than the generation), suggesting that Li-ion batteries are in the discharging mode. Eq. (6) expresses four charging conditions.

$$\mathrm{L_{ES,t}} \begin{cases} -\varepsilon^{*}\mathrm{Pow_{ES}} \;\; \mathrm{l_{NNS,t}} \geq \mathrm{Pow_{ES}} \text{ and } \overline{\mathrm{Sto}} - \mathrm{Sto_t} \geq \varepsilon^{*}\mathrm{Pow_{ES}} \\ -(\overline{\mathrm{Sto}} - \mathrm{Sto_t})/\varepsilon \; \mathrm{l_{NNS,t}} \geq \mathrm{Pow_{ES}} \text{ and } \overline{\mathrm{Sto}} - \mathrm{Sto_t} < \varepsilon^{*}\mathrm{Pow_{ES}} \\ -\mathrm{l_{NNS,t}} \; \mathrm{l_{NNS,t}} < \mathrm{Pow_{ES}} \text{ and } \overline{\mathrm{Sto}} - \mathrm{Sto_t} \geq \varepsilon^{*}\mathrm{l_{NNS,t}} \\ -(\overline{\mathrm{Sto}} - \mathrm{Sto_t})/\varepsilon \; \mathrm{l_{NNS,t}} < \mathrm{Pow_{ES}} \text{ and } \overline{\mathrm{Sto}} - \mathrm{Sto_t} < \mathrm{l_{NNS,t}} \end{cases} \tag{6}$$

Where, $\overline{Sto}$ is the storage upper limit of Li-ion batteries, Sto_t is the stored electricity at a time 't', ε is the charging efficiency, Pow_{ES} is the installation capacity of Li-ion batteries and $\overline{Sto} - Sto_t$ stands for the charging capacity at time 't' for the specified installation capacity of Li-ion batteries.

Therefore, in Eq. (6), when the net electricity load is higher than or equal to the installation capacity of Li-ion batteries $l_{NNS,t} \geq Pow_{ES}$, and the charging capacity at time 't' is higher than the product of charging efficiency and installation capacity, the charged electricity is of $\varepsilon^{*}Pow_{ES}$. This indicates that the installed capacity of Li-ion is sufficient to take as much as net electricity load at time 't'. However, if the charging capacity at a time 't' is smaller than the product of charging efficiency and installation capacity. It means the installed capacity of Li-ion batteries can only absorb electricity up to $(\overline{Sto} - Sto_t)/\varepsilon$.

If the net electricity load is smaller than the installation capacity of Li-ion batteries $l_{NNS,t} < Pow_{ES}$. When the charging capacity at a time 't' is higher than the product of charging efficiency and installation capacity, the charged electricity at a time 't' is the net electricity load at a time 't'. When the charging capacity at a time 't' is lower than the product of charging efficiency and installation capacity, the charged electricity at a time 't' is $(\overline{Sto} - Sto_t)/\varepsilon$.

Eq. (7) expressed four discharging conditions.

$$L_{ES,t} \begin{cases} \varepsilon^{*}Pow_{ES} - l_{NNS,t} \geq Pow_{ES} \text{ and } Sto_t \geq \varepsilon^{*}Pow_{ES} \\ \varepsilon^{*}Sto(t) - l_{NNS,t} \geq Pow_{ES} \text{ and } Sto_t < \varepsilon^{*}Pow_{ES} \\ -l_{NNS,t} - l_{NNS,t} < Pow_{ES} \text{ and } Sto_t \geq \varepsilon^{*}l_{NNS,t} \\ \varepsilon^{*}Sto(t) - l_{NNS,t} < Pow_{ES} \text{ and } Sto_t < \varepsilon^{*}l_{NNS,t} \end{cases} \tag{7}$$

In the discharging process, if the net electricity load is higher than or equal to the installation capacity, and the stored electricity at time 't' (Sto_t) is higher than or equal to the product of charging efficiency and installation capacity; then the discharged electricity at a time 't' is $\varepsilon^{*}Pow_{ES}$. However, if the stored electricity at time 't' is smaller than the product of charging efficiency and installation capacity, it means that Li-ion batteries can only discharge electricity up to a maximum of $\varepsilon^{*}Sto(t)$ at time 't'.

When the net electricity load is smaller than the installation capacity, and the stored electricity at time 't' (Sto_t) is greater than or equal to the product of charging efficiency and installation capacity, Li-ion batteries can discharge electricity to fully cover the net electricity load at time 't'. If the stored electricity at time 't' (Sto_t) is smaller than the product of charging efficiency and installation capacity, Li-ion batteries can only discharge electricity up to a maximum of $\varepsilon^{*}Sto(t)$ at time 't'.

While adding hydrogen and ETES to assist Li-ion batteries to manage the long-term demand-supply balance. It first needs to calculate the new demand-supply gap (L_{NNS_New}) after adding the Li-ion batteries. After calculating the new demand-supply gap, the following equations Eq. (8) and Eq. (9) demonstrate the charging and discharging process of hydrogen or ETES.

$$\text{If } L_{NNS\_New} > 0 \text{ (charging process)}, L_{H,t} = Sto_{t,H} + P_H/\eta \tag{8}$$

$$\text{If } L_{NNS} < 0 \text{ (discharging process)}, L_{H,t} = Sto_{t,H} - P_H/\eta \tag{9}$$

Where, $L_{H,t}$ stands for the charged or discharged electricity at time 't'. $Sto_{t,H}$ stands for the condition of energy storage at time 't'. P_H stands for the installed capacity of energy storage and η is the charging/discharging efficiency.

If the energy demand still cannot be covered after discharging all added energy storage technologies, then it calculates the loss of electricity at time 't' through Eq. (10).

$$SG_t = l_{NNS,t} - L_{ES,t} \tag{10}$$

In addition, if the renewable energy systems generate excess electricity that cannot be stored in the added storage technologies then the curtailed electricity at time 't' (RA_t) is calculated using Eq. (11).

$$RA_t = \begin{cases} l_{NNS,t} + l_{ES,t} \; l_{NNS,t} > 0 \\ 0 \; l_{NNS,t} \leq 0 \end{cases} \tag{11}$$

Table 5 summarised the key inputs, optimisation purposes and the expected outcomes in the developed economic model.

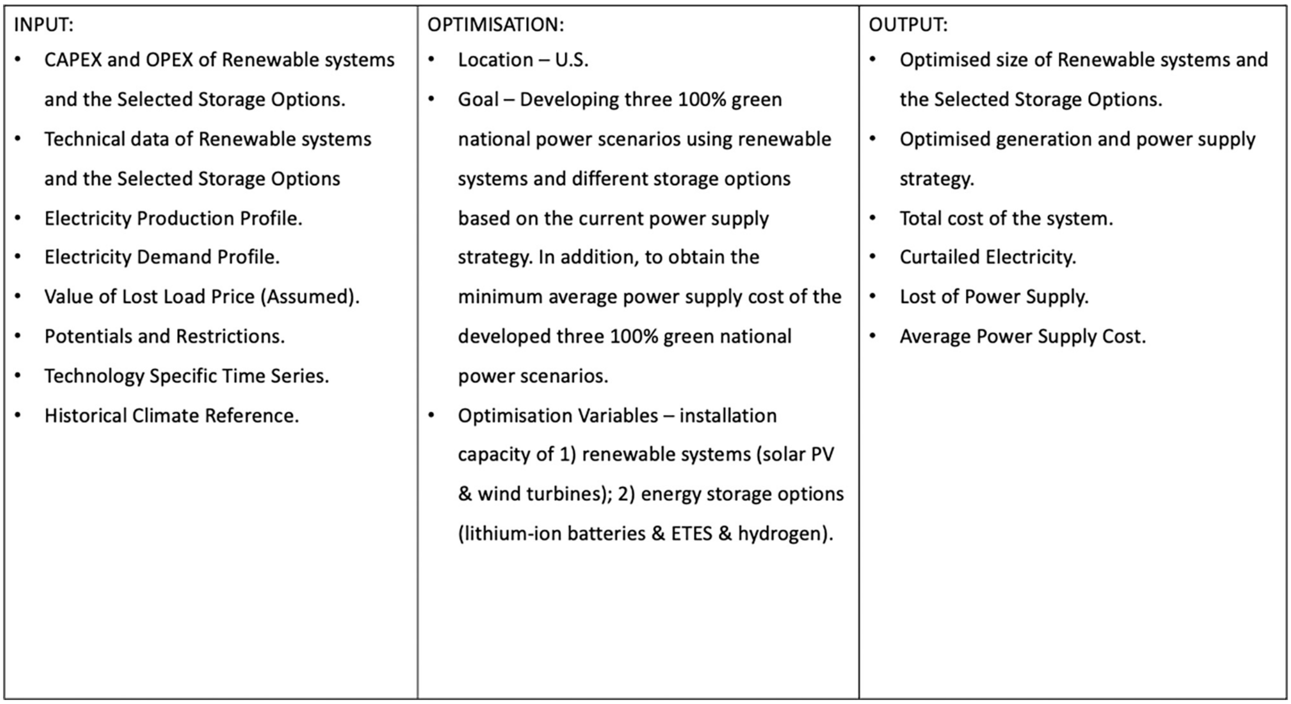
4. Results

This section presents the key outcomes of the aforementioned economic model. Fig. 1 presents the estimated electricity demand used to optimise the size of renewable systems and energy storage technologies.

The electricity demand in Fig. 1 represents the estimated residual energy demand, derived from the total electricity demand from PJM, after deducting the electricity generated by existing nuclear power stations and hydropower. This electricity demand amounts to 550,604,401 MWh and is inputted into the economic model to optimise the size of renewable systems and energy storage technologies in each scenario.

In Fig. 1, two peak demand periods are identified in between April and June, as well as October and December. Long-term energy storage like ETES or hydrogen is beneficial for working alongside Li-ion

Table 5
Summary of inputs, optimisation process, and outputs in the developed economic model.



INPUT:	OPTIMISATION:	OUTPUT:
• CAPEX and OPEX of Renewable systems and the Selected Storage Options. • Technical data of Renewable systems and the Selected Storage Options • Electricity Production Profile. • Electricity Demand Profile. • Value of Lost Load Price (Assumed). • Potentials and Restrictions. • Technology Specific Time Series. • Historical Climate Reference.	• Location – U.S. • Goal – Developing three 100% green national power scenarios using renewable systems and different storage options based on the current power supply strategy. In addition, to obtain the minimum average power supply cost of the developed three 100% green national power scenarios. • Optimisation Variables – installation capacity of 1) renewable systems (solar PV & wind turbines); 2) energy storage options (lithium-ion batteries & ETES & hydrogen).	• Optimised size of Renewable systems and the Selected Storage Options. • Optimised generation and power supply strategy. • Total cost of the system. • Curtailed Electricity. • Lost of Power Supply. • Average Power Supply Cost.

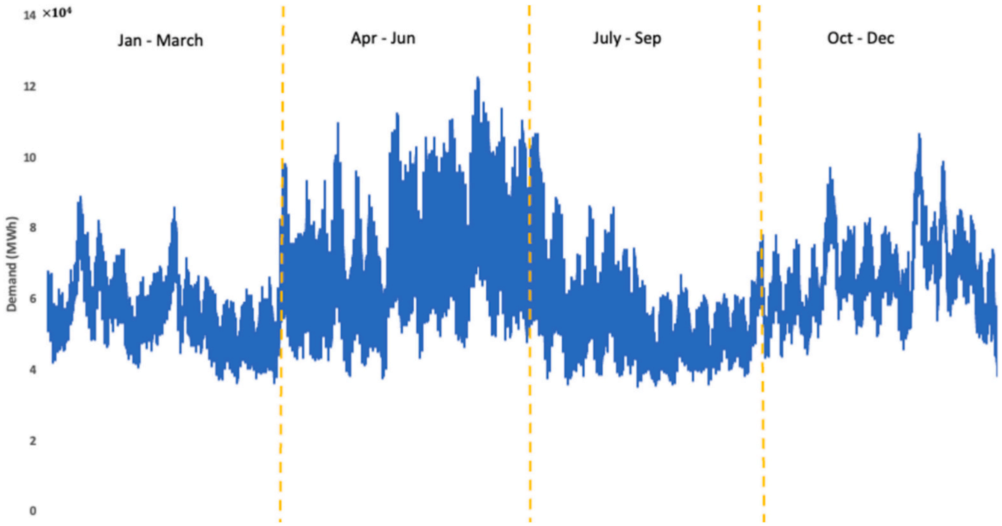


Fig. 1. Residual Sub-Hourly electricity demand (MWh) to be balanced by renewable systems and energy storage for the US.

batteries to manage the demand-supply balance during these identified demand peaks across different seasons in a cost-effective manner. For example, renewable generations can work with inter-seasonal storage to store excess electricity in a lower-demand period to be used in a higher-demand period (Table 6).

In Scenario 1, Li-ion batteries are used to manage both short/long-term demand-supply balance. Given that Li-ion batteries are effective in managing the short-term demand-supply balance, normally up to 24 h [63]. Therefore, Scenario 1 requires a relatively larger size of renewable systems (615,987 MW) and Li-ion batteries (234,956 MW) compared to Scenarios 2 (renewables: 506,459 MW; Li-ion: 53,304 MW) or 3 (renewables: 410,017 MW; Li-ion: 7020 MW), enabling the systems to sufficiently manage the long-term demand-supply balance.

Scenario 3 features the smallest size of renewable systems and Li-ion batteries among the three defined scenarios. This is because hydrogen is employed to manage both short- and long-term power supply balances. The use of hydrogen reduces the size of both the renewable systems and the Li-ion batteries.

In Scenario 2, ETES is introduced to manage the long-term demand-supply balance, resulting in a smaller overall size of the renewable systems and Li-ion batteries compared to Scenario 1. However, unlike Scenario 3, where hydrogen contributes to managing both short- and long-term demand-supply balance; in Scenario 2, ETES is solely used for managing the long-term demand-supply balance, then Li-ion batteries manage only the short-term demand-supply balance. The size of Li-ion batteries in Scenario 2 has not been reduced as much as in Scenario 3.

Table 6

The optimised size of renewable systems and the selected storage options in each defined Scenario.

Indicator	Scenario 1 (Li-ion Battery)	Scenario 2 (Li-ion Battery + ETES)	Scenario 3 (Li-ion Battery + Hydrogen
Wind power capacity (MW)	432,720	324,814	235,327
Photovoltaic capacity (MW)	183,267	181,645	174,690
Li-ion battery capacity (MWh)	234,956	53,304	7020
Maximum ETES capacity (MW)	–	1,810,000	0
Hydrogen Storage Capacity (kg)	–	–	222,287,724
Hydrogen Power Generation Capacity (MW)	–	–	47,009
Electricity Generation (MWh)	1,667,749,086	1,336,935,841	1,051,762,406
Final consumed electricity (MWh)	546,033,010	550,604,041	549,624,460
Percentage of final consumed electricity in the generated electricity (%)	32.7 %	41.2 %	52.3 %

The final consumed electricity (MWh) refers to the amount of electricity delivered by the optimised renewable and energy storage systems to cover the residual electricity demand in Fig. 1. Scenario 1 has the highest electricity generation but is the least efficient; only 32.7 % of the electricity is delivered by the renewable system, and energy storage is used to cover the residual electricity demand. This indicates that approximately 60 % of the electricity from the renewable and storage system is wasted. In contrast, the systems in Scenario 3 are the most efficient; >50 % of the electricity delivered by renewable and energy storage systems has been used to match the residual electricity demand.

The deficit electricity and the loss of power probability (LOPP) are introduced to reflect the demand gap that the optimised renewable generations and energy storage cannot fill in each Scenario. In Scenario 2, the deficit electricity is approximately ‘0’, indicating that the electricity delivered from the systems (including renewable systems, Li-ion batteries, and ETES) can cover nearly the entire estimated residual electricity demand of 550,604,041 MWh, with LOPP being much <0.01 %. LOPP is slightly higher in Scenario 1 and Scenario 3, with figures of 0.83 % and 0.18 %, respectively. The high deficit of electricity, or LOPP, indicates a greater likelihood of power supply disruption, resulting in a high cost of VOLL. VOLL (assumed unit cost of $1409/MWh) in Scenarios 1 and 3 are $8365 million and $1793 million, respectively. However, VOLL is about $4 million in Scenario 2, far smaller than VOLL in Scenarios 1 and 3. The higher VOLL would lead to an expensive and unreliable power supply strategy that is unlikely to be accepted by the public as a future power supply strategy. Section 5.2 continues to discuss the power supply stability of renewable systems and the selected energy storage options in the defined scenarios.

Fig. 2 presents the total cost of the renewable systems and the shortlisted storage technologies, as well as the estimated average power supply cost of the systems in each defined Scenario. The total cost of renewable systems and the shortlisted storage technologies in each defined Scenario ranged between $ 4000 and 6000 million.

The total cost refers to the overall installation cost, indicating that >4000 million U.S. dollars are expected to be invested in deploying renewable systems and the selected storage options to achieve a 100 % national power supply strategy based on the assumed current installed capacity of systems in each scenario.

The average power supply cost for the defined scenarios ranges between $75 and $100 per megawatt-hour (MWh). The lower average power supply costs are $77.6/MWh and $76.6/MWh in Scenarios 2 and 3, respectively. Given that long-term energy storage is included in these scenarios, such storage technologies can effectively reduce the average power supply cost.

The average power supply cost in Scenarios 2 and 3 is similar, albeit the size of the renewable systems and Li-ion batteries in Scenario 2 is

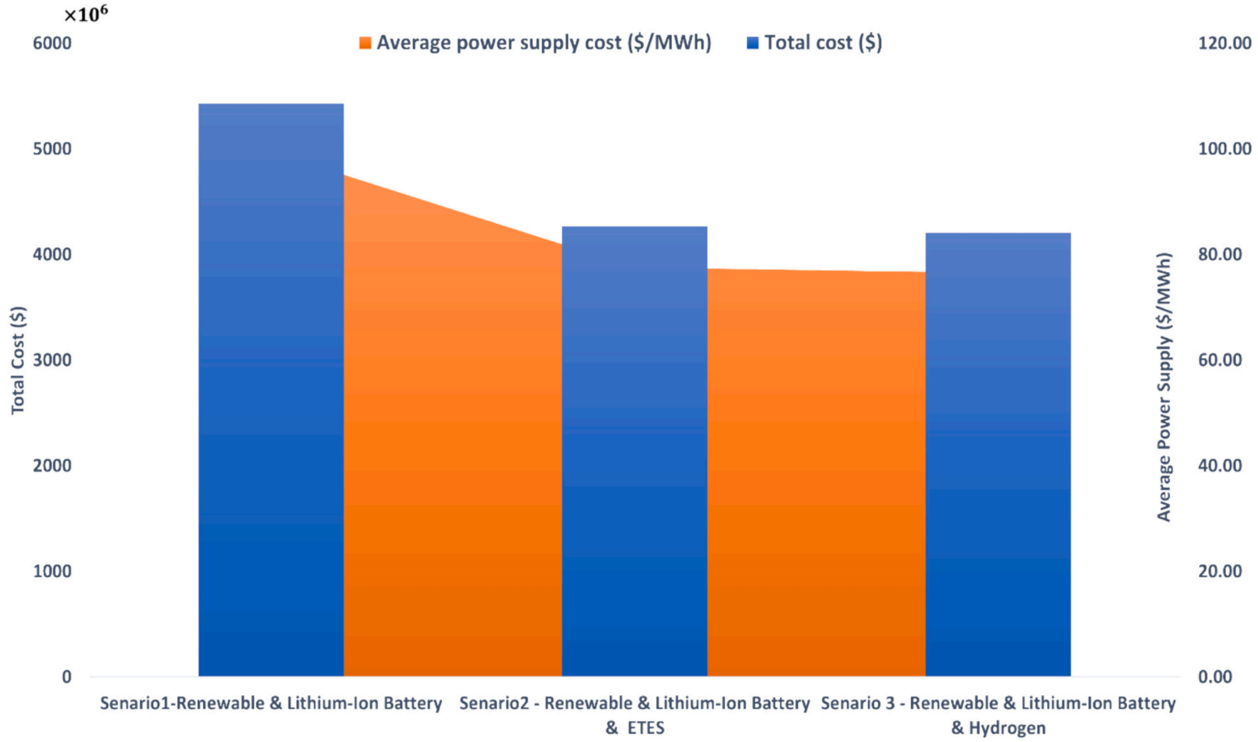


Fig. 2. Total cost of the systems and the average power supply cost in each defined Scenario.

about 8 times larger than in Scenario 3. The cost of the more extensively deployed Li-ion batteries in Scenario 2 might be offset by the cheaper CAPEX and smaller size of ETES compared to the more expensive and extensively deployed hydrogen in Scenario 3.

This research assumes the electricity cost for green hydrogen production is zero. However, the existing scale of renewable systems cannot generate sufficient curtailed electricity to support the estimated demand for hydrogen production in Scenario 3. It is unlikely that electricity will be free of charge to produce the estimated amount of hydrogen in current practice. Consequently, factoring in the current electricity market, the average power supply cost in Scenario 3 would likely be considerably higher than that in Scenario 2. The detailed economic comparison between ETES and hydrogen will continue to be discussed in section 5.3.

The most expensive average power supply cost is found in Scenario 1 ($99.5/MWh). The average power supply cost in Scenario 1 is attributed to the absence of long-term energy storage. Therefore, a larger size of the Li-ion batteries and the renewable systems is needed to manage short-term and inter-seasonal power supply balance. Consequently, the increased system size leads to a higher total cost and a higher average power supply cost.

5. Discussion

This section discusses:

- How inter-seasonal energy storage technologies such as ETES and hydrogen contribute to the improvement of security in power supply (Section 5.2).
- The differences in usage levels between short-term and inter-seasonal energy storage technologies (Section 5.3).
- How the results and benefits of adding inter-seasonal energy storage can contribute to future energy policy (Section 5.3).

5.1. Electricity balancing and flexibility discussion between the fossil fuel and renewable system-based power supply strategies

The balanced power supply is an important factor in assessing the performance of various power supply strategies in the defined scenarios. Lower power supply stability indicates a higher likelihood of power disruptions, which requires additional support from backup services.

Using more unplanned electricity from backup services leads to higher electricity supply costs. Therefore, ensuring a stable and affordable electricity price is essential while maintaining high power supply stability.

This subsection discusses the power supply stability and flexibility among renewable systems and energy storage options in the defined scenarios compared to current fossil-fuel-based power generation systems. Two indicators—1) deficit electricity and 2) curtailed electricity—are used to measure power supply stability across different power supply strategies.

Based on Fig. 3, Scenario 2 demonstrates a more stable electricity supply capability compared to Scenarios 1 and 3 due to a lower deficit electricity. The deficit electricity is approximately 0.002 MWh, indicating that only around 0.002 MWh of electricity demand cannot be met through the power supply strategy in Scenario 2. In contrast, the deficit electricity is 4,571,031 MWh in Scenario 1 and 979,581 MWh in Scenario 3. Based on the discussion, the power supply strategy in Scenario 1 has the highest probability of power loss, which is likely to result in higher power delivery costs compared to the other two scenarios.

Fig. 4 presents the performance of electricity curtailment in three scenarios. The term ‘curtailed electricity’ refers to the excess electricity generated by renewable systems that exceeds current demand and surpasses the maximum capacity of the installed storage. This excess electricity would then be abandoned without other distribution strategies.

The curtailed electricity in Scenario 1 is about 7 % and 23 % higher than in Scenarios 2 and 3, respectively. This is because Li-ion batteries cannot manage long-term (inter-seasonal) peak demands. A larger size of renewable systems is therefore installed to balance inter-seasonal peak demands in Scenario 1. The installed larger size of systems results in a significant surplus of electricity, which exceeds the maximum capacity of the installed Li-ion batteries and is subsequently wasted. Scenario 1 shows a higher level of curtailed electricity than the other two Scenarios.

The addition of inter-seasonal energy storage solutions like ETES and hydrogen helps to reduce the size of renewable systems required to meet peak demand across seasons. The main difference between Scenarios 2 and 3 is that hydrogen can manage both short-term and inter-seasonal demand-supply balances, resulting in a further reduction in the size of renewable systems in Scenario 3. As a result, the amount of curtailed electricity in Scenario 3 is lower than in Scenario 2.

Whilst curtailed electricity in Scenarios 2 and 3 is lower, it remains higher than the current level of electricity curtailment in fossil fuel-dominated power supply strategies). IEA [32,64,65] studied the relationship between renewable energy curtailment percentage and the percentage of renewable systems integrated into the power supply

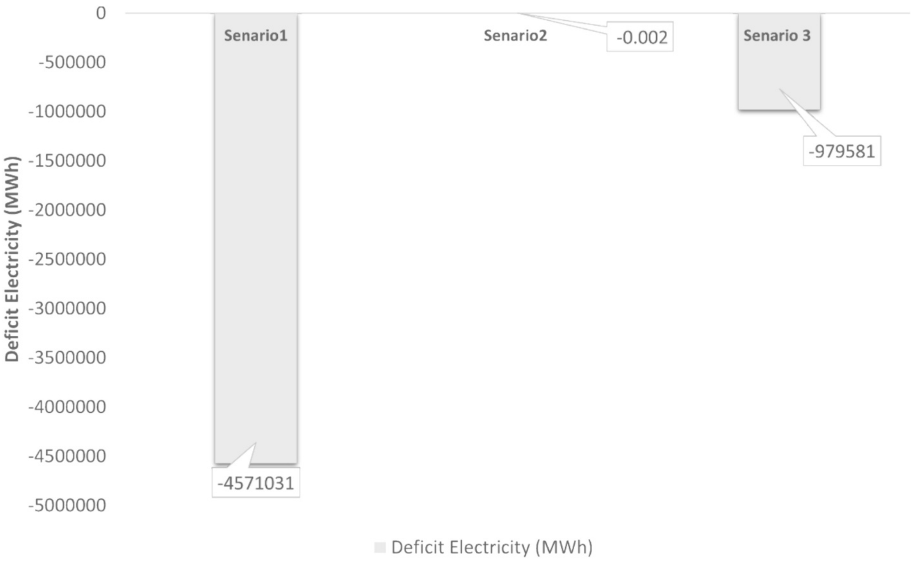


Fig. 3. The power deficit in the defined scenarios.

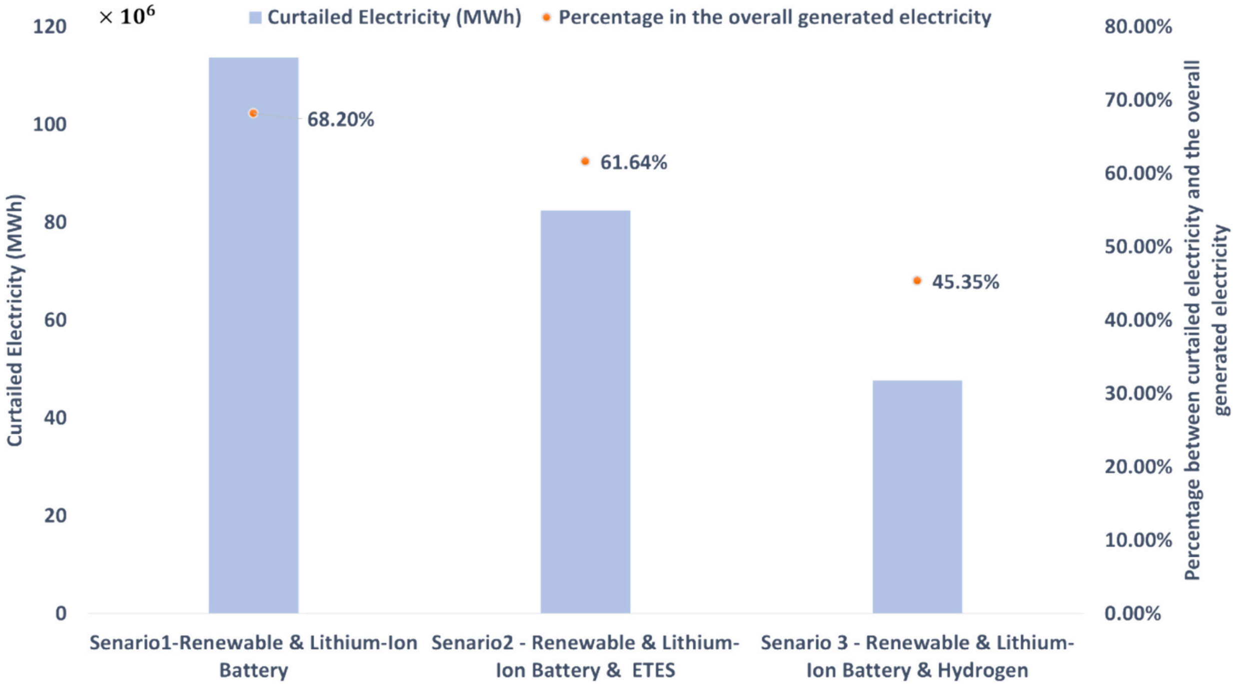


Fig. 4. Curtailed Electricity in different scenarios.

strategy in 10 selected G20 countries. The results demonstrate that with up to 40 % integration of the renewable system, the percentage of electricity curtailment from the integrated renewable system remains below 18 %. This lower curtailment percentage is attributed to fossil fuels still accounting for the majority of power generation (above 60 %) in the study. Fossil fuels demonstrate greater flexibility in adjusting the demand-supply balance compared to renewable systems.

For the supply side, it is therefore necessary to consider integrating a specific quantity of fossil fuels with CCUS (Carbon Capture, Utilisation, and Storage) into renewable systems to enhance power supply flexibility, especially during the energy transition phase. Nonetheless, future research is encouraged to investigate the exact amount of fossil fuels required and whether this quantity aligns with the established climate change agenda. Additionally, future research should explore whether the required implementation of CCUS can generate lasting economic benefits.

On the distribution side, the current distribution structure and strategy should be updated to accommodate the adoption of a large number of renewable systems in the power supply. The updated distribution structure can mitigate the inflexibility of renewable systems by introducing an ancillary market and backup services, alongside the integration of short-term and inter-seasonal energy storage, gradually phasing out fossil fuels.

5.2. In-depth discussion of the usage level between short-term and inter-seasonal storage

This subsection uses two technical indicators: 1) the monthly supply gap; and 2) the utilisation status of the installed storage, to discuss the differences in storage systems across the three scenarios. Fig. 5 presents

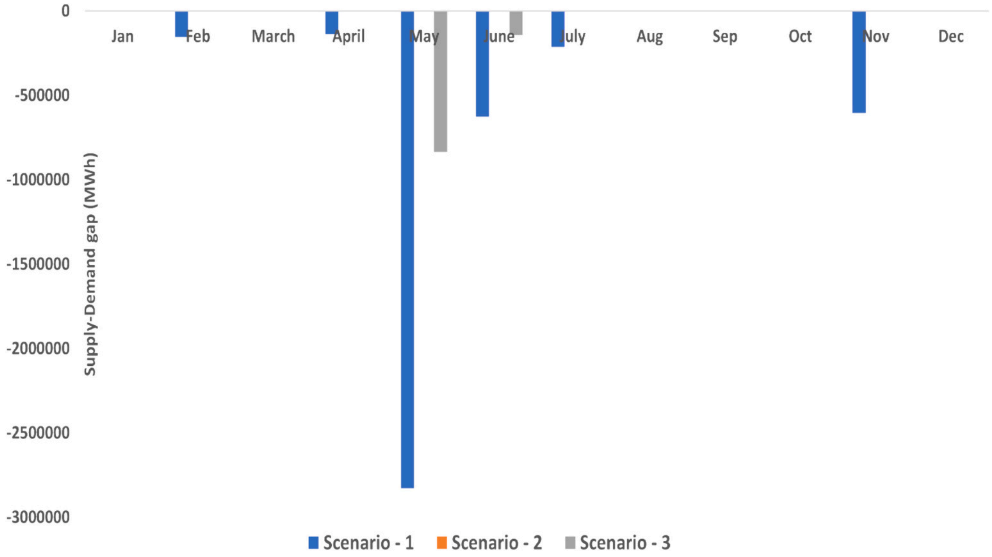


Fig. 5. Supply Gap in different scenarios.

supply-demand gap for three defined scenarios.

Based on Fig. 5, the maximum supply-demand gap in all three scenarios occurs between April and June, aligning with the period of the maximum peak demand identified in Fig. 1.

In Scenario 1, the supply gap is observed throughout most months of the year due to the limited capability of Li-ion batteries to manage inter-seasonal demand-supply balances. In Scenarios 2 and 3, with the incorporation of inter-seasonal storage solutions such as ETES and hydrogen, the supply-demand gap occurs only during the maximum peak demand period (April–June). The appearance of the supply-demand gap is because, during such periods, the demand exceeds the optimised capacity of renewable systems and storage within the respective scenarios. Adding inter-seasonal storage in Scenarios 2 and 3 enables power supply strategies to store excess electricity during off-peak periods and subsequently meet another peak demand identified in Fig. 1 (October – December).

Fig. 6 presents relationship between the utilisation condition of the installed overall storage capacity and loss of power probability across the three scenarios. In diagram, *x* stands for storage discharge condition, '0' stands for the storage has been fully discharged and '1' stands for the storage has been fully charged. F_x stands for the probability of the specific condition (x) to happen.

Under Scenario 1, the storage volume is discharged <20 % of the time; >80 % of the time, the storage is at full capacity. The discharging time has been slightly improved in Scenarios 2 and 3, with <80 % of the time that storage is at full capacity. The addition of inter-seasonal storage (ETES and hydrogen) helps reduce the size of the Li-ion batteries and increases the utilisation of the installed storage to some extent. Regarding the added inter-seasonal storage, the installed storage has been used more frequently in Scenario 3 than in Scenario 2. This is because the hydrogen in Scenario 3 also assists the Li-ion batteries in managing short-term power shortages while maintaining the inter-seasonal demand-supply balance.

In Scenario 1, the storage remains fully charged almost 90 % of the time, and it has not been fully discharged at any time. The reason is that the oversized Li-ion batteries are installed in Scenario 1 to avoid a significant power shortfall due to the limited capability of using Li-ion batteries to manage the seasonal peak demands. However, in Scenarios 2 and 3, there is a range of 10–20 % time that the installed storage has been fully discharged. The full discharge time suggests that the storage system has not been oversized, and the system can reasonably match the required demand from an economical perspective, resulting in the storage being used more frequently than in Scenario 1. Inter-seasonal storage prevents the oversizing of Li-ion batteries while

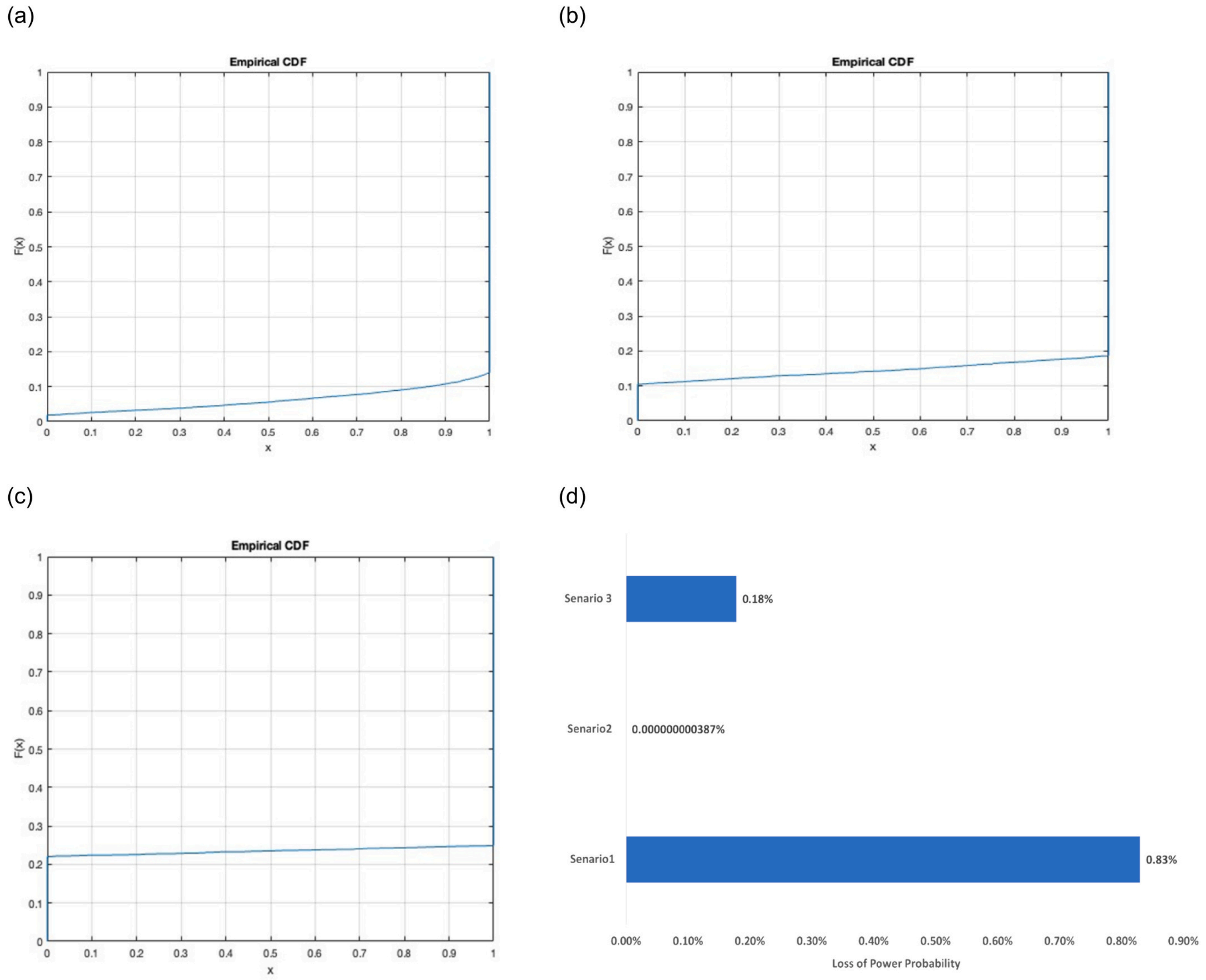


Fig. 6. Storage usage condition and loss of power probability across the three scenarios. (a) reflects the storage utilisation condition in Scenario 1; (b) reflects the storage utilisation condition in Scenario 2; (c) reflects the storage utilisation condition in Scenario 3; and (d) loss of power probability in three scenarios.

improving the utilisation condition of the total installed energy storage. Although the discharge time in Scenarios 2 and 3 has improved compared to Scenario 1, the utilisation condition remains <30 %. This indicates that >70 % of the time, the storage remains in a fully charged condition and is not used. Additional strategies such as demand-side management should therefore be introduced to improve energy balancing and increase the utilisation of energy storage.

In addition, the storage in Scenario 1 is less effective at balancing demand and supply compared to Scenarios 2 and 3. As shown in Fig. 6 (d), the loss of power probability in Scenario 1 (0.83 %) is higher than Scenario 2 (nearly zero) and Scenario 3 (0.18 %). The result indicates that the oversized Li-ion batteries are less efficient at managing the long-term (e.g., inter-seasonal) demand-supply balance compared to ETES and hydrogen. The findings also suggest that combining inter-seasonal storage solutions, like ETES or hydrogen, with Li-ion batteries enhances the stability of the power supply in renewable systems, enabling them to better manage peak demands across different seasons.

5.3. *The importance of inter-seasonal storage and suggestions for the future energy policy*

The previous two sections discussed how additional inter-seasonal storage could stabilise a fully green power supply system, reducing curtailed renewable electricity and bridging supply gaps throughout the year. They also explored how inter-seasonal storage enhances the flexibility of power supply strategies. Furthermore, the sections highlighted how inter-seasonal storage increases the utilisation percentage of installed storage capacity, thereby preventing the need for oversized systems designed solely to meet maximum peak demand. Inter-seasonal storage thus emerges as a solution to maintaining reliable power supply using renewable systems, reducing electricity curtailment, and achieving a relatively lower average national power supply price.

This subsection discusses the practical application of the selected two inter-seasonal storage options and the suggestions for the future energy policy that can better support the development of inter-seasonal storage options.

It firstly discusses the response time of energy storage, which is the time required for storage to react to the loss of power supply. Existing hydrogen fuel cells can generate electricity in just a few seconds, however, ETES might take up to a few minutes to complete the process from releasing heat to turn the turbines to produce electricity [66]. With its rapid response capability, hydrogen can manage unexpected power shortages while also reducing the reliance on larger Li-ion batteries to balance anticipated power supply gaps in inter-seasonal conditions. ETES emerges as a preferred solution for addressing anticipated inter-seasonal power shortages. This explains why the capacity of Li-ion batteries in scenario 3 is smaller than in scenario 2, as ETES cannot respond to unexpected short-term power shortages.

ETES is a more economically viable option than hydrogen as an inter-seasonal storage. The similar average power cost in Scenarios 2 and 3 is due to the curtailed electricity considered to produce hydrogen in Scenario 3 (Levelized cost of hydrogen = \$2.7/kg – based on the calculation method explained in subsection 3.3). The average power supply cost is expected to increase to \$83/MWh when using dedicated offshore wind turbines for hydrogen production (Levelized cost of hydrogen = \$5.4/kg [67]). The electricity cost is a key factor impacting the production cost of green hydrogen (The U.S. [36]). The curtailed electricity can only support limited green hydrogen production [67], and the produced hydrogen may not meet the required demand for inter-seasonal storage purposes. Scaling up hydrogen production would necessitate dedicated renewable systems. Using hydrogen for inter-seasonal electricity storage is anticipated to be more expensive than ETES from a production perspective, factoring in the electricity cost from these dedicated renewable systems.

Storage and delivery costs are two additional factors that support ETES as a more cost-effective solution for inter-seasonal storage compared to hydrogen. ETES generally involves lower CAPEX and OPEX, along with a longer lifespan of around 20 years. Unlike hydrogen storage tanks, which require specific materials for manufacturing, ETES can utilise existing thermal storage infrastructure that can be retrofitted for inter-seasonal storage purposes [68,69]. Whilst hydrogen can be stored in the salt cavern as an economical solution [70], some countries may not utilise salt caverns for hydrogen storage due to geographical constraints. Additionally, the cost of hydrogen transport infrastructure remains significant, whether it involves repurposing existing natural gas networks or developing new hydrogen-specific networks [71].

The following suggestions contribute to the future energy policy based on the in-depth discussion above.

- The electricity market supply mechanism in certain countries (e.g., European Union and the UK) needs to evolve to align with the transition towards renewable-based power systems. As discussed in subsection 5.2, fossil fuels currently offer greater flexibility in power generation compared to renewable systems. While oversized generation systems and energy storage can enhance the flexibility of power supply using renewables, they also risk increasing wasted electricity (curtailed electricity). Moreover, the deployment of oversized generation and storage solutions could result in higher power supply costs, making them economically impractical solutions.

  Therefore, as summarised in subsection 5.2, fossil fuels can potentially complement renewable systems as backup options, particularly when coupled with Carbon Capture, Utilisation, and Storage (CCUS) technologies. This approach helps to maintain power supply flexibility during the transition towards fully renewable-based systems. However, it is crucial that the government introduces clear plans to quantify the necessary capacities for CCUS and fossil fuels. Overplanning CCUS capacity could potentially delay achieving agreed climate change targets.
- The ancillary services that assist grid operators in maintaining a reliable power supply become increasingly vital during the transition from fossil fuels to renewable-based power generation. Energy storage technologies such as Li-ion batteries, ETES, and hydrogen are employed as ancillary services to bolster the stability of the power supply. Future energy policies should focus on establishing a fair pricing system for ancillary services that reflects the following factors: the CAPEX and OPEX associated with the systems in ancillary services; the anticipated or unexpected demand-supply gap; the required response time; and the duration of supply.
- The current wholesale market price is determined by the marginal cost. However, as we transition to 100 % renewable-based power generation, the marginal cost is expected to approach zero or even become negative. This situation poses challenges for renewable systems and energy storage to generate adequate profits to recoup their upfront investments [26,72]. A new pricing methodology for the wholesale market needs to be developed to ensure that renewable systems and storage can achieve sufficient profitability throughout their expected lifespan.
- Energy storage, particularly inter-seasonal storage (as discussed in subsection 5.3), plays a crucial role in a 100 % renewable system-based power supply. Currently, the government lacks inter-seasonal storage integrated with renewable systems in the national grid power supply. However, some governments have begun incorporating inter-seasonal storage as part of their net-zero strategies. For instance, the UK government recognises the importance of inter-seasonal storage in its net-zero plan and has allocated £32 million to promote the development of longer-duration storage solutions [63]. In addition, the UK government plans to implement a policy on long-duration energy storage in 2024 [12]. In addition to relevant supportive policies, the government should introduce incentives with specified funding to support the development of advanced long-duration energy storage, aiming for practical installation within the agreed timeline. Additionally, the government should promote

research to explore the optimal combination of different storage options in conjunction with 100 % renewable systems, aiming to deliver the most affordable and sustainable electricity.

6. Limitation and future research

This research developed three scenarios of using 100 % renewable systems with different selected energy storage to replace fossil-fuel-based power systems supplying electricity at the national level. The research also discussed the supply stability, flexibility, and economic performance between the systems in the defined scenarios and the fossil-fuel-based power systems. The UK government has planned the new development of CCUS to work with fossil-fuel-based power systems to reduce GHG emissions [73]. However, this research investigates the economic performance of fully green (100 % renewables) power supply systems with different storage options. The power backup option, like fossil-fuel-based power systems with CCUS, is not in the scope of this research and has yet to be explored. In addition, this research assumes the capacity of nuclear and hydropower remain the same, the future capacity of nuclear and hydrogen power may change in some countries.

Future research will explore the role of fossil-fuel-based power systems with CCUS for a renewable system-dominated national power supply strategy in the energy transition period.

In addition, future research will continue to explore the following topics:

- The economic and environmental performance between fully green power systems with energy storage and fossil-fuel-based power systems with CCUS from a long-term perspective.
- The uncertain changes in electricity usage behaviour while considering the impact of electric vehicles (EVs) and variable electricity tariffs.
- The role and possible pricing systems in the ancillary service to explore the optimal solution of renewable systems and energy storage options in a 100 % green power supply scenario.

7. Conclusion

Energy storage plays a pivotal role in managing the power supply-demand balance in a highly renewable-integrated grid due to the generation intermittency of renewable systems. Existing studies have explored the techno-economic performance of using Li-ion and pumped hydrogen in a highly green grid. However, there has been limited exploration into the integration of promising storage technologies such as electric thermal energy storage (ETES) and green hydrogen alongside Li-ion batteries in a fully green grid. ETES and green hydrogen technologies are employed to balance seasonal peak demand, whereas Li-ion batteries are primarily used for managing short-term peak demand. The findings will shed light on whether integrating ETES or green hydrogen can yield greater economic and technical benefits, leading to reduced power delivery costs and a more secure power supply strategy.

This research investigates a fully green power generation system incorporating Li-ion batteries, ETES, and hydrogen in three defined scenarios from an economic perspective using a developed economic model. The economic model is developed in MATLAB to evaluate the economic performance of the systems in the defined scenarios. The results show that the average power supply cost for the systems with Li-ion batteries only is higher ($99.5/MWh) than those with a combination of Li-ion batteries and ETES or Li-ion batteries ($77.6/MWh) and hydrogen ($76.6/MWh). This is because Li-ion batteries perform better in managing short-term power shortages but are limited in their ability to manage long-term power shortfalls. The power supply strategy of using Li-ion batteries only as storage requires an oversized capacity (234,956 MWh in Scenario 1) to manage the power supply variations during periods of low power generation but high demand. The installed capacity of Li-ion batteries in Scenario 1 is approximately four times higher than in Scenario 2 and thirty-three times higher than in Scenario 3. ETES and hydrogen can store excess generated electricity for use across seasons. For example, they can store excess electricity generated during a season of high supply but low demand, and then use it during a season of low supply but high demand. The application of inter-seasonal storage options like ETES and hydrogen contributes to reducing the size of renewable systems and Li-ion batteries and lowering the average power supply cost.

This research discusses the flexibility between renewable systems and energy storage options in the defined scenarios, comparing them with fossil-fuel-based power systems based on existing studies. The discussion results indicate that present fossil-fuel-based power systems offer higher flexibility than renewable systems and energy storage options in power supply management. Curtailment of electricity in fossil-fuel-based power systems is lower (<18 %) compared to renewable systems and energy storage options [64]. This is because current power generation infrastructure allows flexibility in controlling power generation using fossil energy (e.g., linepack for natural gas) [72]. However, such control systems do not exist in renewable-based power generation systems. Although inter-seasonal storage helps increase flexibility for a fully green power supply strategy, changes in the demand side (e.g., energy usage behaviour) are also necessary in a fully green energy supply scenario to maintain supply stability, ensure affordability, and reduce wasted electricity.

The research also suggests that future energy policies should focus on providing incentives to support the development and practical application of inter-seasonal storage. This technology is crucial and beneficial for achieving a fully green power supply system in line with the agreed climate change targets by 2050. Furthermore, it recommends reconsidering the current wholesale electricity cost calculation method, which may not be suitable for a 100 % renewable systems-based power supply mechanism. Implementing a newly designed wholesale electricity cost could encourage and guide changes in energy usage behaviour.

CRediT authorship contribution statement

John Zhehao Cui: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chunping Xie:** Writing – review & editing, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wei Wu:** Methodology, Conceptualization. **Samuel D. Widijatmoko:** Writing – review & editing. **Yan Hong:** Writing – review & editing. **Yongliang Li:** Writing – review & editing, Supervision, Funding acquisition. **Gary A. Leeke:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: John (Zhehao) Cui reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Most data is available in the manuscript

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