Journal of Energy Storage 109 (2025) 115057

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

A comprehensive review of modeling approaches for grid-connected energy storage technologies

Andrew J. Hutchinson [e],*, Chris M. Harrison [a], Thomas S. Bryden [b], Arman Alahyari [c], Yiheng Hu [d], Daniel T. Gladwin [e], Jonathan Radcliffe [a], Daniel J. Rogers [b], Charalampos Patsios [c], Andrew Forsyth [d]

[a] University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom
[b] University of Oxford, Wellington Square, Oxford, OX1 2JD, United Kingdom
[c] Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, United Kingdom
[d] University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
[e] University of Sheffield, Western Bank, Sheffield, S10 2TN, United Kingdom

ARTICLE INFO

Keywords:
Grid-scale storage
Energy storage modeling
Flywheels
Compressed air
Batteries
Hydrogen
Supercapacitors

ABSTRACT

Energy Storage Systems (ESSs) play a pivotal role in the evolving landscape of electrical generation, distribution, and consumption worldwide. As these systems are increasingly developed and deployed across diverse applications, the need for effective and efficient modeling has become more critical. This work provides a comprehensive overview of key Energy Storage Technologies utilized in electrical applications, highlighting their strengths, limitations, and roles across various use cases. The review offers in-depth analysis and commentary on the current state of energy storage modeling, addressing the challenges and opportunities within this research domain, and providing a novel resource for researchers in this field. To assist researchers in selecting appropriate modeling approaches, this paper explores three levels of modeling complexity, examined through the lens of five prominent energy storage technologies. By evaluating the trade-offs of different approaches and their suitability for various applications, the study serves as a state-of-the-art resource for researchers pursuing new energy storage studies. Furthermore, it examines trends in software and hardware adoption, including case studies and hardware-in-the-loop implementations, while identifying research gaps and opportunities for innovation. The review concludes with insights into future challenges in the field and proposes avenues for advancing energy storage modeling and application research.

Contents

* Corresponding author.
E-mail address: andrew.hutchinson@sheffield.ac.uk (A.J. Hutchinson).

https://doi.org/10.1016/j.est.2024.115057
Received 8 July 2024; Received in revised form 4 December 2024; Accepted 14 December 2024
Available online 27 December 2024

Nomenclature

AM	Application Modeling
BESS	Battery Energy Storage System
BM	Bucket Model
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CF	Capacity Factor
COE	Cost of Energy
DER	Distributed Energy Resource
DOD	Depth of Discharge
DT	Digital Twin
ECM	Equivalent Circuit Model
EM	Electrical Model
ERM	Energy Reservoir Model
ESM	Energy Storage Modeling
ESS	Energy Storage System
EV	Electric Vehicle
FESS	Flywheel Energy Storage System
H_2ESS	Hydrogen Energy Storage System
HIL	Hardware-in-the-loop
HVS	Hardware Verification Study
O&M	Operation and Maintenance
P2G	Power to Gas
PEM	Power Energy Model
PHS	Pumped Hydro Storage
PM	Physical Model
PMSM	Permanent Magnet Synchronous Motor
PV	Photovoltaic
RFB	Redox Flow Batteries
RTS	Real Time Simulation
SC	Supercapacitor
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SOH	State of Health
TES	Thermal Energy Storage
TM	Technology Modeling
U.K.	United Kingdom
VSHP	Variable Source Heat Pump

1. Introduction

With the deployment of ESSs increasing rapidly in order to meet net-zero targets across the world, accurate modeling and simulation of such systems is a crucial area that is receiving extensive research and development. In the United Kingdom (UK) achieving 'Net Zero' carbon emissions by 2050 has been declared as a major target, and in order to reach this target extensive further deployment of ESSs will be required. The field of modeling ESSs is a rapidly growing research area with significant advancements having been made in the past decade. The approach to modeling an ESS can vary significantly depending on the technology, the objectives, and the equipment available.

ESSs have been a part of the electricity distribution system since the early 1900s in the form of Pumped Hydro Storage (PHS). This still dominates worldwide Energy Storage Systems (ESSs) capacity [1]. As the electricity system has evolved the requirement for a wide variety of different ESSs has increased, leading to a vast range of different types of storage as seen in Fig. 1. In fact, ESSs are now becoming so prevalent that in June 2022, the energy exported to grid over the month in the U.K. consisted of 1.0% from ESSs, higher than the 0.4% generated from coal [2].

The scope of this paper encompasses three different model-level approaches to modeling five different energy storage technologies and the approach most suitable for different applications. This paper aims to provide a novel resource to assist researchers in choosing appropriate modeling techniques based on criteria including storage technology, application, computational efficiency and the level of detail required for the parameters in the model.

Through an extensive investigation of the most recent developments in ESM from the novel viewpoint of an application-centric approach, this paper allows examples to be drawn from a wide range of studies to demonstrate how different modeling techniques are applied in practice for various storage technologies. A commentary on the relative

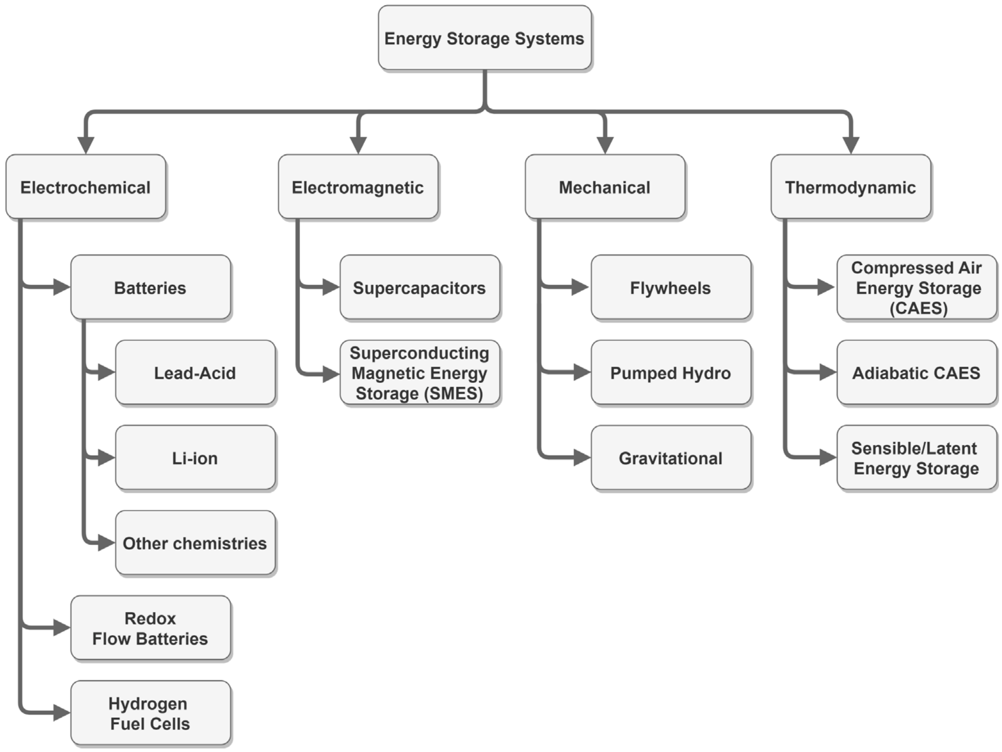


Fig. 1. Categorization of different energy storage technologies.

strengths and weaknesses of different approaches for given scenarios is provided to inform researchers of the potential drawbacks of certain methods. The paper concludes with an exploration of the future challenges faced by the field of ESM, presenting an insight into potential research directions for contemporary researchers. The review presented here will improve the understanding of the existing and future state of energy storage modeling and provide a valuable tool for researchers in this field.

1.1. Energy storage technologies

ESSs can fall broadly into one of four categories as seen in Fig. 1. Each storage technology has its own advantages, disadvantages and specific use cases, ranging from second-by-second power response to long-term seasonal storage of energy. In this section, a brief overview of selected energy storage technologies is presented to provide context for the modeling discussions.

In this review, the various methods of modeling are contextualized for five different energy storage technologies, Battery Energy Storage Systems (BESSs), Flywheel Energy Storage Systems (FESSs), Hydrogen Energy Storage Systems (H_2ESSs), Compressed Air Energy Storage (CAES) and Supercapacitors (SCs). BESSs in the context of this review are assumed to be Lithium-ion, as the most widely deployed technology of its type.

These technologies have been chosen to represent the spectrum of different duration energy storage technologies available, ranging from very short duration (FESSs and SCs) to seasonal storage (H_2ESS and CAES), as well as the widely explored and deployed BESSs. These technologies are relatively mature and will likely form the bulk of ESS capacity over the next 20 years. PHS has been excluded as it is unlikely that there will be a high demand for modeling of this technology given its very mature and widely technologically understood status [3].

Since the installation of the first PHS site in 1963, the vast majority of electrical energy storage capacity in the U.K. has been provided by four PHS facilities in Scotland and Wales. These assets offer the grid around 2.8 GW of installed capacity. Since 2016, with growing penetrations of intermittent forms of renewable generation, there has been a sizeable upturn in the number of grid-scale BESSs. 1.3 GW of further storage capacity was installed in the last decade, with a further 1.9 GW under construction as of January 2023 [4]. These installations have been enabled partly by falling capital costs and an improving regulatory and market framework for storage [5]. There has been a modest but growing number of residential battery systems installed in the U.K., currently estimated at 128 MW of total residential storage capacity [6].

An overview of recent literature discussing energy storage technologies, their costs, and the roles that they typically play in grid connected applications is contained in Table 1. Redox Flow Batteries (RFBs) and Superconducting Magnetic Energy Storage (SMES) have been included to illustrate the range of technologies that the recent reviews investigate.

1.2. Technology comparison

These technologies have been chosen due to their varying characteristics including cycle life, energy storage capacity and power capacity. In this section, a brief overview of the characteristics of each technology is provided to highlight the various advantages and disadvantages of each technology. Radar plots of the typical values for energy density, power density, cycle life, efficiency and cost are presented in Fig. 2.

In terms of energy density (Wh/kg), BESSs are the best-performing of the ESS technologies selected. This is one of the main criteria that has led to them being widely deployed in energy storage applications [28]. Flywheels can often have a high energy density, although this is dependent on the material used and many FESSs have very low energy densities [29]. CAES and SCs have traditionally lower energy densities although this can vary from system to system [13]. Generally, applications where energy is required to be stored in bulk and for longer durations require a higher energy density, for example transferring peak loads from one period of time to another (peak shifting) or seasonal storage services.

Table 1
Recent literature reviewing energy storage technologies, costs and applications.

Ref	Year	Li-Ion BESS	FESS	SC	H_2ESS	CAES	SMES	RFB	Technology overview	Cost overview	Application overview
[7]	2019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[8]	2019	✓	✓	✓	✓			✓			✓
[9]	2019	✓		✓				✓			✓
[10]	2019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[11]	2020	✓	✓	✓	✓	✓	✓	✓	✓		✓
[12]	2020	✓	✓	✓	✓	✓	✓	✓	✓	✓	
[13]	2020	✓	✓	✓	✓	✓		✓		✓	✓
[14]	2020	✓	✓		✓	✓		✓	✓	✓	✓
[15]	2020	✓	✓	✓		✓	✓	✓	✓	✓	✓
[16]	2021					✓		✓	✓		✓
[17]	2021	✓	✓		✓	✓		✓	✓		✓
[18]	2021	✓			✓	✓				✓	✓
[19]	2021	✓	✓	✓	✓		✓	✓	✓		✓
[20]	2021	✓			✓			✓	✓		✓
[21]	2021	✓	✓	✓	✓	✓	✓	✓	✓		
[22]	2021	✓	✓	✓	✓	✓	✓	✓	✓	✓	
[23]	2022	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[24]	2022	✓	✓	✓	✓	✓	✓	✓	✓		✓
[25]	2022	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[26]	2022	✓	✓		✓	✓	✓	✓	✓	✓	✓
[27]	2022	✓	✓	✓	✓	✓	✓	✓	✓		✓

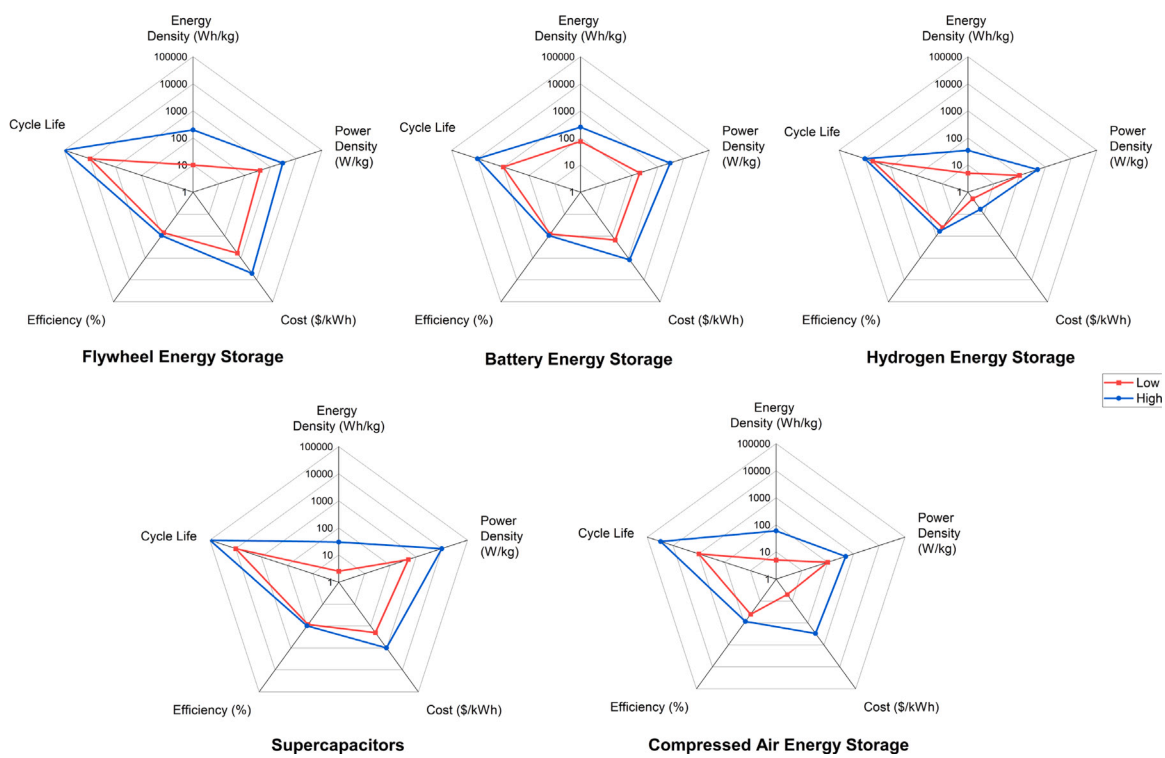


Fig. 2. Radar plot of the characteristics of each energy storage technology discussed in this paper showing each technologies energy density (Wh/kg), power density (W/kg), cycle life, efficiency and cost ($/kWh).

SCs have the highest power density (W/kg) among the technologies, with values significantly higher than many other technologies [30]. This is followed by FESSs, which are again capable of being constructed to meet a wide range of power densities. BESSs are also capable of relatively high power densities in certain conditions, whilst H_2ESSs and CAESs both have lower power densities. A high power density is useful in applications where short bursts of high power are required, for example in frequency regulation or grid resilience.

In terms of efficiency, SCs, BESSs and FESSs can all achieve high levels of efficiency with quoted values reaching 95% and above for all three technologies [12]. Conversely, H_2ESSs and CAESs both experience very low levels of efficiency. Whilst CAES systems can achieve slightly higher levels of peak efficiency than H_2ESSs, they are still both regularly quoted in the literature as having efficiencies below 50% [26].

Finally, both SCs and FESSs are able to withstand significant lifetime cycles before reaching end-of-life [30,31]. They are often stated to be able to perform over 100,000 cycles over the course of their usable lifetime with some estimates reaching 1,000,000 cycles. The main drawback of BESSs is illustrated in this metric, where they are generally able to perform the lowest number of total cycles before reaching end-of-life. For certain applications where there are minimal daily cycles required, for example, peak shaving, cycle life is not a significant variable. However, in applications (for example frequency regulation) where multiple cycles may be performed hourly, this metric becomes increasingly important. These disparities in technical characteristics

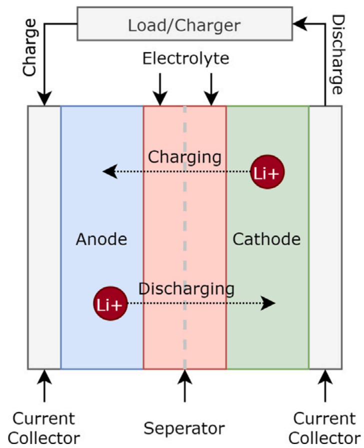


Fig. 3. Diagrammatic representation of a Li-ion battery showing charging and discharging mechanics.

make the chosen technologies ideal when comparing modeling techniques and can provide insight into when similar modeling approaches may not be suitable for all ESSs.

1.2.1. Li-ion batteries

The International Energy Agency stated that Li-ion BESS systems consisted of 93% of the total annual installed capacity of non-PHS storage in 2018 [32]. Whilst Li-ion systems are the dominant ES technology, alternative types of BESS are either being actively developed or deployed.

Fig. 3 shows a diagram of a typical Li-ion BESS. The basic configuration consists of a positive (cathode) and negative (anode) electrode within a liquid electrolyte with a porous separator in between. The anode will typically be made of a carbon-based material (for example graphite), whilst the cathode will be constructed from a metal (for example Cobalt, Nickel or Manganese). During charging, ions are transferred from the cathode to the anode through the application of a potential difference across the terminals, and the discharging process is this reaction in reverse [33].

Li-ion batteries offer an excellent level of energy density (up to 200 Wh/kg specific energy density [34]) along with a good power density (up to 2000 W/kg [21]). These two factors combined, result in a highly versatile ESS suited to a wide range of applications when compared to other ESSs. They are also commonly characterized as having low self-discharge rates, with most systems generally suffering a loss of state of charge (SOC) in the region of 0.2%–5% of per day depending on the specific design of the system.

The major drawback of Li-ion batteries is their limited operational lifetime under high cycling applications, where the lifetime is reduced by both cycle based degradation and calender degradation. It is for this reason that Li-ion systems are often specified with narrow tolerances for operational regions where operating the system outside of these zones will result in a rapidly decreasing lifetime of the BESS. Factors including C-Rate, temperature, energy throughput, Depth of Discharge (DOD), and SOC have all been shown in the literature to have significant impacts on battery lifetime [35,36]. BESSs are generally considered to reach the end of life when their capacity falls to 80% of the original capacity.

1.2.2. Flywheels

FESSs fall under the category of ‘mechanical energy storage’. At their base level, they primarily consist of a rotating mass that can be accelerated (charged) or decelerated (discharged). This is achieved by using a bi-directional electrical machine connected to the rotor that can be used as a motor to spin the flywheel faster, or that can be driven by the flywheel rotor as a generator when discharging. Detailed FESS overviews are found in [37–39].

Fig. 4 shows a diagrammatic representation of a flywheel, with the key elements consisting of the rotor, the housing (or containment), the electrical machine and the bearings. The representation in Fig. 4 is of a horizontal axis FESS which are more common than vertical axis FESSs.

On a fundamental level, the operation of a flywheel is governed by a set of equations. In Eq. (1), the energy density of the flywheel is determined where E is energy in joules, V is the volume of the flywheel, K is the shape factor of the flywheel and σ_{max} is the maximum hoop stress in megapascals.

$$\frac{E}{V} = K\sigma_{max} \tag{1}$$

The primary positive characteristic of FESSs is their resistance to cycle-based degradation. Much of the literature quotes the cycle lifetime of flywheels to be anywhere between 10,000 to 1,000,000 full charge–discharge cycles before failure [31,40,41]. The main method of degradation within a FESS is the wear on mechanical bearings (where present) although this is reversible with regular, inexpensive maintenance [29,42]. Another main method of degradation occurs within the Motor/Generator, with increased heat causing the windings to degrade. In terms of calendar lifetime, a figure of 20 years is the most often quoted statistic but this can vary based on manufacturers’ specifications and warranties.

Magnetic bearings represented a significant advancement in the viability of flywheels for an increased range of applications. Whilst they offer a much-decreased level of self-discharge along with increased lifetime and higher speeds, they also represent a significant increase in the costs of the overall system primarily due to the complexity of design and control [29,37]. They are mainly utilized for high-speed flywheels.

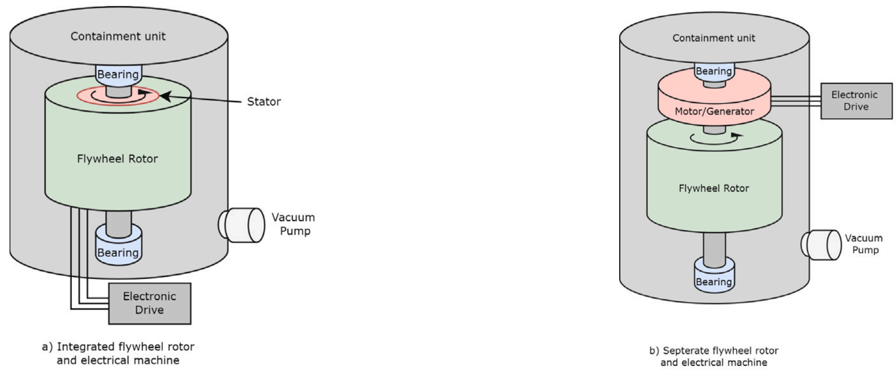
Another commonly discussed feature of FESSs is their high levels of self-discharge, often referred to as spinning losses. A flywheel will typically lose between 20%–100% of its stored energy over the course of a day [43,44]. It is for this reason that flywheels are generally most suited to applications where there will be frequent charge/discharge operations enabling them to minimize time spent in an idle state.

1.2.3. Supercapacitors

The main ESS medium that competes in a similar space to FESSs is Supercapacitors (SCs), also sometimes referred to as Ultracapacitors. They generally consist of two metal plates with a thin separator between them but differ from traditional capacitors in the fact that the plates are contained within an electrolyte which allows them to create a small ‘double layer’ of charge between the two plates, thus allowing them to store more energy due to vastly increased surface area. The basic construction of a supercapacitor is shown in Fig. 5.

SCs operate over a similar range of power ratings to flywheels with both capable of exceeding 1 MW of output power. Supercapacitors share many features with FESSs, primarily in the fact that they are mostly resistant to cycle-based degradation with potential cycle limits in the hundreds of thousands [13] and are also often quoted as having high-efficiency levels exceeding 95%. The caveat of this cycle life is that whilst they are capable of significant numbers of cycles, they generally store less energy than other ESSs (for example BESSs). They are therefore highly suited to high-cycle intensive, short-duration applications like frequency support.

However, there are also drawbacks to using Supercapacitors, one being another feature shared with FESSs, the significantly high self-discharge rates which have been quoted throughout literature in the region of 40% loss of charge per day [43,44]. Eq. (2) shows how the energy stored within a supercapacitor is calculated where E_{ESS} is the energy stored within the supercapacitor, C is the capacitance and V is the voltage. It can be seen that the energy is proportional to the square of the voltage, with the voltage range for most Supercapacitor modules



(a) A FESS consisting of integrated flywheel rotor and electrical machine

(b) A FESS consisting of a separate flywheel rotor and electrical machine

Fig. 4. Structure of a Flywheel Energy Storage System with (a) an integrated flywheel rotor and electrical machine (b) a separate flywheel rotor and electrical machine.

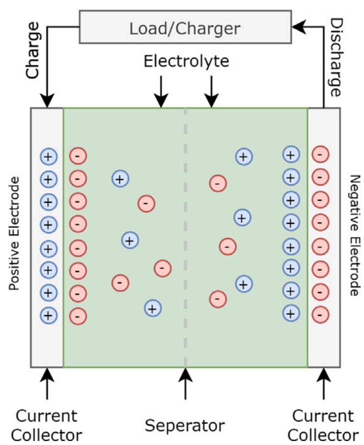


Fig. 5. Diagrammatic representation of a supercapacitor showing charging and discharging mechanisms.

covering 25–125 V where 25 V represents full discharge and 125 V represents full charge.

$$E_{ESS} = \frac{1}{2}CV^2 \tag{2}$$

As the supercapacitor is discharged, the voltage will fall linearly. Therefore, to extract the same amount of power at lower SOCs, the associated current will become larger. This results in significant losses when operating at lower voltages, as well as additional copper requirements and increased component sizes to account for this characteristic. To access all of the energy stored, the entire voltage range needs to be utilized, meaning this issue is unavoidable and cannot be circumvented by connecting further SC modules as the limits of the Power Conversion System will be reached, which would in turn lead to further costs. SCs are generally used in applications where short high-power loads are present, and in cycle-intensive applications that do not require significant stored energy. Overview articles for SCs can be found in [45–47].

1.2.4. Hydrogen energy storage systems

Hydrogen Energy Storage Systems (H_2ESSs) in the context of this research refer to systems where the energy transfer is two-directional, i.e where electricity can be converted to Hydrogen which can subsequently be converted back to electricity, as opposed to some areas of research which focus on Power-to-Gas (P2G) which is subsequently used for alternative purposes. An overview of the basic processes of a grid-connected H_2ESS is shown in Fig. 6.

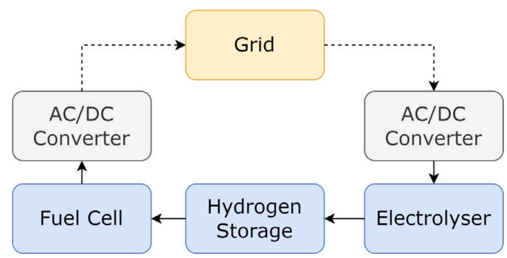


Fig. 6. Basic process of a power-to-power H_2ESS with respect to its interaction with the grid.

in The storage of energy over long periods of time (i.e. seasonal storage) offers interesting challenges and opportunities for both engineers and policy-makers alike. The possibility of hydrogen energy storage systems (H_2ESS) provides arguably the most promising and flexible of options in this regard.

Importantly, H_2ESS is much less restricted by the geographic constraints that limit the deployment of other alternatives (e.g. PHS). Although free hydrogen (H_2) does not exist in significant quantities in nature it can be produced from a number of naturally abundant sources. With respect to electrical energy storage, hydrogen produced from water, via the process of electrolysis is of interest. A single electrolysis cell is comprised of two electrodes (an anode and a cathode), separated by a central ion-conducting membrane. Fundamentally, the electrolyzer cell draws on a power supply to split water molecules into gaseous hydrogen and oxygen [48].

Individual cells are sized and stacked to achieve a targeted power capacity. There are a number of types of electrolyzers available on the market (e.g. alkaline, solid oxide, PEM). A good overview of these is found in [49]. Once hydrogen is produced it can be stored in gaseous form (e.g. tanks, vessels or caverns), in liquid form (i.e. cryogenic tanks), in alternative chemical carriers (e.g. ammonia, NH_3) or dissolved in solids (e.g. metal hydrides). The supply of hydrogen can then be drawn on to produce power during periods of deficit. This can be achieved electrochemically (i.e. reversing the electrolysis process in a fuel cell) or via combustion (e.g. H_2-CCGT). In some cases, bi-directional fuel cells are also possible (i.e. a single device to perform both the electrolysis and fuel cell steps).

Currently, the round-trip efficiency for power-to-gas-to-power (P2G2P) is generally specified in the region of 30%–50% [21] which is the main drawback to utilizing this storage technology at grid scale. Further research and development will need to be undertaken to allow this technology to become an active part of the electrical network.

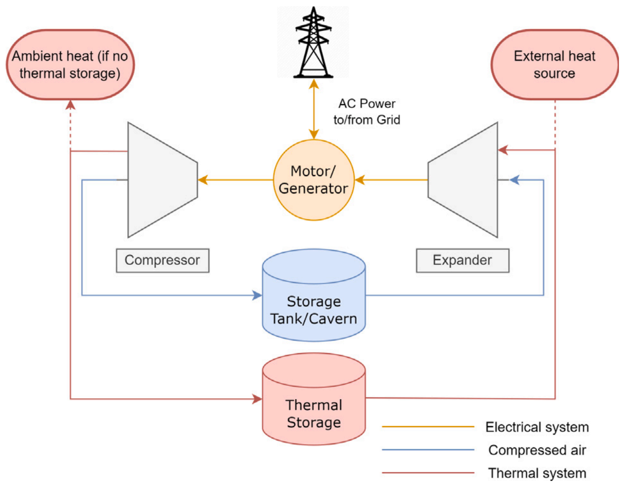


Fig. 7. Basic process of a CAES with respect to its interaction with the grid including electrical, compressed air and thermal systems.

Perhaps most importantly for seasonal energy storage, and unlike conventional BESS technology, energy and power capacity can be de-coupled via the employment of H_2ESS. In basic terms, the size of the energy store is limited only by the size of the vessel into which the H_2 is stored whilst the power capacity can be separately determined by the electrolyzer sizing. This is a trait shared with RFBs, which also feature the ability to de-couple the power and energy capacities, as discussed in [50].

1.2.5. Compressed air energy storage

Compressed Air Energy Storage (CAES) is mechanical energy storage and includes three main stages, compression (charging), compressed air storage, and expansion (discharging), seen in Fig. 7. During compression, ambient air from the atmosphere is compressed using one or more compressors, which are driven using electricity. The compressed air is stored in a pressurized environment, for large-scale CAES this is normally in underground salt caverns, while for smaller-scale CAES, pressurized tanks may be used. During expansion, the stored compressed air is passed through one or more turbines, which are used to generate electricity.

A key challenge with CAES is the fundamental inefficiencies of compression and expansion. During compression, the air temperature increases, and waste heat is generated, while during expansion, the air temperature decreases and so heat is required. For large-scale CAES (>50 MW), a combustion chamber using natural gas is often used before the expansion stage [51]. To reduce these inefficiencies, multistage compression and expansion are used, where the air is allowed to cool or warm back to ambient in between the stages. An ideal CAES facility would be isothermal, meaning heat would need to be continuously removed from the air during compression and continually added during expansion [52]. The efficiency of CAES can also be improved by including thermal storage, to store the heat from compression to be used during the expansion stage, known as adiabatic-CAES (A-CAES) [53].

Two large-scale CAES plants are operational in the world: Huntorf Germany, 321 MW, 2 h discharge, operational since 1978 [54] and McIntosh USA, 110 MW, 26 h discharge, operational since 1991 [55]. These large-scale plants both store the compressed air in underground salt caverns at around 70 bar. Each has high storage capacity and long cycle lives, however both require natural gas to operate meaning the round trip efficiencies are quoted as low as 30% [56]. Smaller scale, more efficient, up to 70%, demonstrators are being developed using isothermal or adiabatic CAES, however, the technology is not yet deployed commercially [56].

1.3. Review contribution

This paper provides a detailed overview of Energy Storage Modeling (ESM). For the first time, a model-centric review is presented covering a wide range of modeling techniques for a variety of different energy storage technologies and focusing on providing a resource for researchers to select appropriate modeling approaches for future studies. The innovation provided by this review is in the assessment of ESM techniques through the perspective of application based modeling, and the framework produced for assisting researchers in determining the most suitable approach for different types of ESS studies.

The work provides commentary on different approaches for modeling ESSs for application-specific studies and the software most commonly utilized for these works. It also provides a first-of-its-kind review on real-time simulation and hardware implementation, giving an overview of multiple different ESSs rather than focusing on one technology.

1.4. Review methodology

The literature review has been conducted by focusing on recent studies where the modeling of energy storage and its applications are the main objectives of the research. This rules out studies where the modeling of energy storage is minimal, or incidental as part of a larger study that focuses on non-storage elements of electricity generation, distribution, and consumption.

Studies conducted prior to 2018 have not been included in order to concentrate on the recent advancements in this research area. Occasional reference may be made to studies conducted prior to 2018 if they encompass foundational aspects of energy storage modeling.

In Section 4, the methodology concentrates only on studies where the energy storage system being researched is an active part of either the real-time element or the hardware element. Studies where the energy storage is not modeled in real time, or included as hardware in the loop, are not considered.

2. Energy storage modeling

When considering which method of ESM is most appropriate for the study being conducted, there are a number of different aspects to consider in order to choose the most suitable method. Firstly, the purpose of the study is paramount when choosing a modeling approach. Within this review, the two main purposes for modeling ESSs have been divided into two categories; 'Technology Modeling' (TM) and 'Application Modeling' (AM). The first of these, TM, covers all studies where analysis of the ESS technology itself is the goal of the study, for example when investigating a new method of modeling a FESS [57] or representing the degradation rates of certain Li-BESS chemistries [58].

The second of these purposes, AM, covers the studies where the ESS is being deployed for a specific application and the objective is to assess its technical, economic, or techno-economic performance. Examples of this could include assessing an SC/BESS hybrid for electric vehicle applications [59], or the feasibility of deployed CAES for wind generation support [60]. The other main aspect for determining a modeling approach is to ensure it is appropriate for the intended duration of the simulation. In this review, the durations of simulation are categorized as follows;

- Short Duration — 0 to 60 s
- Medium Duration — 60 s to 1 day
- Long Duration — Longer than 1 day

The simulation duration is essential in choosing the correct modeling approach, as using a computationally intensive approach to simulate a long-duration application may result in prohibitively long simulation times. For this reason, there are trade-offs between advantages and disadvantages for each modeling approach [61,62]. In this section, each approach will be introduced in detail, with examples of existing literature discussed and commentary provided on what scenarios may suit the approach best.

Table 2
Different methods of modeling and simulation of ESSs.

Type	Description	Use Case	Advantages	Disadvantages	Ref
Bucket (Power/Energy) (Energy reservoir)	This method represents the ESS as a 'black box' where the bucket is either filled or emptied (charged or discharged) according to set limits.	Long-duration studies where the physical operation of the ESS is not studied. This method is most effective when considering larger-scale applications and where the ESS in question is a known quantity with easily identifiable parameters.	Simplicity, Fast computational speed, Easy parameter control, Ability to introduce additional complexities as required, Fast adaptation to different applications	Is not technology specific in base form, Minimal data on the response of ESSs to instantaneous events	[63–69]
Electrical (Equivalent circuit)	This method seeks to represent a given ESS as an electrical circuit, modeling the system overall in terms of voltages and current to and from the ESS and a given application.	Investigations, where the electrical operation of the system is of interest, for example for fault, ride through, voltage drop, transient harmonic distortion and short-duration frequency response analysis.	Increased complexity, Ability to analyze response to instantaneous events, Required for certain types of study	Longer computational times, More specific parameter identification is required, Slower to switch between different applications due to need for specific electrical system information	[68,70–74]
Physical (Electrochemical) (Concentration based)	When discussing a BESS, this method is referred to as an 'Electrochemical model'. For a BESS, this would represent modeling the specific chemical reactions that take place within the battery. For a FESS, this method would consist of modeling the mechanical kinetic operation of the flywheel.	Investigations where the specific operation or degradation of the ESS itself is of interest. This could consist of studies into the ageing of different battery chemistries or in the design of different flywheel form factors.	Very high accuracy, Degradation and other mechanisms are more easily modeled, Essential in scenarios where analysis is needed at the pre-fabrication stage	Significantly longer computational times, Parameter identification required to be extensive, Will often need to be combined with other methods if application specific information is required	[70,75–79]

2.1. Types of energy storage modeling

The field of ESM and simulation can be categorized into three distinct types of approaches, as detailed in the following sections. In Table 2, an overview is given of Bucket, Electrical and Physical modeling approaches including use cases as well as advantages and disadvantages.

2.1.1. Bucket model

The first of these is referred to in this work as the 'Bucket Model' (BM) approach, although it is also commonly referred to as an 'Energy Reservoir Model' (ERM) and the 'Power-Energy Model' (PEM). The basic approach to this method is to model the ESS as an ideal unit, where the energy currently stored within the ESS is based upon either adding or subtracting energy from that which was stored at the previous time step. This method of modeling can be made more complex by introducing other aspects (for example efficiencies, degradation and self-discharge rates) [63,64].

In practice, this is achieved through modeling the energy storage using Eq. (3), where SOC_{t} is the SOC as a % of overall capacity at time t, $S_{\mathrm{t\text{-}1}}$ is the SOC as a % of overall capacity at the previous timestep, L_{t} is the storage losses due to self-discharge, E_{ESS} is the energy capacity of the ESS, η_{ch} and η_{dis} is the charging and discharging efficiency respectively, P_{ch} is the charging power delivered over the timestep t and P_{dis} is the discharging power delivered over the timestep t. Further exploration of this modeling approach can be found in [65,67,80,81].

$$SOC_t = SOC_{t-1} - \frac{L_t}{E_{ESS}} + \frac{(P_{ch}\eta_{ch} - P_{dis}\eta_{dis})}{E_{ESS}} \tag{3}$$

The main benefit of this method is when seeking to perform system-level studies that will be performed over significant periods of time. As it removes the requirement for more complex calculations, the computational requirements are lower and hence long periods of time can be simulated rapidly. This method also lends itself to studies where the performance of storage in regard to specific applications is being assessed, rather than the technical response of the storage itself. It also benefits from not requiring detailed knowledge of the parameters of the ESS being studied and therefore can be utilized as a generic representation of all types of ESS. This model also provides an easier base from which to easily modify the study for different applications.

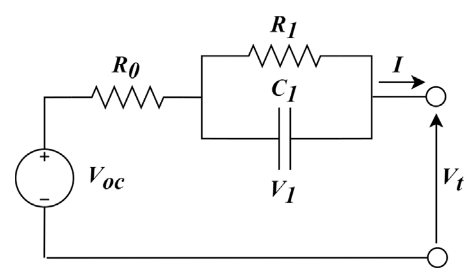


Fig. 8. First-order equivalent circuit model of a BESS.

However, the drawback remains that the method as a whole is the least technically detailed of the three methods presented in this review. Whilst complexities can be added to the model to create a more representative system, the lack of modeling of the mechanisms of the ESS means that certain studies are not possible, or inadvisable from a technical standpoint, to be undertaken using this model. For example, whilst voltage and current can be implemented in the BM approach through appropriate conversions, it is less accurate than modeling these characteristics from the start in an Electrical Model.

2.1.2. Electrical model

The second category of ESS modeling is referred to in this work as the 'Electrical Model' (EM) although it is also commonly referred to as an 'Equivalent Circuit Model'. This approach consists of representing the ESS from an electrical point of view, where the electrical characteristics of both the system as a whole and the ESS are modeled, usually with the main variables being studied within the application being Voltage and Current. There are many different levels of EM, from a basic simplified model to complex electrical representations.

Electrical models can be implemented in a number of ways, but the most common approach in the literature is to represent the system as an equivalent circuit. A first-order equivalent circuit approach to modeling a BESS is shown in Fig. 8. The governing equations and approaches to using this model can be found in [82–84]. This example is for a BESS EM, examples of EM for other technologies can be found throughout the literature including for a FESS [57], SC [85], H_2ESS [86] and CAES [87].

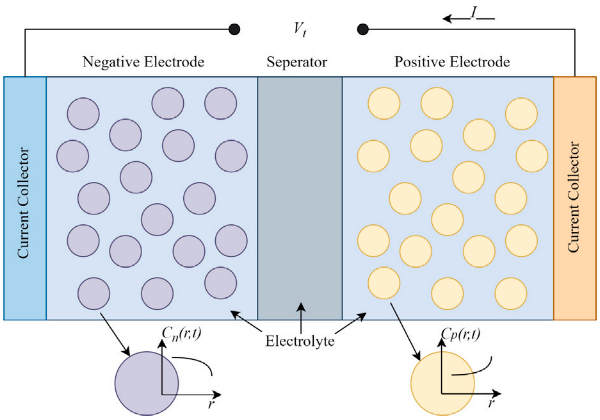


Fig. 9. Diagrammatic representation of a physical (concentration based) model of a BESS.

The main advantage of utilizing this method is the ability to study transient events from an electrical perspective, for example when modeling power quality applications or instantaneous frequency response. This method offers greater detail than the BM, although that comes with the requirement for more detailed knowledge of the parameters of the ESS being modeled. The electrical characteristics are required to provide an accurate model, and in some cases, further information will be required. The electrical distribution characteristics of the system being modeled are also required, which can make switching between different applications from the same base model more difficult.

It should also be noted that the individual short-term electrical behavior of the ESS being modeled is 'hidden' behind the power converter, and hence from the viewpoint of the electrical interface with the ESS, the majority of different technologies will operate identically through the power converter.

2.1.3. Physical model

The final category of ESS modeling discussed in this work is referred to as the 'Physical Model' (PM). In the context of BESSs, these are often referred to as an 'Electrochemical Model' or 'Concentration Based Model'. For this approach, the physical or chemical characteristics of the ESS are modeled. They are primarily used when the objective of the study is to simulate the inherent properties of specific ESS types, such as a particular Li-Ion cell or a new type of steel for a FESS. It also encompasses scenarios where the degradation of an ESS is being modeled, and where the application is of limited impact on the study.

Fig. 9 shows a diagrammatic representation of the concentration-based model approach for a BESS, and detailed explanations of the governing equations and approach to utilizing this modeling approach can be found in [88–90]. This example is for a BESS, but examples of physical modeling for other storage technologies can be found throughout the literature including for a FESS [91], SCs [92], H_2ESS [86] and CAES [93].

The key advantage of this model is its high degree of accuracy and very detailed level of output. It is critical to understand the design and operation of the ESS itself when utilizing this type of model. It also enables new materials to be simulated prior to fabrication, and can also be used to characterize different types of ESS. These models require extensive knowledge of the specific ESS being modeled, such as material type, cell chemistry or other proprietary knowledge. They also often require significant simulation durations. They should only be utilized when the ESS being used is well-defined with detailed information on its construction.

Table 3
Qualitative assessment of modeling approaches considering different design factors.

	Bucket	Electrical	Physical
Grid interaction	Low	High	Low
Computational requirements	Low	Moderate	High
Degradation modeling	Moderate	Low	High
Flexibility for different applications	High	Moderate	Low
Efficiencies	Moderate	High	Moderate
Sensitivity analysis	High	Moderate	Low

2.2. Selecting a modeling approach

This section explores the different aspects that affect the choice of modeling approach for the storage technologies discussed. It considers factors including computational speed, degradation requirements, system complexity, efficiencies and the ability to perform sensitivity analyses. This section aims to provide researchers with the information needed to select the most appropriate approach for a given study with a qualitative assesement of the different approaches presented in Table 3.

This review paper focuses on grid-scale application of storage technologies, and as such it is important to consider what modeling approaches are best suited for studies where the storage technology is directly interacting with the grid on an electrical basis, for example when modeling voltage support or frequency response. For these types of studies, regardless of the energy storage technology, the electrical model is the most appropriate as it can model the interconnection between grid characteristics and energy storage. This has been shown in applications including grid resilience [94], power quality [95] and frequency regulation [96].

Should the study be conducted to focus on the storage technology itself, then the BM approach can also be useful. This will generally be utilized when there is no requirement for the ESS to impact the grid operation, for example when modeling a frequency response service [67, 97]. If the effect of ESS operation on the electrical characteristics of the grid is not required, then the BM can be a more computationally efficient means of analyzing a system.

A key consideration of modeling is the computational resources required to run the developed models. However, it should not be a primary driver to minimize this, some cases will inevitably lead to high computation resources to achieve the desired study outcomes, for example in complex degradation studies. However, it is important to note this selection criteria as it can place restrictions on the speed at which studies can be completed, and the equipment required to run these studies.

The PM approach can lead to high computational requirements due to complex equations and very small timesteps being utilized [61,64]. However, in some scenarios, the EM approach will also require significant computational power, including scenarios where entire grid systems are being modeled [98] or where different electrical systems are interfacing with small time steps [99]. Of the three approaches, the BM method is the least computationally intensive as it usually represents a simplified version of an ESS and can be run over higher time-steps [80,100].

Analyzing the degradation of a given storage technology for various applications is a fundamental part of many research activities within the field of energy storage. It is often complex, with multiple variables that need to be considered. Each ESS technology discussed in this paper has different degradation mechanisms, and the external factors which affect degradation are also variable depending on the technology chosen. It is often the PM approach that is utilized to produce accurate degradation due to the focus on governing equations and highly detailed storage models [77–79]. If assessing the degradation mechanisms of a system is the primary objective, then the PM approach is recommended to capture the correct level of detail.

In [101], the authors present a new method for modeling the whole-life-cycle SOC prediction in Lithium Ion BESSs. This approach considers current, voltage and temperature variations in order to predict the SOC across the lifecycle of a BESS. The modeling approach is a mathematical one that operates in between the EM and PM approaches and is accompanied by experimental verification. This study highlights that in some scenarios, the study is not easily bracketed into a specific ESM approach and this is common when the study considers a combination of different model types. This approach is also seen in other studies across the literature including [102] which predicts the remaining useful life of Lithium Ion BESSs.

For some technologies, primarily BESSs, the degradation mechanisms are widely researched and can be readily implemented into a variety of different modeling approaches by using defined equations produced as the result of characterization studies [35]. Similar equations exist for H_2ESS [103] and SCs [104], whilst FESSs and CAES are considered to have minimal degradation characteristics beyond simple efficiency losses [39,105]. Where such equations exist, they can be implemented using the BM approach in software (for example MATLAB/Simulink), presenting an opportunity to consider the effects of degradation on system performance in studies where the mechanisms of degradation are not the primary objective [106].

When considering incorporating efficiencies of the storage technology itself, multiple variables need to be considered. The efficiencies of a given storage system can be affected by many different aspects, for example, both internal and external temperatures, charging/discharging rates, state of health and age. All three approaches to modeling can represent these aspects in different ways. In a bucket model, these can be represented as modifications to the changes to the SOC of the ESS at each time step [64]. Many electrical modeling packages will account for internal efficiencies within pre-set blocks [107,108]. Whilst this factor needs consideration when selecting a modeling approach, all three approaches can include good representations of storage efficiency regardless of the technology chosen.

Separate from storage-specific efficiencies are those related to the system as a whole. In this context, these efficiencies relate to non-storage aspects, for example, ancillaries within the containment unit or power electronics that connect the storage unit to the grid. EM and PM approaches will often cater for this automatically within the modeling software chosen or contain mechanisms for including this aspect [109]. For the BM approach, these efficiencies will need to be accounted for through compensation of the request to/from the ESS to account for these aspects [67]. System level efficiencies are common across all storage types, as they will all interface with the grid using similar power electronic systems that can be accounted for within each approach.

Sensitivity analyses are a useful tool for analyzing how variables affect the performance of a system. Often, this will involve modifying one or more variables for each run of a simulation and comparing the results. This can sometimes involve using optimization techniques, including genetic algorithms [110,111] which offer good integration with EM and BM approaches. Due to their relatively low computational requirements, BMs are an ideal candidate for studies where many runs of a simulation will be required [66]. More complex models, particularly using the PM approach, are less suited to large sensitivity studies but can be utilized in this way with appropriate hardware.

To conclude, the modeling approach selected should be carefully considered based on the application being modeled and the scale of study required. Overall, the BM approach is the most flexible and can usually be adapted to suit most scenarios but at the cost of low-level detail. When considering detailed electrical characteristics, an EM approach is likely to be the most appropriate selection whilst for studies focusing on low-level physics-based interactions or high-resolution studies a PM approach should be considered. Another important distinction to make is that the user should ensure that the appropriate modeling approach is taken to avoid unnecessary over-complex models. For example, the user should carefully consider whether the benefits of a higher complexity modeling approach (for example PM) provides sufficient additional benefit and context to the results produced. This should be compared to a simpler approach (for example BM) that could achieve acceptable results but using fewer computation resources that could achieve much faster simulation times. Throughout this review, examples will be given highlighting different modeling approaches for similar applications to provide commentary on the flexibility of all three model types.

2.3. Modeling review studies

This section first details the review papers available in the literature. The majority of previous work in reviewing ESM concentrates on reviewing modeling approaches specifically for BESSs, with an overview of previous works in this area contained in Table 4.

Several different studies provide an overview of the three main types of models presented in this paper [80,118,120]. This is most often performed purely from a BESS perspective as in [66] which provides detailed commentary on the modeling of BESSs (mostly Li-ion but with some consideration given to other technologies) for electrical network analysis. It also explores the methods of modeling the network itself and briefly discusses other energy storage technologies and their applicability to this application.

In [61], another exploration of approaches to BESS modeling is presented. This paper provides a more detailed analysis of the different models, with three sub-categories of PM presented, in order of increasing complexity they are referred to as the 'Single Particle Model', the 'Pseudo-Two-Dimensional Model' and the 'Detailed Electrochemical Simulation Models'. Significant time is dedicated to the State of Charge (SOC) modeling and the advantages and disadvantages of different approaches along with an exploration of thermal and degradation modeling of Li-Ion BESSs. The paper focuses on providing an analysis of the effectiveness of the different models with a focus on optimal control of a physical system.

Another study in [62] performs an analysis of how utilizing different models affects the SOC and State of Health (SOH) estimations, and how this subsequently impacts BESS lifetime and financial calculations. It concludes that the choice of model can have significant impacts on the results of the study, showing that the BM can lead to oversized plant and that more detailed BMs which include degradation algorithms can be a suitable solution.

There are many different subsections of EM in terms of BESS modeling, with [116,117,121] detailing the types of equivalent circuit models available and commentary on their use cases, advantages and disadvantages. The work tracks the improvements made in equivalent circuit modeling over the previous decade and the key challenges for future research are discussed, highlighting parameter estimation and machine learning as two key areas.

The wide-ranging study in [121] explores EM for BESSs, H_2ESSs and SCs. It reviews the different simplified electrical models available for each technology as well as the characteristics and requirements for using them. The study then explores different practical applications of the models in the field of power system dynamics and shows that oversimplification of the models can lead to unreliable results. The study indicates that areas including the modeling of power converters and the development of more detailed models as crucial future research challenges. With respect to H_2ESS models, this is particularly important as the generally lower round trip efficiency plays a significant part in determining the effectiveness of the system. The work in [122] details an overview of the 'Digital Twin' (DT) approach to modeling and the state of the literature for different ESSs. The work explains the DT architecture for a range of different storage technologies and discusses the main research challenges in this field which center around the application, ageing mechanisms and system architecture.

[119] provides an overview of degradation modeling of Li-ion BESSs, exploring the different stress factors that are included in the modeling process and the approaches that different papers have taken in representing the ageing of a BESS. Key stress factors include SOC,

Table 4
Recent literature providing an overview of ESM techniques.

Ref	Year	Summary
[66]	2019	Presents an overview of the three main models of BESSs, 'Bucket Model', 'Equivalent Circuit Model' and 'Electrochemical Model' but mostly concentrates on providing commentary on BESSs for use domestically in electricity network improvements
[61]	2019	An extensive review of a wide range of different BESS modeling approaches discussing the 'Energy Reservoir', 'Equivalent Circuit', 'Concentration Based' and 'Temperature' models. Explains the motivation behind utilizing each technique along with the required parameters and how degradation is implemented into the models.
[112]	2019	Gives an overview of the range of mathematical models available for planning and operation of ESSs exploring both linear and non-linear models and gives recommendations for their usage
[113]	2019	This study looks into the 'Equivalent Circuit Model' and the 'Electrochemical Model', with insight given into the different sub-categories of the model available and the different variables and parameters required. It also looks at how these models are linked together with thermal management, battery management and control.
[114]	2020	Provides a review of different electrochemical and equivalent circuit approaches to modeling BESSs, with a focus on battery management and state estimation
[62]	2020	Compares three different types of BESS models, with two Bucket models with varying approaches and an electrical model studied. Shows the effect that the choice of model can have on the solutions gained from modeling and simulation, and the simulation time required to execute studies.
[115]	2021	Details the electrical and electrochemical approaches to modeling BESSs including an in-depth look at data-driven modeling and State of Health (SOH) estimation. Also looks at the different machine-learning algorithms available for estimating different BESS parameters.
[116]	2021	Looks specifically at various types of equivalent circuit models with a focus on State of Charge (SOC) estimation. Also discusses the different learning and optimization algorithms available for the purpose of estimating SOC.
[117]	2021	This review looks at different approaches to modeling BESSs using the 'Equivalent Circuit Model' approach, discussing the benefits and drawbacks of each approach and conducting analysis on the methods with a focus on the state of power estimation for electric vehicles
[118]	2022	Discusses the concepts of three different types of battery modeling techniques, namely the 'Power-Energy Model', the 'Voltage-Current Model' and the 'Concentration-Current Model'. Explores the characteristics of each model, the applications they can be used for and how they impact degradation assessment.
[119]	2022	Concentrates on the degradation aspect of BESS modeling, highlighting the different stress factors that are used to inform each model and the applications that they are used in
[120]	2022	This article presents a detailed exploration of different approaches to BESS modeling, with a comprehensive overview of how BESS energy management can be optimized for different objectives and using different approaches.
[80]	2022	Details the 'Bucket Model', 'Equivalent Circuit Model' and 'Electrochemical Model' with a perspective of second life Li-Ion BESSs for stationary applications. Also discusses aspects of energy management strategies and the advantages of using different approaches.
[121]	2023	Focuses on 'Equivalent Circuit Models' for BESSs, SCs and H_2ESSs, and the different types of models available within this category. Mainly discusses the approaches for BESSs, and gives an overview of existing installations.
[122]	2023	Gives an overview of the approaches to utilizing the 'Digital Twin' approach to modeling energy storage, discussing it in relation to a range of different ESS technologies and applications with the benefits and drawbacks of this modeling strategy also presented.

Depth of Discharge (DOD), temperature, operational time, cycle count and energy throughput. Different models are also shown to approximate ageing in different ways, for example through rainflow counting [123] or through experimentally verified models [124]. In a similar study, [115] looks at battery modeling techniques with an emphasis on the parameterization of BESSs using machine learning algorithms, in order to efficiently determine the required values. The work concludes that equivalent circuit modeling represents the best middle ground between oversimplified models and those requiring extensive parameter input.

Overall, the majority of literature reviews already conducted in this area focus primarily on BESS modeling with very little previous work conducted that considers other technologies that are considered in this work, including FESSs, CAES and H_2ESS. To expand the discussion in this field, the following section performs an overview of the modeling of 5 different ESS technologies discussing the methods used when considering a range of applications.

3. Application of energy storage modeling

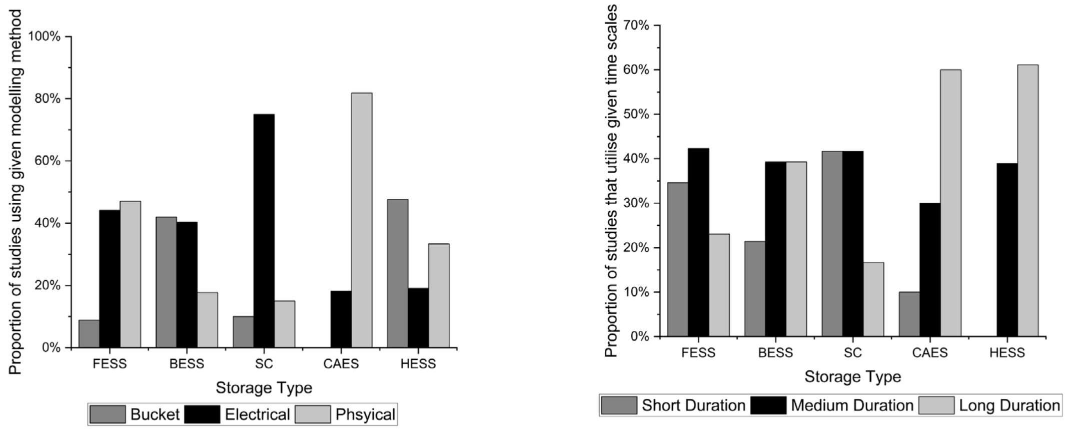
This section explores the literature available for different ESS technologies including the simulation duration, the modeling objective, the model utilized and the software used to carry out the simulation. An overview of the literature review as part of this study is contained in Table 5.

First, some statistics from the literature review are analyzed. In Fig. 10(a) the proportion of times that each model type is used in literature for each technology is presented. Note that in some studies multiple approaches are used. From this data, it can be seen that the approach utilized is highly dependent on the storage technology being researched. For example, a FESS is modeled using the BM method in only 8.8% of the literature surveyed whilst it is utilized in 41.9% of BESS studies reviewed. Another key aspect to note is that modeling of an SC is most commonly conducted using the EM approach with 75% of literature utilizing an electrical model.

Whilst H_2ESS and BESS studies contain high proportions of BM approaches, there are no studies utilizing this approach for CAES and less than 10% for both FESSs and SCs. This suggests that there may be an opportunity for future studies to develop these models to provide a greater range of tools and subsequently flexibility for the study of these technologies.

The duration of the simulations within the literature, according to the ESS technology being studied, is shown in Fig. 10(b). Again there are some immediate conclusions to be drawn from this figure, notably that for CAES and H_2ESS the general trend is for mostly long-duration simulations with some medium-duration simulations. Due to both these technologies being considered long-duration assets, it is unlikely that short-duration studies would be required unless the focus of the study is on the operation of the ESS itself. Short-duration simulation is prominent for SCs and FESSs which is to be expected considering their position as limited energy capacity assets. The versatility of the BESS is illustrated in the fact that the duration of the simulation is spread fairly evenly across all three durations.

Finally, the software that has been utilized for each study is shown in Fig. 11. MATLAB/Simulink dominates the software distribution with 57 out of 94 studies analyzed utilizing this software. Other than MATLAB/Simulink, the software HOMER and DigiSELENT Power Factory are both used in several studies whilst an algorithmic modeling approach is used in 7 studies. Some other packages (for example Python or Aspen Plus) are used occasionally, but it is apparent that MATLAB/Simulink dominates the software approach to ESM.



(a) Modeling approach in literature for varying technologies as a proportion of total literature studied

(b) Simulation durations in literature for varying technologies as a proportion of total literature studied

Fig. 10. Number of times in reviewed literature as a proportion of studied literature that (a) a given modeling approach is used (b) a given simulation duration is used.

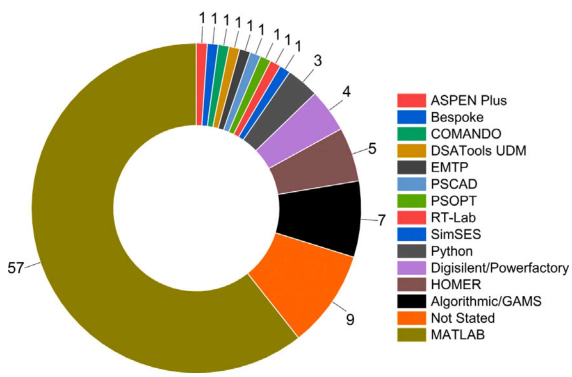


Fig. 11. Number of times in reviewed literature that a given software package is used for ESM.

3.1. BESSs

The application of BESS models spans many different purposes and approaches. Multiple different models have been proposed and utilized for modeling the physical mechanisms of BESSs, with a wide range of models discussed in literature concentrating on modeling the degradation of a BESS. This is a key aspect of BESS operation; therefore, it is important that the models utilized are accurate, which often leads to significant complexity.

In [73] a complex life cycle model which utilizes a combination of equations and electrical modeling to expand a BESS model to include a cycle-life calculator. This model also incorporates thermal aspects and power loss and utilizes equivalent cycle counting to predict the maximum number of cycles that a BESS can withstand at different DODs. This work is an example of developing and applying a BESS model with a specific application-neutral approach where the focus is on modeling the technology itself.

A similar approach is taken in [126] which includes an assessment of the single particle method of modeling. In this work, the degradation of a BESS is modeled for different ageing parameters, with the effectiveness of the three model types (PM, EM and BM) compared for this application. The single particle model is shown to be the most accurate, with accuracy decreasing with decreasing model complexity. This further illustrates the need for detailed physical modeling when attempting to simulate the technical characteristics.

A combination of EM and PM is utilized in [58] where the outputs of an equivalent circuit model are used as an input to the battery degradation model that uses experimental data, literature models, and datasheets to estimate battery lifetime. This combined approach is effective in accurately modeling the degradation of the BESS and shows the ability of different models to be used together to provide a more effective result.

EM is utilized in a significant number of studies within the literature, with many varied approaches for model development and deployment. In [129] two different approaches to modeling BESSs, a detailed and average electrical model. Small modifications are made to the detailed model to reduce computational demand and the two models are then used to simulate the same frequency response events. Whilst it is shown that in many cases the two models are equivalent, there are certain scenarios in which the two models diverge, showing that it is imperative to utilize the correct model for the application being simulated in order to avoid erroneous results.

Elsewhere in [157] a complex electrical model is proposed for grid fault analysis, including detailed converter models and control strategy. The model is then utilized in a case study, again comparing an average value model with a detailed model showing the average model is accurate for usage in this application with only minimal differences between the two.

EM is also used across the literature when considering control strategies, as in [188] which models the BESS as a controlled voltage source behind a resistance, implemented to investigate control strategies based on BESS SOC and wind turbine output power. In these cases, an EM approach is the most appropriate as such control studies are generally predicated on using aspects such as voltage and power to implement control loops.

Many studies utilize EM with a generic BESS element that has been previously developed and included as a pre-installed unit within software (for example MATLAB/Simulink or DigiSILENT PowerFactory). An example of this is seen in [141] which uses the DigiSILENT PowerFactory BESS model within a larger electrical islanded microgrid model. This approach is often utilized in optimization studies like this one where the operation of the BESS itself is not critical to the objectives of the analysis.

The BM method is also used extensively throughout the literature representing an effective method for fast application-specific studies. In [177] this approach is used to simulate capacity degradation in an arbitrage study, an example of introducing additional complexity to a bucket model to achieve the objectives required whilst avoiding over-complication of the model.

Another study that utilizes the BM approach is [192], where the paper investigates dispatch optimization of BESSs with a consideration for degradation effects. Each operation of the BESS is given an associated

Table 5
Summary of literature discussing ESM.

Ref	Year	Technology modeling	Application modeling	Short duration	Medium duration	Long duration	Bucket	Electrical	Physical	BESS	FESS	SC	CAES	H_2ESS	Software
[74]	2018	✓	✓		✓			✓	✓		✓				DSATools UDM
[76]	2018		✓		✓			✓	✓	✓	✓				MATLAB
[85]	2018	✓		✓	✓	✓		✓				✓			MATLAB
[125]	2018		✓			✓	✓			✓				✓	HOMER
[126]	2018	✓				✓	✓	✓	✓	✓					Algorithmic
[91]	2019	✓	✓	✓				✓	✓		✓				MATLAB
[127]	2019		✓			✓		✓	✓		✓	✓			MATLAB
[81]	2019		✓			✓	✓			✓					MATLAB
[128]	2019		✓		✓			✓		✓		✓			MATLAB
[129]	2019	✓	✓	✓				✓		✓					MATLAB
[130]	2019	✓		✓				✓	✓	✓					Bespoke
[92]	2019	✓		✓	✓				✓			✓			MATLAB, COMSOL
[60]	2019		✓			✓			✓				✓		Aspen Plus
[87]	2019	✓	✓		✓			✓	✓				✓		MATLAB
[131]	2019		✓			✓	✓			✓				✓	HOMER
[132]	2019		✓			✓	✓					✓		✓	HOMER
[133]	2019	✓			✓		✓			✓					MATLAB
[134]	2019		✓			✓	✓			✓	✓				HOMER
[135]	2019		✓		✓			✓	✓	✓		✓			MATLAB
[136]	2019	✓		✓			✓			✓					MATLAB
[137]	2019		✓			✓			✓				✓		gPROMS
[138]	2019		✓			✓			✓				✓		Not stated
[139]	2019		✓		✓			✓	✓		✓				MATLAB
[140]	2020		✓		✓			✓				✓			MATLAB
[71]	2020		✓	✓				✓		✓	✓				MATLAB
[73]	2020	✓				✓		✓	✓	✓					MATLAB
[141]	2020	✓	✓		✓			✓		✓					Power Factory
[142]	2020		✓			✓								✓	MATLAB
[143]	2020	✓	✓		✓			✓	✓		✓				MATLAB
[144]	2020	✓	✓	✓	✓			✓		✓		✓			MATLAB
[145]	2020		✓		✓			✓		✓	✓				Power Factory
[146]	2020		✓		✓			✓	✓		✓				MATLAB
[147]	2020		✓			✓	✓			✓				✓	HOMER
[148]	2020	✓	✓		✓			✓	✓		✓				MATLAB
[149]	2020		✓	✓				✓	✓		✓				MATLAB
[150]	2020		✓		✓		✓			✓					MATLAB
[151]	2020		✓		✓		✓			✓					MATLAB
[152]	2020		✓		✓		✓			✓					Algorithmic
[153]	2020	✓				✓	✓			✓					MATLAB
[154]	2020		✓			✓			✓				✓		Not stated
[155]	2020	✓			✓				✓				✓		Not Stated
[59]	2021		✓	✓	✓			✓		✓		✓			MATLAB
[156]	2021	✓	✓		✓			✓	✓		✓				RT-LAB
[157]	2021		✓	✓				✓		✓					EMTP
[58]	2021	✓				✓		✓		✓					MATLAB
[158]	2021	✓	✓			✓			✓				✓		MATLAB
[93]	2021		✓			✓			✓				✓		MATLAB, EES
[159]	2021						✓			✓				✓	MATLAB
[160]	2021		✓	✓			✓				✓				GAMS
[161]	2021	✓	✓	✓				✓				✓			Power Factory
[162]	2021	✓			✓			✓				✓			MATLAB
[163]	2021		✓			✓			✓		✓				Not stated
[164]	2021		✓		✓				✓		✓				Power Factory
[165]	2021	✓		✓				✓		✓					MATLAB
[166]	2021		✓			✓	✓			✓					Python
[167]	2021		✓	✓	✓			✓	✓		✓				Not stated
[57]	2022	✓		✓				✓			✓				MATLAB
[168]	2022	✓	✓			✓	✓			✓					MATLAB
[169]	2022	✓			✓			✓				✓			MATLAB
[170]	2022		✓		✓	✓		✓	✓	✓	✓				MATLAB
[171]	2022	✓				✓	✓			✓					MATLAB
[172]	2022		✓			✓	✓			✓					MATLAB
[86]	2022		✓		✓		✓	✓	✓	✓				✓	SimSES
[173]	2022		✓	✓				✓		✓		✓			MATLAB
[174]	2022		✓			✓	✓			✓	✓				MATLAB
[175]	2022		✓		✓	✓	✓			✓		✓			MATLAB

(continued on next page)

Table 5 (*continued*).

[101]	2022	✓			✓	✓		✓	✓	✓					Not stated
[176]	2023		✓	✓				✓		✓					MATLAB, RT-LAB
[177]	2023		✓		✓		✓			✓					Not stated
[102]	2023	✓			✓	✓		✓	✓	✓					Algorithmic
[178]	2024		✓		✓		✓			✓				✓	MATLAB
[179]	2024		✓		✓			✓	✓					✓	GAMS
[180]	2024	✓	✓			✓			✓					✓	MATLAB
[181]	2024	✓	✓			✓	✓				✓				MATLAB
[182]	2024	✓	✓	✓				✓			✓				PSCAD
[183]	2024	✓	✓			✓		✓	✓					✓	MATLAB
[184]	2024	✓	✓			✓		✓	✓	✓				✓	MATLAB
[185]	2024		✓			✓	✓			✓					MATLAB
[186]	2024		✓		✓		✓			✓					Algorithmic
[187]	2024		✓			✓			✓	✓			✓		MATLAB
[188]	2024		✓	✓				✓		✓					MATLAB
[189]	2024		✓			✓	✓			✓					COMANDO
[190]	2024	✓	✓		✓				✓					✓	Python
[191]	2024		✓		✓			✓		✓					PSOPT
[192]	2024		✓		✓		✓			✓					Not stated
[193]	2024		✓		✓		✓			✓				✓	Algorithmic
[194]	2024		✓		✓	✓			✓		✓			✓	MATLAB
[195]	2024	✓		✓					✓		✓				Not stated
[196]	2024	✓		✓					✓		✓				Not stated
[197]	2024	✓			✓				✓				✓		Python
[198]	2024	✓		✓					✓				✓		MATLAB
[199]	2024		✓		✓				✓				✓		MATLAB
[200]	2024		✓			✓			✓				✓		MATLAB
[201]	2024		✓			✓		✓					✓		Algorithmic
[202]	2024		✓	✓				✓				✓			MATLAB
[203]	2024	✓	✓	✓				✓				✓			MATLAB, Sim Power Systems
[204]	2024		✓	✓				✓				✓			MATLAB
[205]	2024		✓	✓				✓		✓		✓			MATLAB
[206]	2024		✓		✓		✓							✓	MATLAB
[207]	2024		✓			✓	✓							✓	Algorithmic

capacity loss value based upon a range of variables including depth of cycle, number of equivalent cycles and C-rate. This study is a good example of introducing additional complexities to a simple BM model to achieve the study objectives.

In many studies, the BM approach is adopted as a result of the ESS operation being incidental to the studies goals. In these studies, such as [189], the BESS is considered in terms of power and energy with minimal additional complexities. However, as the physical operation of the BESS is not of relevance to the study being conducted, this approach allows the remainder of the model to be more complex and still achieve the research objectives. This approach is more common with technologies, such as BESSs, that are well-understood on a technical level and can be assumed to operate as expected.

A range of different techniques are used when implementing a BM, for example in [153] where a memory block within MATLAB/Simulink is used to represent the BESS current state of energy. An alternative approach is shown in [171] where an integrator block, again in MATLAB/Simulink, is used to track the current state of energy. Both studies show effective implementation of these approaches without additional complexities.

3.2. FESSs

Referring back to Fig. 10(a), it is clear that the majority of FESS models reviewed here are of EM or PM types with limited usage of the BM method. However, there are some instances of BM usage for example in [160] which concentrates on primary frequency support in an algorithmic model, representing the FESS using simple state of energy equations. As with BESSs, this approach is focusing on the deployment of a FESS rather than its individual operation.

The BM approach is also utilized in [134] where the flywheel is modeled using the generic library model within the HOMER library, with the focus of this study being on designing a microgrid for the highest renewable penetration. Many studies across the literature utilize generic blocks such as these, where pre-loaded blocks within a simulation package have previously been developed and verified.

Elsewhere in [181], a BM approach is presented with a modular system built in MATLAB/Simulink incorporating additional complexities such as spinning losses and converter efficiencies. This model is then demonstrated with a techno-economic study into the delivery of frequency response services by FESSs. In this scenario, the BM approach is suitable to maintain computational efficiency for long simulations with small time steps.

Far more common for FESSs is the EM approach seen in a significant number of studies within the literature. Often, this comes in the form of representing the FESS using a permanent magnet synchronous motor (PMSM) block in MATLAB/Simulink, which can be seen in [57]. This study aims to accurately model the FESS motor speed and current for usage in future microgrid simulations. Additionally in [149] the same approach is used within MATLAB/Simulink as part of a wind-diesel power system, with the objective of controlling excess active power.

A reduced order model using the EM approach is presented in [182], implementing the FESS as a rigid additional single mass coupled to an induction machine. In this case, the EM approach is the most appropriate due to the study objectives of investigating electromagnetic transients, with the reduced order element aiming to improve computational efficiency. The model is initially implemented offline in PSCAD before being implemented in RSCAD for usage with the RTDS hardware.

The work in [91] combines the PM and EM approaches, modeling the FESS in terms of aspects including rotor speed, electromagnetic torque and stator currents and linking this with a larger electrical microgrid model for power quality applications. This approach is also taken in [127] where the FESS is modeled as an equation for rotating mass linked to a PMSM and subsequently implemented in an electric rail transport system and in [146] where the FESS is modeled with a series of equations within a wind turbine system for power smoothing.

When modeling the physical operation of a flywheel the approach most commonly taken is to develop a series of equations to represent the technical characteristics of the system. This approach is taken in both [164,167]. Firstly, in [164], the model is developed in a step-by-step process taking into account torque, mechanical power, rotational frequency and inertia before being implemented in a Combined Heat and Power Plant model. The model is also validated with field tests showing a good correlation between the model and real-world tests.

In [167] the model is also validated with an experimental set-up as part of a study looking to optimally size the FESS for a frequency regulation application. The FESS is presented as a series of linearized integrated transfer functions accompanied by a closed-loop control system. The non-linear and linear models are then compared under various scenarios followed by experimental verification.

[195] discusses the design and development of a 0.5 kWh FESS, from initial modeling through to experimental verification. The FESS is initially modeled with the PM approach as a series of equations, followed by some EM implementation with respect to the charging and discharging control of the FESS. This study is a good example of the level of detail required when modeling for experimental construction purposes, and as such this study could only be executed by primarily using the PM approach.

An interesting implementation of a FESS model that combines elements of BM and PM modeling is seen in [194], with basic physical equations utilized to model the speed of the FESS which is then implemented as part of a larger study that also considers H_2ESS storage. In this study, the ESSs being investigated are incidental to the overall goal of optimizing a system, so are modeled using basic tools that allow complex system simulation.

3.3. SCs

EM is the most prevalent type of SC modeling within the literature presented in this review. Despite this, there are some instances of the use of the PM and BM techniques. In [175] the SC is represented using a set of equations governed solely by the energy contained within the SC, the SOC limits, and the available power, showing an equation-based representation of the BM. As has been the case for other storage technologies, this approach is used in an optimization study of the size and control of a hybrid system.

In terms of PM, the work in [92] combines an electrical model with a thermal model that approximates the physical state of the SC thermal characteristics during operation. The thermal model is split into a heat generation and heat transfer model, which feeds back into the electrical model. It also gives an overview of the varying complexities of different types of electro-thermal models for SCs.

Numerical approaches are also used in literature, for example in [135] which concentrates on modeling for electric vehicles. The model includes a thermal element, and tests are undertaken to simulate a hybrid BESS/SC system for different driving profiles.

An extensive review of the different equivalent circuit models available for representing SCs is conducted in [85]. This study looks at 7 different types of EM and analyses their effectiveness for modeling energy storage applications, concluding that of the techniques with a reported accuracy level, the 'Classical Equivalent Circuit II' is the most accurate.

In [204] the authors present a simplified SC model using three basic electrical components to represent the SC, namely the capacitance of the SC, a series resistor, and a dielectric leakage resistor. This model is implemented alongside an electrical model of a DC/DC converter in order to investigate providing constant active power and inertia control for a wind power system.

An alternative approach to EM implementation is seen in [205], which derives mathematical models for a BESS and SC from equivalent circuits in the Laplace domain and further derivation of Thevenin equivalent circuits. This paper presents the models as part of an experimental verification process involving pulsed charging in a wind power system.

Another study that looks at a range of different SC EM models is [161]. This work was conducted with the objective of reducing the complexity of the model to a point that the requirements were readily available from datasheets, whilst retaining the required accuracy. This results in scenario-based recommendations where the effectiveness of different models varies based on the application being modeled.

[162] proposes a new EM for SCs utilizing MATLAB/Simulink using a simplified equivalent circuit approach. The SC is modeled by performing simple charge/discharge cycles and follows this with an experimental set-up to verify the model showing good agreement between the datasheets, model and experimental test system.

SC deployment for voltage sag minimization is investigated in [203]. The SC is implemented using an EM approach, with other approaches being unsuitable due to the electrical nature of the study. This example again highlights the dominance of EM approaches throughout the literature, which is driven by the fact that SCs are generally deployed for short-duration power-based applications where their impact on the electrical characteristics of a system is the primary objective.

3.4. CAES

Due to the nature of its operation, CAESs often require the modeling of both physical (air flow, recuperator, expander etc.) and electrical elements. Referring back to Fig. 10(a) none of the studied literature utilized the BM method, with a majority of modeling using the PM method. A common approach to modeling CAESs is mathematical, where a significant number of operational equations can be linked together to form a complex model of the physics behind the operation of the system. This approach is taken in [137,138,155]. In [138] a mathematical model is presented for analyzing the charging and discharging characteristics, with verification undertaken against literature and experimental results.

An implementation of the PM approach that also contains aspects of a BM approach is seen in [201], which investigates optimal energy scheduling. Whilst elements such as the compressor and expander are modeled using an equation-based approach, the energy store itself is modeled using a simple constrained SOC approach common in BM studies. This approach is taken to computationally simplify the study due to the high number of simulations conducted as part of the algorithmic optimization process.

Another study that combines elements of two approaches, in this case EM and BM, is seen in [199]. The primary implementation of the model in this case is EM, but it also uses a constrained SOC representation of the energy store itself. The model is utilized to investigate the capabilities of CAES in supporting an off-grid heating and power network with electric vehicles.

The work in [137] presents another mathematical model including operation strategy, this time with the objective of designing a hybrid CAES and wind turbine system for managing power fluctuations. [155] uses the same approach to develop a micro-CAES which is verified through extensive experimental tests. The range of different mathematical models available for this technology shows that they are an effective method for modeling CAES, and can be deployed for a range of different applications.

In [60], the model is implemented using a combination of Aspen Plus for the compressor and turbines, whilst Microsoft Excel is used to model the cavern itself. This study once again looks at the implementation of CAES for wind power support and shows a different approach to the mathematical model for the same application.

A numerical PM approach is taken in [197] with each component of the CAES model being realized as a series of equations. The model is calibrated for an experimental setup and the paper claims precision and reliability based upon comparisons between the experimental setup and model. As is often the case throughout the literature, this combination of in-depth modeling and experimental verification is undertaken with a focus on the technology itself rather than a specific application.

Finally, [87] provides another mathematical that is executed in MATLAB/Simulink. It develops separate control algorithms for charging and discharging modes and follows this up with a simplified model which is implemented in a case study of the model following different step change profiles. The study shows the extensive knowledge of the system characteristics required to model the system accurately with a significant number of parameters stated to inform the case study from both a control and a system perspective. It highlights that when considering the modeling of a CAES, the complexity of the system often requires a more detailed level of the model than other technologies discussed in this review.

3.5. H_2 ESSs

The software package HOMER is used throughout the literature for H_2ESS studies, including in [125,131,132,147]. The HOMER package has pre-designed blocks for use in power studies that enable the H_2ESS to be effectively studied without the requirement for comprehensive system knowledge and is primarily used in economic studies.

In [125] this approach is utilized to demonstrate the potential of H_2ESSs as long-term storage for high renewable penetration. The H_2ESS presented consists of an electrolyzer, fuel cell and hydrogen tank, with the study concentrating on calculating economic benefits from the deployment of a hybrid BESS/H_2ESS system.

Another use of HOMER for a H_2ESS economic analysis is presented in [147] where a techno-economic analysis is performed for a rural electrification study using a hybrid BESS/H_2ESS system. Again, this approach to application modeling for H_2ESSs is focused on exploring economic benefits for different scenarios and providing insight on the optimum configurations under varying operating conditions. The fact that this approach is found commonly in the literature suggests it is a robust method of H_2ESS modeling for this type of study.

Another PM approach is outlined in [179] as part of a bi-level optimization study in the planning of microgrids. Like other studies discussed here, the model is composed of three distinct components, the electrolyzer, fuel cell and storage tank.

A detailed presentation of a PM approach modeled in MATLAB is discussed in [183], which investigates the sizing of seasonal H_2ESS. The model considers a wide range of parameters such as temperature, degradation and safety. This study is unique in its analysis of the application of H_2ESS from both an economic and safety perspective.

[190] implements a H_2ESS model utilizing the PM approach. The overall model consists of separate electrolyzer, storage tank and fuel cell modules and is implemented using Python. The mathematical approach is subsequently experimentally verified for peak shaving applications. Whilst Python is not extensively used in ESS studies, its usage is growing as additional packages are developed and made freely available and this study is a good example of the versatility it can provide when modeling complex systems.

Equation-based modeling of a H_2ESS system is presented in [142] where the development of a seasonal storage system using hydrogen storage within salt caverns is discussed. In this case, the modeling of the H_2ESS in this way is driven by the complexity of modeling the dynamics of the salt cavern and the long durational nature of the simulation. Through this approach, the significant complexities can be accurately modeled for the given application.

A simulation framework (SimSES), which also includes models for Li-BESSs and RFBs, is presented in [86]. This framework involves interconnected electrical and thermal models, with an integrated techno-economic analysis model. The hydrogen package is split into four modules, a management system, a fuel cell model, an electrolyzer model, and a storage model. The input to the model is power, with a range of analytical outputs available. This package represents a good example of a fully self-contained modeling suite enabling different applications to be studied easily and effectively.

4. Real time simulations and hardware driven studies

So far, most of the works that have been discussed have focused on the offline simulation of ESSs, where the simulated system is purely digital. However, there is a growing area of research utilizing ‘Real Time Simulation’ (RTS) and ‘Hardware-in-the-loop’ (HIL). Additionally, this section considers some studies where a physical system is deployed to verify the results of a simulation, referred to here as a ‘Hardware Verification Study’ (HVS). Fig. 12 shows an example of a HIL study. This represents a typical experimental setup, but there are a number of different approaches that can be taken when implementing these studies. Typically, the system consists of four elements;

1. Firstly, problem formulation must be performed. This can often be achieved by developing a model (e.g for a microgrid), in an appropriate software package and then using the data generated (for example, this could be in the form of a power profile for the system to follow or a dispatch schedule) as the input for the ESS (whether physical or simulated) to react to.
2. The ESS in this example is represented by a physical asset, although there are instances where emulators can be used to simulate a physical asset. The ESS will respond to the control requests and provide an output, usually in the form of voltage and current.
3. This output is then used in real-time in conjunction with either a physical system or a simulated system. A continuous feedback loop is formed between the ESS and the system being studied until the study is terminated.
4. The results of the study are most often recorded in real-time and can subsequently be analyzed on a host PC.

Compared to purely simulation-based studies, those that involve hardware are generally restricted to smaller-scale experiments where the ESS being studied can be built and analyzed within a laboratory environment, although there are occasions where larger systems are integrated, for example in [208] where multiple BESSs and an SC in separate geographic locations were integrated within an ethernet connected network investigating communication delays for aggregated assets. For this reason, studies, where the ESS is generally a large physical system, are not as common. The majority of studies requiring hardware focus on BESSs or other ESSs that are able to be built on small scales, like FESSs and SCs.

This is illustrated in Fig. 13(a) where a significant proportion of the studies focus on BESSs, followed by FESSs. This can be primarily attributed to the scale of the storage systems being analyzed. Whilst it can be straightforward to produce laboratory-scale BESS, FESS and SC systems at a cost achievable by research institutes, the generally large scale and specialist nature of H_2ESS and CAES systems restrict their deployment in this way. This suggests that developing smaller scale systems for laboratory based analysis could be a future priority for this research area.

This review section is organized by application, looking at the different objectives for utilizing this approach with commentary on the software and hardware used in the studies. The distribution of applications within the literature can be seen in Fig. 13(b), where Microgrid applications are most prominent followed by Power quality and Testing purposes. However, it should be noted that the applications seen here span a significant range of smaller scale local grid studies (for example when considering degradation modeling or battery management) to large scale grid emulation (for example when considering power quality or frequency regulation), showcasing the flexibility of an RTS/HIL approach. Table 6 shows an overview of the literature studied in this category, highlighting the software and hardware used in each study along with a description of the work undertaken.

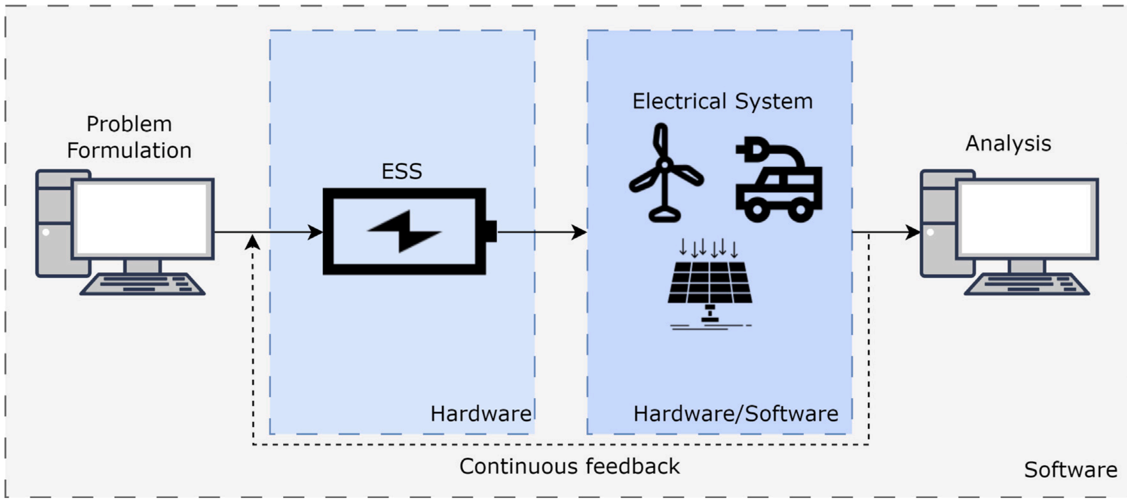
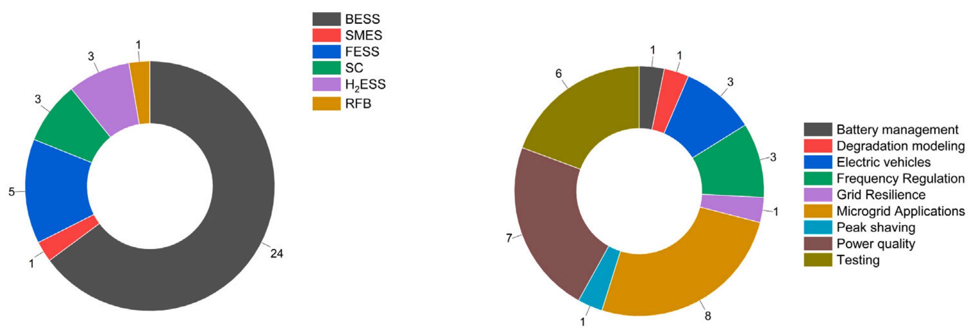


Fig. 12. Example overview of a HIL experimental set up showing the various stages of hardware and software interaction.



(a) Frequency of technology investigation in reviewed RTS/HIL studies

(b) Frequency of application investigation in reviewed RTS/HIL studies

Fig. 13. Number of times in reviewed literature an RTS/HIL study is used to investigate (a) a specific ESS technology (b) a given grid-scale application.

4.1. Frequency regulation

The work in [209] presents a HIL simulation on frequency regulation, deploying a Variable Source Heat Pump (VSHP) and a BESS on a laboratory scale. It utilizes MATLAB/Simulink and LabVIEW as a direct load controller and uses a pre-defined frequency data set. The implemented set-up allows a range of complex experiments to be performed allowing comparison between the developed model and the experimental results. Elsewhere in [210] a laboratory scale FESS is implemented in a HVS using MATLAB/Simulink, for the purposes of frequency control of a university microgrid. Different scenarios are assessed with the simulation being verified against real-world implementation.

[96] uses a combination of the OPAL-RT RTS platform with four Raspberry PI units to control the frequency of a microgrid. The Raspberry PI units are used to represent ESSs whilst the OPAL-RT operates as the system control unit. This is a good example of using RTS without the presence of physical ESSs, instead relying on emulating them through the use of other technology.

4.2. Testing and digital twins

In the context of this review, ‘Testing’ generally refers to studies where the primary objective is to develop systems that will allow further testing to be performed. This could refer to the development of a ‘Digital Twin’ (DT) asset or the foundational work of developing a HIL system without focusing on the application it will be deployed for. A review of DTs for a range of different ESS technologies can be found in [122] which discusses BESSs, H_2ESSs, SCs, PHS and Thermal Energy Storage (TES), highlighting that BESS studies into DT deployment significantly outnumber other technologies.

A good example of this is found in [214] where a HIL simulation facility is developed for testing the performance of grid-connected ESSs. This study focuses on Li-BESSs and utilizes an RTDS and dSPACE real-time platform. The system is verified using step-change power profiles, analyzing the latency experienced by the system as it responds including the communications latency. The verification of this approach then gives the foundation for further experimental works to be performed using this system.

RTS is used in [212] to compare the performance of SCs and FESSs when performing charge and discharge operations. This study is focused on the parameterization of the ESSs being studied, using Simulink Real-Time to act as a controller instructing the ESS to charge or discharge. A significant contribution to the field is found in [229] which focuses on Li-BESS cell degradation analysis. The main advancement in this work is the use of time-scaling to accelerate a HIL cell degradation experiment in tandem with an electro-thermal Li-BESS model. It utilizes the dSPACE real-time simulator running MATLAB/Simulink and using a battery emulator, subsequently comparing the results obtained with experimental parameter extraction.

The work in [222,235], and [230] all consider the development of DTs of Li-BESSs. The purpose of using a DT in [222] is to develop a

Table 6
Literature review of real time simulation and hardware-in-the-loop studies.

Ref	Year	ESS	Application	Software	Hardware	Notes
[209]	2018	Li-BESS	Frequency regulation	LabVIEW, MATLAB	Li-BESS	Implements multiple different hardware for the study, rather than focusing on a simple component. Aims to develop a scheme for grid frequency regulation to reduce frequency deviations through direct load control.
[211]	2018	Li-BESS[a], SMES[a]	Power quality	RSCAD	RTDS	Uses a system built in RTDS representing a BESS and SMES to develop a control method that extends the battery lifetime when compensating for power fluctuations in a microgrid
[212]	2018	FESS, SC	Testing	MATLAB	FESS, SC	Performs testing on a FESS and an SC to determine their capabilities for islanded microgrid operation, and the corresponding drawbacks that are associated with each device.
[213]	2018	FESS[a]	Power quality	MATLAB, Hypersim	OPAL-RT	Uses real time HIL to validate the design of a high speed FESS for LV power quality applications, comparing offline simulations with real time simulations.
[214]	2019	Li-BESS	Testing	MATLAB	Li-BESS, dSPACE, RTDS	Outlines the testing done on a PHIL simulation facility looking at latency for responses to certain power signals, showing that the system can be used for analysis frequency regulation with high accuracy.
[96]	2019	Li-BESS[a]	Frequency regulation	OPAL-RT	OPAL-RT, Raspberry Pi	Uses a laboratory set up with a real-time simulator on a physical communication network with the aim of using a group of ESSs to restore frequency and voltage in the event of disturbances.
[215]	2019	Pb-BESS	Energy management	PSIM	Pb-BESS, Solar panels	Implements four different sets of hardware represented different aspects of an islanded microgrid, for the purposes of testing different energy management strategies and reducing reliance on expensive fuels
[210]	2019	FESS	Frequency regulation	MATLAB	FESS	Uses a laboratory based FESS as hardware in the loop to simulate different scenarios when supporting a diesel generator to limit frequency variations due to sudden load changes
[216]	2019	Li-BESS[a]	Energy management	MATLAB	Typhoon HIL, Solar panel	Implements a nano grid in MATLAB/Simulink integrated with Typhoon HIL, with the objective of managing transactive energy exchanges between different parts of the nano grid through optimization and control.
[217]	2019	Li-BESS[a], H_2ESS	Energy management	MATLAB	RT-LAB	A hierarchical energy management control method is developed focusing on minimising costs in an islanded microgrid which is then tested with a real time simulation.
[94]	2019	RFB[a]	Grid resilience	RSCAD	RTDS	Designs a flow battery ESS in an advanced distribution grid (two interconnected microgrids) for a range of operational metrics including resilience and reconfiguration. Uses physical Flow batteries in a HIL setup for real time simulation.
[218]	2019	H_2ESS[a]	Power quality	OPAL-RT	OPAL-RT, MATLAB	Presents a solar, wind and Hydrogen Fuel Cell microgrid and explores the control strategies to improve power quality, following this with a HIL analysis using OPAL-RT to validate the study.
[219]	2019	Li-BESS[a]	Power quality	MATLAB	OPAL-RT, KEPCO	Outlines the modeling and real time simulation of a BESS using a HIL approach, for the purpose of analyzing the effect on the electrical grid and for providing ancillary services, reducing consumer spending and peak shaving.
[220]	2019	Li-BESS[a]	Energy management	MATLAB	RT-LAB	Utilizes RT-LAB to model a microgrid in real time consisting of a BESS and solar for development of an inverter control strategy for microgrid applications
[221]	2019	Li-BESS[a], SC	Electric vehicles	MATLAB	SC, dSPACE	Explores energy management strategies for a Li-BESS/SC hybrid system for an electric vehicle. It implements a HIL real time simulation where SCs are used to emulate Li-BESSs.

(*continued on next page*)

cloud battery management system that can be used to estimate the SOC and State of Health (SOH) of a physical asset. This is achieved by integrating a hardware system consisting of a battery tester and battery system with a Raspberry Pi that communicates with the cloud-based DT. Elsewhere in [235] the system is implemented over a physical connection rather than the previous cloud-based solution. This study focuses primarily on temperature prediction and degradation analysis, with the DT modeled using an equivalent circuit approach.

Table 6 (*continued*).

[222]	2020	Li-BESS, Pb-BESS	Battery management	Python	Li-BESS, Pb-BESS, Raspberry Pi	Develops a battery management system in tandem with a digital twin. The aims of the study were to improve computational power, data storage and management reliability. It also compares the estimated SOC and SOH through the use of different algorithms.
[223]	2020	Li-BESS[a]	Electric vehicles	MATLAB	MicroLabBox	Presents a SOC estimation and parameter optimization study for electric vehicles using a MATLAB/Simulink simulation, followed by a HIL real-time study to verify the results
[224]	2020	Li-BESS, SC	Energy management	OPAL-RT	OPAL-RT, Li-BESS, SC, Solar	Introduces an algorithm that will maximize the use of different ESSs in a standalone microgrid, with a study conducted using HIL real time simulation of physical assets
[225]	2020	Li-BESS	Energy management	OPAL-RT, MATLAB	OPAL-RT, Li-BESS, Solar emulator	Looks at different scenarios for controlling a microgrid consisting of a BESS, solar, electric vehicles, an office building and emergency generator using real time simulation.
[226]	2021	Li-BESS[a]	Testing	RT-LAB, MATLAB	Opal-RT, Typhoon HIL	Firstly implements a Li-ion BESS simulation on the OPAL-RT real time simulation platform before moving it to Typhoon HIL and verifying the response, showing identical results across the two different platforms.
[95]	2021	Li-BESS[a]	Power quality	OPAL-RT	OPAL-RT	Models a virtual ESS integrated with a grid based on real world data with the objective of minimizing costs based on an optimization framework whilst increasing power quality
[227]	2021	FESS	Peak shaving	MATLAB, FIWARE, Python	FESS, Solar panels	Performs an initial simulation on energy management of a flywheel for peak shaving before following this up with a HIL experimental validation
[228]	2021	Li-BESS	Testing	RT-LAB, MATLAB	Li-BESS, OPAL-RT	Real time simulation of a BESS with a focus on modeling the control and protection elements of the system to provide a platform for BESS development
[229]	2021	Li-BESS	Testing	MATLAB	Li-BESS, dSPACE	Develops a scaled electro-thermal model of a Li-BESS for use in testing cells in accelerated experiments. Utilizes HIL to enable rapid testing for energy management in microgrids.
[230]	2022	Li-BESS	Testing	MATLAB, Python	Li-BESS	Proposes a digital twin of a Li-BESS for estimating the SOC through use of three different algorithms whilst driving a small motor
[231]	2022	FESS, Li-BESS	Power quality	RT-LAB	FESS, Li-BESS	Presents a hybrid FESS/Li-BESS experimental set up for performing HIL testing to explore improving frequency response in a microgrid after disturbances.
[232]	2022	Li-BESS[a], H_2ESS[a]	Electric vehicles	MATLAB	MicroLabBox	Proposes a hybrid Hydrogen Fuel Cell and Li-BESS system for electric vehicles, which is then verified using HIL
[233]	2022	Li-BESS[a], FESS	Energy management	MATLAB	FESS	Implements a microgrid test bench with a physical FESS for real time simulation of an islanded microgrid with the objective of improve BESS lifetime in the hybrid system.
[234]	2022	Li-BESS[a]	Energy management	MATLAB	TRIPHASE, BESS emulator	Presents a strategy for aggregating different services to be provided by an ESS in a grid connected microgrid, which is modeled and validated using HIL real time simulation
[235]	2023	Li-BESS	Degradation modeling	MATLAB	Li-BESS, Digatron MCT ME, Binder MK 240	Uses a digital twin alongside a cell cycler and a temperature controlled environment to perform real time temperature prediction with a focus on modeling the degradation of the cells

[a] Denotes that the ESS being studied is simulated rather than present as hardware.

Finally, [230] concentrates more on the computing power and storage aspects of DT implementation.

4.3. Power quality and grid resilience

A virtual ESS is described in [95] which is simulated in real-time using the OPAL-RT platform. This study looks at both technical and economic objectives (voltage regulation and cost-effective power sharing), and uses three case studies in its assessment. The virtual system consists of 22 distribution nodes, 8 photovoltaic installations, 4 BESSs, and a range of flexible and inflexible loads. This highlights the complexity that can be achieved with this approach, allowing a large system to be simulated in real-time in a techno-economic study.

In [231] physical BESS and FESS units are used in a HIL analysis for improved control of a microgrid, with the RTS being carried out on the RTDS platform. The simulation aspect is responsible for providing the instantaneous frequency events for the physical systems to react to as controlled by the microgrid controller. The FESS utilized is a containerized unit whilst the BESS is laboratory scale.

An example of a purely RTS-based approach without hardware implementation is shown in [213] which develops an RTS model as the foundation for future HIL studies. The RTS model is developed for a high-speed FESS and tested providing frequency and voltage support in an LV distribution network. The real-time model is validated against the non-real-time model.

A H_2ESS is emulated using an OPAL-RT system in [218] for improving the power quality of a renewable system. The model is developed in MATLAB/Simulink before being compiled in RT-LAB for execution on the OPAL-RT platform. This again shows the benefits of the RTS hardware as it allows emulation of ESS technologies that may be difficult to deploy on a laboratory scale. Another example of the emulation-based approach is shown in [211] which uses the RTDS platform to emulate a BESS/SMES system, with the objective of extending BESS lifetime in a microgrid setting.

4.4. Microgrid management

RTS and HIL approaches are effectively deployed for microgrid applications across the literature, as it enables the microgrid system to be simulated in real-time without the requirement of a large-scale physical system. The microgrid is often emulated on a real-time platform with physical assets (for example a BESS) being connected as HIL. An example of this is seen in [225] which utilizes an OPAL-RT to represent a microgrid connected with physical assets consisting of a PV emulator and BESS.

As with other applications, there are some studies that emulate the ESS rather than deploy a physical asset, for example in [216,234]. In [234] a physical microgrid is used with a battery emulator connected via an AC/DC converter, with a simulated network integrated using a TRIPHASE real-time simulator. This approach allows the system to act as if it were connected to a real distribution network, with the simulated network providing the input to the physical system. In [216] the battery is emulated using the Typhoon-HIL platform connected to a physical nano-grid to allow real-time simulation.

Power management of a hybrid ESS is explored in [224] which combines physical SC, BESS and a PV array with real-time simulation in LabVIEW. The objective is to introduce a novel control algorithm for optimal utilization of the two ESSs, and the hardware implementation is used to verify the offline simulation. A similar power management study is detailed in [220] where RT-LAB is used to emulate the proposed system. Finally, in [233] a physical FESS is deployed for a HIL microgrid simulation, with the BESS element part of the simulation. This highlights the different approaches that can be taken for very similar studies, utilizing physical ESSs, using emulation and a combination of both.

4.5. Electric vehicles

Studies concerning Electric Vehicles (EVs) are ideal candidates for utilizing RTS/HIL modeling approaches as the energy storage involved is often laboratory-scale and easily integrated into experimental setups. Li-BESS SOC estimation is a significant area of research for electric vehicle applications and one in which HIL plays a key role. In [223] an adaptive model is developed for estimating the SOC in MATLAB/Simulink, which is then tested and verified in a laboratory setup. This setup uses a MicroLabBox which is used to simulate the system as an emulator but does highlight the limitations of this method, indicating that the experimental results are difficult to compare with the simulated results.

Another HIL study is shown in [232] for fuel cell electric vehicles following the same process of model development and simulation offline, before being implemented on a real-time basis again using the MicroLabBox. This study also notes the requirement for further experimental work utilizing real assets to expand the research.

A BESS/SC hybrid system is implemented in [221] in an EV energy management study. The HIL experimental validation is performed using a physical SC, with the traction and BESS modeled as software on a dSPACE system. The offline simulation is compared with the experimental results produced in real-time. Finally, in [59] another BESS/SC system is analyzed, this time with an ageing model implemented for the BESS. In this study, both the SC and the BESS are implemented as hardware and simulated as a HIL system in real-time using LabView.

5. Conclusions

This work has presented an extensive and novel overview of the existing state of ESM and provides a comprehensive guide for assisting researchers in selecting a modeling approach for their studies. Five different energy storage technologies have been considered, with their advantages and disadvantages discussed and considered in the context of modeling approaches.

A detailed overview of three prominent types of ESM for analyzing ESSs has been presented, discussing BM, EM and PM approaches and outlining the fundamental differences between each, advantages and drawbacks, and providing a resource for understanding the most suitable approach when beginning a study. An important aspect of this overview is the distinction that multiple methods of modeling may be possible for a given application, and the user should therefore consider carefully what elements of the system they wish to concentrate on. For example, low-level electrical modeling methods may require significant resources whereas a simpler power/energy model may suffice.

This aspect was further explored through guidance on selecting a modeling approach according to a range of different factors, these include system attributes to be included (for example degradation and efficiency) to computational power and resources available for the simulation. This guidance allows researchers to understand how these aspects are incorporated within the different ESM approaches. A key conclusion from this section is to ensure that all aspects of a proposed system are considered prior to developing a model. Aspects including whether the model is required to affect the distribution grid, or simply be affected by it, are important distinctions to make.

Following this, an application-based assessment was conducted, presenting examples of how different models are applied in practice for a range of storage technologies and model types. Commentary was provided to analyze the effectiveness of these approaches and offers practice when considering conducting similar studies. This revealed interesting trends within the literature, highlighting that some ESS technologies (for example CAES and FESSs) have minimal available literature describing BM approaches, a factor that could be developed further to provide a wider range of available tools. On a similar note, EM or PM approaches for H_2ESS systems are under-represented within the literature.

The final section of the paper considers RTS and HIL studies, identifying trends in hardware and software utilized for different applications and providing commentary on literature to provide an overview of the current research landscape. This section identified that a significant proportion of studied literature using RTS/HIL focuses on BESS studies, suggesting possible research gaps in utilizing other storage technologies. The distinction between deploying physical ESSs for HIL studies and the emulation of these ESSs was also highlighted, where in some scenarios emulation is preferable due to an ESSs physical dimensions making it difficult to deploy on laboratory scale.

The work presented here is an innovative assessment of the existing research landscape of energy storage modeling, with a new perspective of application-based modeling approaches providing new insight into the decision making process of modeling energy storage technologies.

Overall, this paper provides a state-of-the-art review of ESM, and acts as a comprehensive guide to researchers which will provide a starting point when considering modeling options for new ESS grid applications studies. Throughout the paper, insight has been provided into the different approaches available as well as why and how these approaches should be utilized.

6. Future challenges

Based upon the trends highlighted and discussed, the following points are presented as future challenges and recommendations for the future of this research area;

6.1. Generic modeling

As has been discussed extensively in this review, there is a clear distinction between detailed modeling that requires in-depth knowledge of the operational characteristics of a given ESS, and the more generic modeling that treats the ESS as a simple approximation of the technology as a whole.

The generic approach presents many advantages, for example the ability to model a system without the requirement of datasheets or operational characteristics, and the commonly faster computational time of the simpler models. However, as the field of ESS research continues to expand, the difference between different subcategories of technologies tends to become more noticeable. For example, the difference between modeling a Li-BESS of two particular chemistries, or a carbon-fiber high-speed flywheel and a steel-based low-speed flywheel.

The challenge that faces the field of ESM is how to appropriately account for these low-level differences whilst retaining the benefits of the generic models. Additionally, some of the assumptions made at the creation of models that are heavily relied upon throughout the literature may need revisiting as the research and technologies advance.

Finally, it is important to note that different applications can increase or decrease sensitivity to model parameters (for example efficiency), which further emphasizes the requirement to carefully select the appropriate generic model if that approach is utilized. It illustrates that whilst generic models are highly effective in certain situations, to be effectively applicable to a range of scenarios they will need to be easily tuned for specific requirements as needed.

6.2. Distributed storage

When considering system-level studies, storage is often aggregated together for simplicity. However, as Distributed Energy Resources (DERs) grow in popularity, the challenge presented is one of defining what distributed storage means, and how this affects the models that are used. Significant focus is now being placed not only on how ESSs are deployed but on the location in which they are deployed as well. It is therefore important that geographical elements are incorporated into existing models, giving consideration to the effects that ESS deployment will have on the future transmission network.

In addition to this, it is crucial that the role of DERs is suitably identified, and a key research objective going forwards should be to appropriately define the boundaries of what a DER is, along with the most appropriate modeling framework to represent them correctly as part of an agile future electricity network.

6.3. Digital twins

DTs are being readily developed and deployed for Li-BESSs due to their well-known and easily measurable characteristics, along with their suitability for laboratory-scale experiments. However, this field needs further exploration of other storage technologies discussed in this study. This presents a significant challenge for technologies that are not easily deployable on a laboratory scale and will require more complex studies to be undertaken potentially in tandem with existing installations that can be utilized for research purposes. DTs are valuable tools for analyzing the performance of various storage technologies in new and experimental applications. It is crucial to apply the knowledge gained from numerous BESS DTs to the ongoing research of DTs for other storage technologies.

6.4. Laboratory scale systems

As discussed in Section 4, whilst BESSs are well-represented in the field of RTS/HIL studies, the remaining technologies considered within this review are not regularly deployed in this manner. Considering the examples given of the range of research being carried out using laboratory scale BESS systems, the development of similar low-cost small-scale systems for the remaining technologies should be prioritized. Specifically, H_2ESSs and CAES are both under-represented in this field, and whilst challenges are apparent in producing these systems at a smaller scale, this should be a priority for future research to enable more detailed operational studies to be conducted.

6.5. Storage technology diversification

The extensive literature review presented in this work has looked into a range of different storage technologies, however, the conclusion is reached that BESSs continue to dominate the field of energy storage research, significantly outweighing the other technologies in terms of literature available. Whilst BESSs are extensively researched for many different reasons, particularly their versatility and comparatively low cost, the significant concentration of studies in this area means that many of the practices commonly used for modeling BESSs are subsequently being used for other technologies. Although it can accelerate the research of new technologies by building on the groundwork laid by BESS modeling, it is crucial to acknowledge that other ESSs may require customized approaches. Whilst there are many benefits to BESSs, there are also limitations to their deployment. Therefore, research methods and modeling techniques must be adapted and improved to create solutions for other storage technologies.

CRediT authorship contribution statement

Andrew J. Hutchinson: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Chris M. Harrison:** Writing – original draft. **Thomas S. Bryden:** Writing – original draft. **Arman Alahyari:** Writing – original draft. **Yiheng Hu:** Writing – original draft. **Daniel T. Gladwin:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jonathan Radcliffe:** Writing – review & editing. **Daniel J. Rogers:** Writing – review & editing. **Charalampos Patsios:** Writing – review & editing. **Andrew Forsyth:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC), UK in the form of the ‘Energy Storage Integration for a Net Zero Grid’ project under grant code EP/W02764X/1.

Data availability

No data was used for the research described in the article.

References

[1] IEA, Informing Energy Sector Transformations, Tech. Rep., IEA, 2017, [Online]. Available: www.iea.org/etp/tracking.

[2] National Grid ESO, Britain' s Electricity Explained : June 2022, Tech. Rep. June, National Grid ESO, 2022.

[3] A.H. Alami, A. Yasin, R. Alrashid, S. Alasad, H. Aljaghoub, G. Alabsi, L. Alketbi, A. Alkhzaimi, A. Alteneji, S. Shikhli, Experimental evaluation of compressed air energy storage as a potential replacement of electrochemical batteries, J. Energy Storage 54 (2022) 105263, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22012610.

[4] Department for Energy Security and Net Zero, Renewable energy planning data, 2023, [Online]. Available: https://www.gov.uk/government/collections/renewable-energy-planning-data.

[5] BEIS and OFGEM, Transitioning to a net zero energy system Smart Systems and Flexibility Plan 2021, Tech. Rep. July, BEIS, 2021, p. 89, [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment{_}data/file/1003778/smart-systems-and-flexibility-plan-2021.pdf.

[6] Solar Power Europe, European Market Outlook, Tech. Rep., Solar Power Europe, 2020, [Online]. Available: https://www.solarpowereurope.org/insights/thematic-reports/european-market-outlook-for-residential-battery-storage-1.

[7] N. Khan, S. Dilshad, R. Khalid, A.R. Kalair, N. Abas, Review of energy storage and transportation of energy, Energy Storage 1 (3) (2019) 1–49.

[8] S. Hajiaghasi, A. Salemnia, M. Hamzeh, Hybrid energy storage system for microgrids applications: A review, J. Energy Storage 21 (November 2018) (2019) 543–570, [Online]. Available: https://doi.org/10.1016/j.est.2018.12.017.

[9] M. Khalid, A review on the selected applications of battery-supercapacitor hybrid energy storage systems for microgrids, Energies 12 (23) (2019).

[10] F. Nadeem, S.M. Hussain, P.K. Tiwari, A.K. Goswami, T.S. Ustun, Comparative review of energy storage systems, their roles, and impacts on future power systems, IEEE Access 7 (December 2018) (2019) 4555–4585.

[11] T.S. Babu, K.R. Vasudevan, V.K. Ramachandaramurthy, S.B. Sani, S. Chemud, R.M. Lajim, A comprehensive review of hybrid energy storage systems: Converter topologies, control strategies and future prospects, IEEE Access 8 (2020) 148702–148721.

[12] H.A. Behabtu, M. Messagie, T. Coosemans, M. Berecibar, K.A. Fante, A.A. Kebede, J. Van Mierlo, A review of energy storage technologies' application potentials in renewable energy sources grid integration, Sustainability (Switzerland) 12 (24) (2020) 1–20.

[13] S. Koohi-Fayegh, M.A. Rosen, A review of energy storage types, applications and recent developments, J. Energy Storage 27 (November 2019) (2020) 101047, [Online]. Available: https://doi.org/10.1016/j.est.2019.101047.

[14] M.M. Rahman, A.O. Oni, E. Gemechu, A. Kumar, Assessment of energy storage technologies: A review, Energy Convers. Manage. 223 (August) (2020) 113295, [Online]. Available: https://doi.org/10.1016/j.enconman.2020.113295.

[15] A.Z. A.L. Shaqsi, K. Sopian, A. Al-Hinai, Review of energy storage services, applications, limitations, and benefits, Energy Rep. 6 (2020) 288–306, [Online]. Available: https://doi.org/10.1016/j.egyr.2020.07.028.

[16] G.F. Frate, L. Ferrari, U. Desideri, Energy storage for grid-scale applications: Technology review and economic feasibility analysis, Renew. Energy 163 (2021) 1754–1772, [Online]. Available: https://doi.org/10.1016/j.renene.2020.10.070.

[17] N. McIlwaine, A.M. Foley, D.J. Morrow, D. Al Kez, C. Zhang, X. Lu, R.J. Best, A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems, Energy 229 (2021).

[18] D. Groppi, A. Pfeifer, D.A. Garcia, G. Krajačić, N. Duić, A review on energy storage and demand side management solutions in smart energy islands, Renew. Sustain. Energy Rev. 135 (April 2020) (2021).

[19] K.M. Tan, T.S. Babu, V.K. Ramachandaramurthy, P. Kasinathan, S.G. Solanki, S.K. Raveendran, Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration, J. Energy Storage 39 (April) (2021) 102591, [Online]. Available: https://doi.org/10.1016/j.est.2021.102591.

[20] M.A. Hannan, S.B. Wali, P.J. Ker, M.S. Rahman, M. Mansor, V.K. Ramachandaramurthy, K.M. Muttaqi, T.M. Mahlia, Z.Y. Dong, Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues, J. Energy Storage 42 (August) (2021) 103023, [Online]. Available: https://doi.org/10.1016/j.est.2021.103023.

[21] Z. Zhang, T. Ding, Q. Zhou, Y. Sun, M. Qu, Z. Zeng, Y. Ju, L. Li, K. Wang, F. Chi, A review of technologies and applications on versatile energy storage systems, Renew. Sustain. Energy Rev. 148 (January) (2021).

[22] A.G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M.A. Abdelkareem, A.H. Al – Alami, Critical review of energy storage systems, Energy 214 (2021) 118987, [Online]. Available: https://doi.org/10.1016/j.energy.2020.118987.

[23] A. Gayathri, V. Rukkumani, V. Manimegalai, P. Pandiyan, A comprehensive review on energy storage systems, Smart Electr. Grid Syst. (2022) 211–251.

[24] S. Choudhury, Review of energy storage system technologies integration to microgrid: Types, control strategies, issues, and future prospects, J. Energy Storage 48 (July 2021) (2022) 103966, [Online]. Available: https://doi.org/10.1016/j.est.2022.103966.

[25] A.A. Kebede, T. Kalogiannis, J. Van Mierlo, M. Berecibar, A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration, Renew. Sustain. Energy Rev. 159 (2022) 112213, [Online]. Available: https://doi.org/10.1016/j.rser.2022.112213.

[26] M.R. Chakraborty, S. Dawn, P.K. Saha, J.B. Basu, T.S. Ustun, A comparative review on energy storage systems and their application in deregulated systems, Batteries 8 (9) (2022).

[27] J. Mitali, S. Dhinakaran, A. Mohamad, Energy storage systems: a review, Energy Storage Saving 1 (3) (2022) 166–216, [Online]. Available: https://doi.org/10.1016/j.enss.2022.07.002.

[28] Imeche.org, Report shows huge scale of UK energy storage boom, 2021, [Online]. Available: https://www.imeche.org/news/news-article/report-shows-huge-scale-of-uk-energy-storage-boom.

[29] B. Bolund, H. Bernhoff, M. Leijon, Flywheel energy and power storage systems, Renew. Sustain. Energy Rev. 11 (2) (2007) 235–258.

[30] B.K. Saikia, S.M. Benoy, M. Bora, J. Tamuly, M. Pandey, D. Bhattacharya, A brief review on supercapacitor energy storage devices and utilization of natural carbon resources as their electrode materials, Fuel 282 (2020) 118796, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0016236120317920.

[31] M.E. Amiryar, K.R. Pullen, A review of flywheel energy storage system technologies and their applications, Appl. Sci. 7 (3) (2017).

[32] International Energy Agency, Innovation in Batteries and Electricity Storage, IEA, 2020, p. 98, [Online]. Available: epo.org/trends-batteries%0Aiea.li/battery-innovation.

[33] I. Mexis, G. Todeschini, Battery energy storage systems in the united kingdom: A review of current state-of-the-art and future applications, Energies 13 (14) (2020).

[34] D.Q. Oliveira, O.R. Saavedra, K. Santos-Pereira, J.D. Pereira, D.S. Cosme, L.S. Veras, R.G. Bento, V.B. Riboldi, A critical review of energy storage technologies for microgrids, Energy Syst. (0123456789) (2021) [Online]. Available: https://doi.org/10.1007/s12667-021-00464-6.

[35] J. Wang, J. Purewal, P. Liu, J. Hicks-Garner, S. Soukazian, E. Sherman, A. Sorenson, L. Vu, H. Tataria, M.W. Verbrugge, Degradation of lithium ion batteries employing graphite negatives and nickel-cobalt-manganese oxide + spinel manganese oxide positives: Part 1, aging mechanisms and life estimation, J. Power Sources 269 (2014) 937–948, [Online]. Available: http://dx.doi.org/10.1016/j.jpowsour.2014.07.030.

[36] C. Liu, Y. Wang, Z. Chen, Degradation model and cycle life prediction for lithium-ion battery used in hybrid energy storage system, Energy 166 (2019) 796–806.

[37] A.G. Olabi, T. Wilberforce, M.A. Abdelkareem, M. Ramadan, Critical review of flywheel energy storage system, Energies 14 (8) (2021) 1–33.

[38] S. Choudhury, Flywheel energy storage systems: A critical review on technologies, applications, and future prospects, Int. Trans. Electr. Energy Syst. 31 (9) (2021) 1–26.

[39] A.A. Arani, H. Karami, G.B. Gharehpetian, M.S. Hejazi, Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids, Renew. Sustain. Energy Rev. 69 (September 2015) (2017) 9–18.

[40] M.A. Awadallah, B. Venkatesh, Energy storage in flywheels: An overview, Can. J. Electr. Comput. Eng. 38 (2) (2015) 183–193.

[41] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications, Renew. Sustain. Energy Rev. 13 (6–7) (2009) 1513–1522.

[42] L.A. Wong, V.K. Ramachandaramurthy, P. Taylor, J.B. Ekanayake, S.L. Walker, S. Padmanaban, Review on the optimal placement, sizing and control of an energy storage system in the distribution network, J. Energy Storage 21 (December 2018) (2019) 489–504, [Online]. Available: https://doi.org/10.1016/j.est.2018.12.015.

[43] B. Zakeri, S. Syri, Electrical energy storage systems: A comparative life cycle cost analysis, Renew. Sustain. Energy Rev. 42 (2015) 569–596, [Online]. Available: http://dx.doi.org/10.1016/j.rser.2014.10.011.

[44] J. Liu, C. Hu, A. Kimber, Z. Wang, Uses, cost-benefit analysis, and markets of energy storage systems for electric grid applications, J. Energy Storage 32 (June) (2020) 101731, [Online]. Available: https://doi.org/10.1016/j.est.2020.101731.

[45] H. Yang, A review of supercapacitor-based energy storage systems for microgrid applications, in: IEEE Power and Energy Society General Meeting, Vol. 2018-Augus, IEEE, 2018, pp. 1–5.

[46] S. Karthikeyan, B. Narenthiran, A. Sivanantham, L.D. Bhatlu, T. Maridurai, Supercapacitor: Evolution and review, Mater. Today: Proc. 46 (2020) 3984–3988, [Online]. Available: https://doi.org/10.1016/j.matpr.2021.02.526.

[47] L. Zhang, X. Hu, Z. Wang, F. Sun, D.G. Dorrell, A review of supercapacitor modeling, estimation, and applications: A control/management perspective, Renew. Sustain. Energy Rev. 81 (June 2016) (2018) 1868–1878, [Online]. Available: https://doi.org/10.1016/j.rser.2017.05.283.

[48] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, Hydrogen energy systems: A critical review of technologies, applications, trends and challenges, Renew. Sustain. Energy Rev. 146 (2021) 111180, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032121004688.

[49] M. Chatenet, B.G. Pollet, D.R. Dekel, F. Dionigi, J. Deseure, P. Millet, R.D. Braatz, M.Z. Bazant, M. Eikerling, I. Staffell, P. Balcombe, Y. Shao-Horn, H. Schäfer, Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments, Chem. Soc. Rev. 51 (2022) 4583–4762, [Online]. Available: http://dx.doi.org/10.1039/D0CS01079K.

[50] E.S. Hanley, G. Amarandei, B.A. Glowacki, Potential of redox flow batteries and hydrogen as integrated storage for decentralized energy systems, Energy Fuels 30 (2) (2016) 1477–1486.

[51] C.R. Matos, P.P. Silva, J.F. Carneiro, Overview of compressed air energy storage projects and regulatory framework for energy storage, J. Energy Storage 55 (PD) (2022) 105862, [Online]. Available: https://doi.org/10.1016/j.est.2022.105862.

[52] S. Donadei, G.-S. Schneider, Compressed air energy storage, in: Storing Energy, second ed., Elsevier, 2022, pp. 141–156.

[53] E.R. Barbour, D.L. Pottie, P. Eames, Why is adiabatic compressed air energy storage yet to become a viable energy storage option? iScience 24 (5) (2021) 102440, [Online]. Available: https://doi.org/10.1016/j.isci.2021.102440.

[54] H. Jafarizadeh, M. Soltani, J. Nathwani, Assessment of the Huntorf compressed air energy storage plant performance under enhanced modifications, Energy Convers. Manage. 209 (November 2019) (2020) 112662, [Online]. Available: https://doi.org/10.1016/j.enconman.2020.112662.

[55] Baldwin EMC, Compressed air energy storage technology: Generating electricity out of thin air, 2023, [Online]. Available: https://www.baldwinemc.com/compressed-air-energy-storage-technology-generating-electricity-out-of-thin-air/.

[56] M. King, A. Jain, R. Bhakar, J. Mathur, J. Wang, Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK, Renew. Sustain. Energy Rev. 139 (January) (2021) 110705, [Online]. Available: https://doi.org/10.1016/j.rser.2021.110705.

[57] S.M. Salam, M.M. Rashid, A new approach to analysis and simulation of flywheel energy storage system, in: 8th International Conference on Mechatronics Engineering (ICOM 2022), 2022, pp. 90–94.

[58] V.S. Diaz, D.A. Cantane, A.Q.O. Santos, O.H. Ando Junior, Comparative analysis of degradation assessment of battery energy storage systems in PV smoothing application, Energies 14 (12) (2021) 3600.

[59] T. Mesbahi, P. Bartholomeus, N. Rizoug, R. Sadoun, F. Khenfri, P.L. Moigne, Advanced model of hybrid energy storage system integrating lithium-ion battery and supercapacitor for electric vehicle applications, IEEE Trans. Ind. Electron. 68 (5) (2021) 3962–3972.

[60] H. Meng, M. Wang, O. Olumayegun, X. Luo, X. Liu, Process design, operation and economic evaluation of compressed air energy storage (CAES) for wind power through modelling and simulation, Renew. Energy 136 (2019) 923–936, [Online]. Available: https://doi.org/10.1016/j.renene.2019.01.043.

[61] D.M. Rosewater, D.A. Copp, T.A. Nguyen, R.H. Byrne, S. Santoso, Battery energy storage models for optimal control, IEEE Access 7 (December) (2019) 178357–178391.

[62] M. Moncecchi, C. Brivio, S. Mandelli, M. Merlo, Battery energy storage systems in microgrids: Modeling and design criteria, Energies 13 (8) (2020) 1–18.

[63] T. Simpkins, C.O. Donnell, Optimizing battery sizing and dispatching to maximize economic return, in: Battcon Stationary Battery Conference, Vol. May, 2017, pp. 1–14, [Online]. Available: www.battcon.com.

[64] J.M. Reniers, G. Mulder, S. Ober-Blöbaum, D.A. Howey, Improving optimal control of grid-connected lithium-ion batteries through more accurate battery and degradation modelling, J. Power Sources 379 (December 2017) (2018) 91–102, [Online]. Available: https://doi.org/10.1016/j.jpowsour.2018.01.004.

[65] L.K. Gan, J. Reniers, D. Howey, A hybrid vanadium redox/lithium-ion energy storage system for off-grid renewable power, in: 2017 IEEE Energy Conversion Congress and Exposition, ECCE 2017, Vol. 2017-Janua (section II) (2017) 1016–1023.

[66] C. Jankowiak, A. Zacharopoulos, C. Brandoni, P. Keatley, P. MacArtain, N. Hewitt, The role of domestic integrated battery energy storage systems for electricity network performance enhancement, Energies 12 (20) (2019) 1–27.

[67] A.J. Hutchinson, D.T. Gladwin, Flywheel energy storage for ancillary services: A novel design and simulation of a continuous frequency response service for energy limited assets, IEEE Open Access J. Power Energy (2024) 1.

[68] S. Ould Amrouche, D. Rekioua, T. Rekioua, S. Bacha, Overview of energy storage in renewable energy systems, Int. J. Hydrog. Energy 41 (45) (2016) 20914–20927.

[69] A. Jaafar, B. Sareni, X. Roboam, M. Thiounn-Guermeur, Sizing and energy management of a hybrid locomotive based on flywheel and accumulators, 2010 IEEE Vehicle Power and Propulsion Conference, VPPC 2010 58 (8) (2010) 3947–3958.

[70] R. Arghandeh, M. Pipattanasomporn, S. Rahman, Flywheel energy storage systems for ride-through applications in a facility microgrid, IEEE Trans. Smart Grid 3 (4) (2012) 1955–1962.

[71] L. Shen, Q. Cheng, Y. Cheng, L. Wei, Y. Wang, Hierarchical control of DC micro-grid for photovoltaic EV charging station based on flywheel and battery energy storage system, Electr. Power Syst. Res. 179 (November 2018) (2020) 106079, [Online]. Available: https://doi.org/10.1016/j.epsr.2019.106079.

[72] R. Sebastián, R. Peña Alzola, Flywheel energy storage systems: Review and simulation for an isolated wind power system, Renew. Sustain. Energy Rev. 16 (9) (2012) 6803–6813.

[73] S.N. Motapon, E. Lachance, L.-A. Dessaint, K. Al-Haddad, A generic cycle life model for lithium-ion batteries based on fatigue theory and equivalent cycle counting, IEEE Open J. Ind. Electron. Soc. 1 (August) (2020) 207–217.

[74] D. Peralta, C. Canizares, K. Bhattacharya, Practical modeling of flywheel energy storage for primary frequency control in power grids, in: IEEE Power and Energy Society General Meeting, Vol. 2018-Augus, (November 2017) 2018, pp. 1–5.

[75] J. Li, J. Bi, G. Yan, Y. Ge, P. Jin, Research on improving power quality of wind power system based on the flywheel energy storage system, in: China International Conference on Electricity Distribution, CICED, Vol. 2016-Septe, IEEE, 2016, pp. 1–6, no. Ciced.

[76] S.D. Sessa, A. Tortella, M. Andriollo, R. Benato, Li-ion battery-flywheel hybrid storage system: Countering battery aging during a grid frequency regulation service, Appl. Sci. (Switzerland) 8 (11) (2018) 1–15.

[77] M.P. Bonkile, V. Ramadesigan, Power control strategy and economic analysis using physics-based battery models in standalone wind–battery systems, Sustain. Energy Technol. Assess. 54 (2022) 102828, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138822008761.

[78] B. Nemounehkhah, R. Faranda, K. Akkala, H. Hafezi, C. Parthasarathy, H. Laaksonen, Comparison and evaluation of state of charge estimation methods for a verified battery model, in: 2020 International Conference on Smart Energy Systems and Technologies, SEST, 2020, pp. 1–6.

[79] N. Shamarova, K. Suslov, P. Ilyushin, I. Shushpanov, Review of battery energy storage systems modeling in microgrids with renewables considering battery degradation, Energies 15 (19) (2022) [Online]. Available: https://www.mdpi.com/1996-1073/15/19/6967.

[80] X. Hu, X. Deng, F. Wang, Z. Deng, X. Lin, R. Teodorescu, M.G. Pecht, A review of second-life lithium-ion batteries for stationary energy storage applications, Proc. IEEE 110 (6) (2022) 735–753.

[81] B.M. Gundogdu, D.T. Gladwin, S. Nejad, D.A. Stone, Scheduling of grid-tied battery energy storage system participating in frequency response services and energy arbitrage, IET Gener. Transm. Distrib. 13 (14) (2019) 2930–2941.

[82] M.-K. Tran, A. DaCosta, A. Mevawalla, S. Panchal, M. Fowler, Comparative study of equivalent circuit models performance in four common lithium-ion batteries: LFP, NMC, LMO, NCA, Batteries 7 (3) (2021) [Online]. Available: https://www.mdpi.com/2313-0105/7/3/51.

[83] M.-K. Tran, M. Mathew, S. Janhunen, S. Panchal, K. Raahemifar, R. Fraser, M. Fowler, A comprehensive equivalent circuit model for lithium-ion batteries, incorporating the effects of state of health, state of charge, and temperature on model parameters, J. Energy Storage 43 (2021) 103252, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X2100949X.

[84] S. Nejad, D. Gladwin, D. Stone, A systematic review of lumped-parameter equivalent circuit models for real-time estimation of lithium-ion battery states, J. Power Sources 316 (2016) 183–196, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775316302427.

[85] I.N. Jiya, N. Gurusinghe, R. Gouws, Electrical circuit modelling of double layer capacitors for power electronics and energy storage applications: A review, Electronics (Switzerland) 7 (11) (2018).

[86] M. Möller, D. Kucevic, N. Collath, A. Parlikar, P. Dotzauer, B. Tepe, S. Englberger, A. Jossen, H. Hesse, SimSES: A holistic simulation framework for modeling and analyzing stationary energy storage systems, J. Energy Storage 49 (February) (2022) 103743, [Online]. Available: https://doi.org/10.1016/j.est.2021.103743.

[87] I. Calero, C.A. Cañizares, K. Bhattacharya, Compressed air energy storage system modeling for power system studies, IEEE Trans. Power Syst. 34 (5) (2019) 3359–3371.

[88] F. Bovera, M. Spiller, M. Zatti, G. Rancilio, M. Merlo, Development, validation, and testing of advanced mathematical models for the optimization of BESS operation, Sustain. Energy Grids Netw. 36 (2023) 101152, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352467723001601.

[89] R. Nebuloni, L. Meraldi, C. Bovo, V. Ilea, A. Berizzi, S. Sinha, R.B. Tamirisakandala, P. Raboni, A hierarchical two-level MILP optimization model for the management of grid-connected BESS considering accurate physical model, Appl. Energy 334 (2023) 120697, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261923000612.

[90] M.T. Castro, J.D. Ocon, Development of chemistry-specific battery energy storage system models using combined multiphysics and reduced order modeling, J. Energy Storage 54 (2022) 105305, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22013032.

[91] A. Saleh, A. Awad, W. Ghanem, Modeling, control, and simulation of a new topology of flywheel energy storage systems in microgrids, IEEE Access 7 (2019) 160363–160376.

[92] L. Wei, M. Wu, M. Yan, S. Liu, Q. Cao, H. Wang, A review on electrothermal modeling of supercapacitors for energy storage applications, IEEE J. Emerg. Sel. Top. Power Electron. 7 (3) (2019) 1677–1690.

[93] S.M. Alirahmi, S. Bashiri Mousavi, A.R. Razmi, P. Ahmadi, A comprehensive techno-economic analysis and multi-criteria optimization of a compressed air energy storage (CAES) hybridized with solar and desalination units, Energy Convers. Manage. 236 (March) (2021) 114053, [Online]. Available: https://doi.org/10.1016/j.enconman.2021.114053.

[94] M. Panwar, S. Chanda, M. Mohanpurkar, Y. Luo, F. Dias, R. Hovsapian, A.K. Srivastava, Integration of flow battery for resilience enhancement of advanced distribution grids, Int. J. Electr. Power Energy Syst. 109 (September 2017) (2019) 314–324, [Online]. Available: https://doi.org/10.1016/j.ijepes.2019.01.024.

[95] W. Kang, M. Chen, W. Lai, Y. Luo, Distributed real-time power management for virtual energy storage systems using dynamic price, Energy 216 (2021) 119069, [Online]. Available: https://doi.org/10.1016/j.energy.2020.119069.

[96] T.L. Nguyen, Y. Wang, Q.T. Tran, R. Caire, Y. Besanger, Agent-based distributed finite-time secondary control of energy storage systems in microgrids - controller hardware-in-the-loop validation, in: Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019, IEEE, 2019.

[97] National Grid ESO, Dynamic Containment Overview, Tech. Rep., National Grid ESO, 2020, [Online]. Available: https://www.nationalgrideso.com/document/165496/download.

[98] C.A. Caldeira, A.D.D. de Almeida, H.R. Schlickmann, C.S. Gehrke, F. Salvadori, Impact analysis of the BESS insertion in electric grid using real-time simulation, in: 2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America), 2019, pp. 1–6.

[99] M. Movahednia, H. Karimi, S. Jadid, A cooperative game approach for energy management of interconnected microgrids, Electr. Power Syst. Res. 213 (2022) 108772, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779622008276.

[100] A.V. Vykhodtsev, D. Jang, Q. Wang, W. Rosehart, H. Zareipour, A review of modelling approaches to characterize lithium-ion battery energy storage systems in techno-economic analyses of power systems, Renew. Sustain. Energy Rev. 166 (February) (2022) 112584, [Online]. Available: https://doi.org/10.1016/j.rser.2022.112584.

[101] S. Wang, P. Takyi-Aninakwa, S. Jin, C. Yu, C. Fernandez, D.I. Stroe, An improved feedforward-long short-term memory modeling method for the whole-life-cycle state of charge prediction of lithium-ion batteries considering current-voltage-temperature variation, Energy 254 (2022) 124224, [Online]. Available: https://doi.org/10.1016/j.energy.2022.124224.

[102] S. Wang, Y. Fan, S. Jin, P. Takyi-Aninakwa, C. Fernandez, Improved anti-noise adaptive long short-term memory neural network modeling for the robust remaining useful life prediction of lithium-ion batteries, Reliab. Eng. Syst. Saf. 230 (October 2022) (2023) 108920, [Online]. Available: https://doi.org/10.1016/j.ress.2022.108920.

[103] Y. Pu, Q. Li, X. Zou, R. Li, L. Li, W. Chen, H. Liu, Optimal sizing for an integrated energy system considering degradation and seasonal hydrogen storage, Appl. Energy 302 (2021) 117542, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S030626192100920X.

[104] N. Ma, D. Yang, S. Riaz, L. Wang, K. Wang, Aging mechanism and models of supercapacitors: A review, Technologies 11 (2) (2023) [Online]. Available: https://www.mdpi.com/2227-7080/11/2/38.

[105] A.M. Rabi, J. Radulovic, J.M. Buick, Comprehensive review of compressed air energy storage (CAES) technologies, Thermo 3 (1) (2023) 104–126, [Online]. Available: https://www.mdpi.com/2673-7264/3/1/8.

[106] A.J. Hutchinson, D.T. Gladwin, Modeling and simulation framework for hybrid energy storage systems including degradation mitigation analysis under varying control schemes, in: 2021 International Conference on Electrical, Computer and Energy Technologies, ICECET, (December) 2022, pp. 1–6.

[107] Mathworks, Behavioral battery model, 2024, [Online]. Available: https://uk.mathworks.com/help/simscape-battery/ref/battery.html?s{_}tid=doc{_}ta.

[108] T.S. Bryden, D.J. Rogers, A.J. Hutchinson, D.T. Gladwin, C.M. Harrison, J. Radcliffe, A. Alahyari, T. Rawat, C. Patsios, Y. Hu, A.J. Forsyth, Real-time energy storage simulators for the electricity grid, in: 2024 IEEE Electrical Energy Storage Application and Technologies Conference, EESAT, 2024, pp. 1–5.

[109] Mathworks, Average-value inverter (three-phase), 2024, [Online]. Available: https://uk.mathworks.com/help/sps/ref/averagevalueinverterthreephase.html.

[110] S. Breban, Genetic Algorithm Optimization of an Energy Storage System Design and Fuzzy Logic Supervision for Battery Electric Vehicles, i, Intech, 2016, p. 13, no. Optimization Algorithms- Methods and Applications compared.

[111] B.C. Cheung, R. Carriveau, D.S. Ting, Multi-objective optimization of an underwater compressed air energy storage system using genetic algorithm, Energy 74 (C) (2014) 396–404, [Online]. Available: http://dx.doi.org/10.1016/j.energy.2014.07.005.

[112] C. Eyisi, A.S. Al-Sumaiti, K. Turitsyn, Q. Li, Mathematical models for optimization of grid-integrated energy storage systems: A review, in: 51st North American Power Symposium, NAPS 2019, 2019.

[113] M. Shen, Q. Gao, A review on battery management system from the modeling efforts to its multiapplication and integration, Int. J. Energy Res. 43 (10) (2019) 5042–5075.

[114] Y. Wang, J. Tian, Z. Sun, L. Wang, R. Xu, M. Li, Z. Chen, A comprehensive review of battery modeling and state estimation approaches for advanced battery management systems, Renew. Sustain. Energy Rev. 131 (March) (2020) 110015, [Online]. Available: https://doi.org/10.1016/j.rser.2020.110015.

[115] S. Tamilselvi, S. Gunasundari, N. Karuppiah, A. Razak Rk, S. Madhusudan, V.M. Nagarajan, T. Sathish, M.Z.M. Shamim, C.A. Saleel, A. Afzal, A review on battery modelling techniques, Sustainability (Switzerland) 13 (18) (2021) 1–26.

[116] W. Zhou, Y. Zheng, Z. Pan, Q. Lu, Review on the battery model and SOC estimation method, Processes 9 (9) (2021).

[117] R. Guo, W. Shen, A review of equivalent circuit model based online state of power estimation for Lithium-Ion batteries in electric vehicles, Vehicles 4 (1) (2021) 1–31.

[118] A.V. Vykhodtsev, D. Jang, Q. Wang, W. Rosehart, H. Zareipour, A review of modelling approaches to characterize lithium-ion battery energy storage systems in techno-economic analyses of power systems, Renew. Sustain. Energy Rev. 166 (May) (2022) 112584, [Online]. Available: https://doi.org/10.1016/j.rser.2022.112584.

[119] N. Shamarova, K. Suslov, P. Ilyushin, I. Shushpanov, Review of battery energy storage systems modeling in microgrids with renewables considering battery degradation, Energies 15 (19) (2022) 1–18.

[120] Y. Yang, S. Bremner, C. Menictas, M. Kay, Modelling and optimal energy management for battery energy storage systems in renewable energy systems: A review, Renew. Sustain. Energy Rev. 167 (March 2021) (2022) 112671, [Online]. Available: https://doi.org/10.1016/j.rser.2022.112671.

[121] I.A. Razzhivin, A.A. Suvorov, R.A. Ufa, M.V. Andreev, A.B. Askarov, The energy storage mathematical models for simulation and comprehensive analysis of power system dynamics: A review. Part II, Int. J. Hydrog. Energy 48 (15) (2023) 6034–6055, [Online]. Available: https://doi.org/10.1016/j.ijhydene.2022.11.102.

[122] C. Semeraro, A.G. Olabi, H. Aljaghoub, A.H. Alami, M. Al Radi, M. Dassisti, M.A. Abdelkareem, Digital twin application in energy storage: Trends and challenges, J. Energy Storage 58 (November 2022) (2023) 106347, [Online]. Available: https://doi.org/10.1016/j.est.2022.106347.

[123] L.R. GopiReddy, L.M. Tolbert, B. Ozpineci, J.O. Pinto, Rainflow algorithm-based lifetime estimation of power semiconductors in utility applications, IEEE Trans. Ind. Appl. 51 (4) (2015) 3368–3375.

[124] D.I. Stroe, M. Swierczynski, A.I. Stan, R. Teodorescu, S.J. Andreasen, Accelerated lifetime testing methodology for lifetime estimation of lithium-ion batteries used in augmented wind power plants, IEEE Trans. Ind. Appl. 50 (6) (2014) 4006–4017.

[125] S. Kharel, B. Shabani, Hydrogen as a long-term large-scale energy storage solution to support renewables, Energies 11 (10) (2018).

[126] J.M. Reniers, G. Mulder, S. Ober-Blöbaum, D.A. Howey, Improving optimal control of grid-connected lithium-ion batteries through more accurate battery and degradation modelling, J. Power Sources 379 (January) (2018) 91–102, [Online]. Available: https://doi.org/10.1016/j.jpowsour.2018.01.004.

[127] M. Khodaparastan, A. Mohamed, Flywheel vs. Supercapacitor as wayside energy storage for electric rail transit systems, Inventions 4 (4) (2019).

[128] W. Yaici, L. Kouchachvili, E. Entchev, M. Longo, Dynamic simulation of battery/supercapacitor hybrid energy storage system for the electric vehicles, in: 8th International Conference on Renewable Energy Research and Applications, ICRERA 2019, 2019, pp. 460–465.

[129] F. Calero, C.A. Cañizares, K. Bhattacharya, Detailed and average battery energy storage model comparison, in: Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019, 2019.

[130] M. Dubarry, G. Baure, C. Pastor-Fernández, T.F. Yu, W.D. Widanage, J. Marco, Battery energy storage system modeling: A combined comprehensive approach, J. Energy Storage 21 (August 2018) (2019) 172–185, [Online]. Available: https://doi.org/10.1016/j.est.2018.11.012.

[131] Z. Abdin, W. Mérida, Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis, Energy Convers. Manage. 196 (January) (2019) 1068–1079, [Online]. Available: https://doi.org/10.1016/j.enconman.2019.06.068.

[132] D.N. Luta, A.K. Raji, Optimal sizing of hybrid fuel cell-supercapacitor storage system for off-grid renewable applications, Energy 166 (2019) 530–540, [Online]. Available: https://doi.org/10.1016/j.energy.2018.10.070.

[133] G. Rancilio, A. Lucas, E. Kotsakis, G. Fulli, M. Merlo, M. Delfanti, M. Masera, Modeling a large-scale battery energy storage system for power grid application analysis, Energies 12 (17) (2019).

[134] A.M. Aly, A.M. Kassem, K. Sayed, I. Aboelhassan, Design of microgrid with flywheel energy storage system using HOMER software for case study, in: Proceedings of 2019 International Conference on Innovative Trends in Computer Engineering, ITCE 2019, Vol. February, IEEE, 2019, pp. 485–491.

[135] L.H. Saw, H.M. Poon, W.T. Chong, C.T. Wang, M.C. Yew, M.K. Yew, T.C. Ng, Numerical modeling of hybrid supercapacitor battery energy storage system for electric vehicles, Energy Procedia 158 (2019) 2750–2755, [Online]. Available: https://doi.org/10.1016/j.egypro.2019.02.033.

[136] D. Saji, P.S. Babu, K. Ilango, SoC estimation of lithium ion battery using combined Coulomb counting and fuzzy logic method, in: 2019 4th IEEE International Conference on Recent Trends on Electronics, Information, Communication and Technology, RTEICT 2019 - Proceedings, IEEE, 2019, pp. 948–952.

[137] H. Jin, P. Liu, Z. Li, Dynamic modeling and design of a hybrid compressed air energy storage and wind turbine system for wind power fluctuation reduction, Comput. Chem. Eng. 122 (2019) 59–65, [Online]. Available: https://doi.org/10.1016/j.compchemeng.2018.05.023.

[138] C. Li, D. Wang, D. Liu, J. Wu, Y. Li, C. Mao, J. Wang, Mathematical modelling of large-scale compressed air energy storage systems, in: ICAC 2019 - 2019 25th IEEE International Conference on Automation and Computing, Vol. September, Chinese Automation and Computing Society in the UK - CACSUK, 2019, pp. 5–7.

[139] M.E. Amiryar, K.R. Pullen, Assessment of the carbon and cost savings of a combined diesel generator, solar photovoltaic, and flywheel energy storage islanded grid system, Energies 12 (17) (2019).

[140] A. Kadri, H. Marzougui, A. Aouiti, F. Bacha, Energy management and control strategy for a DFIG wind turbine/fuel cell hybrid system with super capacitor storage system, Energy 192 (2020) 116518, [Online]. Available: https://doi.org/10.1016/j.energy.2019.116518.

[141] K.S. El-Bidairi, H.D. Nguyen, T.S. Mahmoud, S.D. Jayasinghe, J.M. Guerrero, Optimal sizing of battery energy storage systems for dynamic frequency control in an islanded microgrid: A case study of Flinders Island, Australia, Energy 195 (2020) 117059, [Online]. Available: https://doi.org/10.1016/j.energy.2020.117059.

[142] P. Gabrielli, A. Poluzzi, G.J. Kramer, C. Spiers, M. Mazzotti, M. Gazzani, Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage, Renew. Sustain. Energy Rev. 121 (2020) 109629, [Online]. Available: https://doi.org/10.1016/j.rser.2019.109629.

[143] M. Mansour, M.N. Mansouri, S. Bendoukha, M.F. Mimouni, A grid-connected variable-speed wind generator driving a fuzzy-controlled PMSG and associated to a flywheel energy storage system, Electr. Power Syst. Res. 180 (November 2019) (2020) 106137, [Online]. Available: https://doi.org/10.1016/j.epsr.2019.106137.

[144] M. Sahin, F. Blaabjerg, A hybrid PV-battery / supercapacitor system and a basic active power control proposal in MATLAB/simulink, Electronics 9 (1) (2020) 129.

[145] M. Kheawcum, S. Sangwongwanich, A case study on flywheel energy storage system application for frequency regulation of islanded amphoe mueang mae hong son microgrid, in: 17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, ECTI-CON 2020, 2020, pp. 421–426.

[146] M. Nadour, A. Essadki, T. Nasser, Power smoothing control of DFIG based wind turbine using flywheel energy storage system, in: 2020 International Conference on Electrical and Information Technologies, ICEIT 2020, 2020, pp. 0–6.

[147] M.A.V. Rad, R. Ghasempour, P. Rahdan, S. Mousavi, M. Arastounia, Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran, Energy 190 (2020) 116421, [Online]. Available: https://doi.org/10.1016/j.energy.2019.116421.

[148] E. Elbouchikhi, Y. Amirat, G. Feld, M. Benbouzid, Z. Zhou, A lab-scale flywheel energy storage system: Control strategy and domestic applications, Energies 13 (3) (2020) 1–23.

[149] R. Sebastián, R. Peña-Alzola, Flywheel energy storage and dump load to control the active power excess in a wind diesel power system, Energies 13 (8) (2020).

[150] H.S. Dhiman, D. Deb, Wake management based life enhancement of battery energy storage system for hybrid wind farms, Renew. Sustain. Energy Rev. 130 (May) (2020) 109912, [Online]. Available: https://doi.org/10.1016/j.rser.2020.109912.

[151] C. Jankowiak, A. Zacharopoulos, C. Brandoni, P. Keatley, P. MacArtain, N. Hewitt, Assessing the benefits of decentralised residential batteries for load peak shaving, J. Energy Storage 32 (April) (2020) 101779, [Online]. Available: https://doi.org/10.1016/j.est.2020.101779.

[152] D. Rosewater, R. Baldick, S. Santoso, Risk-averse model predictive control design for battery energy storage systems, IEEE Trans. Smart Grid 11 (3) (2020) 2014–2022.

[153] R.H.G. Tan, G.K. Tinakaran, Development of battery energy storage system model in MATLAB/Simulink, Int. J. Smart Grid Clean Energy (1) (2020) 180–188.

[154] J. Bai, W. Wei, L. Chen, S. Mei, Modeling and dispatch of advanced adiabatic compressed air energy storage under wide operating range in distribution systems with renewable generation, Energy 206 (2020) 118051, [Online]. Available: https://doi.org/10.1016/j.energy.2020.118051.

[155] S. Chen, A. Arabkoohsar, T. Zhu, M.P. Nielsen, Development of a micro-compressed air energy storage system model based on experiments, Energy 197 (2020) 117152, [Online]. Available: https://doi.org/10.1016/j.energy.2020.117152.

[156] S. Karrari, G. De Carne, M. Noe, Model validation of a high-speed flywheel energy storage system using power hardware-in-the-loop testing, J. Energy Storage 43 (September) (2021) 103177, [Online]. Available: https://doi.org/10.1016/j.est.2021.103177.

[157] M. Berger, I. Kocar, E. Farantatos, A. Haddadi, Modeling of Li-ion battery energy storage systems (BESSs) for grid fault analysis, Electr. Power Syst. Res. 196 (2021).

[158] S.B. Mousavi, P. Ahmadi, A. Pourahmadiyan, P. Hanafizadeh, A comprehensive techno-economic assessment of a novel compressed air energy storage (CAES) integrated with geothermal and solar energy, Sustain. Energy Technol. Assess. 47 (July) (2021) 101418, [Online]. Available: https://doi.org/10.1016/j.seta.2021.101418.

[159] P. Puranen, A. Kosonen, J. Ahola, Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates, Sol. Energy 213 (October 2020) (2021) 246–259, [Online]. Available: https://doi.org/10.1016/j.solener.2020.10.089.

[160] S. Saberi Oskouee, S. Kamali, T. Amraee, Primary frequency support in unit commitment using a multi-area frequency model with flywheel energy storage, IEEE Trans. Power Syst. 36 (6) (2021) 5105–5119.

[161] M. Krpan, I. Kuzle, A. Radovanovic, J.V. Milanovic, Modelling of supercapacitor banks for power system dynamics studies, IEEE Trans. Power Syst. 36 (5) (2021) 3987–3996.

[162] M. Şahin, Modelling of supercapacitors based on simplified equivalent circuit, CPSS Trans. Power Electron. Appl. 6 (1) (2021) 31–39.

[163] M.M. Rahman, E. Gemechu, A.O. Oni, A. Kumar, The development of a techno-economic model for the assessment of the cost of flywheel energy storage systems for utility-scale stationary applications, Sustain. Energy Technol. Assess. 47 (June) (2021) 101382, [Online]. Available: https://doi.org/10.1016/j.seta.2021.101382.

[164] C. Strunck, C. Rehtanz, Development of a dynamic combined heat and power plant and flywheel energy storage system model validated with field tests, in: 2021 IEEE Madrid PowerTech, PowerTech 2021 - Conference Proceedings, IEEE, 2021.

[165] A. Al-Quraan, M. Al-Qaisi, Modelling, design and control of a standalone hybrid PV-wind micro-grid system, Energies 14 (16) (2021).

[166] Y. Manoharan, A. Headley, K. Olson, L. Sombardier, B. Schenkman, Energy storage versus demand side management for peak-demand reduction at the Hawaii ocean science and technology park, in: Proceedings of the ASME 2021 15th International Conference on Energy Sustainability, ES 2021, 2021, pp. 1–7.

[167] H.A. Moghaddam, M.H. Saeedinia, S. Mohamadian, M.S. Mahdavi, G.B. Gharehpetian, Integrated modeling of power network and connected flywheel energy storage system for optimal power and energy ratings of flywheel, IEEE Trans. Energy Convers. 36 (3) (2021) 1589–1599.

[168] L. Zhang, Y. Yu, B. Li, X. Qian, S. Zhang, X. Wang, X. Zhang, M. Chen, Improved cycle aging cost model for battery energy storage systems considering more accurate battery life degradation, IEEE Access 10 (2022) 297–307.

[169] Z. Cabrane, S.H. Lee, Electrical and mathematical modeling of supercapacitors: Comparison, Energies 15 (3) (2022).

[170] H. Lu, B. Sun, Z. Hu, Research on energy management strategy of battery-flywheel hybrid energy storage electric vehicle, IAENG Int. J. Comput. Sci. 49 (4) (2022).

[171] A.J. Hutchinson, D.T. Gladwin, Verification and analysis of a Battery Energy Storage System model, Energy Rep. 8 (2022) 41–47, [Online]. Available: https://doi.org/10.1016/j.egyr.2022.05.042.

[172] P.L.C. García-Miguel, A.P. Asensio, J.L. Merino, M.G. Plaza, Analysis of cost of use modelling impact on a battery energy storage system providing arbitrage service, J. Energy Storage 50 (February) (2022) 104203, [Online]. Available: https://doi.org/10.1016/j.est.2022.104203.

[173] C.R. Arunkumar, U.B. Manthati, P. Srinivas, Accurate modelling and analysis of battery–supercapacitor hybrid energy storage system in DC microgrid systems, Energy Syst. 13 (4) (2022) 1055–1073, [Online]. Available: https://doi.org/10.1007/s12667-021-00467-3.

[174] A.J. Hutchinson, D.T. Gladwin, Techno-economic assessment of novel hybrid energy storage control strategies for Dynamic Frequency Response, J. Energy Storage 55 (2022) 105694, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22016826.

[175] J. Li, W. Zou, Q. Yang, F. Yi, Y. Bai, Z. Wei, H. He, Size optimization and power allocation of a hybrid energy storage system for frequency service, Int. J. Electr. Power Energy Syst. 141 (February) (2022) 108165, [Online]. Available: https://doi.org/10.1016/j.ijepes.2022.108165.

[176] J. Kumar, M. Mekkanen, M. Karimi, K. Kauhaniemi, Hardware-in-the-loop testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid, Energy Rep. 9 (2023) 447–454, [Online]. Available: https://doi.org/10.1016/j.egyr.2023.01.068.

[177] P.L. Camunas, J. Lopez Merino, A.P. Asensio, M. Garcia Plaza, S.A. Gomez, Analysis of methods to improve energy storage arbitrage benefit considering capacity degradation, in: Proceedings of the IEEE International Conference on Industrial Technology, Vol. 2021-March (2021) 573–578.

[178] M. Li, R. Fu, T. Yaxiaer, Y. Zheng, A. Huang, R. Liu, S. Lin, Two-stage optimal scheduling of community integrated energy system, Energy Eng.: J. Assoc. Energy Eng. 121 (2) (2024) 405–424.

[179] Q.M. Nguyen, D.L. Nguyen, Q.A. Nguyen, T.N. Pham, Q.T. Phan, M.H. Tran, A Bi-level optimization for the planning of microgrid with the integration of hydrogen energy storage, Int. J. Hydrog. Energy 63 (March) (2024) 967–974, [Online]. Available: https://doi.org/10.1016/j.ijhydene.2024.03.253.

[180] C. Xu, X. Wu, Z. Shan, Q. Zhang, B. Dang, Y. Wang, F. Wang, X. Jiang, Y. Xue, C. Shi, Bi-level configuration and operation collaborative optimization of shared hydrogen energy storage system for a wind farm cluster, J. Energy Storage 86 (PA) (2024) 111107, [Online]. Available: https://doi.org/10.1016/j.est.2024.111107.

[181] A.J. Hutchinson, D.T. Gladwin, Flywheel energy storage for ancillary services: A novel design and simulation of a continuous frequency response service for energy limited assets, IEEE Open Access J. Power Energy 11 (February) (2024) 434–445.

[182] D.S. Vilchis-Rodriguez, O. Marjanovic, R. Preece, M. Barnes, Reduced order model of a flywheel energy storage system for efficient electromagnetic transient simulation, in: 13th International Conference on Power Electronics, Machines and Drives, Vol. 2024, 2024, pp. 345–351, no. 3.

[183] L. Li, Y. Sun, Y. Han, W. Chen, Seasonal hydrogen energy storage sizing: Two-stage economic-safety optimization for integrated energy systems in northwest China, iScience 27 (9) (2024) 110691, [Online]. Available: https://doi.org/10.1016/j.isci.2024.110691.

[184] N. Qi, K. Huang, Z. Fan, B. Xu, Long-term energy management for microgrid with hybrid hydrogen-battery energy storage: A prediction-free coordinated optimization framework, Appl. Energy 377 (PB) (2025) 124485, [Online]. Available: https://doi.org/10.1016/j.apenergy.2024.124485.

[185] A.O. Maka, T.N. Chaudhary, Performance investigation of solar photovoltaic systems integrated with battery energy storage, J. Energy Storage 84 (PA) (2024) 110784, [Online]. Available: https://doi.org/10.1016/j.est.2024.110784.

[186] P. Sharma, K.K. Saini, H.D. Mathur, P. Mishra, Improved energy management strategy for prosumer buildings with renewable energy sources and battery energy storage systems, J. Mod. Power Syst. Clean Energy 12 (2) (2024) 381–392, [Online]. Available: http://dx.doi.org/10.35833/MPCE.2023.000761.

[187] W. Zhuang, S. Zhou, W. Gu, S. Ding, S. Lu, T. Zhang, Y. Ding, C.C. Chan, S. Zhang, Optimal planning of electricity-gas coupled coordination hub considering large-scale energy storage, Energy Convers. Manage. 300 (August 2023) (2024) 117917, [Online]. Available: https://doi.org/10.1016/j.enconman.2023.117917.

[188] P. Liu, W. Zhao, J. Shair, J. Zhang, F. Li, P. Xv, X. Xie, Modeling of battery energy storage systems for AGC performance analysis in wind power systems, Int. J. Electr. Power Energy Syst. 155 (PA) (2024) 109478, [Online]. Available: https://doi.org/10.1016/j.ijepes.2023.109478.

[189] P. Glücker, T. Pesch, A. Benigni, Optimal sizing of battery energy storage system for local multi-energy systems: The impact of the thermal vector, Appl. Energy 372 (June) (2024) 123732, [Online]. Available: https://doi.org/10.1016/j.apenergy.2024.123732.

[190] M. Fochesato, C. Peter, L. Morandi, J. Lygeros, Peak shaving with hydrogen energy storage: From stochastic control to experiments on a 4 MWh facility, Appl. Energy 376 (PA) (2024) 123965, [Online]. Available: https://doi.org/10.1016/j.apenergy.2024.123965.

[191] J. Gonzalez-Saenz, V. Becerra, Optimal battery energy storage dispatch for the day-ahead electricity market, Batteries 10 (7) (2024).

[192] M. Graner, V.T. Tanjavooru, A. Jossen, H. Hesse, Dispatch optimization of battery energy storage systems considering degradation effects and capacity inhomogeneities in second life batteries, in: Proceedings Ofthe International Renewable Energy Storage and Systems Conference (IRES 2023), Atlantis Press International BV, 2024, pp. 20–27, [Online]. Available: http://dx.doi.org/10.2991/978-94-6463-455-6{_}4.

[193] H.N. Duong, L. Tran, T.V.T. Vo-Duy, B.a.H.N. N, A global optimal benchmark for energy management of microgrid (GoBuG) integrating hybrid energy storage system, IEEE Trans. Smart Grid 15 (6) (2024) 5429–5440.

[194] M. Elkholy, S. Schwarz, M. Aziz, Advancing renewable energy: Strategic modeling and optimization of flywheel and hydrogen-based energy system, J. Energy Storage 101 (PA) (2024) 113771, [Online]. Available: https://doi.org/10.1016/j.est.2024.113771.

[195] B. Xiang, S. Wu, T. Wen, H. Liu, C. Peng, Design, modeling, and validation of a 0.5 kWh flywheel energy storage system using magnetic levitation system, Energy 308 (July) (2024) 132867, [Online]. Available: https://doi.org/10.1016/j.energy.2024.132867.

[196] S. Venturini, S.P. Cavallaro, A. Vigliani, Windage loss characterisation for flywheel energy storage system: Model and experimental validation, Energy 307 (July) (2024).

[197] E. Dormoy, B. Le Lostec, D. Haillot, Aboveground compressed air energy storage systems: Experimental and numerical approach, Energy Convers. Manage. 321 (September) (2024) 119073, [Online]. Available: https://doi.org/10.1016/j.enconman.2024.119073.

[198] S. Cui, L. Chen, S. Chen, Z. Sun, S. Mei, Dynamic modeling and analysis of compressed air energy storage for multi-scenario regulation requirements, J. Energy Storage 100 (July) (2024).

[199] F. Khalafian, N. Iliaee, E. Diakina, P. Parsa, M.M. Alhaider, M.H. Masali, S. Pirouzi, M. Zhu, Capabilities of compressed air energy storage in the economic design of renewable off-grid system to supply electricity and heat costumers and smart charging-based electric vehicles, J. Energy Storage 78 (July 2023) (2024) 109888, [Online]. Available: https://doi.org/10.1016/j.est.2023.109888.

[200] S.M. Alirahmi, T. Gundersen, A. Arabkoohsar, J.J. Klemeš, G. Sin, H. Yu, Process design, integration, and optimization of a novel compressed air energy storage for the coproduction of electricity, cooling, and water, Renew. Sustain. Energy Rev. 189 (January 2023) (2024).

[201] R. Wang, Z. Zhang, K. Meng, P. Lei, K. Wang, W. Yang, Y. Liu, Z. Lin, Research on energy scheduling optimization strategy with compressed air energy storage, Sustainability (Switzerland) 16 (18) (2024) 1–18.

[202] K. Gaspersons, K. Kroics, Development of fast DC bus cascaded voltage controller for supercapacitor energy storage system, in: Advances in Information, Electronic and Electrical Engineering - Proceedings of the 11th IEEE Workshop, AIEEE 2024, IEEE, 2024, pp. 1–5.

[203] M. Khamies, M. Abdel-Salam, A. Kassem, M. Nayel, M. El-Ghazaly, M. Hashem, Evaluating supercapacitor energy storage for voltage sag minimization in a real distribution feeder, J. Energy Storage 101 (September) (2024).

[204] A. Isa, C. Sourkounis, Advanced constant active power and inertia control of wind power system with supercapacitor energy storage system, in: 2024 32nd Mediterranean Conference on Control and Automation, MED 2024, IEEE, 2024, pp. 854–859.

[205] A. Kumar, A. Rathore, Modelling and testing of wind energy fed hybrid battery-supercapacitor energy storage operating in pulsed charging mode, Wind Eng. 48 (2) (2024) 228–242.

[206] M.B. Abdelghany, V. Mariani, D. Liuzza, L. Glielmo, Hierarchical model predictive control for islanded and grid-connected microgrids with wind generation and hydrogen energy storage systems, Int. J. Hydrog. Energy 51 (2024) 595–610, [Online]. Available: https://doi.org/10.1016/j.ijhydene.2023.08.056.

[207] Q. Zhao, A. Basem, H.O. Shami, K. Mausam, M. Alsehli, A.I. Hameed, A. Alshamrani, H. Rajab, M. Ahmed, A.S. El-Shafay, Conceptual design and optimization of integrating renewable energy sources with hydrogen energy storage capabilities, Int. J. Hydrog. Energy 79 (June) (2024) 1313–1330, [Online]. Available: https://doi.org/10.1016/j.ijhydene.2024.07.071.

[208] Q. Zhu, A. Bolzoni, A. Forsyth, R. Todd, M. Smith, D.T. Gladwin, T. John, C. Patsios, G. Jones, D.J. Rogers, Delay compensation amongst aggregated storage assets providing fast frequency regulation, in: 2020 IEEE 9th International Power Electronics and Motion Control Conference, IPEMC 2020 ECCE Asia, 2020, pp. 1402–1408.

[209] Y.J. Kim, J. Wang, Power hardware-in-the-loop simulation study on frequency regulation through direct load control of thermal and electrical energy storage resources, IEEE Trans. Smart Grid 9 (4) (2018) 2786–2796.

[210] M.S. Mahdavi, M. Bagheri, G.B. Gharehpetian, Coordinated frequency control of flywheel energy storage and diesel generator in amirkabir university of technology (AUT) microgrid, in: Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, 2019.

[211] J. Li, R. Xiong, H. Mu, B. Cornélusse, P. Vanderbemden, D. Ernst, W. Yuan, Design and real-time test of a hybrid energy storage system in the microgrid with the benefit of improving the battery lifetime, Appl. Energy 218 (January) (2018) 470–478, [Online]. Available: https://doi.org/10.1016/j.apenergy.2018.01.096.

[212] B. Kedra, R. Malkowski, Comparison of supercapacitor and flywheel energy storage devices based on power converters and simulink real-time, in: Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018, 2018, pp. 5–9.

[213] S. Karrari, M. Noe, J. Geisbuesch, High-speed flywheel energy storage system (FESS) for voltage and frequency support in low voltage distribution networks, in: 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems, IEPS 2018 - Proceedings, Vol. 2018-Janua, IEEE, 2018, pp. 176–182.

[214] R. Todd, H.J. Uppal, T. Feehally, A.J. Forsyth, A.M. Pavan, A power hardware-in-the-loop simulation facility for testing grid-connected storage systems, in: 2019 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2019, 2019, pp. 0–4.

[215] D. Petreus, R. Etz, T. Patarau, M. Cirstea, An islanded microgrid energy management controller validated by using hardware-in-the-loop emulators, Int. J. Electr. Power Energy Syst. 106 (June 2018) (2019) 346–357, [Online]. Available: https://doi.org/10.1016/j.ijepes.2018.10.020.

[216] M. Kezunovic, M. Soleimani, H. Abu-Rub, S. Bayhan, M. Trabelsi, Hardware in the loop simulation of a nano-grid transactive energy exchange, in: 2nd International Conference on Smart Grid and Renewable Energy, SGRE 2019 - Proceedings, IEEE, 2019.

[217] Y. Pu, Q. Li, W. Chen, H. Liu, Hierarchical energy management control for islanding DC microgrid with electric-hydrogen hybrid storage system, Int. J. Hydrog. Energy 4 (2019) 5153–5161.

[218] K. Ravinder, H.O. Bansal, Investigations on shunt active power filter in a PV-wind-FC based hybrid renewable energy system to improve power quality using hardware-in-the-loop testing platform, Electr. Power Syst. Res. 177 (August) (2019).

[219] C.A. Caldeira, H.R. Schlickmann, A.D. De Almeida, L.V. Hartmann, C.S. Gehrke, F. Salvadori, G.F. Da Paz, Modeling and simulation of the battery energy storage system for analysis impact in the electrical grid, in: 2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference, COBEP/SPEC 2019, IEEE, 2019.

[220] M. Mao, J. Hu, L. Chang, Power distribution strategy real-time simulation for VSG-controlled parallel PV/battery microgrid using RT-LAB, in: PEDG 2019 - 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems, IEEE, 2019, pp. 919–924.

[221] B.H. Nguyen, R. German, J.P.F. Trovao, A. Bouscayrol, Real-time energy management of battery/supercapacitor electric vehicles based on an adaptation of pontryagin's minimum principle, IEEE Trans. Veh. Technol. 68 (1) (2019) 203–212.

[222] W. Li, M. Rentemeister, J. Badeda, D. Jöst, D. Schulte, D.U. Sauer, Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation, J. Energy Storage 30 (May) (2020) 101557, [Online]. Available: https://doi.org/10.1016/j.est.2020.101557.

[223] K.V. Singh, H.O. Bansal, D. Singh, Hardware-in-the-loop implementation of ANFIS based adaptive SoC estimation of Lithium-ion battery for hybrid vehicle applications, J. Energy Storage 27 (July 2019) (2020) 101124, [Online]. Available: https://doi.org/10.1016/j.est.2019.101124.

[224] S. Sinha, P. Bajpai, Power management of hybrid energy storage system in a standalone DC microgrid, J. Energy Storage 30 (May) (2020) 101523, [Online]. Available: https://doi.org/10.1016/j.est.2020.101523.

[225] C. Keerthisinghe, D.S. Kirschen, Real-time digital simulation of microgrid control strategies, in: 2020 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2020, 2020, pp. 1–5.

[226] X. Jia, P.M. Adhikari, L. Vanfretti, Cross-platform real-time simulation models for Li-ion batteries in Opal-RT and Typhoon-HIL, in: 2021 IEEE Texas Power and Energy Conference, TPEC 2021, 2021.

[227] L. Tziovani, L. Hadjidemetriou, C. Charalampous, M. Tziakouri, S. Timotheou, E. Kyriakides, Energy management and control of a flywheel storage system for peak shaving applications, IEEE Trans. Smart Grid 12 (5) (2021) 4195–4207.

[228] Y. Li, Y. Shi, Z. Hu, B. Lei, W. Gong, Y. Wu, Hardware-in-loop real-time simulation for battery energy power conversion system based on RT-LAB, in: Proceedings - 2021 International Conference on Power System Technology: Carbon Neutrality and New Type of Power System, POWERCON 2021, Vol. December, IEEE, 2021, pp. 1327–1332.

[229] F. Lacressonnière, A. Varais, X. Roboam, E. Bru, T. Mullins, Scale electro-thermal model of a lithium-ion battery for time-accelerated experiments in a hardware in the loop process, J. Energy Storage 39 (February) (2021).

[230] H. Tang, Y. Wu, Y. Cai, F. Wang, Z. Lin, Y. Pei, Design of power lithium battery management system based on digital twin, J. Energy Storage 47 (July 2021) (2022) 103679, [Online]. Available: https://doi.org/10.1016/j.est.2021.103679.

[231] H. Kikusato, T.S. Ustun, M. Suzuki, S. Sugahara, J. Hashimoto, K. Otani, N. Ikeda, I. Komuro, H. Yokoi, K. Takahashi, Flywheel energy storage system based microgrid controller design and PHIL testing, Energy Rep. 8 (2022) 470–475, [Online]. Available: https://doi.org/10.1016/j.egyr.2022.05.221.

[232] B. Jian, H. Wang, Hardware-in-the-loop real-time validation of fuel cell electric vehicle power system based on multi-stack fuel cell construction, J. Clean. Prod. 331 (August 2021) (2022) 129807, [Online]. Available: https://doi.org/10.1016/j.jclepro.2021.129807.

[233] T. Haring, L. Link, A. Rosin, H. Biechl, Hybrid energy storage lifetime-oriented control strategy in islanded microgrids: A real time simulation case study, in: ENERGYCON 2022 - 2022 IEEE 7th International Energy Conference, Proceedings, Vol. 856602, IEEE, 2022.

[234] T. John, I. Sarantakos, T.T. Teo, Stacking different services of an energy storage system in a grid-connected microgrid, Renew. Energy 195 (2022) 357–365, [Online]. Available: https://doi.org/10.1016/j.renene.2022.06.035.

[235] Y. Yi, C. Xia, C. Feng, W. Zhang, C. Fu, L. Qian, S. Chen, Digital twin-long short-term memory (LSTM) neural network based real-time temperature prediction and degradation model analysis for lithium-ion battery, J. Energy Storage 64 (March) (2023) 107203, [Online]. Available: https://doi.org/10.1016/j.est.2023.107203.