Article

Hybrid Energy Storage Systems based on Redox-Flow Batteries: Recent Developments, Challenges and Future Perspectives

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Abstract: Recently, there is growing appeal for Hybrid Energy Storage Systems (HESS) in multiple application fields, such as charging stations, grid services, and micro-grids. HESS consist of an integration of two or more single Energy Storage Systems (ESS) to combine the benefits of each ESS and to improve the overall system performance, e.g. efficiency and lifespan. Most recent studies on HESS mainly focus on power management and coupling between the different ESS without a particular interest in a specific type of ESS. Over the last decades, Redox-Flow Batteries (RFB) have received significant attention due to their attractive features, especially for stationary storage applications, hybridization can improve certain characteristics on short-term duration and peak power availability. This paper brings a comprehensive overview of the main concepts of HESS based on RFB. Starting with a brief description and a specification of the Key Performance Indicators (KPI) of common electrochemical storage technologies suitable for hybridization with RFBs, a classification of HESS based on battery-oriented and application-oriented KPIs is performed. Furthermore, an optimal coupling architecture of HESS made up of the combination of a RFB and a Supercapacitor (SC) is proposed and evaluated via a numerical simulation. Finally, an in-depth study of Energy Management Systems (EMS) is conducted. The general structure of an EMS as well as possible application scenarios are given to identify commonly used control and optimization parameters. Therefore, the differentiation in system-oriented and application-oriented parameters is applied to literature data. Afterwards, state-of-the-art EMS optimization techniques are discussed. As an optimal EMS is characterized by the prediction of the system's future behavior and the use of the suitable control technique, a detailed analysis of the previous implemented EMS prediction algorithms and control techniques is carried out. The study summarizes key aspects and challenges of the electrical hybridization of RFBs and thus gives future perspectives on newly needed optimization and control algorithms for management systems.

Keywords: Hybrid energy storage systems, redox-flow batteries, key performance indicators, coupling architecture, energy management system, prediction, control techniques.

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1. Introduction

In recent years there has been considerable interest in Energy Storage Systems (ESS) in many application areas, e.g. electric vehicles and renewable energy (RE) systems. Commonly used ESS for stationary applications are Lithium-Ion Battery (LIB), Lead-Acid

Battery (PbA), and Pumped Storage hydropower [1]. However, in the last decade there has been a rapid rise in the use of Redox-Flow Batteries (RFB) due to their independent scalability of power and energy as well as attractive features, like low self discharge, high efficiency and long life[2,3].

While technological features like materials, components or stacking of ESS are constantly improved, stationary applications require advanced control and management techniques to enable highly adaptable flexibility options in future grids. Management Approaches for ESS should consider multiple decision criteria to optimize the operation and design. Often these criteria are only based on technical aspects written in the data sheet, while application-oriented criteria are neglected. The technical approach focuses on the storage technology itself and its functionality under different circumstances. The application perspective describes how the storage system should perform and examines the utilization purpose.

In many applications, a single ESS is insufficient to meet the system important requirements. Hence, the use of multiple distinct ESS, also known as Hybrid Energy Storage System (HESS), is needed to benefit from the complementary characteristics of each single ESS. As a HESS consists of at least two electrically connected single storage components both, the battery perspective of each component as well as the overall application perspective need to be taken into account to develop advanced control strategies. The combination of battery and application aspects lead to an optimized dimensioning of the HESS itself. Figure 1 summarizes the methodology presented in this study. Starting from single storage components (A / B / C...), the evaluation of battery- and application-oriented criteria (step I / II), is performed for single components and the combination within the HESS indicate complementary characteristics and advantages. Moreover, the electrical layout meaning the optimized coupling architectures for single components and design approaches are based on the criteria and the storage technologies selected (step III). In the last step, the evaluation criteria give the input parameters for the Energy Management structure and optimization in step four.

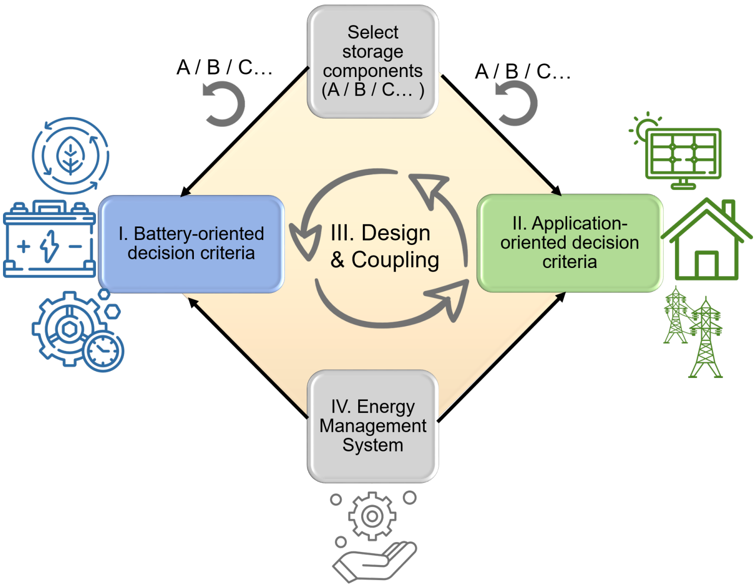


Figure 1. Flow chart of the decision criteria for Energy Management Approaches for HESS.

In this study, the proposed methodology (step one to four) is deeply studied based on literature analysis and results from two research projects, HyFlow and Open Mobility Electric Infrastructure (OMEI), focusing on the hybridization of RFBs, are evaluated. The goal is to summarize the status quo of recent developments in design and energy management approaches for HESS based on RFB. The presented methodology allows the classification of ESS based on key performance indicators (KPI) to identify most suitable candidates for hybridization. An optimization strategy to identify optimal electrical coupling architectures is performed using an exemplary HESS with a RFB and a SC from one of the research projects. Application scenarios are studied and categorized to identify application-oriented criteria which need to be considered while developing the Energy Management System (EMS). The energy management structure, as core control component for every HESS, will be studied deeply and newly available optimization and prediction approaches are analyzed for future perspectives.

The remain of this paper is organized into six sections: Section 2 introduces the terminology of the proposed paper. Starting with a short definition of Electrical Energy Storage (EES) technologies, the definition of a HESS within this publication is proposed. Section 3 describes the evaluation of KPIs. It starts by introducing the selected KPIs. Afterwards a classification of selected single storage components is performed and finally, it applies the classification system to different HESS combinations. Section 4 describes the optimal coupling architecture of a HESS based on a RFB and a SC and reveals a optimization strategy for the electrical layout. Section 5 deals with the EMS for HESS and is separated in two parts. Starting with the general structure of the EMS as well as a definition of application scenarios, control and optimization parameters for EMS are discussed in the first part. In the second part, optimization routines for the EMS especially focusing prediction and programming techniques are highlighted. Section 6 devotes an analysis of some related works. Finally, section 7 concludes the paper.

2. Terminology

The aim of this section is to state the key terminologies used within this paper. First, the technical characteristics of commonly used EES are summarized, then a clear and precise definition of HESS is given.

2.1. Electrical Energy Storage (EES)

A comprehensive overview of existing energy storage technologies and their functionality divided into electrical, mechanical, electrochemical, thermochemical, chemical and thermal technologies can be found in various publications [4–7]. So called batteries are part of the category electrochemical energy storage technologies and can be further categorized into primary batteries, secondary batteries, fuel cells (FC), and electrochemical capacitors (SC) [6]. Due to irreversible reactions, primary batteries are mostly not rechargeable and are typically used in small portable applications, e.g. watches or thermostats [6]. Secondary battery cells are based on a reversible electrochemical process and thus can be recharged several times, depending on their technical characteristics [6]. The storage technologies investigated within this study are summarized as follows. RFB are used as the core storage component. Most suitable hybridization partners are LIB, Sodium-sulphur Battery (NaS) and PbA. Moreover, SC and Superconducting Magnetic Energy Storage's (SMES) are added to the list of technologies investigated, due to their high power density.

2.1.1. Redox-Flow Battery (RFB)

In contrast to the other electrochemical storage's, RFBs offer independent scalability of energy and power, thus being a promising storage technology. First developments in 1949 and further improvements patented during the 1970s, led to the today most commercialized Vanadium-Redox-Flow Battery (VRFB) [2,8–10]. In general, RFBs consist of two half cells with carbon-based high surface electrodes, separated by an ion selective membrane, as shown in Figure 2 [2,3]. A commonly water-based electrolyte is pumped through the half cells and stored in separated external tanks [2,3]. Typically up to 40 cells are electrically connected in series using a bipolar sack design, while hydraulic circuits deliver electrolyte parallel to all cells [3,11,12]. In case of the VRFB, the electrolyte is based on a 1.6-molar solution of Vanadiumpentoxid in sulphuric acid and water [2,13,14]. For the discharging process a consumer is connected to the electrical circuit. Ideally, V5+ is reduced to V4+ on the cathode, while V3+ is oxidized to V2+ on the anode. Reversely, during the charging process a current source is connected to the electrical circuit, as highlighted in Figure 2 and the electrodes change the roles of cathode and anode [2,13,14].

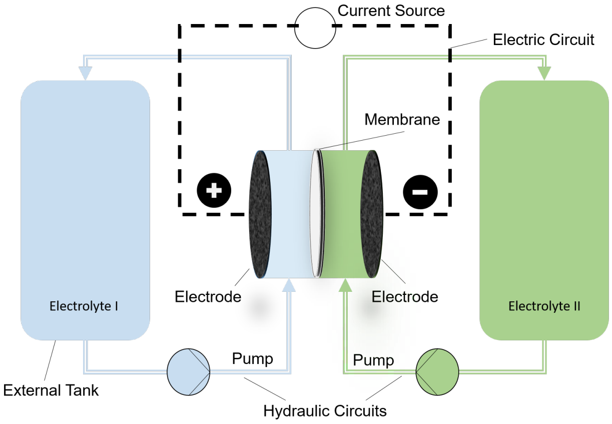


Figure 2. Principle schematic of a RFB cell during charging.

Besides VRFBs, other types of RFBs are currently in different development or industrialization states [12,15–17]. [16] shows a comprehensive review of RFB chemistry's and classifies RFB electrolytes in 1) in-organic redox couples, where VRFB are listed, 2) in-organic metal–ligand complexes, 3) in-organic–organic hybrid systems, 4) dipolar aprotic electrolytes, 5) ionic liquids, deep eutectics, and strong eutectic solvents, and 6) mediated fuel cells [16]. Especially the substitution of critical raw materials, like Vanadium, with abundant material, led to further development in the field of Aqueous Organic-Redox-Flow Batteries (AORFB) presented in [15]. Expectations from research and industry are aiming on organic molecules to enable a higher voltage range, solubility, and stability while having reduced losses due to crossover-mixing and fast reaction kinetics [15]. Highly ranked scientific review [12,15–19,19] have already been made in the field of RFBs. Thus, this review does not aim to give a deep overview of RFBs as single storage components, but focus the aspects of hybridization and the control strategies in application-oriented EMS.

2.1.2. Lithium-Ion Battery (LIB)

In contrast to the conversion type PbA, LIB work as insertion battery, in which the electrolyte is not part of the reaction but works as ion conductor. A LIB is an electrochemical storage, based on the rocking chair effect of Lithium Ions with reversible chemical reactions [20]. A LIB cell is constructed like a galvanic cell and consists of two electrodes, a separator and the electrolyte. The fundamental materials research is due to researchers John B. Goodenough , M. Stanley Whittingham and Akira Yoshino, who were awarded the Nobel Prize in Chemistry in 2019 for their work [21].

As stated in the name and in contrast to the NaS, LIB work with Lithium Ions instead of metallic lithium. This is due to the deposition behaviour of metallic lithium in form of dendrites. These sharp bulges grow during charging process and can cause internal short circuits by damaging the separator causing safety issues [22]. Instead of metallic lithium, electrode active materials are used which show good hosting characteristics: high storage capability for lithium ions as well as structure stability during intercalation and deintercalation processes [23]. On cathode side Lithium-Nickel-Cobalt-Manganese-Oxide (NCM) is usually used. It is a complex oxide trying to combine the advantages of the composed elements. Cobalt shows good electrochemical behaviour as well as an positive influence on structure stability, nickel increases the long-term reversibility whereas manganese is beneficial for costs as well as structure stability [23]. The anode consists in most cases of a graphite component as hosting material [24].

2.1.3. Sodium-Sulphur Battery (NaS)

Ten years after the first double layer capacitor, around 1967, the NaS was invented by N. Weber and J. T. Kummer. They were one of the most important storage technologies for wind power plants in 2010 [3]. In contrast to most battery types, the NaS technology works at 320 °C instead of ambient conditions. The high temperature is necessary to melt the solid electrodes. The working principle is based on liquid electrodes: sodium on cathode side and sulphur as anode. In contrast to that, the electrolyte is solid and consists of beta-alumina [3]. This material is capable to conduct sodium ions for the battery reaction. Due to the sensitivity of metallic sodium against water, the cell is hermetically sealed as well as thermally insulated to remain the high temperature [3].

2.1.4. Lead-Acid Battery (PbA)

The PbA works in ambient conditions and has a long history. It is seen as oldest secondary battery type and goes back to Gaston Planté in 1859 [3]. The cathode consists of lead-dioxide whereas the anode is metallic lead. During discharging lead sulfate is formed at both electrodes. It is non conducting and insoluble [3]. Nevertheless, this reaction is reversible and during charging process the porous lead dioxide as well as the metallic spongy lead is recede. For the reaction both electrodes react with the electrolyte composed of sulphuric acid [3].

2.1.5. Supercapacitor (SC)

First double layer capacitors were invented in 1957, even though first trials go back to 1750s [3]. Unlike accumulators or batteries, the energy in capacitor is stored in an electrical field and consists (at least) of two electrical conductors with a separator in between. Super- or ultra-capacitors belong to the category of the electrical or electrochemical double layer capacitors [25]. These systems are composed of two carbon electrodes, a separator (porous membrane) and an electrolyte for the ion conductivity [17]. Due to the high power density and the comparably small energy density, SC find their applications where high C-Rates (charging and discharging current related to the capacity) and power systems are required. The disadvantages include a high self discharge rate and relatively high specific storage costs [25]. SC are an ideal complement of batteries when a large amount of fast energy exchanges is required. Other advantages of SC are their large operating temperature range and high charge and discharge cycling ability [26].

2.1.6. Superconducting Magnetic Energy Storage (SMES)

Similar to the SC, SMES are typically listed as power component (PC), due to the high power density. The energy is stored in magnetic form with the help of a coil. The system is tempered in most applications in order to optimize the efficiency. The relative high costs, self-discharge rate and the environmental impact of the magnetic field can be identified as the disadvantages of the system [25]. As SMES are quiet new technology not completely commercialized and yet offer no advantages over SC, they are not considered as hybrid component within this review.

2.2. Hybrid Energy Storage Systems (HESS)

Electrical hybridization of EES describes a combination of **two** or **more single storage components** to a system called HESS. By choosing the components carefully, optimized overall characteristics in energy, power, lifetime, or costs can be achieved. On the hardware side, the storage components are connected electrically via cables and power electronics. While on the software side, a so called EMS is applied to control the power flow between the storage components and optimize the behaviour within a system application, e.g. the grid. Depending on the electrical connections the HESS itself can have the following grid connection options. In case the EES are combined on a Direct Current (DC) level, the HESS has one grid connection point. If the EES are connected on Alternating Current (AC) level it is possible to have either separated connection points for every AC converter or one connection point for all converters. Both aspects, electrical hardware and software, need to be optimized for each HESS and application scenario to enable best operation modes.

For HESS, typically two clusters of ESS can be distinguished based on ESS technical characteristics [27]:

1. **Primarily ESS cluster**: has to satisfy the requirements of higher peak power demand and has to handle the fast transient fluctuations, e.g. load or Renewable Energy Sources (RES) production. This cluster is marked by fast response time, high power peaks, high efficiency and high cycle lifetime.
2. **Secondary ESS cluster**: has to comply with the requirement of high storage duration's. This cluster is specified by a low self-discharge rate and high efficiency.

Generally all storage technologies - electrical, mechanical, electrochemical, thermo-chemical, chemical and thermal - can be hybridized. Within this study only the electrical hybridization of RFBs is investigated. Based on the results of two research projects (HyFlow, OMEI) and a comprehensive literature review, recent developments and challenges of HESS based on RFB are presented. As there are only a few demonstration projects and publications of HESS with RFB, this consideration is a recent and innovative effort. For the areas of applications and possibilities, literature reviews for different technologies are included.

3. Evaluation of Key Performance Indicators

KPIs help to characterize the behaviour and enable comparison between different storage technologies. They can be classified in battery- and application-oriented KPIs. Materials or components used as well as design approaches e.g. stacking of single cells influence the technical specifications of a battery and are summarized by battery-oriented KPIs. For this study the following KPIs are chosen: Energy density in Wh/kg, Power density in W/kg, Efficiency in %, Self discharge in %/day, and Reaction time in s. KPIs can also be formulated based on the application for which the ESS is used or are a result from the applications requirements. For the classification approach within this section the following application-oriented KPIs are used: Energy and power related costs in €/kWh and €/kW, Lifetime in cycles, Shelf life in year, Storage duration, Design Flexibility, Ecological Impact, and Safety.

In the following section the KPIs are applied to the selected storage technologies and afterwards evaluated for their utilization as a HESS component.

3.1. Classification of single storage components

A summary of the KPIs applied to the described storage technologies is shown in Table 1. The storage units are classified by Harvey balls in three categories according to their characteristics. Positive characteristics for each category are represented by filled balls, negative ones by empty balls and medium by half-filled balls. The evaluation depends on the KPI. For example is a high power density regarded as positive (filled ball), whereas high costs are seen as negative characteristic (empty ball). For each battery technology, several publications are taken into account [4–7,17,25,27–31].

The collected data are listed and the average is calculated for each category. Afterwards, the average value for all selected battery types for each category is calculated. The classification as shown in the Table is based on this average: positive compared to average equals filled ball, negative equals empty ball and close to average equals half-filled ball. For example the average power density for all selected batteries based on the named literature is 1001.25 W/kg. For SC the literature reveals 3508.33 W/kg resulting in a filled ball in the table, whereas LIB show 982.92 W/kg which is close to the overall average represented by a half-filled ball in the table. Average values below 200 W/kg are given by RFB, NaS and PbA which is below the average and thus is represented as empty ball in the table. In general, high values for energy density, power density, efficiency, lifetime in cycles, shelf life, design flexibility and safety are seen as positive, whereas low values for energy and power related costs, self discharge, reaction time (low values=fast reaction time) and ecological impact are regarded as good. For storage duration a wide time window is preferred. In best case from milliseconds to months. The need of a suitable technology for each time slot lead to the exceptional visualisation in the table without Harvey balls but the found storage duration time window.

With regard to the types of storage considered, LIBs stand out with high efficiencies and energy density [30]. Due to the relatively high power density, the batteries have a smaller size, which is suitable for various transportable devices, for stationary applications and for mitigation of power fluctuation applications [25]. The high acquisition costs, raw material situation as well as safety issues impair the application [4,24,30].

In contrast to LIBs, RFBs have difficulties with energy and power density as well as reaction time [30]. Nevertheless, there are advantages regarding safety, ecological impact, lifetime and self discharge. Above all, RFBs are characterised by independent scaling of power and energy, which enables an extremely flexible design for different applications. These characteristics make the RFB suitable for stationary storage applications [25]. Due to their design, RFBs are often compared to FCs. However, compared to a FC, in a RFB the electrolyte is passed through the half cells, whereas in a FC only the electroactive materials flow through the reactor. In addition, the chemical reaction in a RFB is often reversible [28]. Suitable applications for RFBs include large-scale grid-connected RES, Uninterruptible Power Supply (UPS) and emergency power supply [5].

As large-scale grid connected RES also NaS can be used as well as for grid power quality regulation, voltage regulation and peak load shifting [5,29]. They have high energy densities on the one hand but challenges with self discharge topics due to high operating temperatures up to 300 °C [28]. This goes along with a reduced design flexibility as well as low lifetime.

These are characteristics which also challenge the PbA. Nevertheless, they are a popular storage choice for power quality and UPS, used in commercial and large-scale energy management applications due to their low cost and high reliability [28]. However, when comparing the storage type with other batteries, the limited energy/power density and the mentioned lifetime issues become apparent, especially at low temperatures [28,30]. In addition, the use of lead also results in high maintenance requirements and ecological as well as safety issues regarding toxicity [7,30].

In contrast to battery storage, SCs impress with high efficiency, high power density and a fast response time of less than 10 milliseconds [4]. Additionally, lifetime and ecological as well as safety issues are positive aspects of a SC. The main drawbacks of a SC are high energy losses due to self-discharge as well as low energy density [28,30]. Due to these characteristics SCs are not used for large-scale applications, but for short-term storage and support [17]. Exemplary applications are lifts, distribution grids, microgrids or automotive applications [5].

There are many storage systems available and as shown for the selected types, different technologies are necessary to meet the individual use-case requirements.

3.2. Classification of HESS

The idea of a HESS is to combine different technologies in one system to meet the various requirements in complex use-cases. Therefore, storage technologies with complementary characteristics, are hybridized to enable a broader operation and performance range. By combining two storage technologies, various single application as well as multiple application at once can be realised and disadvantages of the individual storage types can balance each other out.

Complementary characteristics could be opposing as well as similar. For example a combination of high with low power density is a beneficial opposing characteristic. Lifetime is seen as beneficial if combined technologies show similar characteristics, because the lifetime of the combined system depends on the limiting technology. The KPIs regarded as beneficial if the single batteries show opposing features are: energy and power density, reaction time and storage duration. Similar high characteristics are preferred for efficiency, lifetime, shelf life, design flexibility and safety, whereas similar low characteristics are

Table 1. Evaluation of battery- and application-oriented KPIs for different single storage technologies, based on data from [4–7,17,25,27–31].

		LIB	**SC**	**NaS**	**PbA**	**RFB**
Battery oriented	Energy density in *Wh/kg*	●	○	●	◑	◑
	Power density in *W/kg*	◑	●	○	○	○
	Efficiency in %	●	●	◑	○	○
	Self discharge in *%/day*	◑	○	○	●	●
	Reaction Time in *s*	◑	●	○	●	○
Application oriented	Cost in €/*kW*	○	●	○	●	◑
	Cost in €/*kW*	○	○	◑	●	◑
	Lifetime in cycles	◑	●	○	○	●
	Shelf life in years	◑	●	◑	○	◑
	Design Flexibility	○	◑	○	○	●
	Ecologic impact	○	●	◑	○	●
	Safety	○	●	◑	◑	●
	Storage duration	min-days	ms-hour	min-days	min-days	weeks

Legend: ○ = negative characteristics ◑ = medium characteristics ● = positive characteristics

favoured for self discharge, energy and power related costs as well as ecological impact. Main criteria for the selection of HESS is the beneficial combination of storage duration, power density and reaction time resulting in four hybrid systems. These are SC combined with LIB, NaS, PbA and RFB as well as LIB with RFB.

The evaluation summary is shown in Table 2. Besides the previous illustration of results with Harvey balls, colours are invented this time as second evaluation characteristic. The Harvey balls for the hybrid system are formed out of the single system evaluation. For example the SC has a filled ball for power density whereas the RFB power density is described with an empty ball. The result of the combination of both in one hybrid system is a half-filled ball. As described, power density is seen as beneficial if two opposing systems are combined in a HESS. This is illustrated with the colour green. Another example is the KPI safety for the hybrid system LIB+RFB. Here is a combination of a safe system (filled ball) with a system with safety issues (empty ball), also resulting in a half-filled ball for the hybrid evaluation. Nevertheless, the combination leads to potential safety issues in the hybrid system. Thus, the combination has a negative influence for the hybrid system and is marked in red.

According to this evaluation methodology based on the given literature data, the best HESS reveals to be a combination of SC with RFB. This system shows most filled balls, so positive features, as well as green colours, so beneficial characteristics due to the hybridization. The combination results in a storage system that shows high lifetime by the widest window of storage duration, a medium energy density with complementary power and reaction time elements for a medium cost level. Additional, the positive aspects of Design flexibility, safety and ecological impact are also preserved in the hybrid system. Thus, the following section dealing with coupling architectures of HESS focuses the combination of SC with RFB.

4. Coupling Architecture Optimization Strategy

4.1. Coupling Architectures of Hybrid Storage Systems

Different ESSs of a HESS must be coupled in such a way that energy exchanges between them are possible. Given a set of ESSs and a required power exchange capability, there are several possible ways of interconnecting the involved ESSs and related power converters. Each one of these coupling architectures offers different features in terms of cost, efficiency, or performance. One of the main decisions is whether to use AC or DC links on the interconnection between devices. DC grids offer several advantages over AC grids: most common energy storage systems are already in DC by nature, energy management is much simpler in DC than in AC, DC grids does not present stability problems that are

Table 2. Evaluation of different hybrid storage combinations based on complementary battery- and application-oriented KPIs.

		SC+LIB	**SC+NaS**	**SC+PbA**	**SC+RFB**	**LIB+RFB**
Battery oriented	Energy density in *Wh/kg*	◑	◑	◑	◑	●
	Power density in *W/kg*	●	◑	◑	◑	◑
	Efficiency in %	●	●	◑	◑	◑
	Self discharge in *%/day*	◑	○	◑	◑	●
	Reaction Time in *s*	●	◑	●	◑	◑
Application oriented	Cost in €/*kW*	◑	◑	●	◑	◑
	Cost in €/*kW*	○	◑	◑	◑	◑
	Lifetime in cycles	●	◑	◑	●	●
	Shelf life in years	●	●	◑	●	◑
	Design Flexibility	◑	◑	◑	●	◑
	Ecologic impact	◑	●	◑	●	◑
	Safety	◑	●	●	●	◑
	Storage duration	ms-days	ms-days	ms-days	ms-weeks	min-weeks

Hybrid influence: positive influence no/medium influence negative influence
Legend: ○ = negative ◑ = medium ● = positive
○ + ○ = ○ ○ + ◑; ◑ + ◑ = ◑ ◑ + ●; ● + ● = ●

typical in AC grids and the power density of a DC grid is higher than an AC grid. Therefore, DC grids are the best option when interconnecting different energy storage devices. The involved DC/DC converters must face several requirements: 1) they must be bidirectional, 2) they must interconnect ports with a broad range of input or output voltage values, 3) the voltage gain can be low or very large and 4) sometimes galvanic isolation is required.

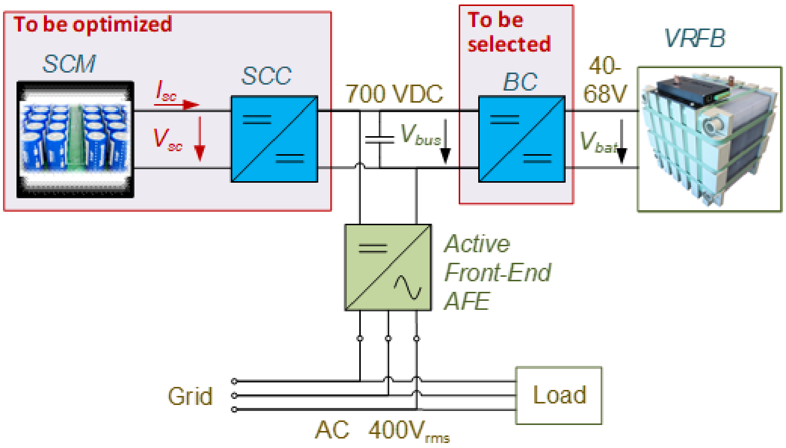
The efficiency and cost of a DC/DC converter depends mainly on the required input to output voltage gain. When dealing with common non-isolated DC/DC converters (e.g. buck, boost, buck-boost), the ratio between the power switched by semiconductors and the converted power is equal to the input to output voltage gain. Therefore, the higher the input-to-output voltage ratio, the higher the converter cost and the lower its efficiency. In the other hand, isolated DC/DC converters perform input-to-output impedance matching. This way the converted power is close to the switched power and high efficiency levels are possible at a reasonable cost. An input-to-output voltage ratio around 4 can be considered the frontier at which the non-isolated DC/DC converter is less competitive than the isolated one.

In this section a HESS application example is used in order to explain a possible coupling architecture optimization strategy. In this particular case, the HESS must exchange energy with a low-voltage (400 VAC) three-phase industrial grid and contains two ESSs: a 5kW RFB with a voltage between 40V-68V and a 25 kW SC bank that must be able to store up to 25 kJ of energy. The voltage of the SC bank is not defined and is one of the degrees of freedom of the optimization.

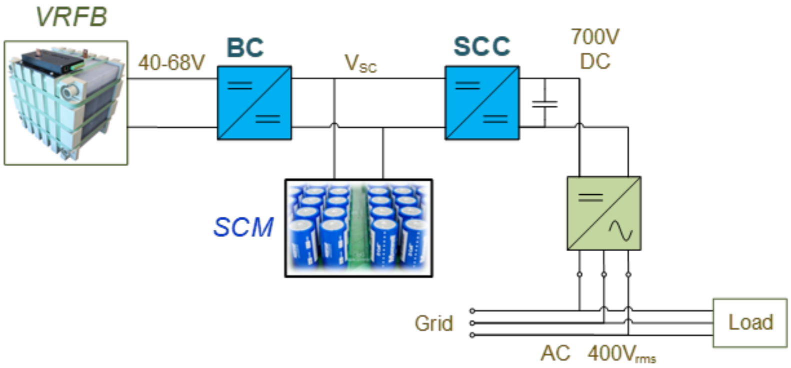
Figure 3 shows the possible three interconnection strategies for the HESS. Option a) is the most evident and straightforward to propose: each ESS has its own converter. Anyway, considering that the voltage gain is a paramount parameter when selecting a converter and therefore has an important impact on the cost, it could be interesting to explore other options like b) and c) architectures, where the DC/DC converters are in cascade and therefore individual input-to-output voltage ratio can be reduced.

In all possible configurations the HESS is connected to the grid through a standard Active Front End (AFE) that is linked with a 700 V DC side. SCM is the supercapacitor module, SCC and BC are the supercapacitor and battery converters, and VSC is the voltage at the supercapacitor module.

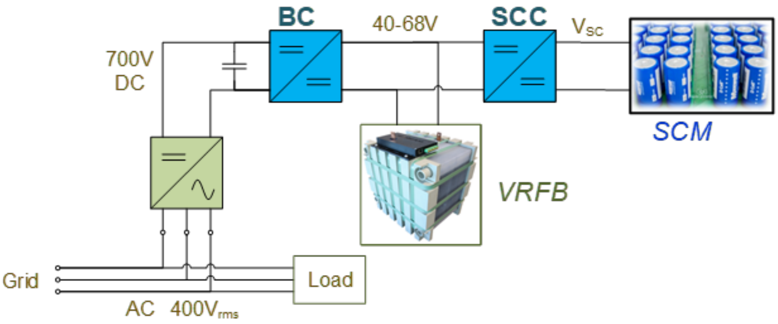
In order to compare these three architecture proposals, several design parameters have been considered, as seen in Table 3.



(a) Active DC coupling.



(b) Semi-active DC coupling with interconnected SCM.



(c) Semi-active DC coupling with interconnected VRFB.

Figure 3. Three possible configurations for HESS coupling architecture.

Table 3. Comparison of different system architectures.

	Architecture proposal			
Design parameter	a	b		c
Power converted by SCC (kW)	25	30		25
Power converted by BC (kW)	5	5		30
Overall Conversion Power installed (kW)	30	35		55
Voltage ratio SCC	TBD	H	L	L
Voltage ratio BC	H	L	H	H
Maximum power processed with low voltage ratio (kW)	25	5	30	25
Minimum power processed with high voltage ratio (kW)	5	30	5	30

In **topology (a)** the voltage ratio of SCC is to be defined and has no impact on any other parameter. In **topology (b)** the SCC voltage ratio conditions the BC voltage ratio. The maximum power with low voltage ratio is the power that can be converted by a non-isolated converter cheaper than the isolated full converter option. The minimum power processed with a high voltage ratio denotes the conversion of power with a high conversion cost. It is important to recall, that the conversion with low voltage ratio is cheaper than the conversion with a high voltage ratio. The first conclusion can be stated. Considering the total amount of power to be converted, **topology (c)** is not well suited, as it requires to convert 55 kW compared to only 30 kW of the **topology (a)**. Moreover, the minimum power processed with high voltage ratio in **topology (c)** is six times bigger than that of the **(a)**. Therefore, we can remove **topology (c)** from the analysis.

Topology (b) offers the degree of freedom of the voltage at the SCM. If a low voltage is chosen, a high voltage ratio is needed at SCC and a low voltage ratio will be enough for the BC. On the other hand, a low SCC voltage ratio leads to a high BC voltage-ratio. As there is more power to convert at the SCC, it is interesting to choose a high SC voltage, i.e. the second column of **topology (b)**. Anyway, **(b)** always requires an overall conversion power that is 5kW higher than the **topology (a)**, and does not offer any advantage in terms of voltage ratios that could lead to any cost improvement. Additionally, **topology (a)** is more flexible than **(b)**, as it can handle any modification on the power or voltage values of any of the storage devices without any implications in the conversion chain of the other storage device. Thus, **topology (a)** is selected as the optimum architecture.

4.2. HESS Optimization Strategy

The BC does not require an optimization, as there is no degree of freedom but the type of converter. Input-output voltages as well as the power to be converted are already defined. The input-to-output voltage ratio is high, so an isolated DC/DC converter is directly selected. In the case of the SCM and SCC, there are two degrees of freedom to be optimized (see Figure 3 a). The Nominal (or maximum) voltage of the SCM, V_{SCmax}, is the maximum voltage value at which the SC will be charged. Depending on this value, more or less SC in series are required, and each SC must be larger or smaller. Therefore, this parameter has an impact on the cost of the SCM. It can also have an impact on the cost of the SCC. On the other hand, for a given amount of discharged energy ΔW, the minimum operating voltage V_{SCmin} depends on the capacitance C of the SCM. The lower the capacitance C, the lower the voltage at which the energy is discharged and therefore, the larger the current. As the cost of the SCC is directly related to the supercapacitor current (ISC), the capacitance of C has a direct impact on the cost of the DC/DC converter. Obviously, the capacitance value also impacts on the cost of the SCM.

Figure 4 depicts the procedure of the optimization of the SCM and SCC. The procedure is based on the analysis of the performance of a large number of different capacitance and voltage values at the SCM.

The input data is a broad range of possible C, V_{SCmax} pairs. Considering the maximum current at the converter and the cost function of the converter, it is possible to compute the cost of the SCC. In the same way, thanks to the knowledge of the capacitance C and the maximum voltage at the SCM, it is possible to compute the number of SC cells in series and the capacitance of each one of them. These last data, combined with the cost per joule and per capacitance of the SC, lead to the cost of the SCM. Finally, both the cost of the SCM and the SCC are added and the optimum one with the minimum cost is identified. Figure 5(a) shows the cost per joule of the SC depending of the cell size.

Both SCC and BC share the same high-voltage DC-CCP at 700V. Figure 5(b) illustrates the cost per 5kW of full power isolated (Isol) and not isolated (Non Isol) converter as a function of the low-side current. As it can be observed the cost is constant in the case of the isolated technology whereas the not isolated one increases its cost as the low-side current increases. One of the advantages of the DC/DC converters is that they can be easily connected in parallel, so it is straightforward to scale in power keeping almost the same

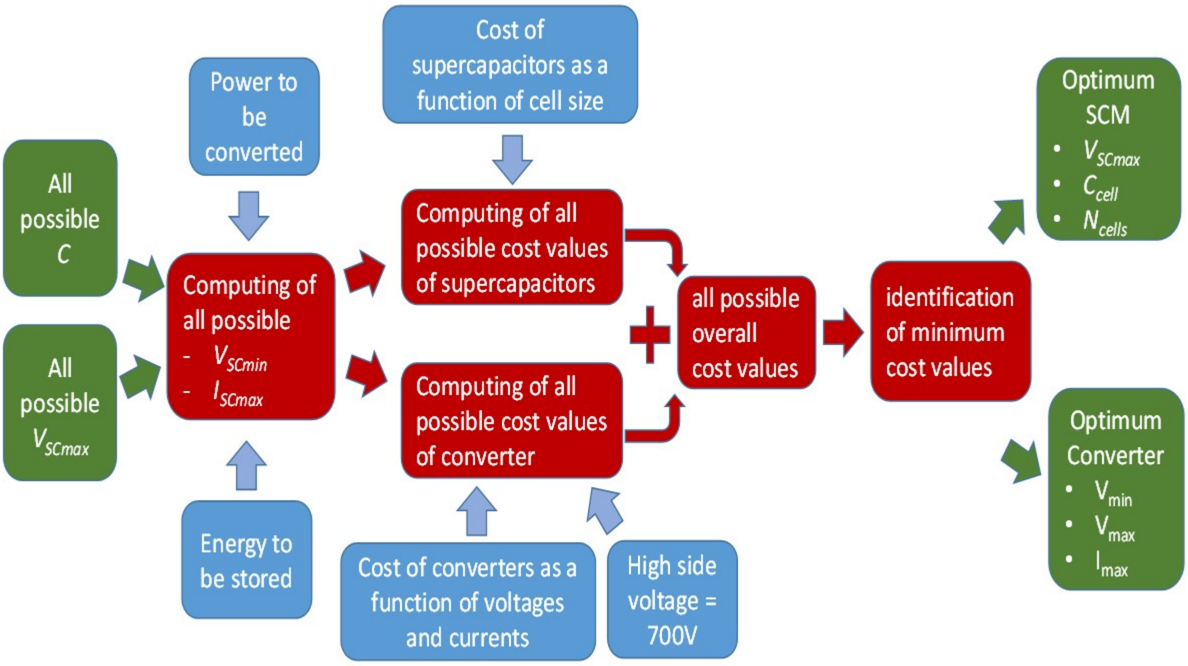
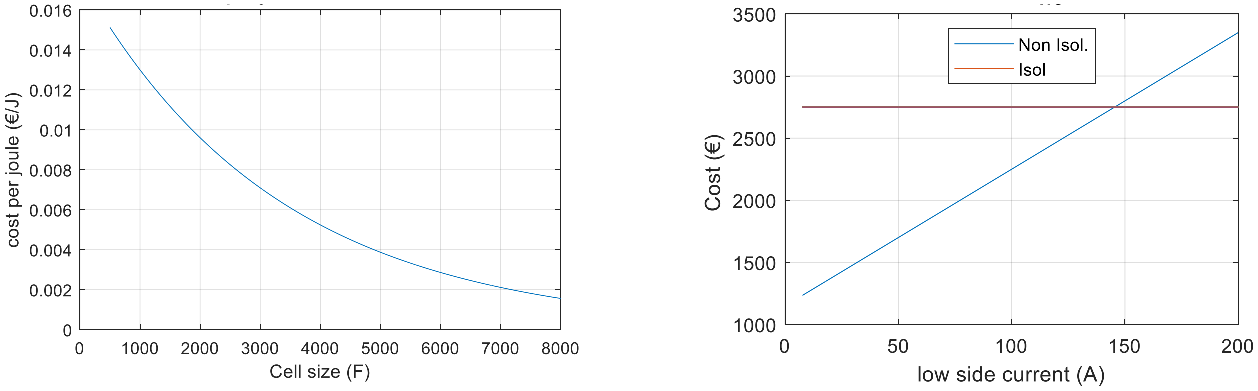


Figure 4. Flow chart of the optimization procedure.

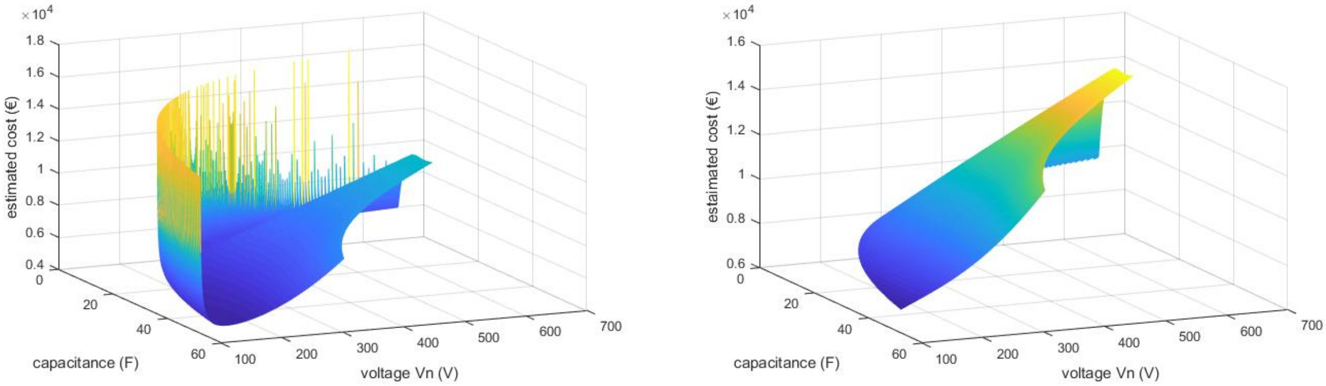


(a) Cost per joule for each cell size

(b) Cost of converters @V$_{HS}$=700V/P=5kW

Figure 5. Cost of elements: a) Cost per joule for each cell size, b) Cost of converters as a function of technology and low-voltage side current.

cost per kilowatt figure. Figure 6 shows the estimated overall cost of the SCM plus SCC pack, considering both not isolated (Figure 6(a)) and isolated (Figure 6(b)) converters. As it can be observed, the minimum cost of the non isolated case is lower than the isolated converter is selected. The minimum cost is around 4000€ and is achieved with a maximum SC voltage of 650V. At the minimum cost point the maximum SC and converter current is 58.2 A. The capacitance of the overall module that optimizes the cost is 0.21F, built with 542 cells of 114 F each.



(a) Estimated cost of SC + non isolated DCDC (b) Estimated cost of SC + isolated DCDC

Figure 6. Estimated overall cost considering the SCM and the SCC for (a) non isolated converter and (b) isolated converter.

5. Energy Management System (EMS) for HESS

Besides optimal electrical hardware as presented above, HESS need to be optimized in terms of software and management approaches (EMS). Figure 7 illustrates the schematic of a HESS including all power, information and sensor connections between storage components and the grid. The classification system to choose best fitting storage technologies for hybridization has been discussed in Section 3. Within this study RFBs as a energy component (EC) are studied in an hybrid approach using a complementary PC. The optimal electrical connections of two single storage application in one hybrid system has been discussed in Section 4. The EMS acts now as central control unit for the HESS communicating with all storage components, loads, generation and forecasting units as highlighted in Figure 7. The Battery Management System (BMS) is mostly developed by the battery manufactures and thus is not part of this review. In the following Section the EMS will be deeply studied. Beginning with an outline of the EMS structure and a definition of typical application scenarios, the EMS control techniques are presented based on their control and optimization parameters. The optimization of EMS strategies is afterwards presented with a focus on prediction and currently used control techniques.

5.1. *Energy Management Structure for HESS*

The structure of a general energy management can be realised in different ways. The norm ISO 50001 for example serves a basic structure and can be used as a support for implementation. The standard provides a process to identify necessary framework conditions from collecting all the necessary data, setting strategic and operational energy targets to plan and structure the documentation [32].

The controlling structure for an EMS for HESS is similar to EES systems. The specific parameters and limit values have to be defined for the different application scenarios. Figure 8 shows a method to structure an EMS for HESS. The first step is to define the EMS goals in the specific application scenario. These can be subdivided into system goals and application goals. The applications scenarios are described in subsection 5.1.1. In

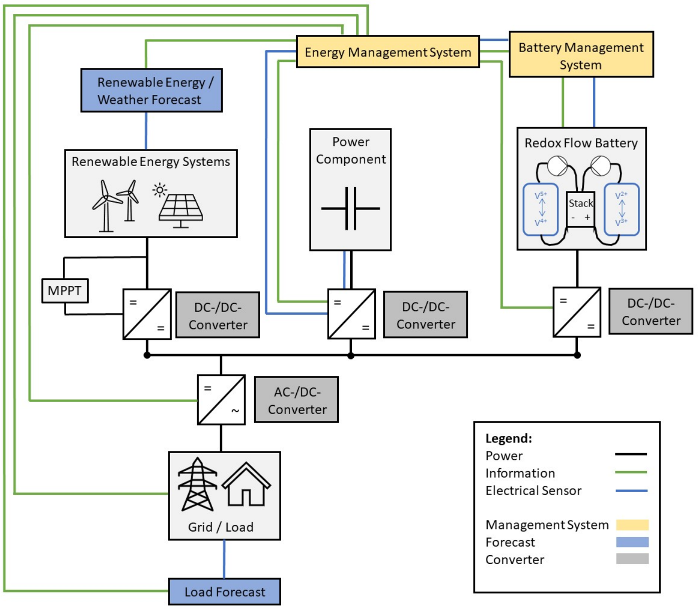


Figure 7. Principle schematic of a HESS including all power, information and sensor connections between storage components and the grid.

advance the legal framework conditions and operating limits must be taken into account [33]. Adapted to the EMS goals the requirements, coupling architecture and dimension can be set on the system components special for the EC and PC. This results in safety boundaries for the system for example system limitation values for power, current and temperatures [34]. Within a permissible operation range the control parameters for the application and system specific optimization have to be defined. These are explained in subsection 5.1.2. Depending on the complexity and number of optimization parameter, the EMS control technique should be defined. In the first instance, a differentiation of classical and intelligent techniques is made here. The subsection 5.2.2 describes the optimization methods and refers to examples.

5.1.1. Application Scenarios

The specific application scenarios serves as input for the EMS design and implementation and influence especially the optimization or control parameters. Applications for EES are widely presented in the literature. By reviewing 22 publications within this study [1,4,35–54], over 80 different types of stationary application has been identified in the first place. Mobile applications are excluded from this study. As different descriptions where referring to similar applications, a classification system developed in [55] has been applied. Duplication's are reduced and the applications are evaluated to sort them into universal application scenarios. Eleven application scenarios with different purpose, placement, duration as well as control parameters have been summed up in Table 4.

Applications with different descriptions but same technical specifications or goals, e.g. frequency stability and frequency control, have been summed up. Moreover, some for which the control parameters are not clearly described, e.g. capacity support, capacity firming or electric supply capacity, are formulated with more specific terms relying on already defined system services in the interconnected grid [42]. Some applications like grid flexibility are to general and control parameters can not be found universally, or some are

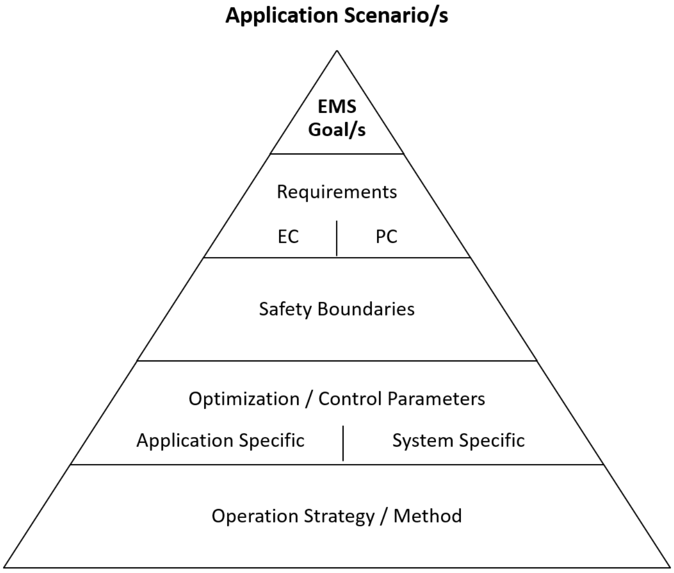


Figure 8. Method of an Energy Management Structure for HESS

more related to the grid operators business and not yet clearly defined as EES scenarios, e.g.investment deferral in grids or operational grid management. These applications are deleted from the final summary. Newly developed applications like Grid Booster are also not listed in Table 4 but could be added once demonstration projects have been finished. The remaining 13 now called application scenarios are classified by their purpose, placement, control level, as suggested by [55]. Newly added items also classify the duration, control parameters and required controller rate for the EMS.

The application **purpose** of using a EES is summed up in three categories:

1. *System (S)* describes storage usage for the general stability and maintenance of interconnected grids and the used stability products, e.g. defined in [42,55].
2. *Grid (G)* describes the local grid operation mode maintaining power quality in distribution grids [55].
3. *Manage (M)* sums up all end-user applications aiming at balancing power flows within their system boundary, which must be smaller than a network section [55].

The **physical placement** influences on the one hand the used infrastructure and involved stakeholders. On the other hand the placement includes not only the physical placement, but also the spatial distribution of control variables for the management system, e.g. frequency, voltage, power [55]. Often both physical and control placement are combined, e.g. in a home storage. For some applications the placement is not specifically determined e.g. black start or island grids. Therefore, physical placement categorized as follows [55]:

1. *Transmission grid (T)*,
2. *Distribution grid (D)*,
3. *Behind-the-meter at end-user locations (E-U)* .

The **control level** is the summarized decision parameter for a management system to decide which operation mode of the ESS is used, at which time and how long it is used. **Power (P)** summarizes all objective functions of EES which are controlled by a power-specific parameter, while **Energy (E)** describes all which are controlled by a energy-specific parameter [55]. All scenarios in Table 4 can be applied to single storage systems or HESS. By using a HESS, it is even possible to combine different applications scenarios complementary to the HESS characteristics. For example a combination of a energy-based (E) and a power-based (P) application scenario, is the commonly used approach in hybrid systems.

The **duration** describes the average operation time and can also be described as the time during which the energy storage system has the same control command. The duration of energy storage has been categorized based on the definition of system services in the grid starting with momentary reserve in milliseconds as immediate grid services, followed by primary, secondary, and tertiary reserve in minutes until exchange within one balancing group starts. The letter describes the smallest unit of the energy market model and refers to a virtual energy account to balance any number of energy inputs and outputs [56]. The duration is only fixed for system services, e.g. frequency control [42]. Other application scenarios, e.g. peak shaving or energy time shifting, show only suggestions of applicable time scales and can be seen as a start of the art from the studies literature data base. Similarly to combining different control levels, e.g. power or energy, HESS can enlarge the usable storage duration by adding a short term storage e.g. SC to a mid- to long-term storage e.g. RFB. Thereby, application scenarios as e.g. momentary reserve and energy time shifting can be combined. Both state of the art research projects, HyFlow and OMEI, built up demonstrators by combining different application scenarios and durations. HyFlow is focusing on four different applications scenarios, whereby always a combination of high-power and high-energy component is foreseen [57]. Thus, momentary reserve, peak shaving and energy time shifting are foreseen for industry grids, weak distribution grids, and UPS [57]. Within OMEI the HESS is used to balanced fast-charging infrastructure and perform peak shaving as well as energy time shifting of renewable generations and load.

The **control parameter** describes the exact values which are used for the management system. These parameters need to be optimized with the momentary load and generation to satisfy the purpose of the storage usage and are thus application-oriented control parameters. Additionally, the used storage systems also have system-oriented control parameters for each battery used in a HESS, as described in the section above. Both need to be taken into account and prioritized for EMS and optimization techniques. The controller rate or sample rate shows the reaction rate of the EMS and thereby defines the communication and electrical requirements of a HESS. Moreover, this is also the time frame in which the optimal operation mode needs to be calculated and raw data from the application case e.g. load or generation need to be measured. If the duration of the application is typically low, the controller rate needs to be high e.g. 20ms for momentary reserve.

Based on the applications scenarios, the following sections describe which optimization routines are applied to identify an optimal power-flow within a HESS.

5.1.2. Control and Optimization Parameters

The application categories in the literature show the potential for HESS. Due to the combination of storage systems not only technical and economical advantages but also application extensions and combinations can be achieved. Table 5 shows the advantages and objectives for HESS of the applications categories and combinations in the considered literature. The Table indicates system and application goals. First and foremost, the storage systems are designed to achieve the application objectives. On the technical side for example the parameters storage capacity demand, power limits, power electronics and time requirements are used for this purpose.

The use of HESS has the advantage to combine the application goals with the option to optimize the system and the operation process by using a hybrid operation strategy. Optimisation targets for the PC and EC are: Dimensioning, efficiency, life time and economic efficiency. These parameters are intended to optimize the HESS systems for the specific application goals. Therefore the control parameters like capacities, power demand and supply, grid quality values (frequency, voltage), response times and energy prices play a major role. Through the optimisation and operation of the HESS, the targets for multiple applications can be achieved. A prerequisite is that the intended purpose takes place at the same placement as shown in Table 4.

Table 4. Classification of storage application scenarios by their application purpose (S:System, G:Grid, M:Manage), placement (T:Transmission, D:Distribution), control level (P:Power, E:Energy), duration, control parameters, and controller rate. Literature review from [1,4,35–55]
.

Source	Application	Purpose	Placement	Control	Duration	Control Parameter	Controller Rate
[35,43–47]	Momentary Reserve	S	T	P	t <msec	f_AC[1]	<20 ms
[1,35, 40,43, 44,46, 47,50, 51]	Primary Control	S / G	T	P	t <msec	P_AC f_AC[1]	<30 sec
[4,35, 39]	Secondary Control	S / G	T	P	sec <t >15 min	P_AC f_AC[1]	<5 min
[4,35, 39]	Tertiary Control	S / G	T	P	min <t >60 min	P_AC f_AC[1]	<15 min
[4,35, 39]	Black Start	S	-	P	sec <t >min	Δ P[3] f_AC[1] U_AC	1-10 sec
[1,4,35, 39,41, 52]	Island Grid[4]	S	-	E	sec <t >days	ΔP[3]	1 sec -1 min
[1,35, 39]	Transmission support & stability	S	T	E	t >hrs	ΔP[3]	1 sec -1 min
[4,35, 39,46, 53,54]	Voltage Support	G /S	T / D	P	15 min <t >hrs	ΔU[2]	1-15 min
[1,4,35, 39,40, 43,46, 47,49]	Distribution Power Quality	G /S	D	P	sec <t >min	ΔP[3]	1 sec -1 min
[4,35, 40,41, 49]	Peak Shaving (all time scales)	M /G	E-U	P	sec<t >15 min	ΔP[3]	30 sec-1 min
[35]	Uninterruptible Power Supply	M	E-U	P / E	sec <t >hrs	P f_AC U	<20 ms
[35,43, 44,46, 47,49, 53,54]	Energy Time Shifting	M	E-U	E	15 min <t >days	Δ P[3] t	1-15 min
[1,35, 40]	Energy Trading, Arbitrage	M	-	E	15 min <t >hrs	Δ P [3] €/kW €/kWh	1-15 min

[1] Allowed frequency range within the German grid 50 Hz +- 0,02 Hz according to DIN EN 50160 [58,59].

[2] Allowed voltage range within the German grid 230V+-10% according to DIN EN 50160 [58,59].

[3] Residual power ΔP refers to the difference of power demand and supply.

[4] Including mini, micro, military, emergency grids or similar.

Table 5. Map of optimization parameters and EMS goals for the hybrid storage application categories (PC: Power Component, EC: Energy Component)

Application		**Voltage support**	**Distribution power quality**	**Peak Shaving**	**Energy time shifting**
	Hybrid Component	PC	PC	PC	PC/EC
Island grids	EC	Improving transient response, increase efficiency/performance and life time of the EC, grid (voltage) quality, supply security [60–62]			Operational limits operation, self sufficiency, economic efficiency, efficiency, reduce energy costs [63,64]
Uninterruptible Power Supply	EC		Utilization of UPS EC, economic efficiency, stability of power system [65]		
Peak Shaving	EC	Minimizing the power fluctuation, self-sufficiency, grid quality, optimizing the capacity ratio of EC, PC [66]	Dimensioning, efficiency, economic efficiency, lifetime, smoothing the current of EC [67]		
Energy time shifting	EC		Dimensioning, efficiency, economic efficiency, lifetime, smoothing the fluctuation of RE [68]	Self-sufficiency, reduce of max. power consumption/generation, utilization of RE, efficiency, dimensioning, lifetime [69]	
Energy Trading/Arbitrage	EC/PC				Economic efficiency (operational costs), efficiency, reduce energy costs [70]

5.2. Energy Management Optimisation for HESS

The main goal of EMS for HESS is to execute the operation strategy in real time and in an optimal manner. This target is reached by increasing the input variables to the HESS by predicting data that fit the technical HESS requirements, and is achieved by selecting the suitable EMS control technique. Figure 9 depicts the real time architecture of an EMS. This architecture is composed of three steps: (1) prediction, (2) optimisation and (3) HESS component. The prediction model uses historical data such as RE production and weather to forecast important data, e.g. load demand and supply. The optimisation model takes as inputs the predicted data, the system parameters and regulations as well as other information tightly linked to the system aims. Once the optimisation is carried out, the HESS implements the calculated operation strategy. Finally, an evaluation and improvement process is executed to assess whether the desired changes or objectives has being achieved, or whether there has been progress toward meeting the system goals.

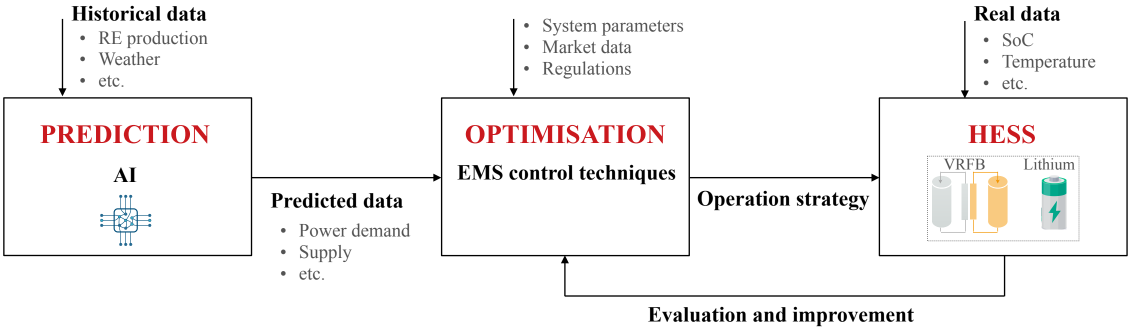


Figure 9. Real time EMS architecture [71]

5.2.1. Prediction

An optimal EMS not only depends on the current external factors and in the present HESS status, but also on the prediction of the system future behavior at a particular time based on historical data (see Figure 9). The predicted data, that differ from one application to another, should be identified according to the system specific requirements and goals and should be as faithfully as possible since it will forecast the application status and conditions. RE production, ESS capacity and weather information are the most widely evaluated data in the last few years [72–76].

Many prediction techniques for ESS are defined in the literature, as highlighted in Table 6. Mixed Integer Linear Programming (MILP) and Neural Network (NN) and its variants Artificial Neural Network (ANN), Recurrent Neural Networks (RNN) and Convolution Neural Networks (CNN) are among the most commonly adopted techniques [74,76,77]. NN is able to perform accurate results in a high speed and is used in many domains, e.g. prediction and optimisation. Recently, there is considerable interest in using Reinforcement Learning (RL) in multiple fields especially in automatic control system, due to its accurate results and high control performance [75,76].

Once built, the performance of any prediction technique should be evaluated. Several evaluation metrics have been standardized in order to give a clear and comprehensive picture of the prediction technique behavior. A set of evaluation metrics are defined in the literature and the well-known metrics are Mean Absolute Percentage Error (MAPE) and Root-Mean-Square Error (RMSE) [72–76]. As the optimisation of an EMS is closely related to the quality of the predicted data, a minimisation of the prediction error is required. This goal can be reached using several methods, including the selection of the best prediction horizon length and the combination of multiple prediction techniques.

Just a small number of research have addressed the issue of predicting data to optimise an EMS and nearly all of these studies adopted a single ESS. Further studies should investigate multiple challengers, in particular prediction data for HESS specifically the identification of the appropriate data to predict and the selection of the best prediction technique.

Table 6. Classification of predicted data

Predicted data	Prediction techniques	Evaluation metrics
Charging demand [77–79]	CNN, LSTM, RNN	MAPE, MAE, NRMSE
RE production [72–74,76]	CNN, MILP, NN, RNN, ARIMA, GAN, MLP, LSTM	MAPE, RMSE
ESS Capacity [75,76]	MILP, MINLP, NN	RMSE
Charging scheduling and pricing [80,81]	MILP, RL, ANN	N/S
Charging station placement [82,83]	GA, RL, Linear Regression, Decision Trees	N/S

N/S: Not specified

5.2.2. EMS control techniques

The selection of the optimal EMS control technique depends on the pre-defined optimisation function (or goal) of the application. Based on the EMS architectural level, optimisation functions can be classified into: low-level optimisation functions and high-level optimisation functions [5,84]:

1. Low-level optimisation functions control the AC/DC bus **voltage** and the electric **current** flow.
2. High-level optimisation functions control many energy management strategies, among which **power** performance, **SoC** monitoring, ESS **charge/discharge** cycles and **energy cost** reduction .

The majority of studies, presented in Table 8, focus on high-level optimisation functions, more especially power allocation strategy. Furthermore, for HESS, power is not the only important variable that needs to be studied but also other parameters such as energy and SoC have to be considered.

Different control techniques were proposed in the literature to attain the main objectives of HESS, including system performance optimisation, system stability improvement and computation cost reduction [5,84]. Figure 10 represents an in depth classification of EMS control techniques for HESS. These techniques are classified into two groups: classical techniques and intelligent techniques:

1. **Classical control techniques** mainly include filtration based control, dead beat control, droop control and sliding mode control. These techniques are the most used in the literature, as proved in Table 8, and are mainly applied for offline implementation apart the filtration based control technique.
2. **Intelligent control techniques** are classified into rule-based techniques and optimisation-based techniques. Rule-based techniques are among the widely adopted in previous work due to their simplicity in implementation (see Table 8). But these techniques are still far from perfect, as they require deep knowledge of the domain and the definition of rules for a complex system is a challenging task. Recently, there has been considerable interest in real-time optimisation techniques with the rapid rise in the use of Deep Learning (DL) and Machine Learning (ML) algorithms, e.g. Neural Network (NN) and Reinforcement Learning (RL). ML techniques deliver accurate

results in real time, but on the other hand they need a lot of training data and suffer from high computational complexity.

More details on these techniques can be found in [5].

As the majority of current HESS based applications are online implemented, Table 7 summarizes the advantages and limits of real-time control techniques. It is recommended from Table 7 to adopt real-time optimisation techniques for complex systems that require accurate results.

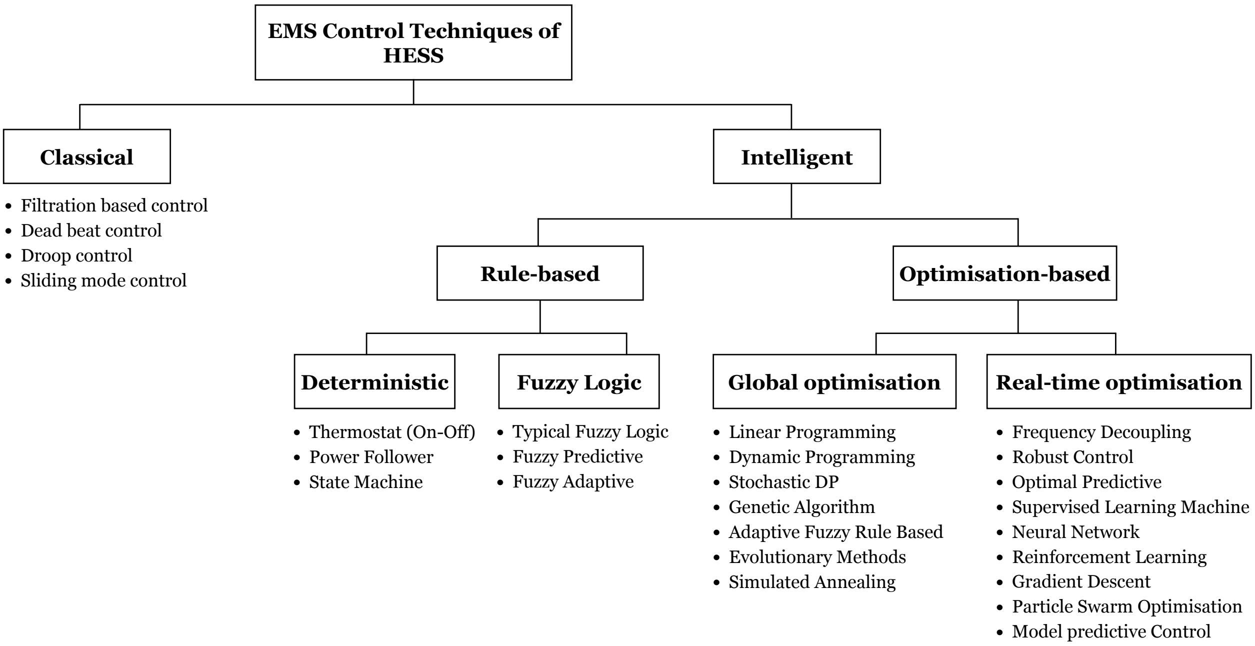


Figure 10. EMS control techniques of HESS [5]

6. Related Work

A large number of existing surveys in the broader literature have examined HESS technology. This section outlines the recent reviews on this topic.

In [27] an overview of the different HESS aspects is given. After a brief definition, the author presents the significant advantages and application prospects of HESS. This study shows that HESS is gaining increasing attention in several domains, including smart grid, electric vehicles and RE park power management. Additionally, it is proved that LIB play a big part in most of the current HESS applications and they are adopted either as "high energy" or "high power" storage. Then, the different coupling architectures in HESS are investigated and it comes out that "the two DC/DC converters connected in parallel" is the most commonly used one due to its better use of the storage capacity. This paper also examines the EMS control techniques and classifies them into rule-based and optimization-based techniques according to the power as main control variable. This study briefly points out the main aspects of HESS.

In [5] two fundamental aspects of HESS, namely (1) coupling topologies and (2) EMS control techniques, are investigated. The first part of this work focuses on the architecture, the advantages and the limitations of the following coupling topologies: "passive", "semi-active" and "active". The widely used topology in HESS and especially in power systems is "active". The remainder of this study is devoted to an analysis of existing EMS control techniques. The authors identified many techniques and classified them into two groups: classical and intelligent. For each technique, the principle, the features as well as the

Table 7. A summary of the main real-time EMS control techniques

Real-time EMS control techniques			**Advantages**	**Limitations**
Classical		Filtration [85]	• Widely adopted for real-time application • Highly computational efficiency • Strait forward	• Complexity of designing filters • Require accurate mathematical model • Inefficient to reduce the peak power demand
Intelligent	**Rule-based**	Fuzzy logic [85–88]	• Simple implementation • Faster response • Efficient hybrid control strategy • High reliability • Low computational complexity	• Rules are defined based on an expert of the domain • Real-time implementation is control strategy • Sensitive to change in system parameter and components
	Real-time optimisation	MPC [5,87,89]	• Accurate real-time application • Prediction of application future behavior • Avoiding problems • High scale application control • Easy incorporation of constraints	• Require accurate mathematical model • Sensitive to model parameter variations • High computational complexity
		NN [5,74]	• Accurate real-time application • Low computational complexity • High speed to process results	• Require lots of training data • The prediction accuracy depends on the data sample quality
		RL [82]	• Accurate real-time application • High control performance	• It is a data-hungry • It needs a lot of computation
		PSO [66,90]	• Accurate real-time application • Easy implementation • Limited number of parameters	• High computational complexity

application domains are specified. Examples of classic techniques are: filtration based control and sliding mode control and for instances of intelligent techniques, we have: robust control, Model Predictive Control (MPC) and hierarchical control. Although this paper mainly presents intelligent control techniques for EMS, the research in the technical characteristics of HESS remains limited.

In [84] a survey on SC based HESS for standalone DC microgrids is carried out. The paper begins by outlining the different HESS coupling topologies, e.g. passive, semi-active and full active. Furthermore, EMS are investigated. After identifying the goals and the structure of EMS, intelligent control techniques are discussed. They are classified into rule-based control techniques and optimisation-based techniques. This study explores one type of coupling topology and describes just few examples of EMS control techniques.

Previous surveys on HESS have mainly investigated the coupling topologies between distinct ESS and the selection of the suitable EMS control techniques without a particular focus in a specific type of ESS. Furthermore, RFB have gained increasing interest in the last decade in multiple application domains. Thus, the purpose of this paper is to study the different aspects of HESS based on RFB.

7. Conclusion

HESS offer a high potential to optimize stationary storage applications. The analysis of the KPIs shows the advantages and disadvantages of the different EES. In many cases, the requirements in the application do not fit perfectly to one storage characteristic of a system. Frequently the energy and power density limits the operation scenarios. In individual applications, this can usually be compensated by over dimensioning of the storage system. However, this has negative effects due to sustainable or economic requirements of the system. Therefore, a specific combination of different storage systems offers a feasible solution. The RFB technology profits with a combination of SC or LIB in many KPIs (described in Table 2) resulting in high lifetime by the widest window of storage duration, a medium energy density with complementary high power and fast reaction time for a

Table 8. Classification of HESS studies

Paper	Energy storage system	Electric topologies	Optimisation		General control techniques	Used data
			Optimisation function	Real time		
[91]	(H_2/Br_2) RFB, SC	DC coupled	Power	Yes	Mathematical model	Microgrids
[92]	Battery, SC	DC coupled	Power allocation of different ESS	Yes	Classical Real-time optimisation	Microgrids/Simulated
[93]	Battery, SC	DC coupled	Reduces measurement inaccuracies	N/S	Classical	N/S
[94]	VRFB, SC	Active topology	Current, SoC	No	Classical Fuzzy logic	EV charging park/Real
[95]	Li-Ion battery, SC	DC coupled	N/S	N/S	Fuzzy Logic	Ships
[86]	VRFB, SC	Active topology	Power thresholds	No	Rule-based	Industrial grid – Real/Synthetic EV charging park
[60]	Batteries, SC	DC coupled	Constant voltage to the DC bus	No	Classical	PV, AC- and DC Loads/Simulated
[90]	Battery, SC	DC coupled	N/S	N/S	Global optimisation Real-time optimisation	Electric vehicle
[96]	Li-Ion battery, SC	DC coupled	Meet power demand Reduce the cost of energy storage device	Yes	Classical Real-time optimisation	Ship load
[85]	Battery, SC	DC coupled	Power allocation	Yes	Classical Rule-based	EV application
[61]	Fuel cell, Battery, SC	DC coupled	Provide power for load in time Good tracking performance of HESS current Obtain a stable voltage of the dc bus	Yes	Projection operator adaptive law	N/S
[66]	Battery, SC	DC coupled	Minimizing the power fluctuation Optimizing the capacity ratio of each ESS	Yes	Real-time optimisation	N/S
[87]	Battery, SC	N/S	N/S	Yes	Rule-based Global optimisation Real-time optimisation	Electric vehicle
[97]	battery, SC	DC coupled	Power Charge/Discharge cycle	Yes	Real-time optimisation	PV power generation
[64]	Li-Ion battery, SC	AC coupled	Optimize the cycle life of the HESS	Yes	Mathematic model	Microgrids
[69]	Battery, SMES	DC coupled	Control charge/discharge prioritization	No	Classical	Off-grid load profile/Simulated Sea wave energy conversion/Simulated
[65]	Battery, fuel cell,	AC coupled, On grid	Power	N/S	N/S	Grid data/Real
[98]	Battery, SC	Three-level NPC Converter	N/S	N/S	Classical	Electric vehicle
[68]	Battery Superconducting magnetic ESS	One DC/AC converter Two DC/ DC converters	Smoothing the fluctuations of the wind power output	N/S	Device/system-level control strategies	Wind power generation
[88]	Battery, SC	DC coupled	N/S	N/S	Rule-based	Electric vehicle
[70]	Battery, fuel cell, electrolyzer	DC coupled, On grid AC	Energy costs, power	N/S	Rule-based	Predicted daily data
[63]	Fuel cell, battery, SC	DC coupled, Off grid	Power	Yes	Real-time optimisation	Grid data/Real
[62]	Battery, SC	DC coupled	N/S	N/S		Microgrid
[99]	PbA and Li-Ion battery, SC	Three different architectures	Maintain the grid power and voltage	No	Classical	Residential load/Literature data
[89]	battery, SC	DC coupled	Current, voltage	Yes	Real-time optimisation	N/S
[100]	Fuel cell, SC	DC converters	Voltage	No	Classical	Electric vehicle/Simulated
[67]	Battery, SMES	DC coupled, On grid	Current	N/S	N/S	Grid data/Real
[101]	Fuel cell, Battery, Electrolyzer	AC bus and DC bus considered	N/S	Yes	Real-time optimisation	Residential load

N/S: Not specified

medium cost level. In this HESS the RFB acts as energy component (secondary cluster) while SC or LIB take the role of the power component (primary cluster).

Depending on hybrid components and application scenarios the coupling architecture of the systems have to be optimized. A DC coupled system offers several advantages regarding efficiency and system prices and is selected as optimized solution for a RFB-SC combination. A coupling architecture optimization strategy is proposed for the selection of the SC module as well as the converter to optimize efficiency, voltage and costs.

According to the technical system design, the control strategies for the specific application s offer further optimization potential for HESS. The structure of an EMS is similar to EES but the possibilities and also the complexity increases. In the first place the application specific goals have to be defined. Application examples and the control parameters to realise these are summarized in Table 4. In addition, hybridization enables the possibility to add system specific operation goals like optimize the dimensioning, efficiency or the economic rentability. As a supplement, Table 5 shows a map where HESS systems are used for a combined application scenario described in the literature.

Due to the complexity and capabilities of HESS applications, intelligent control techniques like artificial intelligence are used. As a supplement of real time operation, prediction data are used to optimize operational efficiency and achievement of the remaining EMS goals.

The use and the advantages of HESS in different combinations and applications are reported in numerous publications. In Table 8 considered publications are listed and itemised according to application specifications. A number of gaps and shortcomings regarding EMS for HESS remain to be addressed:

- The advance of a real time optimisation of EMS came at a very high **computational cost**. One solution to address this issue is the use of the **Digital Twin** (DT) concept. DT uses real world data to create a simulation that predicts system future performance [102]. DT has been recently adopted in many application fields due to several advantages, in particular energy management and operation optimisation improvement.
- The majority of research carried out on HESS mainly adopted two distinct ESS, as illustrated in Table 8 and only three studies have included a RFB [86,91,94]. Further work needs to be done on HESS that contain **more than two distinct ESS** and **at least one RFB**.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
AFE	Active Front End
ANN	Artificial Neural Network
AORFB	Aqueous Organic-Redox-Flow Battery
ARIMA	Auto Regressive Integrated Moving Average
BC	Battery Converter
BMS	Battery Management System
CNN	Convolution Neural Networks
D	Distribution Grid
DC	Direct Current
DT	Digital Twin
E	Energy
EC	Energy Component
EES	Electrical Energy Storage
EMS	Energy Management System
ESS	Energy Storage System
E-U	Behind-the-meter at end-user locations
FC	Fuel Cell
GA	Gradient Descent
GAN	Generative Adversarial Network
HESS	Hybrid Energy Storage System
ISC	Supercapacitor Current
Isol	Isolated
G	Grid
KPI	Key Performance Indicator
LIB	Lithium-Ion Battery
LSTM	Long Short Term Memory
M	Manage
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MDPI	Multidisciplinary Digital Publishing Institute
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MLP	Mixed Linear Programming

MPC	Model Predictive Control
NaS	Sodium-sulphur Battery
NCM	Lithium-Nickel-Cobalt-Manganese-Oxide
NN	Neural Network
Non Isol	Not isolated
NRMSE	Normalized Root Mean Square Error
N/S	Not specified
OMEI	Open Mobility Electric Infrastructure
P	Power
PbA	Lead-acid Battery
PC	Power Component
PSO	Particle Swarm Optimisation
RE	Renewable Energy
RES	Renewable Energy Sources
RFB	Redox-Flow Battery
RL	Reinforcement Learning
RMSE	Root-Mean-Square Error
RNN	Recurrent Neural Networks
S	System
SC	Supercapacitor
SCC	Supercapacitor Converter
SCM	Supercapacitor Module
SoC	State of Charge
SMES	Superconducting Magnetic Energy Storage
T	Transmission Grid
UPS	Uninterruptible Power Supply
VRFB	Vanadium-Redox-Flow Battery
VSC	Voltage at Supercapacitor Module

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