A REVIEW ON REVIEWS OF ENERGY STORAGE SYSTEMS: DO WE KNOW ENOUGH TO MAKE A SUSTAINABLE DECISION?

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Abstract

This study presents a review of current parameters of various Energy Storage Systems (ESTs) considered in overview documents and assesses the frequency of appearance of parameters and the transparency in reporting. A literature research was carried out, followed by a frequency analysis to identify relevant studies and most frequently reported parameters. In total, 14 studies are chosen, reporting values for 18 different parameters of 61 ESTs. Additionally, the chosen studies were filtered for parameters representing the three pillars of sustainability, namely economy, environment and society. It was found that technological and economic parameters are well-integrated in the reviewed studies while environmental and social impacts are assessed qualitatively and less frequently. A general issue that affects studies collecting and comparing parameters of multiple storage systems is the lack of explanation on how parameters where exactly calculated.

Introduction

Storage technologies for energy systems are mainly selected based on their technological and economic parameters. Though, every EST bears different environmental impacts even before being commissioned due to various structure and material composition. Therefore, choosing the right storage technology should not only be of financial interest, but at the same time it should expose less harm to the environment. Numerous studies quantify potential environmental impacts of individual storage technologies in terms of global warming potential, acidification potential, eutrophication potential or others, e.g. (Mostert et al., 2018; Oliveira et al., 2015). Even though the quantification of ESTs is broadly available in literature, overviews of ESTs fail to include such impacts. The aim of this paper is to analyse whether reviews of ESTs provide sufficient information in order to identify the most sustainable technology. To specify which information in particular is looked for, the sustainability concept is briefly introduced in the methods section. Afterwards, further details about the literature research itself as well as the reported characteristics will be given in the method section. Afterwards, more details about the selected studies and main observations are presented. Even though this research does not aim at thoroughly comparing and evaluating values of particular technologies, the result section ends with an exemplary presentation of six different parameters of four EST classes. Before the paper concludes, a discussion sums up main findings.

Methods

Sustainability

In 1983, the World Commission on Environment and Development defines sustainable development as ‘development that meet the need of the present without compromising the ability of future generations to meet their own needs.’ (World Commission on Environment and Development, 1987). Therein, the concept of sustainability was defined to be built on three pillars: the economy, the environment and the society (World Commission on Environment and Development, 1987). Over the years, many efforts to operationalize the concept of sustainability were undertaken. Among these, the United Nations defined 17 Sustainable Development Goals (SDGs) and SDG seven addresses affordable and clean energy. Even though SDG seven promotes the raise of renewable energy share in the total final energy consumption, evaluation and selection of corresponding technologies remain unclear (United Nations Statistics Division, 2021). Furthermore, ESTs are presented as a solution to address variability and reliability of renewable energy sources, such as solar, wind and hydro, and are considered as a key element to decarbonize energy supply (Fuchs et al., 2012). However, there is still a great variety of ESTs available and it is not evident, which of them can really contribute to a more sustainable future.

Review

We conducted a literature review of commercial and scientific publications reporting on multiple storage technologies. Scopus and google (scholar) search engines were used to explore publications related to the search string “energy storage technologies overview”. This exploratory study concentrates on overview publications reporting on multiple storage systems that already gather data from thousands of publications on individual storage types and technologies. We kept studies reporting, in a structured form, on various storage technologies and constructed a data base of parameters based on these. Therefore, the technologies were classified into mechanical, electrochemical, electromagnetic and thermal technologies. Afterwards, the parameters in the selected studies were observed. Even though studies entail the same parameter, it did not necessarily allow direct comparison as they have used different units. Wherever possible, units were homogenized (e.g. from MWh to kWh or from hours into minutes). Prices given in USD were translated into Euros utilizing an exchange rate of 1,13 USD/EUR ((European Central Bank, 2021). However, unit conversion was not for all parameters possible. For instance (Kousksou et al., 2014) and (Mahlia et al., 2014) report energy density values in Wh/kg, while the majority reports values on a Wh/l or a kWh/m^3 unit. In such cases, values of the two studies for energy density were excluded from the overview. As a next step, the parameters were fed into a frequency analysis. Parameters were considered if three or more studies reported values for the same parameter. Furthermore, all values are assessed quantitatively except for technology maturity and environmental impact, which were always reported qualitatively. Whenever included, minimum and maximum values for each parameter were taken into account. Out of these numbers, average values were calculated. In case only one value was reported, this value was directly considered as average value in the database. To answer the research question, the studies will be scanned for information about the three pillars of sustainability, namely whether they contain data about the economy, the environment or society. However, neither detailed explanations about functionalities of every technology is contained, nor an in-depth analysis of all included values is conducted. Undertaken steps are depicted in Figure 1.

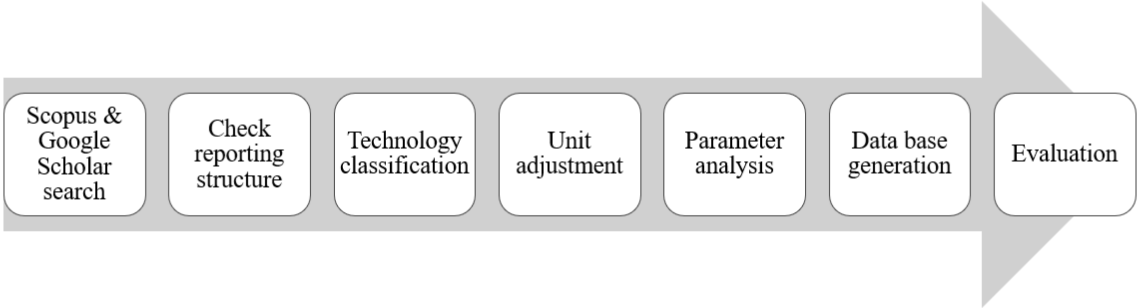

Figure 1: Flow chart of methodological approach

Results

In total, 14 studies have been selected. Eight of the publications are scientific papers, four are reports of research institutes or universities and two are reports from industry. More details are provided in Table 1. These studies report on 61 different technologies, which are classified as following: 17 mechanical, 31 electrochemical, four electromagnetic and 9 thermal ESTs. Further information regarding technological specifications presents Figure 2. Numbers in parenthesis correspond to the amount of included technologies.

	Publication in scientific journal	*Reports of research institutes/universities*	*Report from industry*
(Akinyele & Rayudu, 2014)	1		
(Aneke & Wang, 2016)	1		
(Cho & Gabbar, 2019)	1		
(Connolly, 2010)		1	
(Deloitte, 2015)			1
(JU, 2015)		1	
(Fuchs et al., 2012)		1	
(Gallo et al., 2016)	1		
(Khan et al., 2019)	1		
(Kousksou et al., 2014)	1		
(Lazard, 2018)			1
(Mahlia et al., 2014)	1		
(Mongird et al., 2019)		1	
(Sabihuddin et al., 2015)	1		
Total	8	4	2

Table 1: Classification of included studies

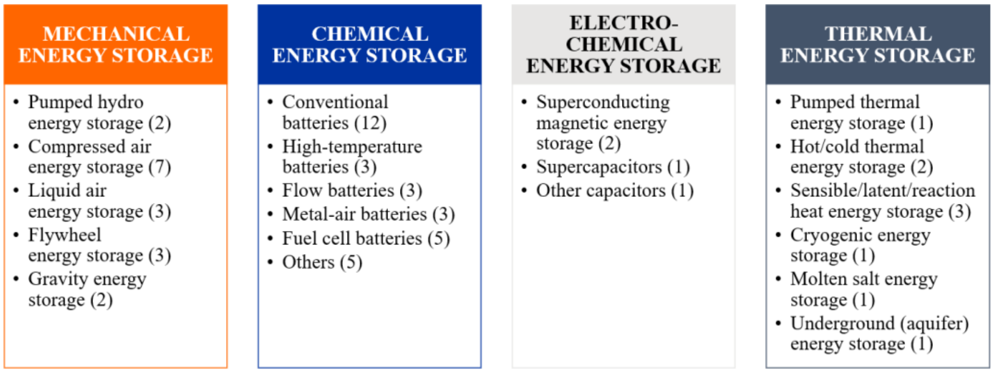

Figure 2: Classification of technologies (included technological specification)

The studies present values for about 80 different parameters of ESTs. These 80 parameters can be distributed as following: 41 technological parameters, 32 economic parameters and 7 other parameters (see Table 2). Out of these 80 different parameters, 18 parameters are presented by at least three or more studies (Table 2). The three most reported parameters are technical ones including lifetime (12 times), energy density (9 times) and life cycles (9 times). The first six parameters are technological parameters, whereas economic parameters are observed to be less frequently reported. Further included technological parameters are efficiency (8 times), power rating (6 times), response time (6 times),, power density (6 times), round trip efficiency (5 times), daily self-discharge (5 times), storage time (5 times) and discharge time (4 times). Considered economic parameters are energy costs (6 times), power costs (5 times), CAPEX (4 times) and fixed and variable OPEX (3 times each). Other parameters that are found to be relevant are technology maturity (5 times) and, concluding the frequency list, environmental impacts (3 times).

Technological parameters			Economic parameters			Other parameters		
Parameter	*Unit*	*n*	*Parameter*	*Unit*	*n*	*Parameter*	*Unit*	*n*
Power rating	MW	6	Power cost	€/kW	5	Technology maturity	Text	5
Energy density	Wh/l	9	Energy cost	€/kWh	6	Environmental impacts	Text	3
Power density	W/l	5	CAPEX	€/kWh	4			
Round trip efficiency	%	5	Fixed OPEX	€/kW	3			
Daily self-discharge	%	5	Variable OPEX	€/kWh	3			
Efficiency	%	8						
Storage time	Hours	5						
Discharge time	Hours	4						
Response time	Minutes	6						
Lifetime	Years	12						
Lifetime	Cycles	9						

Table 2: Overview of included parameters (n = frequency of reported parameter)

Moreover, some studies lack a proper definition of parameters, for example when talking about efficiency. Eight studies report data on efficiency, but only (Kousksou et al., 2014) and (Connolly, 2010) defined efficiency. (Connolly, 2010) defines efficiency as ‘the quantity of electricity which can be recovered as a percentage of the electricity used to charge the device’. Contrary, (Kousksou et al., 2014) provides a more detailed efficiency definition: ‘The process of storing and withdrawing energy can cause considerable losses. Many auxiliary components of the energy storage system have a constant power demand, and in addition, there are energy losses inherent in the storage principle’. Similar observations can be found when analysing the power rating. Eight studies present data about power rating of different storage technologies, none of them providing a definition of the parameter. Such fundamental definitions provide the readers with information whether the comparability of the similar parameter is possible or not. Another result was encountered when describing the dimension of ESTs. For the description of the dimension, three different parameters are utilized: power rating, capacity and scale. Out of all considered studies, only (Kousksou et al., 2014) defines capacity to describe the dimension of the storage technology before reporting values about it.

One first finding was that only three out of 14 studies report environmental impacts (Connolly, 2010; Kousksou et al., 2014; Sabihuddin et al., 2015). However, these studies conducted only a qualitative assessment of this parameter. (Connolly, 2010) for example described the environmental impact of pumped hydro energy storage as “reservoir”, but without providing clear explanations or numbers about how much resources are being used by installing the required reservoirs. In the same report environmental impacts of compressed air energy storages are described as “gas emission". Without providing neither explanations nor numbers about these impacts, e.g. how much resources are being used or how much CO_2 emissions are issued by a particular technology, readers will find it impossible to select the most environmental friendly storage technology. Table 3 lists the reported environmental impacts of the consulted studies.

Source	Evaluation of environmental impacts	Further qualitative explanations	Quantitative assessment of environmental impact
(Sabihuddin et al., 2015)	Very low Low Medium/Low Medium High/Medium High Very high Very very high Uncertain	No	No
(Kousksou et al., 2014)	Small Negative Almost Benign	Yes	No
(Connolly, 2010)	Reservoir Gas emissions Lead disposal Toxic cadmium Chemical handling Emissions	No	No

Table 3: Reporting of environmental impacts of considered studies

Equally important to environmental impacts are social impacts. However, only (Connolly, 2010) included one social impact, namely safety issues. In this study, safety issues were classified qualitatively: 'Exclusion area', 'Pressure vessels', 'Lead disposal, H_2', 'Toxic cadmium', 'Thermal reaction', 'Chemical handling', 'Containment', 'Magnetic field' (Connolly, 2010). Indicated issues are linked with the direct application of the EST. Broader impacts due to the application of certain EST for society, such as human rights or health issues of workers along the supply chain of EST are not evaluated in any of the consulted studies.

Lifetime in years, energy density and lifetime in cycles are the three most frequently reported technological parameters, while energy cost, power cost and CAPEX are the most frequently reported economic parameters. Exemplarily, these parameters are explored in Figure 3 - Figure 5. All presented values are average values gathered from the consulted studies. For reasons of better illustration, lifetime, in years and cycles, energy density, CAPEX and energy and power costs are aggregated and presented per mechanical, chemical, electro-chemical and thermal EST. It can be observed that mechanical EST have the longest lifetime in years, while the range of lifetime cycles for electro-chemical EST is widest ranging from 10.000 to 1.000.000. Chemical EST on the contrary state lowest values for lifetimes in both years and cycles (see Figure 3).

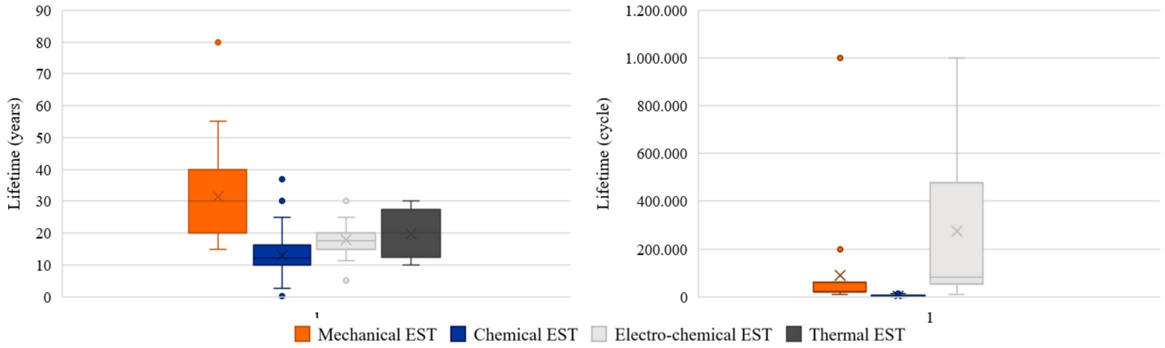

Figure 3: Average lifetime of different EST classifications

Highest energy densities can be found when choosing chemical EST. For better result visualization, four particularly high energy densities have been left out of Figure 4. Well over the observed energy densities of chemical EST are metal air batteries. The reported average energy density of these batteries is 5.250 Wh/l (Akinyele & Rayudu, 2014; Aneke & Wang, 2016; Khan et al., 2019). Another outlier with an average energy density of 4.600 Wh/l is power-to-gas energy storage, utilizing methane as energy carrier (Gallo et al., 2016). Clearly, the widest spread for average energy density can be found in chemical EST. With a narrower range, average energy densities of thermal EST spread around the same level as chemical EST. The wider range for chemical EST can be explained by the fact that this category covers a higher number of different technologies, in particular 31, all bringing along their particular characteristics. Contrarily, thermal EST take only nine different technologies into account. Lowest average energy densities are identified for electro-chemical EST, while mechanical EST perform better than electro-chemical EST. At the same time, mechanical EST have cheapest CAPEX, with two exceptions: CAPEX for flywheel EST are 2.654,87 €/kWh (Aneke & Wang, 2016) and 3.318,58 €/kWh (Cho & Gabbar, 2019). (Cho & Gabbar, 2019) declared the costs as initial cost in USD/kWh, however neglecting further explanation. According to (Aneke & Wang, 2016), the high CAPEX for flywheel EST are offset by low costs per cycle and therefore such EST are well suited for applications with high power output within a short time (Aneke & Wang, 2016). Unfortunately, no other consulted study provided CAPEX values for flywheel EST. Considerably higher are thus average CAPEX for chemical EST, while highest average CAPEX is found for electro-chemical EST.

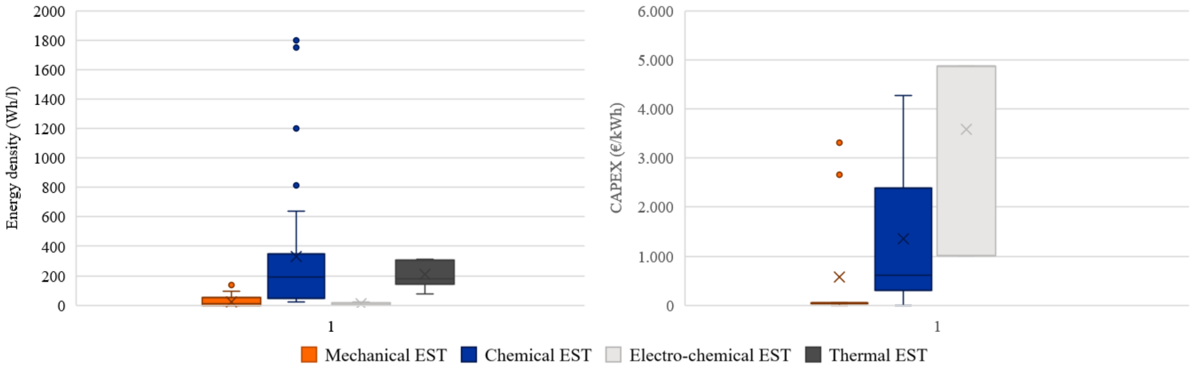

Figure 4: Average energy density (left) and average CAPEX (right) of different EST

Additionally, energy and power costs are described in Figure 5. Minimal energy costs are identified for thermal EST, followed by chemical EST. Highest energy costs and widest spread can be observed for electro-chemical EST. However, three energy costs were neglected for the group of electro-chemical EST: 111.051,33 €/kWh (Sabihuddin et al., 2015) and 63.716,81 €/kWh (Connolly, 2010) for superconducting magnetic EST and 72.566,37 €/kWh (Connolly, 2010) for supercapacitors. Besides of these values, energy costs of electro-chemical EST range from 265,49 €/kWh up to 15.000,00 €/kWh. Similar to previous reported parameters, some exclusions were undertaken for power costs as well for improved illustration. According to (Sabihuddin et al., 2015), average power costs are 3.487.856,19 €/kW, 62.831,86 €/kW and 11.061,95 €/kW for respectively a zinc silver oxide battery, a fuel cell battery based on direct methanol and a nickel iron battery (Sabihuddin et al., 2015). Even though higher power costs for the silver oxide battery due to a high silver price might be justified, compared to other batteries the average power cost of 3.487.856,19 €/kW seems very unrealistic. Neglecting these and other outliers of the chemical EST, the widest range can be found for thermal EST. Thermal EST range from 39,82 €/kW up to 4.144,25 €/kW. On the other hand, average power costs for mechanical EST are considerably lower and have a much smaller range. Lowest average power costs and a minimal range are detected for electro-chemical EST (see Figure 5).

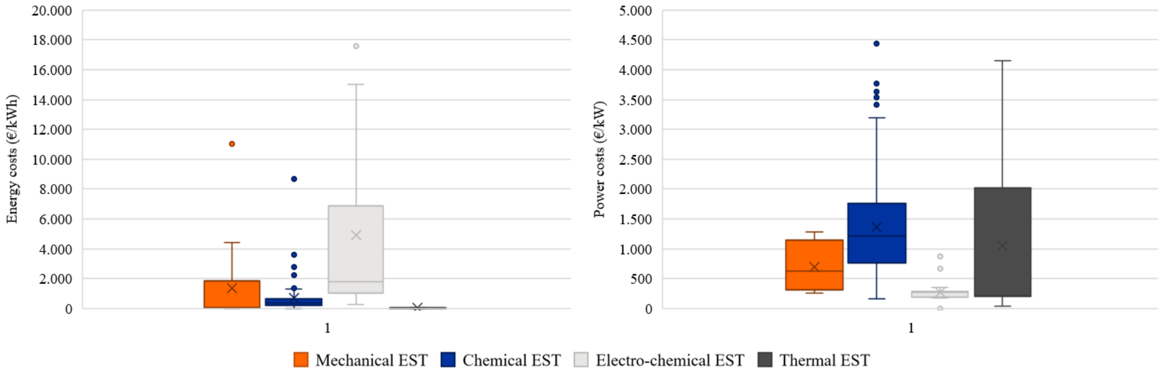

Figure 5: Average energy costs (left) and average power costs (right) of different EST

An overall observation form this brief analysis is that no technology class surpasses in all parameters. Mechanical EST can be used over many years, but have comparable low energy density, while costs are low to moderate. Chemical EST on the other hand have very high energy density, but lower lifetime and moderate to high costs, compared with other ESTs. Electro-chemical EST come along with rather high costs, low energy density, but long lifetime. Thermal EST have considerable energy density over a reasonable lifetime, but come along with high costs.

Discussion

As observed, the consulted studies report on a great variety of different parameters. The amount of parameters multiply as not all studies consider the same parameters, partly fail to properly define the included parameters or report on different units. Additionally, when analyzing the four technology classifications, no class was found to perform best amongst all the parameters. This circumstances hampers in a first step the comparison of ESTs and thereby also the selection of most suited EST. To address this shortcomings, a guidance or standard should be developed to provide orientation about which parameters should be considered and on what units' values should be reported. Furthermore, social and environmental impacts are found to be underrepresented. Only one study qualitatively reported safety issues, besides no other social impacts were found. Depending on the system boundaries of a study and the selected social impacts, e.g. health and safety or human rights, the assessment of social impacts for EST can easily become very complex. In addition, the expression in single quantities remains at the moment objects of future research. At the same time, environmental impacts have been addressed in at least three studies. Even though a qualitative assessment of environmental impacts is a starting point, it still denies comparing various technologies from an environmental point of view. To determine environmental impacts, future reports on EST might have to study the various technologies from a system perspective. One methodology that allows to follow such an approach is life cycle assessment (LCA). Life cycle assessment studies environmental impacts occurring over a products life cycle (Deutsches Institut für Normung e.V., 2009). By following a relative approach, environmental impacts of an LCA can be reported per functional unit, for example per kWh of provided electricity or per kWh of installed capacity. Under the same studied system and functional unit, environmental impacts of different EST can be compared. As many LCA studies of different EST already exist, the quality of future reviews of EST would benefit from including such results or entailing LCA results from own calculations. Unfortunately, this is not the case for the consulted studies. After taking all points into account, it can be concluded that the consulted studies do not entail sufficient information for selecting the most sustainable EST. This is mainly due to the lack of quantitative environmental impacts as well as social impacts in general. Therefore, future research can further investigate to define a general guideline for reporting EST containing solid definition of included parameters and addressing all pillars of sustainability. In addition, further research can be dedicated to the development of a tool or checklist that offers to select the most sustainable EST for a particular system.

Conclusions

A thorough review of overviews on storage systems has shown that there is a concerning lack of standardization on reporting about parameters of storage systems. There is little transparency on how parameters are calculated, and social and environmental impacts seem to play a secondary role. As a consequence, further studies should start their work with well-defined metrics in order to provide readers with highest transparency. Additionally, the qualitatively assessed environmental impacts do not provide sufficient information in order to identify the most sustainable EST. As a result, environmental impacts of ESTs by itself but also from a system perspective should be quantified and included into future overviews. Moreover, most parameters of the reviewed studies address more technological than economic or other parameters. On one hand, this is reasonable as these values are used to describe the system under study and give the reader an idea about it. On the other hand, sustainability is gaining more and more importance nowadays, particularly in an energy system that is designed to mitigate climate change. Therefore, when choosing an EST for an energy system, technological, economic, social and environmental parameters should be considered equally. Furthermore, future authors of EST overviews are asked to include besides technological and economic parameters also quantifiable and reproducible environmental impacts, such as carbon dioxide, sulphur dioxide and methane. For representing all three sustainability pillars, social impacts, for example health issues or compliance of labour rights along the supply chain of the different energy storage technologies should be addressed in addition.

Acknowledgments

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