Energy Storage in Industrial Case Studies: A Literature Review

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Abstract: Several industrial sectors are characterized by significant energy requirements and wastes. Energy efficiency measure implementation, as well as decarbonization and diversification of energy supply, play a prominent role in reaching sustainability goals. Energy storage technologies can support such objectives. However, challenges in energy storage implementation arise from costs, efficiencies, size and overall management. The study aims to investigate how energy storage technologies can improve the efficiency and sustainability of industrial operations, and how the appropriate technology can be selected basing on the specific needs of each industry. An analysis of energy storage implementation in various industrial case studies is presented. First an overview of the current state of the art of energy storage technologies is summarised. It then delves into case studies, including a range of industries from different sectors, each characterized by peculiar energy requirements and challenges. The implementation of energy storage solutions in these industries is examined focusing on the benefits from the energy, environmental and economic points of view, as reported in the analysed case studies.

Keywords: Sustainability, Energy storage system, Industrial applications, technology selection

1. INTRODUCTION

In 2021 industrial sector accounted for 25.6% of energy consumption in the EU, with electricity and natural gas accounting for the 33.2% and 32.7%, respectively (EUROSTAT, 2023). The European Union (EU) has delineated primary objectives for the 2030 Agenda, which encompass a 55% reduction in greenhouse gas (GHG) emissions, an increase of renewable energy sources to constitute 42.5% of the total, and an overall energy efficiency target of 36% (European Commission (EC), 2023a).

In light of the European Union's objectives, a systematic enhancement of energy efficiency is required. Concurrently, it is crucial to pursue the decarbonization of the industrial sector as a strategic measure towards these ambitious climate goals. To address the dual challenges of climate change and increasing energy consumption, it's crucial to establish a strategy for harnessing renewable energy. Indeed renewable energy sources are progressively increasing their contribution, accounting for the 22.5% of the total EU energy demand in 2022 (European Environment Agency (EEA), 2024). However, their availability is not consistent throughout the day and the year, making them unable to meet the energy demand without an effective energy storage system (El Alami et al., 2020). Therefore, energy storage technologies should be tailored to each facility to cover energy demand. Storing energy allows to postpone energy utilization to high request periods, reducing energy cost and environmental harm. Industrial sector has significant capacity to reduce energy demand costs through energy storage to trim peak load from the power grid (Elio et al., 2021).

As a consequence of the great research interest and the resultant rapid cost reduction, the sector exhibits optimism regarding future evolutions, attributing to energy storage a major role in changing professional perspectives on the power sector (European Commission (EC), 2023b). Moreover, the development of novel business models is imperative to fully harness the potential of storage. This is particularly relevant when formulating cost models and evaluating the benefits of storage, which are predominantly influenced by the actual applications. Consequently, the importance of case studies has been increasingly recognized.

Several review articles have been published focusing on the development and operation of different energy storage technologies (Al Shaqsi et al., 2020; Aneke and Wang, 2016; Rana et al., 2023). However, a study resuming the benefits deriving from the implementation of energy storage in industrial sector is still missing.

To this end, the paper aims at providing a state-of-the art analysis, in order to identify current literature advancement regarding economic and environmental benefits deriving from application of energy storage in the industrial sector. Among the several energy storage technologies commercially available, those of major interest for industrial plants have been considered, as explained in the following section. Thus, the following research questions will be answered:

- RQ1: what are the most utilized energy storage technologies in the industrial sector, how are they modelled and which case studies are available in the literature?

- RQ2: which benefits can derive from energy storage adoption and which methodologies can guide the selection of the proper energy storage system?

The remainder of this paper is structured as follows: in section 2 an overview of the available energy storage technologies is presented while in section 3 the procedure followed for the literature review is explained. The results of the literature analysis are reported in section 4. Finally in section 5 conclusions are drawn.

2. ENERGY STORAGE TECHNOLOGIES OVERVIEW

Due to recent shift towards green energy and enhanced efficiency goals, the request for energy storages surged. The demand motivated research for innovative energy storage methodologies with increased efficiency and able to provide consistent power supply. One way to categorize different energy storage technologies is based on the energy form utilized for the storage (Mitali et al., 2022; Olabi et al., 2021):

- Thermal energy storage (TES): are used to store heat or cold in a medium. These systems are commonly used in both industrial settings and residential buildings for applications like space and process heating or cooling, water temperature regulation, and electricity generation. The various applications can be categorized basing on the process exploited to store energy, such as sensible heat, latent heat, and absorption and adsorption systems;

- Mechanical energy storage (MES): energy is stored by converting it into both mechanical and electrical forms. During periods of low demand, electrical energy is transformed into mechanical energy using principles of potential, kinetic, or pressurized gas. Conversely, during periods of high demand, this energy is converted back into electrical energy. The advantage of these systems is that stored energy can be easily converted back into electrical or mechanical form. Common examples of such systems include pumped hydro storage (PHS), flywheel energy storage (FES), compressed air energy storage (CAES), and gravity energy storage systems (GES);

- Electrochemical energy storage (EcES): this is the most widely known energy storage system, whose operation is based on three main processes, i.e. ionization, charge transportation, and charge recombination. It can be divided into two sub-types: Battery Energy Storage (BES) where energy is stored within the electrode, and Flow Battery Energy Storage (FBES) where the charge is initially stored within the fuel and subsequently supplied externally to the electrode surfaces;

- Electrical energy storage (EES): energy is stored in an electric field without converting the electrical energy into other forms of energy. EES systems can be categorized into two types: electrostatic energy storage systems and magnetic energy storage systems. The capacitors and supercapacitors are examples of the first kind, while the superconducting magnetic energy storage is an example of the latter;

- Chemical energy storage (CES): energy is stored in the form of material atomic and molecular bonds, and is released through chemical reaction. As the stored energy is released, there is a material composition change due to both the breaking of original chemical bonds and formation of new ones. Example are represented by traditional fossil fuels, innovative biofuels and hydrogen.

All the abovementioned technologies can serve different purposes based on the specific energy and power densities and start-up time. Moreover many of these technologies are still in early development stage and are not ready for commercialization and real world implementation (Amir et al., 2023). Since the aim of this paper is an analysis of the reported benefits of energy storages integration in industrial settings, we decided to focus on mature technologies for load shifting and renewables penetration, namely TES and BES.

3. METHODOLOGY

The literature review has been systematically conducted utilizing the Scopus database. The literature search has been structured in four different steps, as synthesized in Table 1. The first step consisted in a keyword search by using: "thermal energy storage" OR "battery energy storage" AND "industr*" AND "case study". As a result, a first set of 270 papers have been obtained. Since our analysis focused on current technologies implementation, in order to restrict the search to recent articles, a time constraint, limiting the search between 2020 and 2024, has been introduced. Moreover, only English language articles have been considered and subject area has been restricted to "engineering" or "energy". At the end of this step 135 papers have been found according to the selected criteria. Then, a screening procedure based on title and abstract has led to remove off-topic articles, leading to a set of 85 papers. At the end, a content analysis has been accomplished thoroughly reading the articles to identify the final set of papers. The final set of articles consisted in 22 papers.

Table 1. Steps adopted through the review process

Step	Activity	Selection criteria	Papers
1	Identification	Keyword search: Title, Abstract, Keywords = "thermal energy storage" OR "battery energy storage" AND "industr*" AND "case study"	270
2	Field restriction	Limit to document type = "article" or "conference" AND limit to date = "from 2020" AND limit to language = "English" AND limit to subject area = "Engineering" or "Energy"	135
3	Screening	Content screening through title and abstract reading	85
4	Eligibility	Content screening through paper reading	22

4. CASE STUDIES ANALYSIS

Table 2 summarizes the identified papers on energy storage case studies following the procedure described in section 3, including technology adopted, modelling approach applied, industry application and objectives of the study. The literature analysis results are reported in the following subsections: in section 4.1 TES applications are discussed while BES application results are disclosed in section 4.2.

4.1. Thermal Energy Storage

Zuberi et al. (2020) applied pinch analysis for heat integration in batch processes through a sensible heat TES (STES) implementation for energy efficiency increase and costs reduction. The energy storage system has been applied to a medium size European textile plant. Results showed that 29% of total thermal energy demand and CO_2 emission reduction can be reached thanks to TES integration. De Ridder et al. (2021) presented a study of a shared heat storage based on a water sensible heat energy storage system for the horticulture industry in Belgium. It utilizes a linear programming model to minimize the operating costs. A cost reduction of more than 7% resulted from the storage implementation, showing how energy flexibility can reduce operation costs. Knudsen et al. (2021) developed a dynamic simulation and model predictive control approach to investigate peak heating reduction through water sensible heat storage. The model has been applied to a case study of a district heating system located in Norway, with 90% of its heat supplied by an industrial plant. They concluded TES allows for added resilience against unpredictable variation in supply and demand. Koçak (2021) carried out estimation based on experimental results in a lab scale integration a packed bed sensible thermal energy storage system. The investigated system has been applied to the food industry, in order to reduce energy cost and increase implementation of renewable energy sources. The author concluded that the integration of TES leads to a solar system efficiency of more than 39%, as well as a reduction in natural gas consumption and GHG emissions. Puschnigg et al., (2021) conducted a qualitative evaluation of different TES technologies application in various industrial branches at different temperature levels, to facilitate the selection of potential TES project based on different KPIs such as: the temperature level and application range, TRL, specific TES costs, storage density, and storage capacity. A case study of application to a cement plant has been provided. Results showed that TES integration is dependent on the fossil fuel prices related to existing energy supply. The saved energy and costs must compensate for the cost of TES system integration, in order for TES to be economically viable. They concluded that economic feasibility requests appropriate conditions and incentives. Another way to produce fresh water through thermal desalination has been proposed by Wang et al. (2021), introducing an absorption based TES (ATES) to mitigate the mismatch between the unstable heat supply and the stable need of thermal desalination. To illustrate the application and the energetic and economic performance of the system a case study is carried out, utilizing industrial waste heat as driving heat source. They concluded that the presented system is an energy efficient and economically feasible way of utilizing low level heat for desalination. Möhren et al. (2022) aimed at increasing energy efficiency integrating water STES in industrial processes. A MILP model has been developed for a multiperiod heat integration problem, aiming at minimizing energy demand and costs as well as GHG emissions. The model has been applied to a cosmetic manufactory case study, showing that TES integration allowed a reduction up to 44.3% of energy demand, highlighting TES capacity to allow good energy and environmental performances when integrated in a suitable operating environment. Walden et al. (2023) developed a methodology to model a multi component industrial energy system, composed by a high temperature heat pump, a concrete based STES and a wind turbine to supply super-heated steam. The system is described by a nonlinear surrogate model solved using the local interior point optimizer (IPOPT). The optimized operation reduces operational costs by 6%. Zheng et al. (2023) presented a low carbon ethylene production system with the integration of carbon capture and utilization technologies, wind turbine, solar heat collector, electric boiler and molten salt TES. A MILP model has been developed aimed at minimizing the total annual cost of the system. The model has been applied to a real case study plant. TES integration leads to approximately 13% of GHG reduction and 10% of total annual cost reduction. Zoratti et al. (2023) analysed the integration of a solar thermal plant for indirect steam generation in a typical industrial process with thermal energy

Table 2. Summary of the selected papers

Year	Authors	Storage type	Methodology	Application	Objectives
2020	Zuberi et al.	STES	Pinch analysis	Textile plant	Energy efficiency increase and costs reduction
2021	De Ridder et al.	STES	Linear programming	Horticulture	Reduce operative cost
2021	Knudsen et al.	STES	Dynamic simulation and model predictive control	District heating	Minimize peak heating
2021	Koçak	STES	Experimental lab scale	Food industry	Decrease energy cost and increase renewable integration
2021	Puschnigg et al.	TES	KPIs benchmarking	Cement plant	Economic benefits and GHG emission reduction
2021	Wang et al.	ATES	Analytical modelling	Desalination process	Cost reduction
2022	Möhren et al.	STES	Mixed integer linear programming	Cosmetic industry	Minimize energy demand, costs, and GHG emissions
2023	Walden et al.	STES	IPOPT	Not specified	Minimizing costs and GHG emissions
2023	Zheng et al.	STES	MILP	Ethylene production plant	Minimizing total annual cost and GHG emission
2023	Zoratti et al.	STES	Analytical modelling	Food processing plant	Increasing solar energy utilization
2020	Puradbhat et al.	Li-ion BES	Linear programming	Manufacturing plant	Minimizing system costs
2022	Fleschutz et al.	Li-ion BES	Linear programming	Chemical plant	Minimize total annualized cost
2022	Liu et al.	BES	Multi-objective genetic algorithm	Manufacturing plant	Reduction of energy demand and minimization of operating costs
2022	Manikyala Rao and Singh	Lead-acid BES	Heuristic forward-chaining algorithm	Chemical plant	Maximize renewable sources utilization
2022	Oertli et al.	Li-ion BES	Not specified	Petrochemical plant	Improve grid stability
2022	DeSantis et al.	BES	Simulation model	Not specified	Load levelling
2023	Guamán-Molina et al.	Li-NMC BES	Simulation model	Not specified	Reduce energy consumption
2023	Lv et al.	Li based BES	MILP	Industrial park	Maximize revenues
2023	Neri et al.	Li-ion BES	MILP	Industrial park	Minimize total costs
2023	Shakrina et al.	BES	MINLP	Manufacturing plant	Maximize profit
2023	Zahari et al.	Li-ion BES	Simulation model	Not specified	Decrease peak demand and increase and improve operational efficiency
2024	Mottola et al.	Li-NMC BES	Taguchi arrays-based method	Not specified	Minimizing total cost

requirements, with rock based STES integration. A system of differential equation has been developed to simulate the system, applying it to a food processing plant. Results showed that TES implementation is beneficial only for solar energy utilization share above a limit value.

4.2. Battery Energy Storage

Puradbhat et al. (2020) proposed a new methodology for sizing systems adopted for peak shaving in a manufacturing facility, developing a linear programming model to solve the problem. They concluded Li-ion BES implementation could reduce operating costs by 11.28%. Fleschutz et al. (2022) investigated the effect of the German regulatory system (e.g. fixed peak demand grid fees and intensive grid usage) on the implementation of renewable source and BES in industrial facilities. To this aim they applied linear programming to optimize the design and operation of an energy system consisting in a Li-ion BES and photovoltaic system, integrated within a chemical plant case study, to minimize total annualized cost. Results showed that the regulatory systems can incentivize BES installation, which can enhance plant energy flexibility. Liu et al., (2022) proposed an optimal scheduling strategy for generic BES and electric vehicles charging in a manufacturing plant, aiming to enhance demand shifting and cost saving. A multi-objective genetic algorithm has been implemented to this purpose. The investigation highlighted that the integration of BES can flatten the power demand curves with a lower energy cost. Manikyala Rao and Singh (2022) applied a heuristic forward-chaining approach to control the charge and discharge cycle of a lead-acid BES integrated with photovoltaic panels with the aim to increase renewable energy penetration. A chemical plant has been considered as a case study. In the analysis a payback time of 1.72 years has been obtained. Another study (Oertli et al., 2022) investigated the economic viability of Li-ion BES implementation within a petrochemical plant for spinning reserve purposes. Results of the considered case study showed a 27% IRR, showing that BES is a viable solution to provide critical power system function within the oil and gas industry. De Santis et al. (2022) consider the application of BES within a not specified industrial plant to flatten the power generation reducing the power demand difference between daytime and night time. The study is based on a simulation model developed in MATLAB/Simulink. Results show that from a technical point of view BES implementation is possible, however economic advantages are very limited with a return on investment above 10 years. The work of Guamán-Molina et al. (2023) presents a proposal for peak shaving system using solar photovoltaic and Li-NMC BES, installed in a generic industrial facility to reduce energy consumption. The study concluded that the proposed system is a viable solution. Lv et al. (2023) proposed an optimization model for the operational optimization of an industrial park considering demand side response through a lithium based BES. A MILP model aimed at maximizing the total revenue has been developed. Results show that the investigated system effectively optimizes the operation of the industrial park. The study by Neri et al. (2023) presents a MILP optimization model that introduce microgrid based support for distributed renewable energy sources and BES, aiming at minimizing total costs in an industrial park. Li-ion BES integration allowed an increase in renewable energy utilization of 8% and a total cost reduction of 10%. The work presented by Shakrina et al. (2023) focused on profit maximization through BES implementation within a manufacturing plant. the model has been formulated in the form of a mixed integer nonlinear programming model. Moreover, a sensitivity analysis has been carried out to illustrate the impact of the BES installation cost on the results. They concluded BES has an important role in maximizing profits of industrial facilities. Zahari et al. (2023) utilized a MATLAB/Simulink model to investigate solar photovoltaic and Li-ion BES integration within an industrial facility for demand side management, aiming at decreasing peak demand and improving operational efficiency. They observed that energy consumption could be significantly reduced thereby minimizing reliance on grid energy supply and reducing carbon emissions. Mottola et al. (2024) presented a methodology to optimally size a Li-NMC BES in hybrid industrial microgrids. A Taguchi arrays-based probabilistic procedure developed on evaluation of total cost is employed. The work concluded that optimal BES sizing allows the industrial facility to reduce costs. Moreover they suggested that optimal BES sizing depends on its management strategy.

5. CONCLUSIONS

This paper summarises the main results of a literature review carried out on scientific documents published between 2020 and 2024, investigating the implementation of thermal and battery energy storage system in industrial case studies.

Concerning the first research question (RQ1), the most common modelling approaches for energy storage integration are linear programming, mixed-integer linear programming and mixed-integer non-linear programming, while there's a limited application of genetic algorithms. Case studies are adopted to prove the validity of the modelling approach for energy storage integration in industrial contexts, rather than reporting a real implementation of the investigated system.

Regarding the second research question (RQ2) it can be concluded that energy storage implementation in industrial facilities can provide both environmental and economic benefits. Both technologies allow energy recovery and higher renewable sources penetration leading to a greater energy efficiency and a reduced utilization of fossil fuels. Nevertheless, especially for BES adoption, economic advantages depend on the energy market situation, so great attention should be paid for each case study. Most analysed case studies are focused on the energy system sizing while the technology appears like a hypothesis of the modelling approach. To this end for TES water sensible energy storage appears the preferred choice, while for BES instead, Li-ion batteries, are the most adopted solution. Case studies comparing, for the same industrial problem, different storage technologies alternatives analysing the factors leading to the optimal solution is still missing.

Concerning the limitations of this study, the search on scientific literature has been limited to paper published between 2020 and 2024 and focused on two already well established energy storage technologies.

The review of existing literature and case studies suggests that the integration of energy storage systems provides a feasible pathway to increase the resilience and sustainability of industrial operations. Further studies should aim to develop new solutions that can be effectively integrated into industrial contexts. Such investigation can be the premise for the development of multi-objective models to promote innovative system integrating energy storage in order to pursue diversification and decarbonisation of energy supply, while gaining economic and environmental benefits for the industrial sector.

Nomenclature

ATES	Absorption thermal energy storage
BES	Battery energy storage
CAES	Compressed air energy storage
CES	Chemical energy storage
EcES	Electrochemical energy storage
EES	Electrical energy storage
FBES	Flow battery energy storage
FES	Flywheel energy storage
GES	Gravity energy storage
GHG	Green-house gases
IPOPT	Interior point optimizer
IRR	Internal rate of return
KPI	Key performance indicator
Li-ION	Lithium ion
Li-NMC	Lithium nickel manganese cobalt
MES	Mechanical energy storage
MILP	Mixed-integer linear programming
PHS	Pumped hydro energy storage
RQ	Research question
STES	Sensible thermal energy storage
TES	Thermal energy storage
TRL	Technology readiness level

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