RSC Advances

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2023, **13**, 26380

A mini-review on liquid air energy storage system hybridization, modelling, and economics: towards carbon neutrality

Ahmed M. Salem *[a,b] and Ahmed M. Khaira[a]

The rapid increase in energy consumption around the world is the main challenge that compromises and affects the environment. Electricity generation, which mainly depends on fossil fuels, produces around 80% of CO_2 emissions released into the atmosphere. Renewables are a remarkable alternative for energy production. However, they are intermittent sources of energy. Liquid air energy storage (LAES) is a medium-to large-scale energy system used to store and produce energy, and recently, it could compete with other storage systems (*e.g.*, compressed air and pumped hydro), which have geographical constraints, affect the environment, and have a lower energy density than that of LAES. However, the low efficiency, high payback periods, and profit values of LAES hamper its commercialization. LAES is premature to be fully studied because lack of actual operating conditions and results from large plants, which affect the techno-economic predictions, in turn, affecting technology commercialization. Furthermore, the off-design conditions are not fully covered although it is a crucial step in system performance evaluation. To this end, the current mini-review sheds light on the LAES design, history, types, limitations, and the associated techno-economic analysis. In addition, state-of-the-art modelling tools are widely explained with benefits and shortage. Furthermore, LAES integration with other systems is explained widely, as it was found to boost the system performance and increase the profit with lower payback periods.

Received 6th July 2023
Accepted 22nd August 2023

DOI: 10.1039/d3ra04506d

rsc.li/rsc-advances

1. Introduction

The gradual increase in energy demand in developed and emerging countries, besides rich countries, poses major challenges. The depletion of non-renewable/conventional energy sources (*i.e.*, oil, gas, and coal) is followed by the increase in global warming that comes from the ever-increasing emissions of greenhouse gases (GHG).[1,2] Consequently, it requires the managed and appropriate use of renewable energy sources. Renewable energy is commonly produced from solar, wind, tide, biomass, and geothermal sources.[3,4] A rapid increase in electricity generation depending on renewables has been recently found due to the policies of clean production that are followed in most countries.[5] It is advised that CO_2 emissions should be decreased by 90% by 2050,[6] so that the global warming effect could be reduced below 2 °C as advised. Therefore, the energy production sector will have to be fully decarbonized and dependency on renewables increased.

Unlike conventional energy, the renewable sources are clean, easily available, and inexhaustible. They are growing fast and do not require thousands of years to be formed. Therefore, based on researchers' expectations, it will replace many conventional energy sources and will majorly contribute to energy production around the world.[7,8] Clean and renewable energy sources are required to potentially solve the issues of global energy crisis and environmental pollution caused by the heavy use of fossil fuels.[9,10] During the COVID pandemic and quarantine situations around the world, the need to produce energy from renewables has raised. An increasing interest has risen with the exponential growth in fossil fuel depletion to meet the global needs especially for electricity production.[11,12] Renewable energy sources have several types *e.g.*, hydropower,[13] solar,[14] geothermal,[15] biomass,[9,16] and wind power.[17]

However, renewable energy sources have some limitations. They depend on weather conditions; besides, they do not support a continuous feed of energy supply (intermittent).[18–20] Additionally, they produce low electricity levels compared to fossil fuels. Furthermore, the imbalance between supply and demand, and lower capacity margin make it less flexible and could be major disadvantages to the energy production sector.[21] The utilization of natural, and unlimited energy resources from the environment with the aim of converting them into electricity, while ensuring the environmental aspect, gives renewable energy sources numerous advantages in their use, primarily the protection of environment. This is evident by the

---

[a] *Mechanical Power Department, Faculty of Engineering, Tanta University, Tanta, 31521, Egypt. E-mail: Ahmed_salem@f-eng.tanta.edu.eg*

[b] *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK*

fact that renewable energy sources account for almost zero percent of greenhouse gas emissions and other air pollution. A potential way to support integration of renewables' intermittency is the Electrical Energy Storage (EES).[22] The EES combines a wide technology and can be classified depending on the energy transfer and storage. For large-scale energy applications, the thermal and electro-mechanical storage systems are used. The dominant energy storage in the world is covered by pumped hydro storage (PHS), followed by compressed air technology (CAES).[23] However, such systems are strongly dependent on geographical constraints and, consequently, have environmental concerns.

Recently, air has been used alternatively for grid-scale energy storage in a technology named liquid air energy storage (LAES).[24] As a result, it started to draw the attention in research and academia. During off-peak, renewable energy is used to power the unit of air liquefaction, while, whenever energy is required, the liquefied air is pumped, and expanded through turbines to generate electricity.[25,26] LAES technology overcomes the limitation of PHS and CAES because it has no geographical limitations, the components are commercially available, and it has high energy density, besides it could be integrated with other energy production sources (hybrid units).[27] The PHS and CAES are mature technologies and have been built on a commercial scale so far. However, commercialization level, socio-economic aspects, and technical risks associated with energy storage systems are defining the maturity level of the technology.[22] As a result, LAES technology is still under industry demonstration level, and needs further development because of lower efficiency, liquid yield, and response time.[28]

LAES cycle performance is measured by different techniques including experimental and modelling aspects. Moreover, the techno-economic analysis plays a vital role in such systems. However, both modelling of the cycles and their economic and market influence are very limited in the literature.[29] The current LAES systems are designed with energy recovery units and/or other energy production *e.g.*, liquefied natural gas, Rankine, and ORC cycles. As a result, the techno-economic studies are carried out on hybrid systems. A hybrid LAES-CAES system study was carried out by ref. 30. The study proposed a control strategy to achieve maximum profit from the hybrid system. Kapila *et al.*[31] illustrated that the economic studies are not fully covered in most of the studies and only data and outcomes about the unit's capital cost and capacity are mentioned without any further detailed economic assessments.

Based on the abovementioned challenges, the current review will try to shed light on renewable energy sources with more critical focus on liquefaction, particularly air liquefaction systems. Comparisons with present systems (*e.g.*, PHS, and CAES) will be illustrated with reference to the previous studies reported in the literature. LAES principle, components, and cycles will be elaborated. The LAES performance, coupling, and heat recovery will also be further explained. The vital role of techno-economic analysis in LAES, and the system (hybrid, and poly) generation coupling will be illustrated. The modelling techniques in this field will also be discussed. Based on the literature review, modelling, economic, and market influences are very limited in previous studies. As a result, these challenges will be addressed to present the maturity development and limitations in LAES.

2. Energy storage systems, and types

Based on the discussion, literature review illustrated the renewable energy sources and their types, advantages, and disadvantages; the main issues that could tackle the direct use of renewable energy sources are their intermittency, besides a lower energy content than fossil fuel production. Consequently, the potential use of clean energy sources is still facing competitive efforts to increase its efficiency, transportation, and continuous/direct use. Remarkable solutions for intermittency are all focusing on energy storage systems.[32–34] However, energy storage systems gained widespread interest due to the need to store the produced energy for further continuous use when needed.

Different types are used for energy storage over the past few decades. The pumped hydro showed the major portion with nearly 99% (Fig. 1), followed by compressed air energy storage, and chemical energy storage systems.[36,37] PHES has the largest energy storage capacity. It uses the energy stored by pumping water uphill using the peak-off energy, while using the energy from water flowing downhill and driving the generator to produce electricity when needed.[38] However, PHES lacks finding a suitable place because of large reservoir required areas. Moreover, this will affect the land available and the nature environment. Although new approaches in building up an underground reservoir give more flexibility, but it is still under development and costly process.[39,40] Other energy storage system examples are flywheel energy storage (FES),[41] electrical energy storage,[42] thermal energy storage,[43] and hydrogen energy storage systems.[44]

3. Air liquefaction system

Liquefaction of a gas is a process by which a gaseous substance is converted into the liquid state. As the pressure of the gas increases, the molecules move closer together, and the temperature of the gas rises. In the process of gas liquefaction, the reduction in gas temperature requires additional cooling

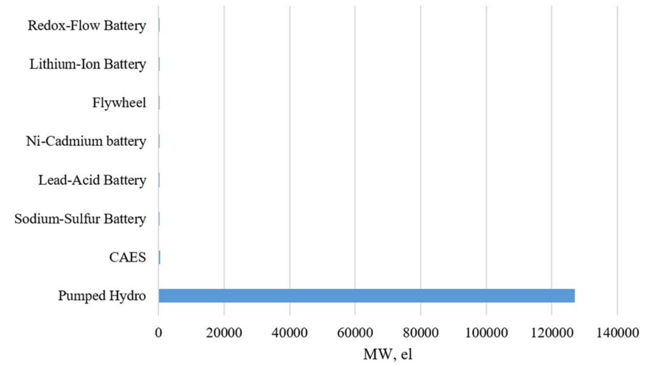

Fig. 1 Worldwide energy storage systems for electricity production.[35]

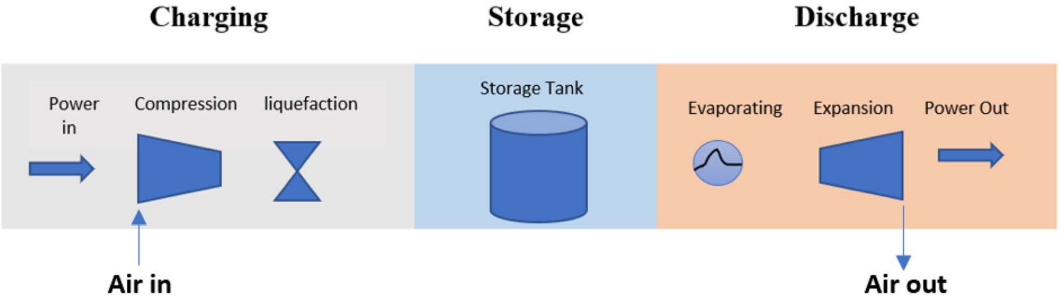

Fig. 2 LAES cycle principle of work.

operations. The critical pressure of a gas is the minimum pressure required to liquify a gas at the critical temperature. However, critical temperature of a gas is the temperature at or above which no amount of pressure will liquify the gas, no matter how high the pressure will be.[45,46] Such systems are called cryogenic energy storage (CES), which provide several advantages including mature technologies, small losses, and long-life cycle. Additionally, it is the only storage system that has no geographical constraints or environmental impacts.[26,47] CES systems use different gases for energy storage including H_2, CO_2, liquefied natural gas (LNG), and air. However, air seems to be the most widely used because of its availability everywhere and no additional costs of extraction or capture like other gases.

Air liquefaction is a specific case of CES, which gained widespread interest compared to other cryogenics. State-of-the art technology is still under development since no commercial plants have been built up.[48] LAES is still under development due to different factors including the technical risks associated, and the economic benefits.[22] Air is liquefied at around −195 °C and stored in cryogenic insulated tanks, *i.e.*, liquid air energy storage technology (LAES). Air is compressed, liquefied, and stored using renewable energy sources at off-peak times. However, when energy is required, the liquefied air is pumped and expanded into turbines after reheating to produce the required power.[49] LAES is a compact technology which does not use large storage volumes because of higher energy density compared to CAES or PHS. As a result, it can offer a large storage scale without any geographical constraints. Additionally, the cold from cryogenic could be used in different (co-recovery) applications such as refrigeration, frozen and chilled food.[23,50] The LAES first pilot plant (300 kW/2.5 MW h) was developed by the University of Leeds and Highview Power,[27] and further was patented by ref. 51. The plant used a liquefier based on a Linde–Hampson liquefaction cycle in which liquid air is stored in a low-pressure cryogenic tank.

3.1 Principle of the liquefaction process and its components

An air liquefaction cycle is mainly composed of 3 main phases: charging, storage, and discharge (Fig. 2). Air is compressed and cooled during off-peak times to form the liquid air, which was then stored in insulated tanks. The stored liquefied air could be used later in discharge cycle, whenever energy is required.

In a typical one-stage liquefaction process, air is compressed up to 40 bars, cooled down in a heat exchanger before expanding in a Joule–Thomson (J–T) valve, and then stored in a storage tank. During discharge, air is used to feed a combustor working with LNG, while the liquefied air is used to cool down the stream in a heat exchanger simultaneously.[52]

3.2 Liquid air energy storage cycles

Three main configurations of LAES cycles are commonly used in liquefaction systems, namely, Linde–Hampson, Claude, and Kapitza cycles. The following section will illustrate different components and arrangements for each showing the differences between them.

3.2.1 Linde–Hampson cycle. The Linde–Hampson cycle has a simple construction and is based on the vapor-compression refrigeration cycle. The main components are illustrated in Fig. 3.

Air is entering at the mixture point 1 to be compressed into high pressures (up to 20 MPa). The pressurized high-temperature stream (point 2) is cooled down at constant pressure in the heat exchanger to point 3 (liquid–gas mixture). Air is cooled down by the return stream from the liquid tank. The mixture (3) is then further cooled down in Joule–Thomson valve (isenthalpic expansion 3–4) to ambient pressure. The expansion process and pressure reduction result in temperature reduction and more liquid air to be formed. As a result, the mixture is separated where the liquid air is drained from the liquid tank, and the gaseous air is further used (recycled) in cooling down

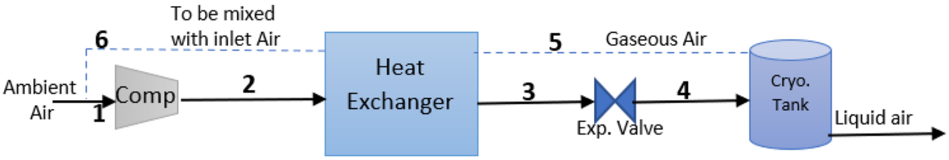

Fig. 3 Linde–Hampson air liquefaction cycle.

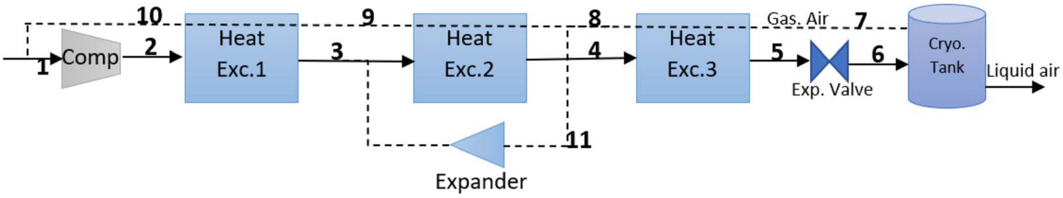

Fig. 4 Claude air liquefaction cycle.

the compressed air at the cycle inlet for optimizing the heat exchange process at the heat exchanger.

Several studies were conducted on the Linde–Hampson cycle.[53,54] They revealed that a minimum temperature should be achieved before the expansion valve. Otherwise, the liquid air will not be created. Such cycle is not commercially viable and is used on a very narrow scale because of several limitations including poor liquid yield, very high pressures, low exergy efficiency, and cycle irreversibility.[55] Therefore, the research carried out on this cycle is limited and further work has been carried out on Claude and Kapitza cycles.

3.2.2 Claude cycle. George Claude proposed the Claude cycle (Fig. 4) in 1902, with two-expansion mechanisms including the J–T valve, and a cryogenic turbine/expander. The system has a higher efficiency, with higher work production compared to Linde–Hampson cycle.

Fig. 4 shows the different parts of the Claude LAES cycle. Ambient air is mixed at point 1 with return air from the cold box (heat exchangers 1, 2, and 3), where it is compressed into intermediate pressures (up to 5 MPa). The compressed air with high temperature is cooled down in the first heat exchanger under constant pressure (process 2–3). Afterwards, a large fraction of the cold air (point 3) is passed through an expander (or cryoturbine) to generate power and expanded to the ambient pressure and low temperature (point 11), where it is further mixed with the return stream (point 8) to cool down air at the second heat exchanger. Process 3–11 is a simple isentropic expansion process. The cold air vapor (point 4) is cooled down in heat exchanger 3 to achieve the required temperature before flowing through the expansion valve. After the expansion valve, a mixture of vapor and liquid air needs to be separated before storing and reuse in the discharge cycle.

Claude cycle works in lower pressures, and lower specific consumption, with higher efficiencies compared to the Linde–Hampson cycle. However, it is very crucial to achieve the optimal recirculation fraction for every component (the expander and return vapor) to guarantee the liquid air production and optimum specific consumption at the maximum pressure (charging). The optimal recirculating fraction is the ratio between the mass flow rate through the expansion JT valve to the total mass flow rate entering the compressor.

3.2.3 Kapitza cycle. Kapitza carried out a modification on the Claude cycle where he removed the third heat exchanger, as shown in Fig. 5. Besides the economic design, the third heat exchanger does not achieve much cooling for the air before the JT valve.

The air flow after the first heat exchanger (point 3) is separated into two streams. The first stream is passed through the second heat exchanger and further expanded in the JT expansion valve. The second stream is expanded in a turbo-expander where Kapitza was the first to test and use such expander in a liquefaction cycle. The turbo-expander allows more power generation for the cycle with reducing air pressure and temperature to be used with the return vapor from the cryo-tank. Several studies further discussed the Kapitza cycle efficiency and enhancements.[45,56]

The comparison between the three cycles is illustrated by Table 1. For each cycle, the specific consumption, exergy efficiency, and operating optimal pressure are shown. The results indicated that Claude and Kapitza cycles have the higher efficiency with moderate pressures compared to the other cycles. Borri *et al.*[45] carried out a study for the optimal configuration and operating conditions for a LAES cycle, and compared between the use of Claude, Kapitza, and Linde–Hampson cycles. They showed that the lowest specific consumption is achieved for a single stage compression at 10 MPa, and 0.1 recirculating fraction. Additionally, they found that a two-stage

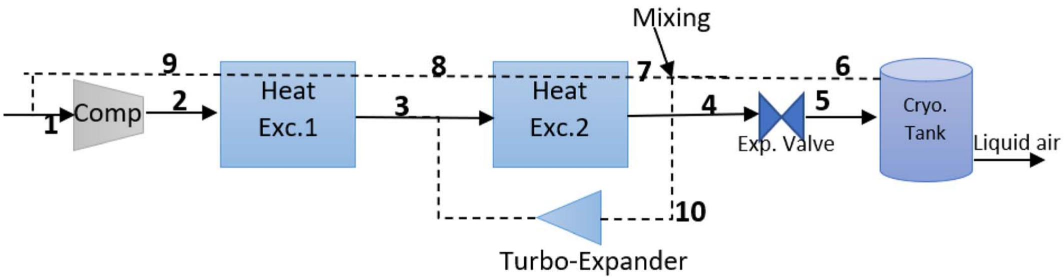

Fig. 5 Kapitza air liquefaction cycle.

Table 1 Comparison between the cycles' performance.[57,58]

Cycle	Heat storage	Cold storage	η_{RT}	η_{Ex}	P_{ch}	P_{dic}	SP. cons. (kW h kg^{-1})
Linde–Hampson	Thermal oil, pressurized water, or PBTES	Methanol-propane, PBTES, multi-component fluids, or propane, or PBTES	35–62	2.47	4–35	2–20	2.5–2.6
Precooled Linde–Hampson	Thermal oil, pressurized water, or ethylene glycol	Methanol-propane, methane-R218	—	2.47	20	10–16	2.5–2.6
Claude	Therminol oil	PBTES, or air generator	31–60	12.16	5–20	7.5–20	0.52–0.73
Kapitza	Therminol oil, or pressurized water	Air generator, PBTES-polypropylene and polyethylene	40–59.4	12.1	5.8–18	8–20	0.52–0.72

compression and the use of a pressurized phase separator help in reducing the specific work.

4. State-of-the-art modelling of LAES and hybrid systems

The mathematical modelling of LAES is still under development because of the wide variety of variables and machinery included, *e.g.*, compressors, heat exchangers, pumps, expansion valves, cryo-turbines, and packed bed thermal energy storage units. Several modelling tools are being used for simulation including MATLAB, ASPEN, COMSOL, and EES. The modelling is used for the units' design, linking components, and test system level performance. However, the highest challenge is dedicated to increase the plant round trip efficiency, and liquid yield. Consequently, LAES cycles are integrated and coupled with other power cycles to increase their overall exergy.

4.1 LAES modelling

Li *et al.*[59] introduced an algorithm optimization method to model and optimize the exergy efficiency of LAES. While Guizzi *et al.*[60] proposed a thermodynamic model for LAES to study the round-trip efficiency. They found that a round trip efficiency could be increased up to 55% with the recent technologies. However, Sciacovelli *et al.*[6] developed a novel model to test the performance of LAES. They used a hybrid modelling approach to describe each component in the system. The charge and discharge cycles were modelled using the EES software,[61] where the conservation of mass, momentum, and energy was specified. Additionally, the packed beds for cold storage were modelled using COMSOL.[62] Furthermore, the MATLAB environment was used to load and run different parts of the model when required. The model was validated against experimental data and found Fair agreement. They found that LAES efficiency was increased by 50% for the use of packed beds. In a recent study by S. Wu *et al.*,[63] they proposed an integrated system for LAES and thermochemical energy storage. The system was built and examined using the ASPEN PLUS software, where it showed energy density and round-trip efficiency higher by 34%, and 13.3% than those of a standalone LAES system.

A hybrid model of LAES and refrigeration system was modelled using NIST REFPROP by a basic thermodynamic modelling method.[64] The results were verified using the ASPEN HYSYS model as a part of the CRYOHUB European research project. The model describes the liquefaction, cold-energy storage, and discharge cycles. It was further used to discuss the parametric analysis to achieve better performance and round-trip efficiency.

A recent hybrid LAES with ORC was built based on LNG utilization.[65] They proposed a mathematical model including exergy and energy analysis to study the cycle performance and its influence on the key parameters. The ASPEN HYSIS software was used in the model, and the results indicated a higher density and electricity energy storage. Peng *et al.*[66] recovered the cold energy released during the process of LNG and used it in LAES cycle. They developed a MATLAB model coupled with ASPEN assuming a steady state with no heat losses in piping. They achieved higher liquid yield (~89%), lower power consumption (~32%), and higher exergy efficiency (~28%) less than those of a standalone LAES respectively, with a round trip efficiency (78–89%) compared to (~60%) of the LAES systems.

A novel integrated system of LAES with the Kalina power cycle and a thermo-electric generator was developed by ref. 67. Such system proved to increase the development of renewable engines, LAES, and assists in the grid stability. The analysis showed an increase in round trip efficiency up to 61.6%. Additionally, the system has a total storage energy density (~109.4 MJ m^{-3}). During the economic book-life of the proposed green system, it indicates a payback time of 3.5 years and a profit of $26 million.

An integrated system for LAES with a combined power plant was introduced by ref. 68. The thermodynamic model is proposed to recover the wasted heat and cold energy for peak shaving. It investigates the effect of ambient, inlet temperatures, and NG pressure on the system, and achieved the highest system efficiency of 99.39%.

Vecchi *et al.*[69] proposed thermodynamic modelling off-design for LAES to understand the market requirements and system performance. The model was designed and validated against experimental data reported in the literature. The model could carry out an assessment for the LAES to add to the electricity grid and markets and provide support for low-carbon power system development. They found that liquid air consumption and round-trip efficiency are varying up to 30% at the off-design operation, which might lead to £10 per kW of missed revenue. Additionally, the off-design is affecting all LAES components with the turbines mostly affected with low pressures.

To the best of authors' knowledge and based on the state-of-the-art of LAES modelling, a LAES system has low round-trip efficiency, and liquid yield. As a result, the studies recommend the coupling of modern LAES with other power cycles (*e.g.*, LNG, Rankine, ORC, thermo-chemical, and refrigeration). Such integrated systems have high round-trip efficiency, exergy, and liquid yield. Additionally, the modelling tools in the off-design area are scarce and need further development. The profit, payback, and economic analysis of the integrated cycles will further be discussed in the following section.

4.2 Novel LAES systems and its hybridization

Nuclear power system flexibility is introducing a wider variety of integration for renewable energy systems. A novel system for the mechanical integration of nuclear station with LAES is proposed by ref. 70 to achieve higher flexibility and economic viability of the whole system. During off-peaks, the energy is recovered by evaporation and expansion through the LAES system, while both the integrated and stand-alone LAES systems are examined for comparison. During off-peak hours, the excess steam from the nuclear plant is used to drive steam turbines coupled with the air compressors of the LAES, whereas during peak hours, the stored energy is released by evaporation and expansion. Thermodynamic and economic analyses for both systems were performed to examine the proposed system. The results show that energy density and round-trip efficiency for the proposed cycle were 116 kW h m^3 and 51% respectively, which are competitive to the grid scale applications. The estimated levelized cost of stand-alone LAES and the integrated system were 219, and 182.6 $ per MW h respectively with 17% reduction in costs of the LAES cycle. The proposed system is expected to achieve better performance, lower costs, and gives potential for renewable energy integration with the grid scale sizes.

Another recent study by ref. 71 examined the feasibility of sub-critical LAES systems in terms of exergy, economic, exergo-economic, energy, and environmental impacts. The design was aimed to minimize the costs of the LAES cycle to reduce the complexity, improve its performance, and recover the waste exergy during the regasification of natural gas in the terminals. Additionally, a comparison with five different systems was carried out as follows: the conventional LAES, CAES with single- and two-stage expansion, and a combination of artificial neural networks with genetic algorithms. The optimal proposed design was able to store during off-peak and generate power during peak hours by 27.2, and 182.7 MW h respectively. The system round trip and exergy efficiencies were 77.1, and 68.8% respectively. They showed that the system payback period was 1.8 years with a net profit of $151 M. Furthermore, for optimum conditions, the total cost was 461 $ per h, and the round-trip efficiency was 68%.

LAES is also integrated and driven by biomass gasification for heat and power generation. A novel system is introduced by ref. 72 using a thermoelectric generator and domestic hot water for waste heat recovery during the compression process. The proposed system compresses 1 kg s^{-1} of air by consuming 3964 kW h during the charging, which generates 3795 kW h of heat and 9041 kW h of power. The system has energy and exergy efficiencies of 79.2% and 51.8% respectively. They reported that the gasification unit is responsible of 65% of the whole system exergy. However, the optimization data of the plant shows that the novel system is able to provide constant power for three days in February, July, and December by 2615, 120.4, and 1425 MW respectively. Additionally, for December and February, the system income from electric generation was estimated to be 1 M$, while it was 20.045 M$ in July.

An off-design LAES modelling system was proposed by ref. 73 to decarbonize the increasingly distributed systems of energy. The system was integrated with a micro-grid mixed integer programming framework. The integrated system aims to investigate the optimum ratio of energy to power of the LAES cycle, optimal sizing for the units, and achieve the balanced environmental and economic benefits. They reported that optimum charge/discharge energy to power is 27/14 h with 75% obtained wind power. As a result, it leads to 60% reduction in carbon emissions. The model importance was concluded in its ability for micro-grid hybrid-LAES application design and

Table 2 State-of-the-art advances in integrated LAES systems

System	η_{RT}, %	Cost, units vary	Ref.
LAES	56.8	219 $ per MW h	70
LAES-nuclear	51	182.6 $ per MW h	70
Sub-critical LAES	68.8	461 $ per h	71
LAES-biomass gasification	79.2	—	72
Pumped thermal-LAES	58.7–63.8	—	74
Poly generation LAES	63.6	9.51×10^7 US$	75
AI for LAES-gas turbine	83	Up to 300 $ per MW h	76
LAES-ORC-CHP	—	—	77
H_2 liquefaction-LAES	58.9	7.0 $ per kg LH_2, total $135 M	78
Transcritical CO_2-LAES	59.9–66.26%	—	79
Biomethane liquefaction-LAES	—	$6.3 M	80
Solar-LAES	90.49	—	81
Solar-LAES-ORC	73.33	143.4 $ per MW h	82

prediction of different scenarios under design and off-design conditions.

Recent research by ref. 74 introduced a novel system for pumped thermal system integrated with the LAES (PTLAES). The proposed system converts electricity into liquid air and heat during off-peak hours and re-convert them again into electricity during peak hours. The integrated system offers a high density for the energy storage. Three integrated systems for the PTLAES were introduced and thermodynamically studied including the basic cycle, precooled, and multi-stage under different pressures. The proposed systems introduced higher round trip efficiencies between 58.7 and 63.8%, while the energy storage density reached values up to 107.6 kW h m^3 when the basalt was used as a thermal storage medium which is 1.3–2 times higher than LAES systems.

Another research by ref. 75 introduced the integration of flash desalination with the LAES for poly-generation. They conducted exergy, energy, economic, and environmental assessments for the proposed design. The system was able to provide heat, cooling, electricity, hydrogen, sodium hypochlorite, and fresh water. The integrated system was composed of three main subsystems: multi-stage flash desalination, LAES, and CCHP unit. The round trip and exergy efficiencies were reported to be 63.6% and 61% respectively. Additionally, the system was able to produce hydrogen, fresh water, and sodium hypochlorite by 10.2×10^5 m^3 per year, 4.8×10^3 m^3 per year, and 43.2 tons/year respectively. The economic evaluation of the integrated system showed a payback period of 3.4 years, whereas the highest costs were towards the LAES system (~92.1%).

The recent advances of the integrated systems with LAES are further presented in Table 2 where the highest round-trip efficiencies are found for solar integrated systems because of their lower input energy consumption, followed by gasification units and waste heat recovery.

5. LAES market and economy (techno-economic analysis)

Although the current deployment of energy storage is around 164 GW h, it is estimated that it will reach an annual combined deployment of 3046 GW h, and a market value of $546 billion by 2035.[83] Three main sectors of energy storage – mobility, electronics, and stationary storage – are the most well known and used currently and in future, as illustrated in Fig. 6.

Electronic devices (*e.g.*, cell phones, laptops, and drones) are the most familiar in the market of energy storage, which is expected to increase its growing opportunities in future. However, mobility applications such as battery electric vehicles and fuel cells are expanding in manufacturing for increasing its applications and work, whereas the stationary storage systems are widely increasing to support renewables market and meet the grid demands. LAES is classified as a stationary unit, which is expected to grow from $9.1 to $111.8 billion from 2019 to 2035 (Table 3).

LAES technology will have the potential for increasing the grid capacity and lowering energy prices using power generated from renewables. Liquid air could satisfy many energy needs at the same time, *e.g.*, energy production, cooling, and heating in poly-generation systems.[85] LAES also have a high energy density (~5 times) compared to CAES.[50] However, it has to be coupled with other energy recovery systems to achieve economic benefits and revenue.

Hamdy *et al.*[86] carried out exergy and economic analysis of a 100 MW/400 MW h LAES plant. They found that the storage cost could be reduced by 27% with a round trip efficiency

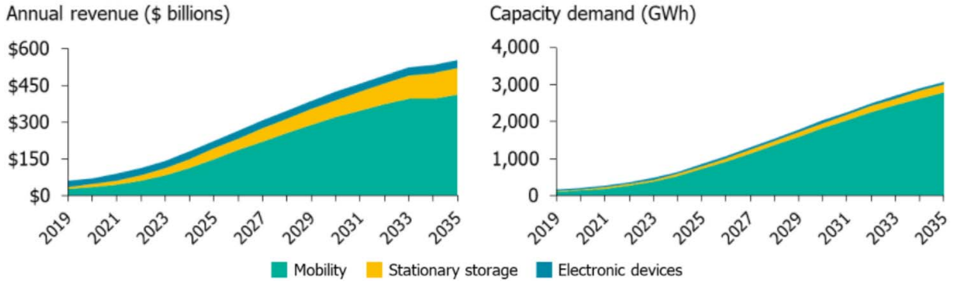

Fig. 6 Total energy storage market forecast.[84]

Table 3 Energy storage market and capacity demand in the next 15 years[84]

	Electronic devices	Personal mobility	Stationary
Market, 2019	$24 billion	$24 billion	$9.1 billion
Market, 2035	$32 billion	$32 billion	$111.8 billion
Capacity demand, 2019	39 GW h	38 GW h	12.5 GW h
Capacity demand, 2035	72 GW h	175.5 GW h	222.7 GW h

Table 4 Techno-economic analysis of LAES integrated systems

System/size	η_{RT}, %	Payback, years	Profit, $M	Ref.
LAES (200 MW)	37.38	36.9–39.4	18.6	59, 60 and 86
Solar (54 MW)	54.05	2.42	137.4	94
LNG (122.2 MW)	78–106	5.7	369.88	65, 92 and 96
Waste heat (200 MW)	50	8.7–9.8	180	89 and 91
Refrigeration (54.81 MW)	71	2.7–3.1	—	64 and 97
Kalina, absorption (5.3 MW)	65.7	3.6	11.3	95

penalized by 7% point. While Zhang *et al.*[65] in their LAES-LNG integrated plant have concluded that this combined plant could increase the storage efficiency by 70%. Other recent studies show similar results for hybrid cycles and recovery systems with LAES, *e.g.*, see ref. 87 and 88.

Lin *et al.*[89] introduced a methodology for evaluating the economic aspects and viability of LAES based on price variations in the UK. They used algorithm for predicting price threshold every 30 minutes under different working conditions. The algorithm is further used in making decisions of the system to charge, discharge, or standby. They found that a 200 MW system of LAES could achieve a net present value of £43.8 M. Additionally, without considering waste heat recovery, the payback period of the 200 MW system could be up to 36.9–39.4 years, whereas if the waste heat is recovered with 150 °C, the payback period will be short as 8.7–9.8 years. Compared to the 300 MW/1800 MW h pumped hydro storage plant[90] with a payback period >40 years, the LAES is very promising, as the payback period could be shortened to 9.8 years with the use of waste heat. However, Xie *et al.*[91] studied the economic feasibility of a hybrid energy storage system considering the market effect. They proposed a methodology for sizing the optimization of individual system components, *e.g.*, charging, discharging, and storing. As a result, it was used to find economic objectives and optimize the net present value from linking such systems with the grid. They found that the payback period could be varied between 5.6 and 25.7 years for a 200 MW system considering making use of the waste heat (0–250 °C). A LAES system can achieve higher profit only by integrating the waste heat or increasing the system scale. Therefore, it always requires higher economic feasibility to integrate LAES with other systems for heat recovery (waste heat, or cold).

An environmental analysis and a thermo-economic study were carried out for a hybrid LAES-LNG regasification and combustion plant.[92] The techno-economic analysis was compared with an adiabatic CAES and a standalone LAES system. The hybrid system showed a higher round-trip efficiency (~74.3%), which proved the good economic performance of the hybrid design.

While Mazzoni *et al.*[93] compared the benefits of using (300–2000 kW h) electrochemical and LAES systems for a building. The cost–benefit analysis and economic dispatch were evaluated, where the electrochemical system shows a relatively higher round-trip efficiency. However, the LAES was a more economic and viable option because of lower capital costs.

In another research,[94] they integrated the LAES with concentrated solar power to study the effect on environment and cycle performance. They found that during peak times, the system could produce a power of 53.9 MW and hot water of 55 kg s^{-1} for domestic use. Higher round trip and exergy efficiencies were achieved as 54.05% and 46.51%, respectively. It also showed a decrease in CO_2 production by 5100 tons for an annual power generation of 25 GW h when applied to San Diego as a case study. Their economic evaluation showed a profit of 137.4 $M, and a payback period of 2.42 years.

A green multi-generation system based on integrating LAES, Kalina cycle, and absorption cycle was proposed by ref. 95. The system can produce cooling and electric power during peak periods. They found that during 3 h, the system can produce 5300 kW, with round trip and exergy efficiencies of 65.7% and 49.7%, respectively. The economic analysis illustrated that a payback period of the system was estimated to be 3.6 years with a profit of $11.3 M by the end of 25 years.

The data illustrated in Table 4 demonstrate the techno-economic effect of LAES hybridization with other power systems. LAES as a standalone system has a poor performance in terms of round-trip efficiency, payback years, and system profit. As a result, for the same system size of 200 MW, the system integration with waste heat recovery shows an increase in round-trip efficiency by 37% than LAES, with a higher profit value and a lower payback time. This is because of maximizing the use of waste energy and increasing overall system exergy. The highest efficiencies (up to 106%) are found for LNG coupling because of higher energy density and content. Additionally, the very low temperatures of LNG (~−150 °C) allows the maximum use for cooling the air in the cold box, and hence, turns it into liquid air. LAES system integration with LNG, solar, waste heat, and refrigeration shows an increase in round-trip efficiency, although different scales are used in comparison. In turn, it shows a lack of economic studies and large-scale data of such systems.

6. Conclusion

The current study discussed different types of renewable energy sources, with their main limitation of intermittency. Liquid air energy storage (LAES) has recently been an attractive solution for energy storage. It is able to compete with other familiar energy storage systems such as CAES, and PHE. The technology has no geographical limitations (like CAES and PHE), its components are commercially available, with high energy density, and it is possible to be used and integrated with other technologies. However, commercial scale units are starting to find its way in the market with economic benefits because of the lower round trip efficiency. LAES types, components, modelling techniques, and techno-economic analysis for standalone and hybrid systems were all carried out in this study, which conclude the following:

- LAES is a novel technology that can afford energy storage with medium and large scale for grid connection and other industrial applications for full/part loads.
- LAES is strongly affected by market requirements and service provided.
- Off-design conditions are not fully covered and do not support the required performance of the LAES system. However, off-design is an important step for the economic assessment and relative financial values. This field needs to be fully covered because of limited previous research and data.
- Highest round-trip efficiencies are found for LNG-solar integrated systems because of lower input energy requirements, followed by the integrated gasification and waste heat recovery.
- Techno-economic analysis suggests the hybridization of LAES and the use of other power cycle integration to increase its performance (efficiency, liquid yield, cost, and electricity prices).
- Payback periods vary between ∼2 and 40 years depending on the system size and level of hybrid units connected with LAES.
- The state-of-the-art technology is still under development (prototypes), because of lack of actual operating conditions and results from large plants, which, in turn, affect the techno-economic predictions.
- The mathematical modelling of LAES is still under development because of the wide variety of variables and machinery included. Most modelling focus on increasing plant exergy and efficiency.

Conflicts of interest

The authors have no conflicts to declare.

References

1 A. M. Salem, Recycling Exhaust Emissions of Internal Combustion Engines Within the Gasification Systems: Performance and Analysis, *Fuel*, 2023, **346**, 128297.

2 A. M. Salem and K. Elserbiny, Innovative concept for the effect of changing gasifying medium and injection points on syngas quality: towards higher H2 production, and free-CO2 emissions, *Energy*, 2022, **26**(B), 125416.

3 K. Bekhrad, A. Aslani and T. Mazzuca-Sobczuk, Energy security in Andalusia: the role of renewable energy sources, *Case Stud. Chem. Environ. Eng.*, 2020, **1**, 100001.

4 M. Antonelli, S. Barsali, U. Desideri, R. Giglioli, F. Paganucci and G. Pasini, Liquid air energy storage: potential and challenges of hybrid power plants, *Appl. Energy*, 2017, **194**, 522–529.

5 G. Ren, J. Liu, J. Wan, Y. Guo and D. Yu, Overview of wind power intermittency: impacts, measurements, and mitigation solutions, *Appl. Energy*, 2017, **204**, 47–65.

6 A. Sciacovelli, A. Vecchi and Y. Ding, Liquid air energy storage (LAES) with packed bed cold thermal storage-from component to system level performance through dynamic modelling, *Appl. Energy*, 2017, **190**, 84–98.

7 D. Azhgaliyev, A. Kapor and A. Liu, Green bonds for financing renewable energy and energy efficiency in South-East Asia: a review of policies, *J. Sustainable Finance Invest.*, 2020, **10**(2), 113–140.

8 A. M. Salem, I. N. Zaini, M. C. Paul and W. Yang, The evolution and formation of tar species in a downdraft gasifier: numerical modelling and experimental validation, *Biomass Bioenergy*, 2019, **130**, 105377.

9 A. Salem, Investigation of biomass gasification processes for the production of high quality syngas, *PhD thesis*, Glasgow, UK, University of Glasgow, 2020.

10 A. M. Salem, Recycling exhaust emissions of internal combustion engines within the gasification systems: performance and analysis, *Fuel*, 2023, **346**, 128297.

11 G. Papageorgiou, Thinking Green: Sustainable Polymers from Renewable Resources, *Polymers*, 2018, **10**(9), 952, DOI: **10.3390/polym10090952**.

12 C. Day and G. Day, Climate change, fossil fuel prices and depletion: The rationale for a falling export tax, *Econ. Modell.*, 2017, **63**, 153–160.

13 N. F. Yah, A. N. Oumer and M. S. Idris, Small scale hydro-power as a source of renewable energy in Malaysia: a review, *Renewable Sustainable Energy Rev.*, 2017, **72**, 228–239.

14 H. L. Zhang, J. Baeyens, J. Degrève and G. Cacères, Concentrated solar power plants: Review and design methodology, *Renewable Sustainable Energy Rev.*, 2013, **22**, 466–481.

15 F. D. Longa, *et al.*, Scenarios for geothermal energy deployment in Europe, *Energy*, 2020, **206**, 118060.

16 A. M. Salem, U. Kumar, A. N. Izaharuddin, H. Dhami, T. Sutardi and M. C. Paul, *Advanced Numerical Methods for the Assessment of Integrated Gasification and CHP Generation Technologies*, Springer, 2018, pp. 307–330, ISBN: 978-981-10-7334-2.

17 S. Yannopoulos, *et al.*, Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide, *Water*, 2015, **7**, 5031–5060.

18 H. Zsiborács, *et al.*, Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040, *Electronics*, 2019, **8**(7), 729.

19 S. Xu and Q. Xu, Optimal pricing decision of tradable green certificate for renewable energy power based on carbon-electricity coupling, *J. Cleaner Prod.*, 2023, **410**, 137111.

20 M. I. Hossain, M. Shafiullah and M. A. Abido, Battery Power Control Strategy for Intermittent Renewable Energy Integrated Modular Multilevel Converter-Based High-Voltage Direct Current Network, *Sustainability*, 2023, **15**(3), 2626.

21 Carbon Trust – Imperial College London, *Can Storage Help Reduce the Cost of a Future UK Electricity System?*, 2015 **https://www.carbontrust.com/resources/reports/technology/energy-storage-report/**.

22 X. Luo, J. Wang, M. Dooner and J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, *Appl. Energy*, 2015, **137**, 511–536.

23 IRENA, *International Renewable Energy Agency, Electricity Storage And Renewables: Costs and Markets to 2030*, 2017.

24 B. Castellani, P. Kaur, A. Sciacovelli, F. Rossi and Y. Ding, Microgrid application of liquefied air energy storage (LAES) systems, *J. Phys.: Conf. Ser.*, 2023, **2509**, 012021.

25 B. Ameel, *et al.*, Thermodynamic analysis of energy storage with a liquid air Rankine cycle, *Appl. Therm. Eng.*, 2013, **52**, 130–140.

26 G. L. Guizzi, M. Manno, L. M. Tolomei and R. M. Vitali, Thermodynamic analysis of a liquid air energy storage system, *Energy*, 2015, **93**(2), 1639–1647.

27 Highview Power, *Highview Power Storage Technology and Performance Review*, 2012.

28 H. Ansarinasab, M. Fatimah and Y. Khojasteh-Salkuyeh, Performance improvement of air liquefaction processes for liquid air energy storage (LAES) using magnetic refrigeration system, *J. Energy Storage*, 2023, **65**, 107304.

29 A. Tafone, A. Romagnoli, Y. Li, E. Borri and G. Comodi, Techno-economic analysis of a liquid air energy storage (LAES) for cooling application in hot climates, *Energy Procedia*, 2017, **105**, 4450–4457.

30 A. J. Pimm, S. D. Garvey and B. Kantharaj, Economic analysis of a hybrid energy storage system based on liquid air and compressed air, *J. Energy Storage*, 2015, **4**, 24–35.

31 S. Kapila, A. O. Oni and A. Kumar, The development of techno-economic models for large-scale energy storage systems, *Energy*, 2017, **140**, 656–672.

32 T. R. Ayodele and A. S. O. Ogunjuyigbe, Mitigation of wind power intermittency: Storage technology approach, *Renewable Sustainable Energy Rev.*, 2015, **44**, 447–456.

33 J. P. Barton and D. G. Infield, Energy storage and its use with intermittent renewable energy, *IEEE Trans. Energy Convers.*, 2004, **19**(2), 441–448.

34 S. Teleke, M. E. Baran, S. Bhattacharya and A. Q. Huang, Rule-Based Control of Battery Energy Storage for Dispatching Intermittent Renewable Sources, *IEEE Trans. Sustainable Energy*, 2010, **1**(3), 117–124.

35 F. Yasmeen, Techno Economical Analysis of Solid Oxide Iron-Air Redox Battery for Power Generation and Energy Storage, *Master's thesis*, 2016, Retrieved from, **https://scholarcommons.sc.edu/etd/3613**.

36 U.S. Department of Energy, *Officie of Renewable Eergy & Energy Efficiency*, Online, available: **https://www.energy.gov/eere/water/pumped-storage-hydropower**.

37 K. C. Divya and J. Østergaard, Battery energy storage technology for power systems—an overview, *Electr. Power Syst. Res.*, 2009, **79**(4), 511–520.

38 G. C. Furtado, *et al.*, Using hydropower waterway locks for energy storage and renewable energies integration, *Appl. Energy*, 2020, **275**, 115361.

39 B. Lu, M. Stocks, A. Blakers and K. Anderson, Geographic information system algorithms to locate prospective sites for pumped hydro energy storage, *Appl. Energy*, 2018, **222**, 300–312.

40 W. F. Pickard, The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage, *Proc. IEEE*, 2012, **100**(2), 473–483.

41 **http://www.activepower.com/**.

42 C. Xie, *et al.*, A Low-Cost Neutral Zinc–Iron Flow Battery with High Energy Density for Stationary Energy Storage, *Communication*, 2017, 14953–14959, DOI: **10.1002/anie.201708664**.

43 A. Sharma, V. V. Tyagi, C. R. Chen and D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renewable Sustainable Energy Rev.*, 2009, **13**(2), 318–345.

44 C. Acar and I. Dincer, Review and evaluation of hydrogen production options for better environment, *J. Cleaner Prod.*, 2019, **218**, 835–849.

45 E. Borri, A. Tafone, A. Romagnoli and G. Comodi, A preliminary study on the optimal configuration and operating range of a "microgrid scale" air liquefaction plant for Liquid Air Energy Storage, *Energy Convers. Manage.*, 2017, **143**, 275–285.

46 H. Ozcan and I. Dincer, Thermodynamic modeling of a nuclear energy based integrated system for hydrogen production and liquefaction, *Comput. Chem. Eng.*, 2016, **90**, 234–246.

47 M. Antonelli, *et al.*, Liquid air energy storage: Potential and challenges of hybrid power plants, *Appl. Energy*, 2017, **193**, 522–529.

48 C. Damak, D. Leducq, H. M. Hoang and D. Negro, Liquid Air Energy Storage (LAES) as a large-scale storage technology for renewable energy integration – a review of investigation studies and near perspectives of LAES, *Int. J. Refrig.*, 2020, **110**, 208–218.

49 G. Brett, and M. Barnett, The application of liquid air energy storage for large scale long duration solutions to grid balancing, in *Proceedings of the EPJ Web of Conferences*, EDP Sciences, 2014, vol. 79.

50 H. Chen, *et al.*, Progress in electrical energy storage system: a critical review, *Prog. Nat. Sci.*, 2009, **19**, 291–312.

51 H. Chen, Y. Ding, T. Peters and F. Berger, Method of storing energy and a cryogenic energy storage system, *US Pat.*, 15/053840, 2016.

52 K. Chino and H. Araki, Evaluation of energy storage method using liquid air, *Heat Transfer – Asian Res.*, 2000, **29**, 347–357.

53 B. Ameel, *et al.*, Thermodynamic analysis of energy storage with a liquid air Rankine cycle, *Appl. Therm. Eng.*, 2013, **52**, 130–140.

54 X. D. Xue, *et al.*, Thermodynamic analysis of a novel liquid air energy storage system, *Phys. Procedia*, 2015, **67**, 733–738.

55 T. Howe, A. Pollman and A. Gannon, Operating range for a combined, building-scale liquid air energy storage and expansion system: energy and exergy analysis, *Entropy*, 2018, **20**(10), 770, DOI: **10.3390/e20100770**.

56 R. F. Abdo, H. T. C. Pedro, R. N. N. Koury, L. Machado, C. F. M. Coimbra and M. P. Porto, Performance evaluation

of various cryogenic energy storage systems, *Energy*, 2015, **90**, 1024–1032.

57 O. O'Callaghan and P. Donnellan, Liquid air energy storage systems: a review, *Renewable Sustainable Energy Rev.*, 2021, **146**, 111113.

58 N. Wen and H. Tan, Modelling and optimization of liquid air energy storage systems with different liquefaction cycles, *Energy Convers. Manage.*, 2022, **271**, 116321.

59 Y. L. Li, X. Wang and Y. L. Ding, An optimal design methodology for large-scale gas liquefaction, *Appl. Energy*, 2012, **99**(6), 484–490.

60 G. L. Guizzi, M. Manno, L. M. Tolomei and R. M. Vitali, Thermodynamic analysis of a liquid air energy storage system, *Energy*, 2015, **93**, 1639–1647.

61 S. Klein, and G. Nellis, *Mastering EES; F-Chart Software*, 2014.

62 COMSOL Multiphysics, https://www.comsol.com/comsol-multiphysics.

63 S. Wu, C. Zhou, E. Doroodchi and B. Moghtaderi, Techno-economic analysis of an integrated liquid air and thermochemical energy storage system, *Energy Convers. Manage.*, 2020, **205**, 112341.

64 D. Negro, *et al.*, Modelling of liquid air energy storage applied to refrigerated cold stores, in *5th IIR International Conference on Sustainability and the Cold Chain*, Beijing, China, 2018, pp. 6–8.

65 T. Zhang, *et al.*, Thermodynamic analysis of a novel hybrid liquid air energy storage system based on the utilization of LNG cold energy, *Energy*, 2018, **155**, 641–650.

66 X. Peng, *et al.*, Liquid air energy storage flexibly coupled with LNG regasification for improving air liquefaction, *Appl. Energy*, 2019, **250**, 1190–1201.

67 M. H. Nabat, S. Sharifi and A. R. Razmi, Thermodynamic and economic analyses of a novel liquid air energy storage (LAES) coupled with thermoelectric generator and Kalina cycle, *J. Energy Storage*, 2022, **45**, 103711.

68 Z. Gao, W. Ji, L. Guo, X. Fan and J. Wang, Thermo-economic analysis of the integrated bidirectional peak shaving system consisted by liquid air energy storage and combined cycle power plant, *Energy Convers. Manag.*, 2021, **234**, 113945.

69 A. Vecchi, Y. Li, P. Mancarella and A. Ciacovelli, Integrated techno-economic assessment of Liquid Air Energy Storage (LAES) under off-design conditions: links between provision of market services and thermodynamic performance, *Appl. Energy*, 2020, **262**, 114589.

70 J. H. Park, J. Y. Heo and J. I. Lee, Techno-economic study of nuclear integrated liquid air energy storage system, *Energy Convers. Manage.*, 2022, **251**, 114937.

71 S. B. Mousavi, M. H. Nabat, A. R. Razmi and P. Ahmadi, A comprehensive study and multi-criteria optimization of a novel sub-critical liquid air energy storage (SC-LAES), *Energy Convers. Manage.*, 2022, **258**, 115549.

72 Y. Cao, S. B. Mousavi and P. Ahmadi, Techno-economic assessment of a biomass-driven liquid air energy storage (LAES) system for optimal operation with wind turbines, *Fuel*, 2022, **324B**, 124495.

73 T. Liang, *et al.*, The optimal design and operation of a hybrid renewable micro-grid with the decoupled liquid air energy storage, *J. Cleaner Prod.*, 2022, **334**, 130189.

74 L. Wang, *et al.*, Thermodynamic analysis and optimization of pumped thermal–liquid air energy storage (PTLAES), *Appl. Energy*, 2023, **332**, 120499.

75 F. Esmaeilion, M. Soltani, M. B. Dusseault and M. A. Rosen, Performance investigation of a novel polygeneration system based on liquid air energy storage, *Energy Convers. Manage.*, 2023, **227**, 116615.

76 A. Ghaseminejad, E. Hajidavalloo and A. Azimi, Artificial intelligence-based multi-objective optimization of a liquid air energy storage system integrated with gas turbine plants for peak shaving, *Int. J. Energy Res.*, 2022, **46**(15), 21397–21417.

77 W. Zhou, *et al.*, Low-carbon economic dispatch of integrated energy system considering carbon trading mechanism and LAES-ORC-CHP system, *Front. Energy Res.*, 2023, **11**, 1134221.

78 Y. Yang, *et al.*, A novel integrated system of hydrogen liquefaction process and liquid air energy storage (LAES): energy, exergy, and economic analysis, *Energy Convers. Manage.*, 2023, **280**, 116799.

79 A. Dzido, M. Wołowicz and P. Krawczyk, Transcritical carbon dioxide cycle as a way to improve the efficiency of a liquid air energy storage system, *Renewable Energy*, 2022, **196**, 1385–1391.

80 A. Rehman, *et al.*, Integrated biomethane liquefaction using exergy from the discharging end of a liquid air energy storage system, *Appl. Energy*, 2020, **260**, 114260.

81 D. Li and L. Duan, Design and analysis of flexible integration of solar aided liquid air energy storage system, *Energy*, 2022, **259**, 125004.

82 X. Ding, L. Duan, Y. Zhou, C. Gao and Y. Bao, Energy, exergy, and economic analyses of a new liquid air energy storage system coupled with solar heat and organic Rankine cycle, *Energy Convers. Manag.*, 2022, **266**, 115828.

83 P. Gordon, Energy storage market to grow to $546 billion by 2035, *Smart Energy International*, 2020, vol. 26.

84 Lux Research, 2019, https://www.luxresearchinc.com/press-releases/lux-predicts-energy-storage-market-will-hit-500-billion-by-2035.

85 E. Borri, A. Tafoni, A. Romagnoli and G. Comodi, A review on liquid air energy storage: history, state of the art and recent developments, *Renewable Sustainable Energy Rev.*, 2021, **137**, 110572.

86 S. Hamdy, T. Morosuk and G. Tsatsaronis, Exergetic and economic assessment of integrated cryogenic energy storage systems, *Cryogenics*, 2019, **99**, 39–50.

87 T. Zhang, X. L. Zhang, Y. L. He, X. D. Xue and S. W. Mei, Thermodynamic analysis of hybrid liquid air energy storage systems based on cascaded storage and effective utilization of compression heat, *Appl. Therm. Eng.*, 2020, **164**, 114526.

88 T. H. Cetin, M. Kanoglu and N. Yanikomer, Cryogenic energy storage powered by geothermal energy, *Geothermics*, 2019, **77**, 34–40.

89 B. Lin, *et al.*, Liquid air energy storage: Price arbitrage operations and sizing optimization in the GB real-time electricity market, *Energy Econ.*, 2019, **78**, 647–655.

90 E. Barbour, I. A. G. Wilson, J. Radcliffe, Y. Ding and Y. Li, A review of pumped hydro energy storage development in significant international electricity markets, *Renewable Sustainable Energy Rev.*, 2016, **61**, 421–432.

91 C. Xie, Y. Hong, Y. Ding, Y. Li and J. Radcliffe, An economic feasibility assessment of decoupled energy storage in the UK: with liquid air energy storage as a case study, *Appl. Energy*, 2018, **225**, 244–257.

92 J. Kim, Y. Noh and D. Chang, Storage system for distributed-energy generation using liquid air combined with liquefied natural gas, *Appl. Energy*, 2018, **212**, 1417–1432.

93 S. Mazzoni, *et al.*, Liquid Air Energy Storage as a polygeneration system to solve the unit commitment and economic dispatch problems in micro-grids applications, *Energy Procedia*, 2019, **158**, 5026–5033.

94 M. H. Nabat, M. Soltani, A. R. Razmi, J. Nathwani and M. B. Dusseault, Investigation of a green energy storage system based on liquid air energy storage (LAES) and high-temperature concentrated solar power (CSP): Energy, exergy, economic, and environmental (4E) assessments, along with a case study for San Diego, US, *Sustainable Cities Soc.*, 2021, **75**, 103305.

95 M. S. Kandezi, S. Mojtaba and M. Naeenian, Investigation of an efficient and green system based on liquid air energy storage (LAES) for district cooling and peak shaving: energy and exergy analyses, *Sustainable Energy Technol. Assess.*, 2021, **47**, 101396.

96 C. Wang, N. Akkurt, X. Zhang, Y. Luo and X. She, Techno-economic analyses of multi-functional liquid air energy storage for power generation, oxygen production and heating, *Appl. Energy*, 2020, **275**, 115392.

97 X. She, *et al.*, Enhancement of round trip efficiency of liquid air energy storage through effective utilization of heat of compression, *Appl. Energy*, 2017, **206**, 1632–1642.