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Review

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

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A B S T R A C T

Electrical Energy Storage (EES) technologies have received considerable attention over the last decade because of the need to reduce greenhouse gas emission through the integration of renewable energy sources. Renewable sources have an intermittent power output to the electrical grid, thus EES represents a strategic solution in balancing electrical grids and enables the decarbonisation of the energy sector.

Cryogenic Energy Storage (CES) is a novel method of EES falling within the thermo-mechanical category. It is based on storing liquid cryogenic fluids after their liquefaction from an initially gaseous state. A particular form of CES, Liquid Air Energy Storage (LAES), has gained growing attention respect to other cryogens. The current state of LAES is still at the development and demonstration stage since no commercial or pre-commercial plants have been built. This technology has been developed in different ways throughout its history (from 1977), and, to the best of our knowledge, no review paper has been published so far about the CES topic.

Therefore, the present paper intends to provide a clear picture of the CES/LAES virtues in the literature as well as the challenges associated to the system to be commercially viable. For this purpose, this review includes: an investigation of the properties of cryogens and different CES processes as well as the main ways the system could be combined to other facilities to further enhance the energy efficiency, in particular the combination to a refrigerated warehouse with cold energy recovery from the cryogen evaporation.

Le stockage d'énergie à air liquide (LAES) comme technologie de stockage à grande échelle pour l'intégration d'énergie renouvelable. Revue des études et des perspectives en lien avec le stockage énergétique d'air liquide

Mots-clés: Stockage d'énergie électrique; Stockage d'énergie cryogénique; Air liquide; Énergie renouvelable; Efficacité globale

Introduction

Oil, coal and natural gas remain the world's leading sources of energy (IEA, 1998). According to World Energy Council, in 2015, the contribution of oil to the global primary energy consumption was 32.9%, while that of coal was 30% and natural gas accounted for 24% of the total World energy council (World Energy Resources, 2016). The power generation sector contributes to 39% of CO_2 emissions worldwide and is more polluting than the transport and industry sectors World energy council (World Energy Resources, 2016).

Renewable Energy Sources (RES) such as wind, solar or ocean energy (Li et al., 2010b) have a lower carbon footprint than conventional electrical energy and so have the potential to reduce carbon

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Nomenclature

Ex	exergy (kJ kg^{-1})
h	enthalpy (kJ kg^{-1})
Liq	liquefaction ratio
s	entropy (kJ kg^{-1})
P	pressure (bar)
T	temperature (K)
Wnet	net power (J kg^{-1})
Pc	power of compressor (J kg^{-1})
Pp	power of pump (J kg^{-1})
Pb	power of blower (J kg^{-1})

Subscripts

0	reference state
c	critical
C	cold
H	hot
in	input
l	liquid state
out	output

Acronyms

CAES	Compressed Air Energy Storage
CCC	Cryogenic Carbon Capture
CEEM	Cryogenic Energy Extraction Method
CES	Cryogenic Energy Storage
ECERS	Enhanced Cryogen Exergy Recovery System
EES	Electric Energy Storage
JT	Joule Thompson
LA	Liquid Air
LAES	Liquid Air Energy Storage
LH	Linde Hampspon
PHS	Pumped Hydro Storage
RTE	Round Trip Efficiency
TRL	Technology Readiness Level

emissions if used effectively (Eurostat, 2017). Nowadays, around 7% of the energy produced comes from renewable sources (REN21, 2016). This value is projected to grow in the next years due to the global awareness of carbon-related environmental issues and the growing share of green technologies and governments' efforts to support the renewable energy sector.

However, the increased ratio of renewable energy generation may cause several issues in the electrical power grid considering the intermittent characteristic of RES. In fact its power generation is locally affected by weather patterns (IEC, 2011) and day/night cycle. Consequently, the use of Electrical Energy Storage (EES) is viewed as one potential way to support integration of variable RES (Luo et al., 2015). EES systems may also provide other useful services such as peak shaving, load shifting and supporting the realization of smart grids (Luo et al., 2015). In a study of electricity storage roadmap up to 2030, electricity storage facilities spreading tend to triple if countries double the share of renewables in the energy system mix (IRENA, 2017).

EES is not a single technology, but rather refers to a portfolio of technologies. Energy storage can be classified depending on the energy conversion and storage. Mainly electro-mechanical and thermal storage are widely used for the large-scale energy storage (IRENA, 2017). Pumped hydro storage (PHS) represented 96% in mid-2017 of worldwide installed electrical storage capacity followed by flywheels and Compressed Air Energy Storage technologies (IEC; IRENA, 2017). Conventional pumped hydro storage systems use two water reservoirs at different elevation, and compressed air technology requires underground storage cavities such as caverns or abandoned mines. So, the main drawbacks of these technologies are the dependence on geographical location and the large land footprint and therefore environmental concerns (ENEA Consulting, 2012; IEC, 2011; IRENA, 2017).

Air has been recently regarded as a Cryogenic Energy Storage (CES) medium, whereby air is liquefied at around −195 °C and stored in insulated tanks (Antonelli et al., 2017). This technology is called Liquid Air Energy Storage (LAES). At off-peak times, energy produced by renewable sources is fed to an air liquefaction unit, while, when electrical energy is needed, the liquid air (LA) could be pumped, heated and expanded into turbines to generate power (Brett and Barnett, 2014).

Liquid air does not require important storage volumes considering significant energy density compared to that of PHS and CAES (Chen et al., 2009). Therefore, LAES is considered as a compact-technology. CAES footprint on the ground "in principle" is not larger than LAES because the compressed air is stored underground therefore no more over ground land is used, but there are constraints on how close multiple storage caverns can be. Therefore, as stored energy increases, the overall footprint increases more substantially than with LAES. Moreover, LAES is one of the few storage technologies which can offer large scale storage without geographical restrictions (IRENA, 2017). This technology gives the possibility for energy "co-recovery", since cold from evaporation of liquid cryogen is not wasted. Cold can be reused in multiple applications, and particularly, in the case of sustainable refrigeration industry and food processing. Refrigerated warehouses for chilled and frozen foods are large energy consumers, and therefore, the reduction of their electrical consumption by restituting some of the cold from the evaporation (at temperature reaching −120 °C) could greatly enhance the profitability of the whole combination.

Cycle efficiency, also known as the round trip efficiency, is the ratio of the system electricity discharged to the electricity stored during the charging phase. The round trip efficiency for the case of LAES is dependent on the effective management of heat flux, but can reach values higher than 80% under ideal circumstances (Luo et al., 2015)

The maturity of EES technologies is related to the level of commercialization, the technical risk and the associated economic benefits (Luo et al., 2015). The CES technology is at pre-commercial stage evaluated with Technology Readiness Level (TRL) at maximum nine (Hamdy et al., 2019). PHS is considered as a mature technology and CAES has already been deployed at commercial scale. On the other hand, LAES needs further development and is currently at industrial demonstration level.

Li (2011) made a thermodynamic assessment of the use of cryogen as a working fluid in an energy storage system and concluded that cryogens can be an efficient energy carrier and storage media. In the nineties, two hi-tech Japanese companies Hitachi Ltd. (Wakana et al., 2005) and Mitsubishi Heavy Industries, Ltd. (Kishimoto et al., 1998) investigated this technology and built prototypes to test the feasibility of a LAES system and assess practical performance. A few years later, Highview Power Storage Ltd (Highviewpower, 2017) built a small 350 kW pilot plant initially located in Slough, UK, while the construction of a pre-commercial plant by the same company began on February 2015 and operation has started from April 2018.

This paper proposes a critical literature review of the LAES technology and its virtues comparing to other large scale storage medium. Different liquefaction and energy recovery principles will be discussed in detail with reference to various studies found in the available literature. In the last part of the review, investigated methods of hybridization of the LAES will be also discussed in order to present the prospects of research and maturity development into LAES.

Table 1
Thermodynamic properties of different cryogens.

Cryogens	Recovery process	Thermodynamic properties			Flammability Y/N
		Exergy available at liquid state (kJ kg^{-1})	*Critical point properties*		
			Tc (°C)	*Pc (bar)*	
Air	ASU	723	−135.65	37.7	No
Helium	Natural gas processing	6702	−267.85	2.3	No
Hydrogen	Hydrogen production methods	11,912	−239.85	13	Yes
Methane	Natural gas processing / microbiological methods	1066	−82.05	46.4	Yes
Nitrogen	Air processing	750	−146.95	33.9	No
Oxygen	Air processing	621	−118.35	50.8	Yes

2. Cryogenic energy and liquid air as an energy carrier

A cryogen is a liquefied gas that boils at a temperature below −150 °C (Li et al., 2010a). According to Li et al. (2010a), the energy stored in the cryogen is different from other heat storage : the energy stored in the cryogen is obtained from decreasing its internal energy and increasing its exergy. So, exergy analysis is more adapted to quantify the potential of stored cryogen than energy analysis.

In the study of the Enhanced Cryogenic Exergy Recovery System, Fyke et al. (1997) defined the exergy contained in cryogens as a thermomechanical exergy. This assumes that there are two components: “thermal exergy” - embodied by the large temperature difference with ambient and “mechanical exergy” - due to a possible pressure differential compared to ambient conditions. Cryogens can also embody chemical exergy, for example the chemical exergy of liquid methane is 48 times higher than its thermo-physical exergy, on the other hand liquid nitrogen does not have any chemical exergy and all exergy is in the thermo-mechanical exergy potential Li et al. (2010a). For example, calculation shows that liquid hydrogen has the highest exergy density using Eq. (1), up to 11, 912 kJ/kg. While, the exergy embodied by liquid nitrogen could be up to 750 kJ kg^{-1}. The latter figure is higher than the potential exergy of rock, which is around 455 – 499 kJ kg^{-1}when used for storing sensible heat Li et al. (2010a). Table 1 presents a comparison between thermodynamic properties of the most commonly used cryogens, values of critical properties of cryogens were taken from ASHRAE (1993). The values of exergy were calculated by the authors using the following formula:

$$Ex = [(h_l - h_0) - T_0(s - s_0)] \tag{1}$$

where the index “l” refers to liquid state and “0” to reference state.

The very low values of critical temperature and relatively low critical pressure of cryogens play a major role during liquefaction, since the exergy lost during the heat exchange process is minimized when the fluid is cooled in supercritical conditions (Venkatarathnam, 2008).

In a practical aspect, air is obviously a non-flammable fluid compared to hydrogen or methane cryogens. However, there are some precautions when it comes to liquid air, because the oxygen fraction tends to separate and get locally enriched within the storage tank. Liquid air can even contain 50% of nitrogen and 50% of oxygen (CLCF, 2013) in some instances. Since oxygen reacts violently with most materials (EIGA, 2016), the potential fire and explosion hazards increase when oxygen concentration in liquid or gaseous air increases. In their report (EIGA, 2016), the European Industrial Glasses Association claims that the maximum safe oxygen concentration in a confined space is 23.5% by volume. Consequently, in reference (CLCF, 2013), there are a list of safety measures to deal with oxygen enrichment: using suitable insulated tanks, monitoring oxygen content and keeping all types of organic materials away from the oxygen sources as they may combust in an oxygen rich environment. Furthermore, few air treatments operations are necessary before energy storage processing compared to hydrogen or nitrogen extraction for example. Finally, due to its instant availability and free use, air has the ultimate potential to the energy storing system as a cryogen.

Liquid air has attracted researchers working on large-scale energy storage based on cryogenic energy conversion. LAES is, henceforth, the particular form of CES where the energy conversion remains in Liquid Air transforming.

3. Process principle

The idea of cryogenic energy storage was firstly proposed by E.M Smith, at university of New Castle in 1977 (Smith, 1977), and tested by Mitsubishi in 1998 (Kishimoto et al., 1998; Sciacovelli et al., 2017) using liquid air as cryogen. The principle of using this type of energy storage is based on 3 main steps shown in Fig 1:(i) liquefaction of gaseous air when energy is available at off-peak times, (ii) storing liquid air in insulated tanks and (iii) expansion of pumped liquid air through turbines to generate power at peak demand period (Abdo et al., 2015; Ameel et al., 2013; Antonelli et al., 2016; Guizzi et al., 2015; Kishimoto et al., 1998; Li et al., 2014; Morgan et al., 2015; Sciacovelli et al., 2017; Smith, 1977)

The state-of-the-art of each of these subsystems will be described in next sections.

3.1. Cryogenic liquefaction cycle

In the literature, mainly 3 major cycles were studied for the liquefaction of cryogens, Linde Hampson cycle, Solvay cycle and Claude cycle (Abdo et al., 2015; Ameel et al., 2013; Atrey, 1998; Chang, 2015; D’Arsonval, 1898; Guizzi et al., 2015; Hamdy et al., 2017; Li, 2011; Sciacovelli et al., 2017; Venkatarathnam, 2008). In 1895, Car von Linde built the first industrial scale air liquefier (Agrawal and Herron, 2000). The Linde-Hampson (LH) liquefier is based on the Joule Thomson (JT) effect taking place in any throttling valve (Venkatarathnam, 2008). Petit (1995) referred to the efficiency of 11% and describes the efficiency of JT liquefaction cycle as “poor”. The JT expansion is responsible for a large loss of exergy due to the important pressure drop in an isenthalpic process. When the isenthalpic expansion device is replaced by an isentropic expansion device, an increase in the exergy efficiency of about 60% is achievable for a compression pressure of 200 bar (Venkatarathnam, 2008). The liquid yield increases considerably and this cycle is known as the Solvay liquefier. This can be done by means of a turbine instead of the JT valve, using a two-phase expander or a cryogenic expander (Kanoğlu, 2001). This technology was not available until recently because it requires accurate prediction of liquid fraction trajectories while it condenses in the expander. This was introduced at industrial scale in methane liquefaction plants with the advent of 3D, multiphase computational fluid dynamics.

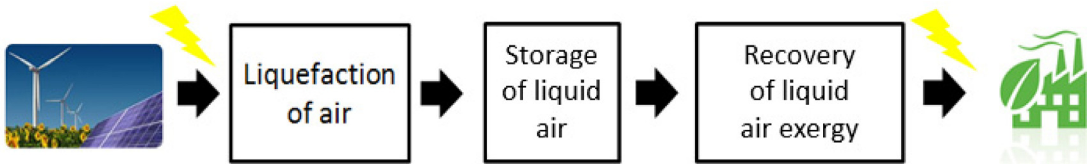

Fig 1. Principle of liquid air energy storage.

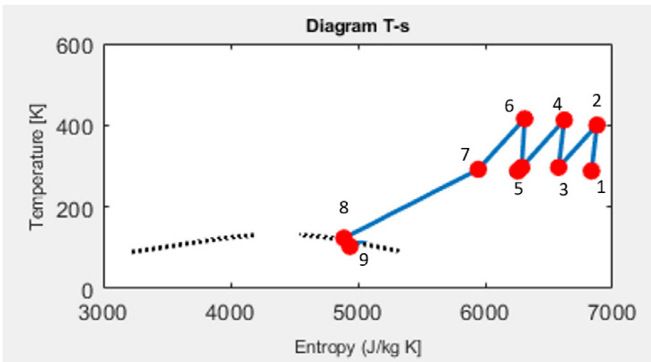

Fig 2. T-s diagram of solvay air liquefaction cycle based on 3 compression stage.

T-s diagram of a Solvay cycle for air liquefaction is represented in Fig 2. The segments 1–2, 3–4 and 5–6 correspond to compression processes while 2–3, 4–5 and 6–7 represent the inter-cooler between compressors. Then, from 7 to 8 an external cold source and a part of returning non-liquefied gas is used to cool down the compressed air. The segment 8–9 is the non-isentropic expansion within a cryo-turbine where production of liquid droplets takes place. In point 9, liquid air is stored in a storage tank.

In 1902, George Claude proposed a system with two expansion mechanisms combining a JT valve expansion with a near-isentropic expansion through a turbine located along a portion of the stream. The Claude cycle has been reported in Fig 3. Claude cycle presents many advantages compared to LH cycle. According to Sciever (2012), the near-isentropic expansion makes the system potentially more efficient and additional work can be produced by the expansion device improving the overall efficiency.

Improved version of Claude cycle was also developed by Highview Ltd, in order to manufacture the first LAES demonstrator without combustion. In their patents (Nelmes et al., 2015) they represent a liquefier with two or more cascading turbines. With this extended version of Claude cycle, more cold is provided within the heat exchanger, henceforth more liquid is produced and so the liquefier efficiency can be enhanced. Multiple configurations were proposed, as well, in patent (Alekseev, 2016) of air liquefaction unit based on Claude cycle. Regarding this fact, more complexity is added to the circuit and CapEx increases as well.

Despite the low values of exergy efficiency of Linde Hampson, many industrials refer to this system to produce liquid air, as in many patents LAES systems were based on the LH liquefier (Gatti et al., 2011; Sinatov and Afremov, 2015; Stiller et al., 2016; Vandor, 2011). This means that the Linde Hampson principle has been regarded for a long time as potential liquefier for industrial application and it is always the case nowadays mainly due to the cost benefit criterion. The cycle that may replace Linde Hampson because of low complexity and enhanced efficiency is Solvay. The replacement of JT valve by a Liquid turbine assures better efficiency with minimum investment.

A revival of the Solvay cycle was proposed in recent studies (Guizzi et al., 2015; Li, 2011; Li et al., 2014) of cryogen liquefaction that involves also some more sophisticated technologies using a Cryoturbine for providing the cooling capacity needed for liquefaction of the cryogen. It has been shown that the use of a Cryoturbine instead of a throttling device in a conventional setup improves considerably the efficiency of the liquefaction unit. For example, in particular conditions, Li (2011) obtained an optimal round trip efficiency of 48% using throttling valve while, this value increased to about 82% by using a Cryoturbine. Kanoğlu (2001) investigated and tested a Cryoturbine used for natural gas liquefaction and the analysis was made using data provided by the Cryoturbine test facility. The objective of the paper (Kanoğlu, 2001) was to compare the efficiency of a throttling valve and a Cryoturbine for cryogen production in order to assess isentropic, hydraulic and exergy efficiencies of the Cryoturbine in a Solvay liquefier.

Another variant of Claude cycle is Heylandt cycle. A turbine is placed along the first heat exchanger and not the second one as it is the case for Kapitza. In a study of the exergy analysis of a CES (Hamdy et al., 2017), Heylandt cycle was used for liquefaction. The authors claimed that this cycle is commonly applied for CES regarding technical and economical reasons.

3.2. Cryogenic Energy Extraction Methods (CEEMs)

Thermo-mechanical exergy of liquid cryogens can be extracted after evaporation through turbines, while the remaining thermal exergy, in form of high-grade cold, can be recovered through heat exchangers and storage medium. This paragraph intends to provide details of some studies/patents of the CES/CEEM and to discuss their results.

In general, four basic methods for Cryogenic Energy Extraction Methods (CEEMs) are mentioned in literature (Hamdy et al., 2017; Li et al., 2010a) (Fig 4). The simplest one is the direct expansion method where the cryogen is pumped, heated by the ambient heat or waste heat and expanded into turbines to generate power (a). In the second method, cryogen is used as a secondary fluid instead of the main working fluid. It is whether used to condensate the working fluid in a Rankine cycle (b) or to cool down the working gas before compression in a Brayton cycle (c). For these two methods (b-c), the cryopump is kept to pump the cryogen in the secondary circuit (blue line) while the expander is used for the main circuit (green line). The fourth method is a combination of the three previous ones (d).

In general, the cryogen is pumped, evaporated and expanded into turbines. T-s diagram for a three-stage expansion recovery cycle, with liquid air as working cryogen is represented in Fig 5. In this case, step 1–2 corresponds to the evaporation of liquid air, 2–3 is a small heat transfer with secondary fluid which exchanges with cold storage device, 3–4, 6–7 and 8–9: super-heating and 5–6, 7–8 and 9–10: expansion into turbines.

An alternative for the cryogenic energy extraction is the so-called “Dearman Engine” (Dearman et al., 2016). Cryogenic engine is extracted in piston engine system similarly to vehicle’s engine. The cryogen is injected by small quantity into the engine cylinder where it is combined with a warm heat transfer fluid. The resulting sudden expansion of the cryogen drives the piston shaft, and therefore cryogenic energy is turned out to mechanical energy. As said in the beginning of this paragraph, one of the most important features of the cryogenic energy storage is that it can

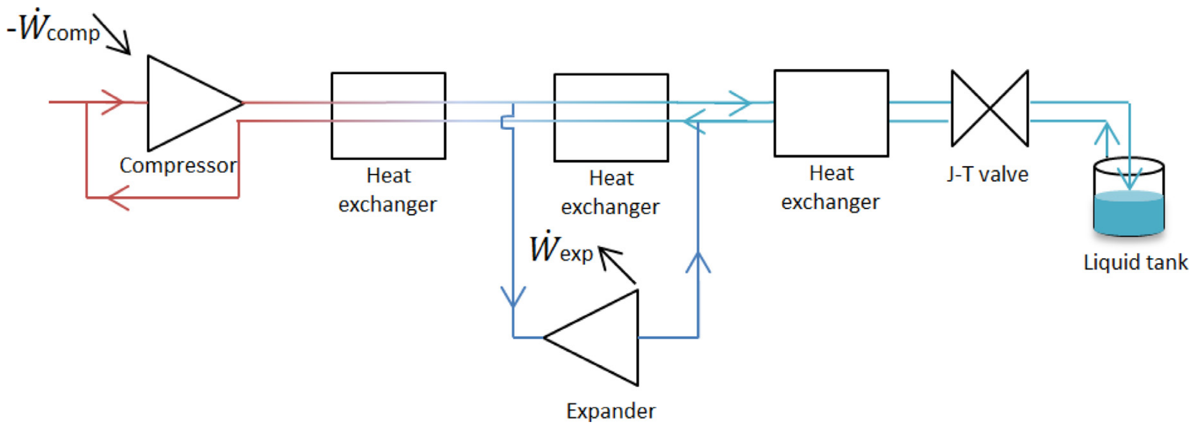

Fig 3. Principle of Claude cycle.

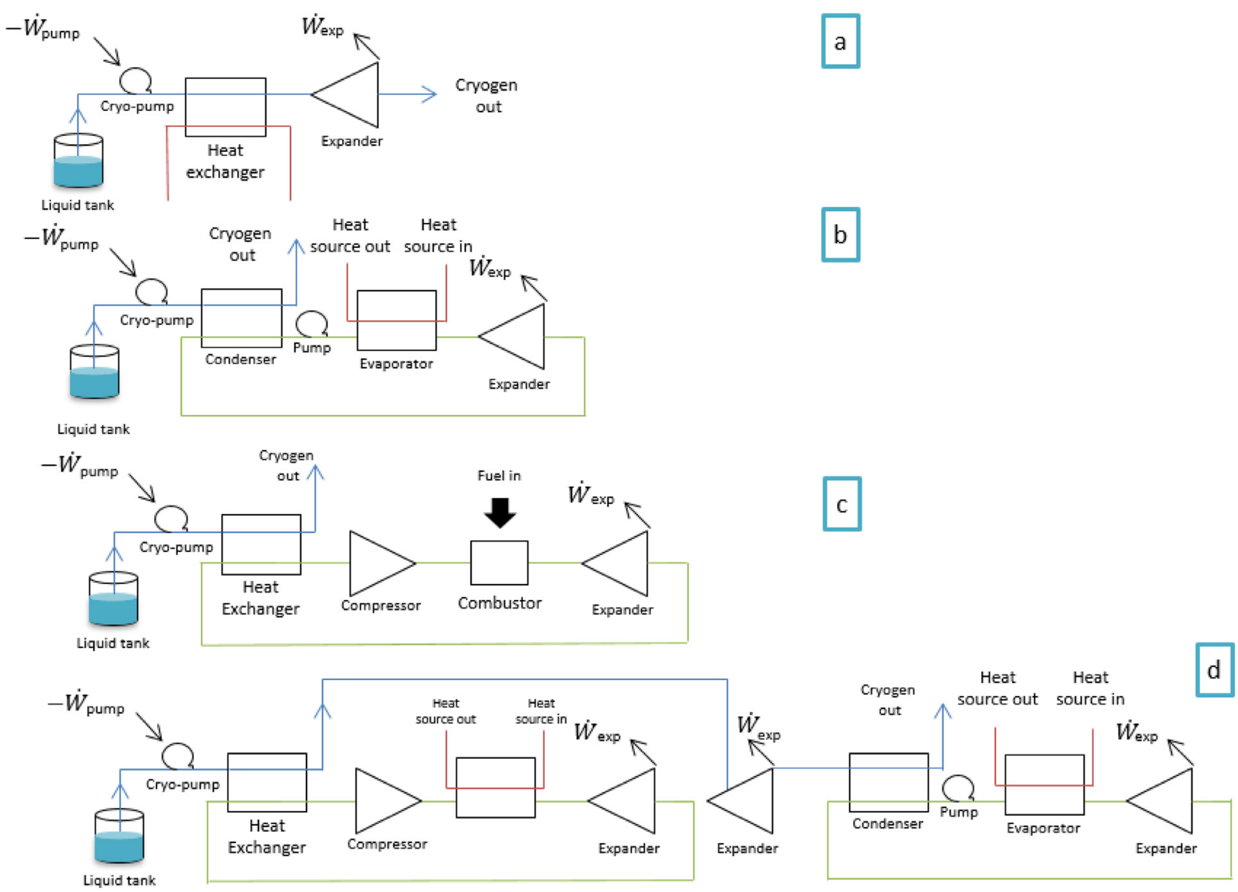

Fig 4. Cryogenic energy extraction, basic methods.

generate both mechanical/electrical energy and cold energy at the same time by the regasification process. Under this same approach, Dearman Company proposed a cogenerated system (Ayres et al., 2015). Therefore, in one of the embodiment proposed, mechanical energy and electrical energy could be extracted alternatively or simultaneously through mechanical coupling (by shaft rotating) or thermal coupling (Indirect Rankine cycle). Dearman vehicle engine cannot be considered as a direct application of the electric energy storage through cryogenic energy conversion, but in some aspects, it could also be considered as a CEEM.

A recovery system was also developed by Mitsubishi (Kishimoto et al., 1998). The generator is a combination of super-heating, combustion and direct expansion method with some modification, as showed by Fig 6. The cryogen is pressurized by a turbopump driven by expansion turbine, evaporated, heated and expanded. The power is produced by using a gas-turbine. The author calculated the thermal efficiency up to 77% (Eq. (5)) as an efficiency of the generation cycle.

Expansion Energy's patent Vandor's Power Storage Cycle (called the VPS Cycle) of LAES includes natural gas fueled power generation as reported in (Vandor, 2011). In Vandor's patent (Vandor, 2011), a LAES that relies on combustion of natural gas with liquid air is presented. To limit CO2 emission, Vandor's proposed a CO2 adsorption chemical process. The final use of the CO2 captured was not mentioned in the patent. In a commercial document of the company that manufactures the system

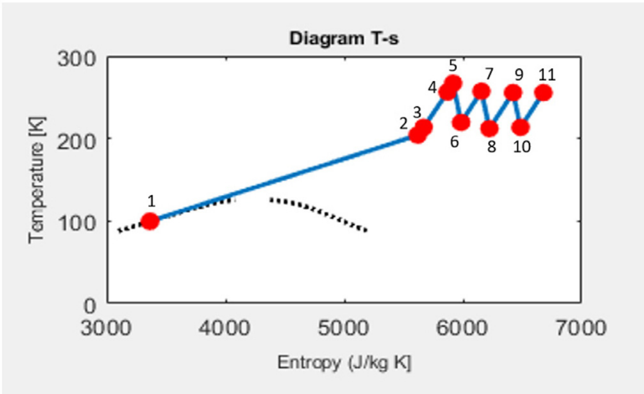

Fig 5. T-s diagram of recovery cycle.

(Liebowitz et al., 2013) the round trip efficiency of the VPS cycle at a commercial scale is claimed to be greater than 95%. The VPS cycle is now subject to a feasibility study and a full scale system installation may be planned at a facility in New York City (Taylor et al., 2012).

3.3. Efficiency of LAES

CEEM and liquefaction system can be completely separated or thermally linked in the case of CES. Therefore, two major groups of LAES are distinguished in literature: "independent subsystems" and "thermally linked subsystems". In the liquefaction process, cold energy is needed and it can be recovered in the LA discharge process and recycled back. Additionally, in order to enhance the LA discharge process efficiency waste, heat is needed. This can be stored and recycled from the rejected heat coming from the compressors in the liquefaction plant. The following studies involve cold and hot energy reuse methods via different storage media which fill the gap between air liquefaction unit and recovery unit needs. High grade hot and cold storage and recycle is included in almost all recent studies related to cryogenic energy storage system for electrical storage applications (Abdo et al., 2015; Ameel et al., 2013; Chino and Araki, 2000; Li, 2011; Li et al., 2014; Morgan et al., 2015; Sciacovelli et al., 2017) where mainly a super-heating based cycle is used for the generation process.

RTE, environmental impact and realization of the system are particularly factors of interest in this paper. In the following, two systems are distinguished the super-heating recovery process referred to with "S" letter and the combustion based recovery process referred by "C" as main Cryogenic Energy Extraction Methods. A comparison between these configurations is made in Table 2 as they were studied in their corresponding mentioned references.

As for all energy storage technologies, the round-trip efficiency is the parameter that represents the ability of the LAES system to recover as much as possible of the input energy that it had initially consumed. The round trip efficiency for a LAES system is the ratio between the electric energy consumed for producing liquid air and the electric energy generated (or saved) during the discharge of LA and it is given by the following equation where $\dot{W}_{net \cdot out}$ is the output energy and $\dot{W}_{net.in}$ is the input energy, both include all input and output energies throughout the system is given by Eq. (2)

$$RTE = \frac{\dot{W}_{net\ out}}{\dot{W}_{net\ in}} \tag{2}$$

Negro et al. (2018) has defined a more detailed $\dot{W}_{net\ out}$ formulation and method of calculation for the heat/cold recovered as follows:

$$RTE = \frac{\sum ElectricalEnergyOutput + \sum ThermalEnergy/COP}{\sum ElectricalEnergyInput} \tag{3}$$

The Coefficient of Performance (COP) is an indicator for the refrigeration cycle as well as heat pump, it is defined on the basis of a level of valorization temperature of the cold recovered.

$$COP_C = \frac{T_C}{T_H - T_C} \tag{4}$$

Kishimoto et al. (1998) defined thermal efficiency as the ratio of the entropy variation due to combustion and the entropy generated by gas turbine (output).

$$Eff_{thermal} = \frac{\Delta s_{combustion}}{\Delta s_{output}} \tag{5}$$

Energy storage efficiency (Chino and Araki, 2000) can also be defined:

$$Eff_{energy\ storage} = \frac{liq \times (Pc - Pp - Pb - Qh)}{Pc} \tag{6}$$

Where: *liq* is the liquefaction ratio, *Pc*: power of compressor, *Pp*: power of liquid air pump, *Pb* : power of blower.

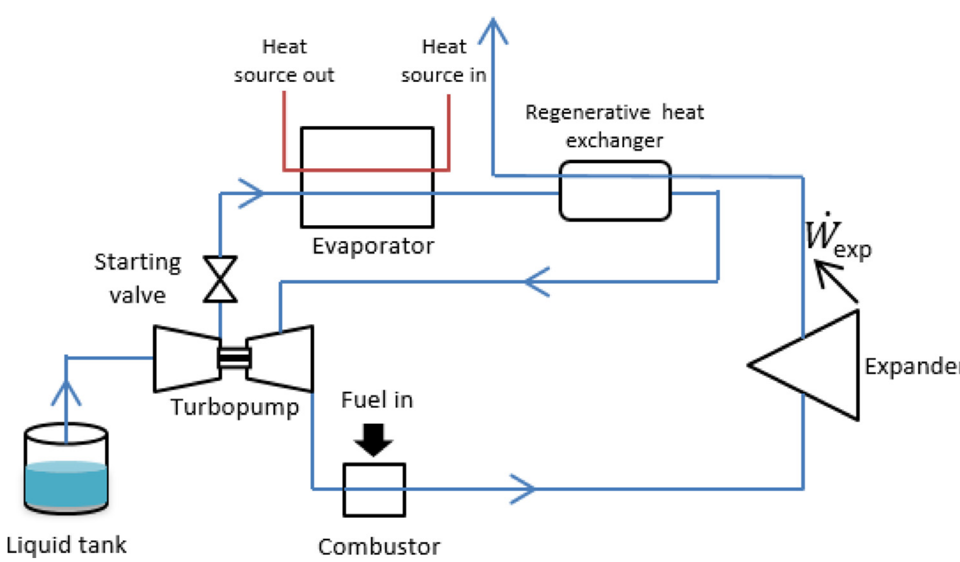

Fig 6. Mitsubishi LAES system.

Table 2
Main CEEMs in the literature .

Ref/System Peculiarities/Innovations	Standalone recovery system C	S	C + +S	Integrated system C	S	Round trip efficiency (%)	Calculation model
Kishimoto et al. (1998)Rankine and Brayton combined			X			77	Eq. (5)
Chino and Araki (2000)Tank of liquid air placed inside a regenerator				X		87	Eq. 6
Vandor (2011)				X		>90	Not mentioned
Conlon (2016)combination of open Brayton air cycle with closed Rankine steam cycle	X					[47–87]	Not mentioned
Ameel et al. (2013)Linde liquefaction cycle and Rankine recovery cycle					X	43	Eq. 2
Li (2011)Superheaters supplied by heat from inter-coolers at the compression stage		X			X	[20–60] / 80	Eq. 2
Morgan et al. (2015)packed bed for storage					X	8 demonstrator value[40–60] theoretical value	Eq. 2
Guizzi et al. (2015)cryoturbine included					X	50	Eq. 2
Sciacovelli et al. (2017)Packed bed for cold storage					X	50	Eq. 2
Antonelli et al. (2016)Natural gas combustion included	X					70	Eq. 2
Negro et al., 2018Cryo-Rankine cycle combined to refrigerated warehouse					X	[20–26]	Eq. 3
Hamdy et al. (2019)Exergy and economic analysis is carried out for 4 different circuits				X	X	[40–55]	Not mentioned

Two systems are distinguished: the super-heating recovery process referred to with "S" letter and the combustion based recovery process referred by "C" as main Cryogenic Energy Extraction Methods.

Negro et al. (2018) investigated multiple possibilities of developing a demonstrator at an industrial site (food factory and refrigerated warehouses). From the parametric analysis, it was shown that 3 parameters can be controlled to enhance the RTE: discharge pressure, waste heat temperature at the expansion stage entrance and pressure in the storage tank. The cold recovered from the evaporation could either be recycled in the liquefaction cycle or used to supply refrigerated warehouse or food freezers. Depending on requirements of the industrial site, the round trip efficiency can be considered also as a variable parameter to the energy efficiency assessment in the refrigeration system. As practical turbomachinery efficiencies were considered, this study has presented lower RTE than other theoretical values obtained in other works.

A complete exergy analysis based on fuel and product approach was conducted by Hamdy et al. (2019) comparing 4 configurations including the combustion process. Waste heat/cold recovered was also investigated in order to evaluate the exergetic efficiency of the CES. Waste energy as defined by the authors is related to the energy that can be vented to the environment. An interesting point of the slight difference between exergetic and energy methods analysis was highlighted through different formula in each of the studied system. The exergy known to be « the true thermodynamic value » of the energy, is claimed to be the best approach for comparison purpose. Contrary to the results found in literature, exergy and energy analysis results of this study show that the use of waste heat of 450 °C represents the highest exergetic efficiency of 55% comparing to 44% with combustion. Depending on the industrial site where the CES is implemented, availability of waste heat source is not certain, and therefore, the of the RTE changes consequently.

RTEs shown in this table are results of theoretical simulation. The only system that was fully built as LAES demonstrator has only 8% compared to the theoretical 49%. According to the author, this poor value is due to the small size of the plant. LAES would be more efficient when scaled-up. Nonetheless, more details and experimental data related to the subject are therefore required to investigate the main energy loss sources in the energy conversion process.

Almost all recent studies (Ameel et al., 2013; Guizzi et al., 2015; Hamdy et al., 2017; Sciacovelli et al., 2017) on the subject of LAES obtained approximate results of exergy efficiency and the round trip efficiency varies at a range of [43–50%]. Architectures studied of LAES are almost focused on Solvay or Claude liquefier cycle with the integration of Cryoturbine for charging phase and the super-heating process of energy extraction process for the discharging phase. Sciacovelli et al. (2017) has carried out a typical configuration of the LAES system based on super-heating process recovery. The proposed system shown in Fig. 7 includes a modified Claude cycle which includes multiple expansion stages and a JT valve. Packed bed filled with quartzite pebbles is integrated in order to store high-grade cold energy. Heat from multiple compressor stages is recovered, as it was the case in the work of Guizzi et al. (2015). Sensible heat is stored in a diathermic oil that acts both as heat transfer and storage medium. The author focused on the integration of the packed bed storage in a dynamic RTE analysis and the impact of this component on the system overall performances. According to the authors, the use of packed beds for cold thermal storage improves the efficiency of liquid air energy storage by around 50%.

According to Table 2, LAES with combustion methods have the highest RTE comparing to super-heating cycle whether in independent or in coupled cycle. Values of theoretical RTE are generally

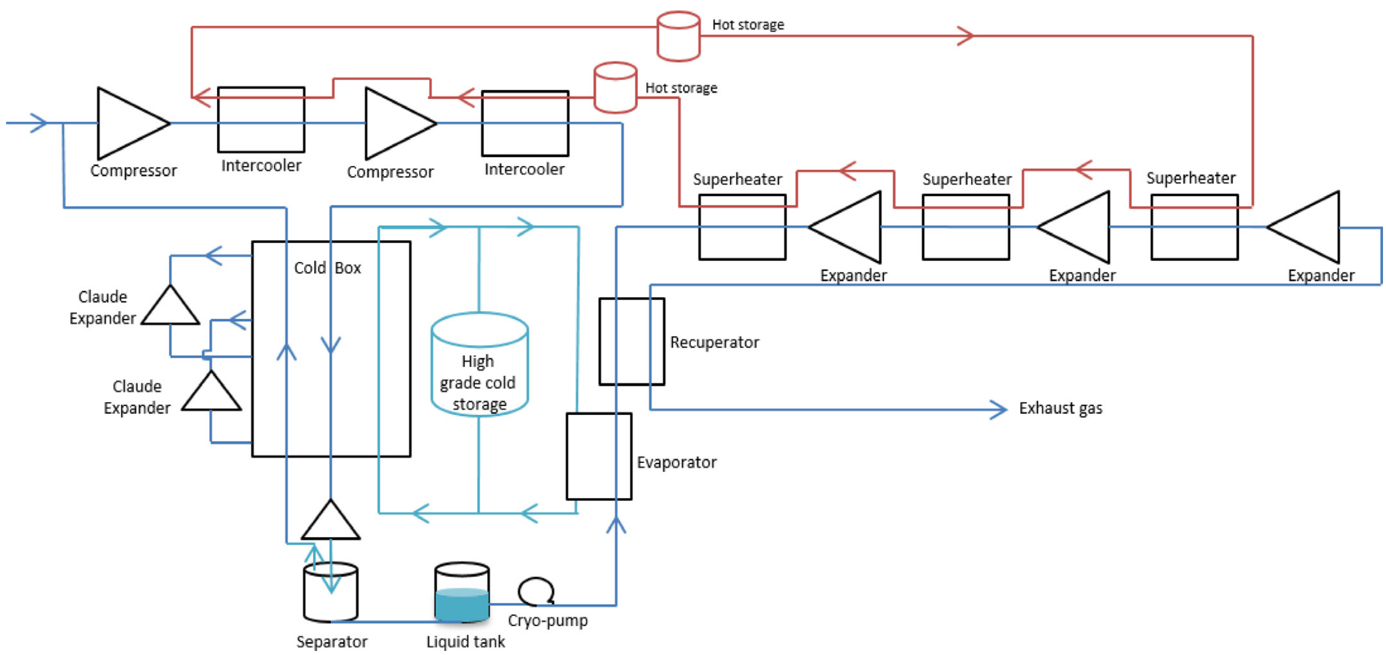

Fig 7. Sciacovelli's LAES process.

higher than 70%, while those of super-heating are limited 40 to 50%. This can be explained by the high chemical exergy (Fyke et al., 1997) contained in the fuel and provided to the system as an extra source of energy in addition to liquid air energy. Besides, combustion leads to high temperature at the turbine inlet before expansion and this provides more work to be recovered from the expansion process. But combustion also includes CO_2 emissions. Carbon capture is a frequent proposed solution (Conlon, 2016). This can be done by use of cryogenic cold energy so as in Li et al. (2011). Nevertheless, combustion still rejects many others toxic particles like CO or NO, O_3, etc. which require additional combustion post treatment processes and could lead to more complexity and expensiveness of the system.

3.4. Pilot plant demonstrators in the history of LAES

The use of liquid air energy storage, as a large-scale energy storage technology, has attracted more and more attention with the increased share of intermittent renewable energy sources connected to the electricity grid. Consequently, some commercial companies got involved in the development of this technology beginning with Mitsubishi and Hitachi (Kishimoto et al., 1998; Wakana et al., 2005) at the end of the nineties and more recently Highview Power Ltd. Tests and performance of the deployed systems did not match theoretical expectations because of technical limitations and real world efficiencies of the equipment.

The first prototype was designed and demonstrated by Mitsubishi Heavy Industry in 1998 (Kishimoto et al., 1998), with no information published about the design of the liquefaction unit. Liquid air was directly pumped from a liquid air storage tank. The only reported performance indicator was the efficiency of the LA discharge system which could reach 77%, without taking into account the energy consumed by the air liquefaction plant, but only accounting for the chemical energy of the fuel burnt in the combustor.

In a second trial of this technology, Wakana et al. (2005) designed a generation circuit that combined combustion with the integration between liquefaction and generation units. As previously described, this design included a form of cold storage unit which is conceived in specifically designed regenerator. The R&D activities were conducted by the Japanese company Hitachi, Ltd. According to the Center for Low Carbon Futures (Taylor et al., 2012), Hitachi made experimental works on the regenerator, and claimed that the system could exceed 70% of storage efficiency depending on the regenerator performance. However there was no full scale pilot plant demonstrator.

Working with the University of Birmingham (UK), Highview Power Storage has built the world's first fully integrated 350 kWh/2.5 MWh liquid air energy storage system Highview Power Storage designed and assembled this LAES pilot (Highviewpower, 2017). It was initially operative in 2011 at Scottish and Southern Energy's 80MW biomass plant in Slough, UK. A self-developed cold storage (Morgan and Dearman, 2013) was used for the full integration of liquefaction and energy generation units. Various tests to assess the system response to load variations were carried out. Results were reported by Morgan et al. (2015). The round trip efficiency obtained was in the range of 8%. But, according to the authors, this low value is due to the small size of the plant and the inefficient cold recycle design. A 100MW/600 MWh "best built" configuration was proposed by the same authors in another paper (Morgan et al., 2014) and a round trip efficiency of 60% was claimed as achievable with current technology.

In February 2014, the UK government awarded Highview Ltd. of a £8 million grant for the realization of a 5MW/15 MWh demonstration plant alongside Viridor's landfill gas generation plant at Pilsworth Landfill facility in Greater Manchester (Highviewpower, 2017; Luo et al., 2015). The waste-heat provided by the adjacent piston engines generators will be used to increase the discharge system power output and it will enhance the overall efficiency of the system. The plant is now in operation and it is providing power for around 200,000 homes during a day (Highviewpower, 2019).

4. Methods of hybridization of cryogenic energy storage

As described in this paper, initial research activities on energy storage and recovery via cryogens had begun with simplified systems using independent liquefaction/recovery subsystems. Then, the overall RTE had been greatly enhanced with the integration of the hot and cold energy storage and recycle. In the following paragraphs, some studies are presented where the CES is hybridized with a second system. The idea is to maximize the cryogenic energy recovery by using additional systems, and secondly to integrate a CES system with another process.

In two papers, Li et al. (2014;2012) suggested to co-locate cryogenic energy storage near an existing electrical plant and make use of waste heat recovery in the cryogenic plant, instead of rejecting it to ambient. In fact, the waste heat recovery has a large impact on the increase of the net power output. In the first study from Li et al. (2014), he suggested the integration with a nuclear power plant. The round trip efficiency of this system could be higher than 70%. Li et al. (2012) studied the hybridization of a CES and a solar thermal power plant in the form of a solar-cryogen hybrid power system. Results of simulation in this study show that the system delivers power 30% greater than the sum of the power outputs of each system individually.

The power generation sector is the main source of CO_2 emissions worldwide. Consequently, several technologies of carbon capture emerged in recent years as a way to limit emissions. Cryogenic Carbon Capture (CCC) is a viable approach to achieve the target of CO_2 emission level (Safdarnejad et al., 2016). A hybrid system of CCC and a CES based on combustion process is studied within three reference papers by Safdarnejad and Li (Li et al., 2011, 2013; Safdarnejad et al., 2016). The process then, separates solid CO_2 in the form of dry ice (Li et al., 2013). To further increase the efficiency of the LA discharge, waste heat from the exhaust gas is recovered to superheat the gaseous nitrogen at the turbine entrance (Li et al., 2013). In the latter study by Li et al. (2013), the air would be separated into liquid oxygen (for the oxy-fuel combustion of the gas turbines), and liquid nitrogen (the working fluid in the circuit and the medium of CO_2 removal). The overall efficiency of the proposed system was claimed to reach 70%.

Antonelli et al. (2017) presented several ways of LAES integration with existing processes. The first suggestion was to include an Organic Rankine Cycle (ORC) where cryogenic temperatures of released liquid air could be used as the lower temperature sink of the ORC. According to the author, the ORC contributes to negligible improvements in the efficiency of LAES, since the energy exploitable is lower compared to that provided in the combustion. A second proposition consisted of a combustion based cycle, where air cooled by cryogen entered the compressor. The advantage of this cycle would be that the compression would be less energy intensive since the working fluid is at a lower absolute inlet temperature. The authors' analysis of this configuration yielded the highest power output and the best round trip efficiency (68%).

According to Fikiin et al. (2017), refrigerated warehouses are an ideal industrial environment to the integration of renewable energy source by switching 'passive' and 'active' modes of the LAES and using both cold and electrical energy of the LAES. A recent innovative European project– (CryoHub, 2019) investigates and extends the potential of large-scale LAES by recovering the stored energy in two forms cold and electrical energy. By employing RES to liquefy and store cryogens, CryoHub balances the power grid, while meeting the cooling demand of a refrigerated food warehouse and recovering the waste heat from its equipment and components. The project is, yet under study and a demonstrator might be deployed in order to supply a refrigerated warehouse.

5. Discussion and perspectives

The cryogen contains high-grade cold as a valuable energy, and we may call it "cold exergy". For this reason, as we could see through paragraphs of this paper, some authors gave a special focus on the recovery of this extra source of energy. Almost all hybrid systems discussed include the integration and recycle of the cold exergy released by the cryogen, i.e. the capture of CO_2, the condensing in an ORC or cooling the fluid in a Brayton cycle.

Aside from capturing and storing the cold exergy of the released liquid air for the liquefaction process, the stored cold energy might also be used in refrigerated warehouses or food/pharmaceutical plants. This idea was first introduced by Fikiin et al. (2017). This is currently under investigation and would be demonstrated as part of a European project (CryoHub, 2019). Integrating the LAES system would enable demand-side energy management and supply of cooling to refrigerated warehouses at the same time. The main objective of this project is to enhance the sustainability of both the power grid and the cold chain.

Using the same approach, but in a different application, Tafone et al. (2017) presented a techno-economic analysis of a LAES providing for daily air conditioning of an existing office building in Singapore (hot climate conditions throughout the year). Results of simulation gave ideally a round trip efficiency of 45% with some assumptions.

Both previous applications explored the concept of a sustainable cold economy, defined in Tafone et al. (2017). The objective would be to make sites requiring refrigeration energetically self-sufficient and increase the share of "green" energy sources used. As main results of the study conducted by Negro et al. (2018), the efficiency of the cold energy recovery sub-system can reach the value of 88%: « this will constitute a key technological enabler for any LAES technology to be commercially viable in the future ».

Many studies and configurations have already been considered theoretically, but, the lack of experimental validation of the simulated LAES systems should be addressed first. LAES technology needs an important investment regarding the size of machinery required (number of compressors and turbines and engineering/conception study price). This explains somehow the lack of experimental validation and industrials reluctance.

In CEEM section (3.2), recovery methods with combustion are proven to be more efficient in terms of RTE than with superheating. However, due to the environmental damage that can occur from the combustion of natural gas with liquid air. Oxy-fuel combustion should be considered since it presents reduced NOx emission than the usual air-firing. Besides carbon capture operation has lower complexity in the oxy-fuel due to the higher CO2 density in the flue gas (Buhre et al., 2005). Oxy-fuel combustion with CO2 capture has been investigated by companies like Air Liquide (Châtel-Pélage et al., 2003) and Alstom (Nsakala et al., 2001) in the case of coal-fired power plant. In our vision, oxy-fuel combustion could represent a way to maintain good electrical efficiency and reasonable environmental impact.

6. Conclusion

This paper provides a review of the current development of LAES technology from both a scientific and technical perspective. CAES and PHS are technologies currently deployed for large-scale energy storage which are constrained by geographical features. LAES, as a particular sub-set of LAES, is a novel EES technology that could respond to grid-scale requirements.

One advantage of this technology is the energy storage density and, secondly, its independence from location constraints like the presence of a gravitational potential (PHS) or underground caves (CAES). A difficulty of using liquid air used as cryogen is that a particular attention should be given to the problem of stratification and oxygen enrichment during storage. Some measures are necessary to avoid the risk of ignition in presence of hydrocarbons.

Linde-Hampson, Claude and Solvay cycles were mentioned in previous works to be the most appropriate for cryogen liquefaction. Super-heating and combustion methods combined to direct expansion are the most popular energy recovery methods in studies related to CES or LAES. Many authors confirmed that the integration between liquefaction and energy recovery units through cold and hot storage considerably enhances the system performance. Potential round-trip efficiency has been claimed to be more than 80% when using combustion for LA discharge cycle. Combustion process has undeniably negative impact on the environment and this goes against the environmentally friendly characteristic of LAES as a solution for the green energy worldly transition. Environmental issue should be carefully assessed and solution like oxy-combustion process with biogas as fuel may represent a potential solution, at the expense of the Operating Expenditure (Opex) of the entire system.

More and more integration possibilities can emerge from LAES in the form of by-products of liquid air production/use. As discussed previously, carbon capture and storage using liquid nitrogen is one of many options already investigated by some authors. In fact, hybridization of LAES is open to multiple opportunities when considering that cryogenics have been used in superconductivity, rocketry, cryosurgery, cooled electronics since the 60′s. The possibility to increase the energy recovery and so the energy efficiency of the system, and to respect the environmental issues in the context of renewable energy integration, makes of the CES a potential method for the large scale EES.

Based on results of mentioned studies in this review, LAES represents an excellent candidate for the energy transition in terms of energy storage technology, regarding theoretical thermodynamic performances. Studies have shown attractive results of thermodynamic efficiency as well as possibilities of cogeneration of cold energy or/and hot energy depending on the industrial site needs where the plant is implemented. The cryogenic energy can also be used for CO_2 carbon capture and for sequestration or more recently for turning it into coal (Cockburn, 2019). Despite the maturity of machinery used for LAES (compressors, expanders, heat exchangers), the lack of experimental validation of theoretical performances is clearly undeniable. This is due to huge investment related to the project, even at a demonstration level. LAES economic viability for investors is not yet virtuous of millions of euros investments. Economic solutions to shorten payback duration are, therefore, required to attract investors. A part of liquefied oxygen or nitrogen can be sold on the market or provided for local use as sub-products, without diverting from the main purpose of storing energy.

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