Liquid Air Energy Storage:

Potential and challenges of hybrid power plants

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ABSTRACT

The current increase in the deployment of new renewable electricity generation systems is making system balancing a more and more difficult task. Solutions including energy storage at small and large scales are becoming of paramount importance to guarantee and secure the supply of electricity. The paper focuses on hybrid solutions including large scale energy storage jointly with power generation and fast responding storage systems. It presents a hybrid plant able to deliver the energy previously stored through an air liquefying process either with or without the contribution of additional energy from combustion. The paper also highlights how such hybrid plants offer the chance of providing the grid with fast regulation services.

An ideal energy storage technology should have a high power rating, a large storage capacity, high efficiency, low costs and no geographic constraints. The use of air as energy carrier has been studied since the 20th century with the first compressed air energy storage (CAES) systems. This technology is still recognized to have potential but it is geographically constrained where suitable geological tanks are available unless compressed air is stored in pressurized tanks with significant costs. Liquid Air Energy Storage (LAES) represents an interesting solution due to its relatively large volumetric energy density and ease of storage. Different process schemes for hybrid plants were modelled with Aspen HYSYS® simulation software and the results were compared in terms of equivalent roundtrip and fuel efficiencies. Interesting equivalent roundtrip efficiencies, higher than 80%, have been calculated showing that the proposed configurations might play an important role in the power systems of the near future.

KEYWORDS – Hybrid Power Plant, Liquid Air Energy Storage, Cryogenic Energy Storage, Air Expansion

NOMENCLATURE AND DEFINITIONS

CAES	Compressed Air Energy Storage

E_{air}	Air Liquefaction Specific Energy [kWh/kg]
E_{CH4}	Methane Combustion Specific Energy [kWh/kg]
E_{tot}	Recovered Specific Energy [kWh/kg]
η_{cc}	Combined Cycle Efficiency [-]
η_{fuel}	Fuel Efficiency [-]
η_{RTcorr}	Corrected Roundtrip Efficiency [-]
LAS	Liquid Air Storage
LAES	Liquid Air Energy Storage
LHV_{CH4}	Methane Lower Heating Value [MkJ/kg]
mf_{air}	Liquid Air Massflow [kg/h]
mf_{CH4}	Methane Massflow [kg/h]
NPP	Nuclear Power Plant
P_{air}	Air Pumping/Compressing Power [kW]
P_{tot}	Total Output Power [kW]
P_{turb}	Turbines Generated Power [kW]
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
T_{max}	Maximum Temperature [K]
T_{amb}	Ambient Temperature [K]

1. Introduction

One of the key strategies to mitigate carbon dioxide emissions from electricity generation is the use of renewable energy. In recent years, a huge renewable power capacity was installed in several countries, with the majority of plants using solar and wind energy, which are intermittent and unprogrammable sources. Renewable power has represented approximately 58.5% of net additions to global capacity in 2014, with significant growth in all regions. Wind, solar PV and hydro power currently dominate the market in terms of generated energy. By the end of the year, renewable energy systems will represent 27.7% of the world power generating capacity, enough to supply an estimated 22.8% of global electricity demand [1]. Further increase in renewable energy in some areas where the installed power has reached almost 50% of the overall capacity cannot be reasonably expected, unless large-scale energy storage systems are installed.

Coping with this situation requires that the reminder of the system (including generation, storage and demand) is able to balance the supply and demand curves. Traditionally, this task has been performed by the bulk generation system (steam and hydro plants). When following the demand curve with pure generation plants is not technically feasible or the associated economical and environmental costs are too high, some storage is needed to balance the supply and demand curves by storing energy in periods of high energy production and releasing it in periods of high energy demand. This has largely been done with hydro pumping plants. But the characteristics of these units do not meet the needs asked for by the amount of renewable generation installed nowadays. A proof of this comes from the statistical data of the energy spent each year in Italy for pumping water up during the low demand hours. In 2003, around 10TWh had been used for this service out of a national electricity balance of around 300TWh. In 2014, when the generation from wind, sun and biomass reached 55TWh still out of a national balance of 300TWh, the energy used for hydro pumping was only 2TWh [2].

New solutions are therefore needed for keeping the system balanced in a more cost and environmental effective way with respect to modulating thermal plants and imposing them a large number of start-up and shut down cycles.

Modulation is needed with various features: daily modulation is used to follow the normal load profile, which ranges between the nightly minimum and the peak demand, and the daily generation profile from renewables; faster modulation is required for coping with the unscheduled differences between demand and generation forecasted curves; finally fast regulation services are needed to provide the grid with primary and secondary frequency regulation.

These requirements can be met by generation plants having the possibility of being regulated, by storage systems with various storage capacity and dynamic performance or by a proper integration of different shapes of generation and storage possibly in a single plant.

At the present time, keeping in mind the timeframe and the energy volumes needed, daily modulation requirements can be met by generation plants or by only two storage technologies which are mature for large-scale energy storage: CAES (compressed air energy storage) and PHES (pumped hydro energy storage). Fast regulation services have been traditionally released by steam plants able to quickly modulate the steam flow through the HP turbine valve. In a scenario where not-controllable renewables cover even more than 50% of the power demand in some hours, and where steam units are being replaced by combined cycles plants with tight constraints on dynamic response, the chance of having enough and fast enough regulation capacity might become a critical issue. Both CAES and PHES have not the chance to offer fast regulation services.

In this framework, hybrid solutions which integrate different generation facilities with one or more storage systems with different dynamic performance are gaining an increased interest from the scientific community [3].

As the paper will show, the use of energy storage in the shape of compressed or liquefied air gives the chance of burning some fuel to heat the compressed air before its expansion in the turbine. In this way the energy released to the grid is not limited only to what was stored time before. Theoretically the system behaves as a turbogas unit with split compression and expansion phases. The overall system (either CAES or LAES: Liquid air energy storage) integrates both the storage and generation features and enables decoupling the size of the compressing/liquefying stage and the combustion/expansion stage. Also the size of the storage tank can be freely chosen to satisfy different kind of requests.

Only the dynamic performance characteristics are intrinsic to the technology, as it happens also in hydro pumping plants, and fast regulation services can not be made available. It is therefore suitable adding some further kind of storage systems showing a faster dynamic behaviour, as electrochemical systems do. Different electrical schemes can be adopted, but the common result is to have an overall system including fast regulation services, long term storage as well as generation. It's worth finally mentioning that some renewable units can be a part of the system and the thermal and storage sections compensate for the lacking of regulation capacity without needing to curtail the renewable generation.

The paper will therefore introduce the concept of hybrid plant and will analyse the state of the art of large scale energy storage technologies. It will then focus on the performance that is expected to be achieved from LAES systems in various configurations with and without gas combustion, and will finally show how to integrate all the features in a single plant.

2. Hybrid power plant

A hybrid power plant is a whatever mix of generation, storage and, in some case, also loads, which is able to exchange a well controlled amount of electrical power with the grid. Hybrid power plants have been developed mainly for compensating the intrinsic intermittent nature of renewable sources and possible principle configurations as well as connection schemes have been largely studied and partly codified [3].

The hybrid structure proposed in this work includes a double level of hybridisation: the LAES system can be a hybrid generation/storage system itself; then the overall hybrid power plant is completed with an electrochemical storage system to achieve the desired fast performance.

The liquefying part of the unit stores liquid air using energy from the grid when surplus power is available. For improving its dynamic performance it might be useful never to stop it but simply modulating its production within its operative range. When energy is needed, the expander is started and part of the energy stored is sent back to the grid. It is worth noticing that the size of the liquefying plant and of the expander can be very different from each other, the expander being the larger. In this way the unit can be used to cover even peak demand even for short times as the expander is a cheap machine compared to the reminder of the system and can therefore be designed for higher mass flow than the liquefying unit without significantly increase the cost. This configuration would not be a hybrid system but a simple storage. Instead of simply expand the liquefied air after having compressed it with a pump, an interesting opportunity comes from the possibility to use such air to burn some natural gas and then expand the heated mix in a gas expander which would be a simple gas turbine. The heat in the exhausts can finally be used to vaporise the compressed liquid air and, potentially, to supply an Organic Rankine Cycle.

A second level of hybridisation concerns the use of an electrochemical storage system connected to the same electrical interfacing point to act as a fast responding storage to provide the grid with fast regulation services which would not be possible with only the LAES system.

Different connection schemes can be used for interfacing all the devices to the grid as the IEEE task force work classifies in [3]. In our work we will refer to just one scheme as the main aim of this paper is presenting the LAES hybrid system principle and its main energetic performances.

With reference to [3], we wish also mentioning that different kind of renewable sources can be directly integrated in the system thus including a further level of hybridisation which includes storage in two shapes, thermo-electrical generation and renewable sources. All the components of the plant can be directly connected to a single DC busbar through each relevant drive or converter, and the overall system finally interfaced with the grid through a single converter and a single connection point. The whole plant can be seen a single unit by the grid operator.

3. State of the art of large scale energy storage systems

Pumped hydro storage is one of the first systems studied in the past two centuries. Today it is mature and shows high roundtrip efficiency obtained thanks to the hydro pump/turbine state of the art. Unfortunately the most attractive sites in developed countries have already been used [4]. In any case, hydro plants are not likely suitable to ensure the required regulation dynamic performance.

CAES has been studied since the 20th century for city-wide scale. In last 50 years, utility-scale plants have been designed and built, from Germany to USA. CAES has a relatively high roundtrip efficiency but it must be employed with large and appropriate underground storage volumes (salt caverns, abandoned mines) to be cost effective. Unfortunately, suitable geological formations with the characteristics suitable for CAES are not common and the alternative of underground steel tanks requires huge investments [5]. On the other hand, liquid air can be stored in smaller, low pressure reservoirs thanks to its high density at moderate pressure. Cryogenic fluids can be stored for many months in low pressure insulated tanks with losses as low as 0.05% by volume per day.

Liquid Air Energy Storage (LAES) represents an interesting solution [6] whereby air is liquefied at about 78K and stored. When required, the liquid air is pumped, evaporated, heated with a higher temperature source and expanded in turbines to generate electricity. Hot and cold storage could significantly improve the roundtrip efficiency [7]. Only few studies on LAES performance are available in the literature.

An interesting opportunity comes from the possibility of integrating the energy stored in the liquefied air by creating a cycle where the liquid air is not only pumped and then vaporised using the environment as a warm source but where the combustion of natural gas overheats the air up to some 1650K before being expanded to produce mechanical and then electrical power.

The very low storing temperature strongly increases the efficiency of using natural gas to produce power, compared to conventional Brayton cycles. The overall plant can therefore be assessed as a hybrid system whose inputs are the electrical energy spent for air liquefying (coming, for instance, from renewable sources) and the chemical energy in the natural gas. The liquid air storage (LAS) enables the system to partly behave as a storage system by shifting the liquefying and the generation phase.

Highview Power Storage has built a small pilot and a medium prototype LAES plant (5MW) in the UK [8]. The company expects roundtrip efficiency up to 0.6 with hot and cold storage. Nuclear power plant (NPP) load shifting with LAES has been studied by Li et al. [9] and claimed to reach 0.7 roundtrip efficiency thanks to the cold storage and the heat available from the NPP.

Ameel et al. proposed a different approach with a liquid air Rankine cycle [6] reaching a maximum of 0.43 for roundtrip efficiency, in combination with a simple Linde liquefaction cycle.

Guizzi et al. [10] simulated a standalone LAES plant aiming at 0.55 roundtrip efficiency with reasonable and conservative assumptions. In the proposed layout the most critical component was the cryoturbine of the liquefaction section that should reach an isentropic efficiency of 0.7.

A similar layout was investigated by Xue et al. [11] focusing on the effects of compressor and cryogenic pump pressures. The maximum roundtrip efficiency achieved was 0.49.

Regarding the power recovery from liquid air, Mitsubishi Heavy Industries carried out two experimental campaigns. In 1997, Kishimoto et al. [12] tested a gas turbine air cooling system with liquid air. They tested a small-size gas turbine (4MW) confirming that liquid air injection was effective in improving turbine performance. In 1998, they assembled and tested [13] a generator for LAES plant with a turbopump to pressurize liquid air, an evaporator and a gas turbine.

The present paper focuses on electrical power generation from liquid air, with and without combustion. Four different process schemes are modelled and compared in terms of roundtrip efficiency and fuel efficiency (defined in paragraph 4). The technology is promising to reach equivalent roundtrip efficiencies ranging among the highest for the storage technologies which may provide long term and site independent energy storage capability.

4. Theory, schemes and calculations

The analysis has been carried out by adopting the Aspen HYSYS® process simulation code [14]. Only six pure components has been selected from HYSYS source database: nitrogen, oxygen, ambient air, methane, water and carbon dioxide. The property package is based on the classical Peng-Robinson equations of state. Only one reaction has been implemented for methane combustion :

$$CH_4 + 2O_2 \text{ -> } CO_2 + 2H_2O \quad (1)$$

Liquid air has been assumed as a mixture of molecular oxygen and nitrogen, respectively 0.76 and 0.24 in mass fractions, stored at 78 K and 2 bar. Pumps, compressors and turbines are considered with an adiabatic efficiency of 75% in ‘conservative cases’ and 88% in ‘best cases’. Heat exchangers are countercurrent flow type with small pressure drops (around 0.5%).

In Figure 1 the baseline layout is sketched with ambient air (298 K @ 1bar) as the upper temperature heat source. Liquid air from storage is pumped at 200 bar, evaporated and warmed in the first exchanger up to 293 K. After the first expansion (to 30 bar) the air is warmed again by ambient air and finally expanded to ambient pressure.

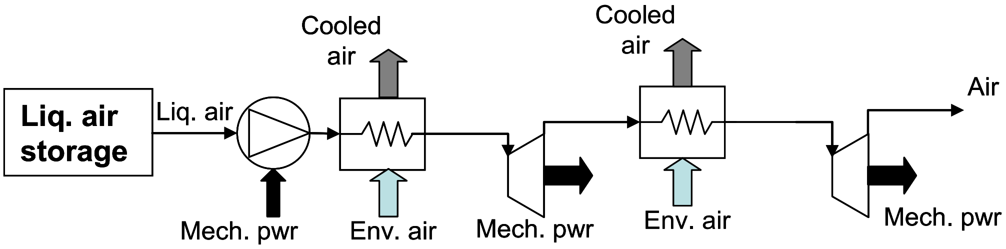

Figure 1 –process air expansion without combustion, *'baseline case'*

This simple process, without any heat addition, has been considered as the baseline case to which all further ideas have been compared. No further external energy is consumed, except the energy spent for liquefying, but the roundtrip efficiency has resulted too low to make it interesting in comparison with any other energy storage system. To increase efficiency and specific work, a second scheme (Fig. 2) with an external heat addition by means of natural gas combustion has been investigated. In this process the first stages (pumping, evaporation and warming by ambient air) are the same as in the first configuration. The two combustion processes have been simulated by means of two conversion reactors where compressed methane is injected for combustion, and a second heat exchanger is introduced to allow the heat in the hot exhaust gases to be recovered.

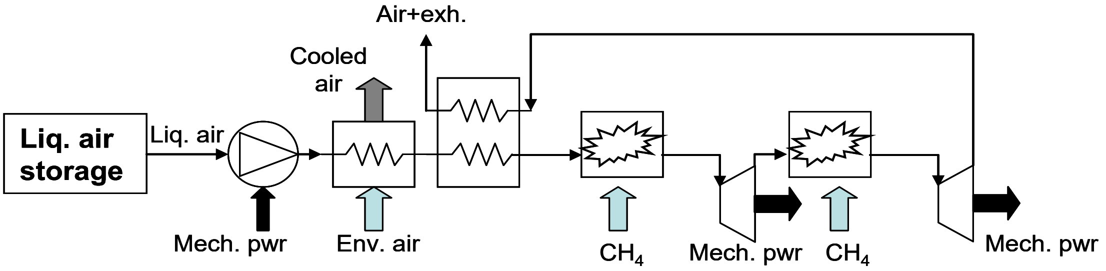

Figure 2 –process air expansion with combustion, *'natural gas case'*

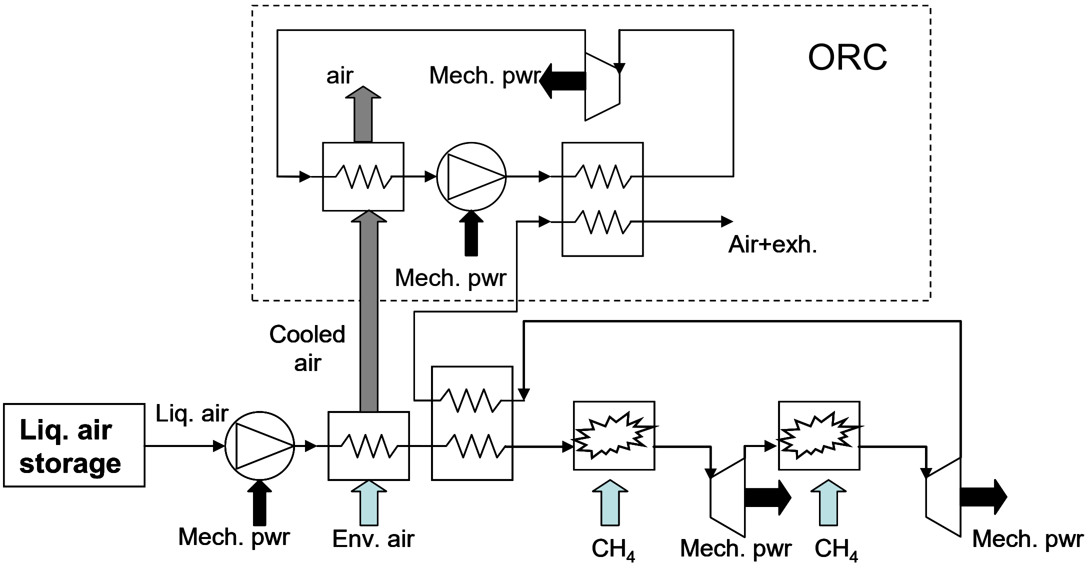

Figure 3 – *cryogenic ORC* simulation case

In a third scheme (Figure 3) the waste cold coming from the evaporator is used as the lower temperature heat sink for a *cryogenic Organic Rankine* Cycle. In this case, r134a is adopted as working fluid, being evaporation and condensation pressures 10 and 0.3 bar respectively.

In the last scheme, indicated as *cold Brayton* (Figure 4) the cooled external air used in the evaporator undergoes a recuperated Brayton cycle (air is compressed at 15 bar).

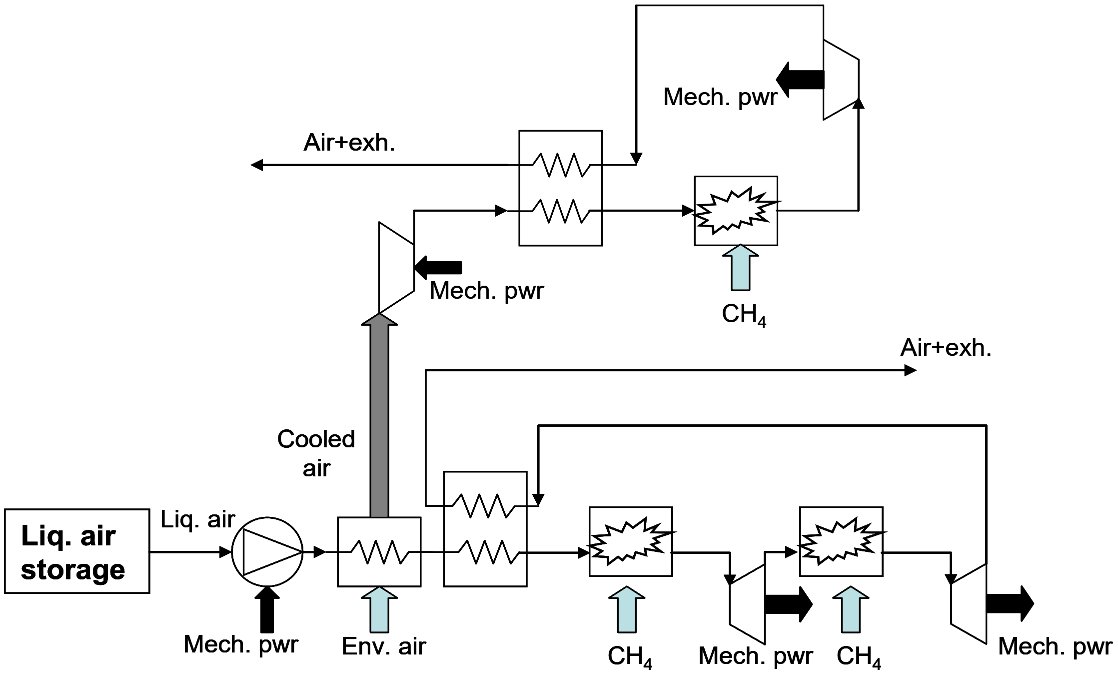

Figure 4 – *cold Brayton* simulation case

The energy required for liquid air production has been assumed to be 0.35 or 0.5 kWh/kg, the bigger one is a quite conservative value [15] in comparison with the most advanced technology for liquid air production reaching the lower value [16]:

$$E_{air} = 0.35 \text{ -- } 0.5 \text{ kWh/kg} \qquad (2)$$

Depending upon the scheme adopted, total output power takes account of the power for liquid air pumping, for either, if included, ORC pumping or Brayton compression and, finally, of the power generated by the turbines:

$$P_{tot} = P_{turb} - P_{air} \qquad (3)$$

Specific energy recovered is defined considering the total output power with respect to liquid air massflow :

$$E_{tot} = P_{tot} / mf_{air} \qquad (4)$$

In case of natural gas combustion the specific combustion energy is calculated with reference to liquid air massflow :

$$E_{CH4} = LHV_{CH4}\ mf_{CH4} / mf_{air} \qquad (5)$$

Since the energy spent for air liquefying and the energy available in the fuel have a different shape, some kind of harmonization should be included to make the resulting efficiency values be meaningful.

The proposed way to compare such values is to convert the fuel energy into the equivalent electric energy that could be generated if the same amount of fuel is used in a state of the art combined-cycle plant having efficiency around:

$$\eta_{cc} = 0.6 \qquad (6)$$

In this way, an equivalent corrected roundtrip efficiency can be defined as:

$$\eta_{RTcorr} = E_{tot} / (\eta_{cc}E_{CH4} + E_{air}) \quad (7)$$

For the natural gas cases, a fuel efficiency defined as in (8) is introduced to evaluate the quality of fuel exploitation:

$$\eta_{fuel} = P_{tot} / LHV_{CH4}\ mf_{CH4} \qquad (8)$$

Liquid air mass flowrate (mf_{air} = 200 kg/h) and pressurization are the same in all the cases. Turbine expansion ratios are identical too. Total natural gas mass flowrate is set to obtain a global excess of air in order to limit the maximum temperature at 1673 K.

5. Calculated performance

Table 1 shows the main parameters and results of simulations.

As already mentioned in paragraph 3, the results of the calculations have proved that the round-trip efficiency of the baseline case is very low. If, however, natural gas combustion is introduced, the high temperatures reached lead to important benefits in terms of total power generated and roundtrip efficiency. Fuel efficiency rises up to a significant value of 0.93, which means that almost all the fuel energy is converted into work. This occurrence does not contradict the second law of thermodynamics since most of the heat is provided at ambient temperature using the environment heat capacity. However, this is an important parameter for the evaluation of different systems configurations.

Table 1 – simulation parameters and results, *conservative* cases

variable	**baseline case,** ***conservative***	**natural gas case,** ***conservative***	**cryogenic ORC,** ***conservative***	**cold Brayton,** ***conservative***
mf_{air} [kg/h]	200	200	200	200
mf_{CH4} [kg/h]	-	6.3	6.3	12.8
P_{air} [kW]	1.67	1.67	1.67 + 0.02	1.67 +25.8
P_{turb} [kW]	11.96	83.08	83.08 + 1.57	83.08 + 83.11
P_{tot} [kW]	10.29	81.41	82.95	140.36
E_{tot} [kWh/kg]	0.051	0.407	0.414	0.702
E_{CH4} [kWh/kg]	-	0.438	0.438	0.89
η_{RTcorr} [-]	0.10	0.53	0.54	0.68
η_{fuel} [-]	-	0.93	0.95	0.79

In the first two cases (*baseline* and *natural combustion*) a remarkable amount of ‘waste cooling power’ results from liquid air evaporation with ambient air. Storage and reutilization in liquefying process or other power generation cycles could be considered and investigated. Upon this consideration, the *Cryogenic ORC* and *cold Brayton* cycles have been introduced to use the cold waste air from the evaporator to improve the equivalent roundtrip efficiency.

Cryogenic Organic Rankine cycle leads to negligible improvements despite the addition of complex and expensive components. The literature about those cycles is limited to few studies applied to LNG regasification [17] and further investigations could be carried out. Nevertheless it seems clear that the amount of energy exploitable is too low in comparison with the one coming from combustion. This solution should be evaluated only for LAES cycles without combustion.

The *cold Brayton cycle* is basically a recuperated gas turbine cycle using the cold air from the evaporator instead of ambient temperature air. Compression of cold air is less demanding in terms of power and allows higher compression ratio. This configuration reaches the highest total power (+80%) and the best equivalent roundtrip efficiency (0.68) despite a larger fuel consumption.

As far as power and efficiency are concerned, it should be pointed out that pump/compressor/turbines isentropic efficiency has been set at 75%, which is a quite conservative value for medium size turbomachines and similar to MHI pilot plant [13]. Furthermore, in the roundtrip efficiency the energy required for liquid air production has been set at E_{air}=0.5 kWh/kg. This value is strictly dependent upon the air liquefaction process and significantly lower values can be encountered in modern industrial processes.

Table 2 - simulation parameters and results, *best* cases

variable	**baseline case, *best***	**natural gas case, *best***	**cryogenic ORC, *best***	**cold Brayton, *best***
mf_{air} [kg/h]	200	200	200	200
mf_{CH4} [kg/h]	-	6.5	6.5	14.7
P_{air} [kW]	1.43	1.43	1.43 + 0.02	1.43 + 20.25
P_{turb} [kW]	14.02	95.84	95.84 + 1.59	96.61 + 97.86
P_{tot} [kW]	12.59	94.41	95.98	172.79
E_{tot} [kWh/kg]	0.063	0.472	0.479	0.864
E_{CH4} [kWh/kg]	-	0.451	0.451	1.02
η_{RTcorr} [-]	0.18	0.76	0.77	0.90
η_{fuel} [-]	-	1.05	1.06	0.85

The so called ‘best cases’ reported in Table 2 adopts efficiencies of 88% for pumps, compressors and turbines (state of art [18]) and E_{air} = 0.35 kWh/kg.

The equivalent roundtrip efficiencies raise to values as high as 0.9, making this processes very attractive in comparison with both batteries and pumping hydro storage.

6. Integration of electrical storage and grid interfacing

From a dynamic point of view, the main drawback of these solutions is the time needed to start and stop the system, to reverse the power flow and to modulate the power output. Also the calculated efficiency values are strongly influenced by the operating point, so a continuous modulation of the operating point might dramatically jeopardize the cost and energy effectiveness of the system.

However, several approaches to solve these issues can be conceived, depending upon the choices operated for connecting the LAES system to the electrical grid.

Interesting and effective solutions can be adopted instead of the basic idea of operating a LAES system using an electric motor directly connected to the grid and driving a compressor during the time when energy must be stored, and a generator moved by an expander when energy must be released to the grid.

As a matter of fact, this simplified scheme has some critical issues which (even without considering dynamic response specifications) push towards the choice of more flexible configurations. First, the operational speed of the standard AC machines (either synchronous or asynchronous) is practically constant, reaching a maximum of 3000rpm for a two-pole machine on a 50Hz AC system. It means that the LAES system must operate at almost constant power. The only way to modulate the power in both the phases of the storing cycle would be to operate on some valves which introduce lamination losses, thus reducing the overall system efficiency. A second consequence of the rotational speed limit is that, to achieve a given power value, the machines will have large dimensions (as the physical size of rotating machines is roughly proportional to the mechanical torque). To reduce the size of the compressor and of the expander some gear boxes can be used thus introducing additional losses. It is therefore practically mandatory resorting to high speed systems able to operate in continuously varying conditions with high speed machines having smaller physical dimensions, lower costs and higher efficiency than traditional directly connected machines. This result can be easily achieved through high speed motor and generator drives connected to the AC grid by power electronic converters.

A basic schematic of the solution is shown in Figure 5.

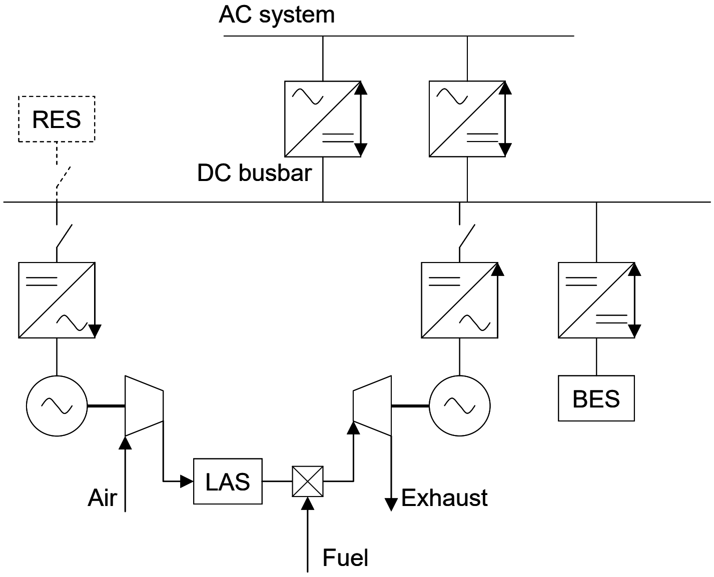

Figure 5: Basic schematic of the LAES system interfacing solution

Instead of using a single AC/AC converter for each of the two machines (one for the compressor and one for the expander) an interesting opportunity comes from the possibility of introducing a intermediate DC busbar (which would be in any case included in each of the converters). This eases also the possibility of coping with multiple stage expansion or compression systems, since; each one can be connected with its own converter to the DC busbar, without increasing the number of interfaces with the AC grid.

The system also includes an electrochemical storage system (battery energy storage: BES), which is able to exchange power with the DC busbar with very fast dynamic performance.

The grid needs several kinds of services for being correctly operated and storage systems have the possibility to offer these services. An overview of the main services can be found in [19]. Some energy services can be directly offered by the LAES system which is likely to have a relatively slow dynamic response but can rely on large energy amounts.

Fast response, which is typically needed for primary frequency response, island system regulation and back-up supply, can only be offered by faster systems such as an electrochemical system as shown in the basic schematic of Figure 5. The converter interfacing the overall hybrid storage system is controlled to deploy the various services. The other converters interfacing the compressor, the expander and the battery storage are then used to keep the voltage on the DC busbar at a constant level by balancing the demand from the AC system. Fast response is assured by the battery system while long term response is obtained by either storing or expanding liquid air.

The AC system interfacing inverter can be easily controlled with a frequency and voltage droop logic as described in previous works [19, 20], to provide the grid with primary frequency regulation while sharing the regulation contribution with all the other sources available in the grid.

The response in Figure 6 shows how the inverter with a droop control system follows the frequency deviations on the grid (green curve with square marks) by adapting the power exchange (red curve with circle marks) according to the slope of the droop characteristic. The graph is taken from a 250kW inverter currently being tested at the University of Pisa.

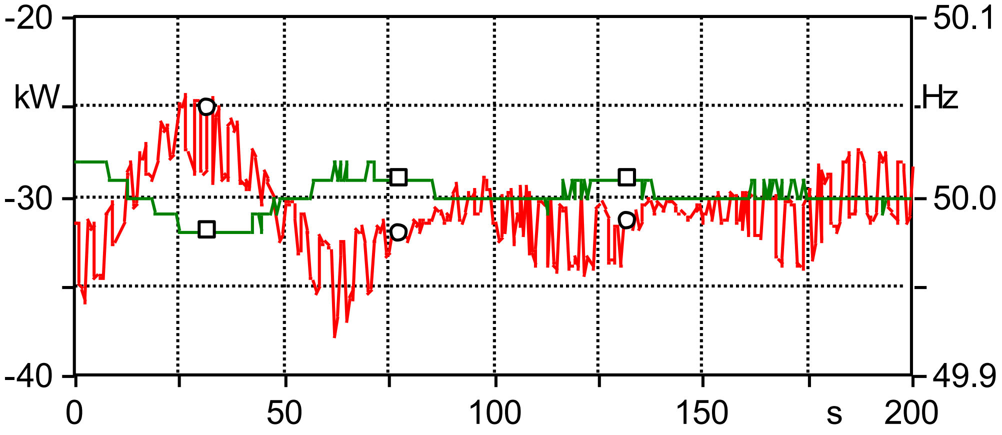

Figure 6: Grid frequency (green, square marks) and real power (red, circle marks) during operation at 2% frequency droop and power setpoint at -30 kW (battery charging)

7. Conclusion

Hybrid plants are very flexible systems which can exploit the best features of several different and new technologies to satisfy grid management needs and can make an optimal use of locally available energy sources.

Hybrid systems, including different storage technologies as well as power generation from fuel and renewable sources, have been described and LAES systems have been investigated as an interesting opportunity for large scale storage, easily enabling the possibility of including conventional generation. The performance of some possible system configurations for liquid air energy storage has been compared with respect to a baseline configuration, where no external energy is used in the regasification of liquid air, except heat from ambient air. The baseline configuration has shown to exhibit a too low roundtrip efficiency (air liquefying-air regasification) to be interesting in comparison with other energy storage options.

However, the development of a hybrid power plant also including an external heat source from natural gas combustion and integrating electrochemical storage for dynamic performance requirements, enables improving the effectiveness in terms of both equivalent roundtrip efficiency and fuel efficiency. A higher than 80% equivalent roundtrip efficiency, as well as a use of fuel efficiency even higher than 100% have been achieved. Since most of the parameters used in the simulation are not optimized, the potential for a further improvement in the performance as energy storage system is wide.

The hybrid plant concept integrating high speed drives for compressor and expander connection together with a small electrochemical storage makes these systems a promising solution even when fast dynamic response is requested. This feature, together with high equivalent roundtrip efficiency, is becoming an essential performance required to manage a power system where the amount of renewable sources is rapidly growing, and where the amount of generating units able to perform regulation services is decreasing.

Therefore, hybrid power plants based on LAES technology may be a promising solution to store energy and use it at peak times with interesting performance. Additional configurations are being studied and will be compared in a future study as well as the integration with the liquid air production systems will be considered.

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