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Liquid Air Energy Storage as a polygeneration system to solve the unit commitment and economic dispatch problems in micro-grids applications

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Abstract

Storage technologies play a crucial role in polygeneration plants that attempt to integrate power, thermal and cooling energy systems in order to maximize process efficiency and reduce operating cost. With the increasing penetration of renewable energy into the plant, storage technologies help to dampen the intermittency problem in their energy supply whilst at the same time perform peak shaving to reduce primary energy consumption, thus mitigating pollutant emission. Among the various storage technologies, Liquid Air Energy Storage (LAES) have gathered research interest due to its capability of simultaneously producing electrical and cooling power. Furthermore, unlike Electrochemical Energy Storage (EES) technologies, the LAES lifetime is not heavily dependent on its duty cycle, thus allowing for a calendar life twice or thrice that of EES. In this paper, the economic dispatch of an Eco-building in Singapore has been evaluated using a mixed-integer quadratic programming solver by comparing the adoption of EES and LAES within a capacity range of 300kWh-2000kWh. At the higher end of the capacity range, the LAES configuration results in a higher Net Present Value after 20 years and a shorter time period to obtain the Return of Investment compared to that of EES. At the lower capacity range, both technologies give similar financial returns. Analysis of the results show LAES to be a promising technology to compete with EES in the context of a polygeneration plant and further technology integration is discussed.

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Nomenclature

EES	Electrochemical Energy Storage
CP	Cooling Power
LAES	Liquid Air Energy Storage
NPV	Net Present Value
P	Power
PV	Photovoltaic
Q	Heat Power
ROI	Return of the Investment
SMES	Smart Multi Energy System
V	Volume (or Capacity)

Subscripts

- / +	taken / given to the buses
ABCH	Absorption Chiller
B	Battery
Exh	Exhaust
G	Grid
HT	High Temperature
L	LAES
VCCH	Vapour Compression Chiller

1. Introduction

Polygeneration is an energy-efficient technology for generating simultaneously power, thermal and cooling energy as well as other energy products (e.g. hydrogen, liquid air/nitrogen, water, etc.) in a single integrated process. With polygeneration a highly efficient energy conversion and the development of the sustainable energy systems is now attainable. In particular, a sustainable energy system meets energy demands locally from renewable energy and high-efficiency polygeneration technologies, and it is characterized by primary energy and cost savings and by pollutant emissions mitigation [1].

By the adoption of a properly integrated energy systems, relevant economic and energy savings are achieved if compared with conventional energy systems providing the same quality of energy services. Due to the potential cascade of heat recovery processes, a more integrated energy system results in higher energy saving. Energy process integration encompasses techniques based on thermodynamic and economic analysis of individual components as well as holistic system studies oriented to maximize the efficiency of resources [2].

Industrial estates are preferential users for polygeneration since they are large energy consumers (such as petrochemical, pharmaceutical, semiconductor, and shipyard industries) of electric, heating and cooling power as well as other products related to the energy conversion process (e.g. packaged gas). In industrial estates, multiple types of distributed energy converter units including gas/diesel reciprocating engines, combined cycles, gas turbines, fuel cells, photovoltaic (PV), solar thermal generator, building integrated photovoltaic, micro gas turbines and wind turbines are integrated in the networks along with energy storage. These integrated energy systems could be in the scale of few hundreds kW to several MW and in some cases, these could be considered as multi-energy grids.

In micro-grid applications, energy storages play an important role since they allow a broader penetration of renewables, improve the overall system efficiency, enable the participation of commercial and industrial facilities in demand response markets without impacting on-site energy use or operations and they contribute to enhance the grid resiliency. Accordingly, storage is perhaps one of the most important component in the Smart Multi Energy Systems (SMES) because of the key role in complementing renewable generation and local generation. With the proper amount and type of storage broadly deployed and optimally controlled an intermittent energy source should be successfully turned out into a dispatchable generation source. Different energy storage systems exist and they are typically classified into electricity, thermal and gas storage [3]. Among the various energy storage systems, Liquid Air Energy

Storage (LAES) are becoming competitive if compared with Electrochemical Energy Storage (EES) [4,5]. Energy storage is essential to balance supply and demand. Peaks and troughs in demand could often be anticipated and satisfied by increasing - or decreasing - generation at fairly short notice. Different levels of energy storage are required for grid flexibility and grid stability and to cope with the increasing use of intermittent electricity. Smart cities, a key energy policy goal, require smart grids and smart storage.

1.1 Liquid Air Energy Storage

When in cryogenic state, packaged gases (e.g. liquid air/ nitrogen) represent a long term/clean energy storage solution with long lifecycle (30 years vs 10years of electrochemical energy storage) and easy to recycle/dispose equipment. Moreover, cryogenic energy storage gives possibility to exploit low grade heat (less than 100°C) in a meaningful way and to harness cold energy released during the regasification process. As with any other energy storage device, the working cycle of cryogenic energy storage consists of three parts: charge, storage and discharge [6–8]. Figure 1 shows one potential layout of a cryogenic energy storage system. The charging process is a liquefaction process based on a Claude cycle; an insulated cryogenic tank works as energy storage; the discharging process consists of a cryogenic pump, a heat exchanger, and the power unit. One of the peculiarities of cryogenic energy storage is that it can produce both electricity and cooling at the same time. Indeed, during the discharging process, electrical power from the generator and cold power from the evaporator can be generated. In the meantime, some heat power made available during the charging phase can be adopted for feeding up absorption chillers, if cooling power is needed, or Organic Rankine Cycles, if water savings and optimization in electricity generation is required [9].

2. Polygeneration Objective and Proposed Arrangement

In industrial estates, cost reduction and energy efficiency are also achieved by considering the electrical grid, fuel grid, and thermal grid as a whole. As part of this paper the authors are looking at polygeneration of multiple energy products (electricity, thermal), their interaction and integration with energy storage solutions. Specifically, the integration of the Liquid Air Energy Storage (LAES) into a micro-grid context has been explored. The paper will compare the adoption of Electrical Energy Storage and Liquid Air Energy Storage as part of a polygeneration system, which includes a cogeneration plant (reciprocating internal combustion engine and absorption chiller), solar PVs and vapour compression chillers, aimed at satisfying the cooling and electrical load of an industrial building located in Singapore. Due to the hot and humid climate, there is no demand/need for heating and the objective is mainly focused on the cooling side. The Smart Multi Energy System (SMES) project[†] - national Singaporean project - for demonstrating the capabilities of Unit Commitment Problem (UCP) and Optimal Dispatch Problem (ODP) solving, a well-referenced building estate has been taken into consideration. The demonstration test case refers to the Clean Tech Park (CTP), in the west district of Singapore; the CTP consists of three buildings for office use. The CTP primary energy consumption is set to satisfy the electricity demands for lighting, chillers and other building requirements. The CTO electricity and cooling demands are known and have been taken as a reference case for this study.

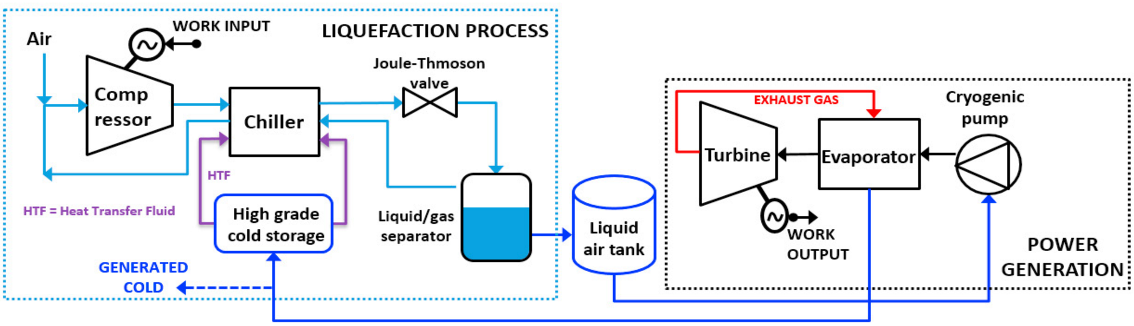

Figure 1: LAES arrangement – Charge, Storage and Discharge process

[†] Refer to the Acknowledgement section for more details.

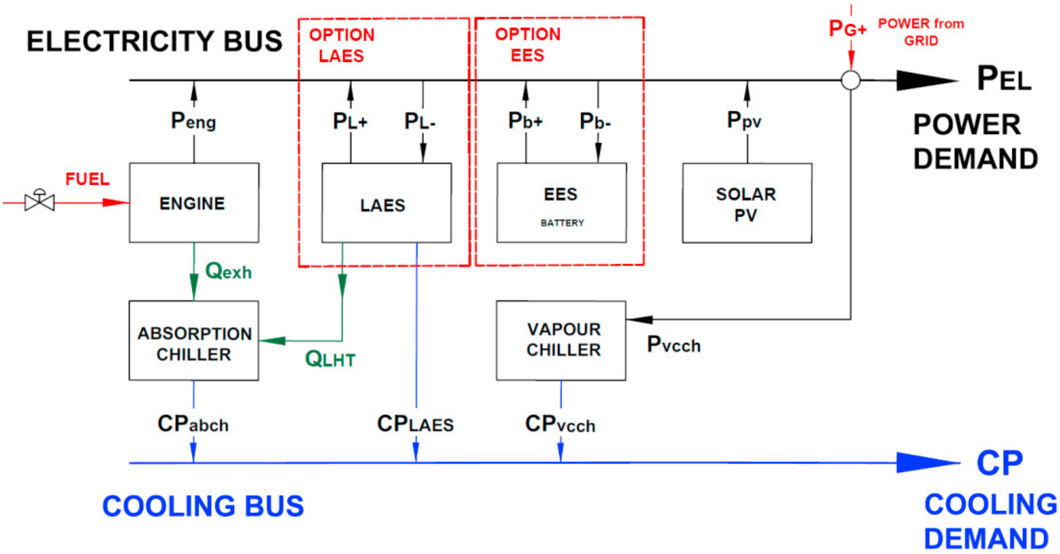

Figure 2: Proposed arrangement for the polygeneration plant equipped with energy storage

In order to satisfy the cooling and electric load (i.e. chilled water and electric work) during a typical working day (24hours, 48 intervals of 30 minutes each), in the present paper the configuration shown in figure 2 has been proposed. On the electricity bus, a gas engine, solar PVs (which size is related to the rooftop surface availability), EES (i.e. battery) or LAES have been considered to satisfy the generation and demands of electric power. On the cooling bus, by means of the proposed gas engine cogeneration arrangement, the cooling demand is satisfied by an absorption chiller, a vapour compression chiller and, when considered, by the cold energy made available by the LAES discharging process. The primary energy sources for running the whole system are highlighted by the red arrows representing the fuel mass flow rate, the electric power purchased from the grid and the power consumed for running the vapour compression chiller. Details on the modelling approach coupled with the proposed solution strategy are given in the following section.

3. Modelling and Optimization Method

For solving the UCP and ODP, the modelling of the polygeneration plant is based on a modular approach that consists in matching the elementary components (i.e. gas engine, solar PVs, EES, LAES and vapour compression chillers) for achieving the whole polygeneration plant simulator. The modelling approach takes into account steady state 0-D component models. For each component the conservation equations of mass, momentum, energy and entropy, constitutive and the auxiliary equations are stated.

The component models are based on lumped performance feature discretization approach, in which boundary surfaces and central nodes are adopted, as described in [10]. The quadratic programming technique has been adopted and coupled with a mixed integer solver (compared with the adoption of genetic algorithms) for ensuring reduced computational costs and robustness of the solution. The adopted approach has been presented by many authors who have proven the benefit of the proposed MIQP programming technique [11]. In this paper, details on the modelling of the LAES will be provided in the next section together with the optimization procedure for solving the ODP. The other modelled component models such as gas engine, PV, chillers are modelled taking into account off-design maps that correlate the load at which each component is operated in respect of the nominal values and the performance of the component itself (i.e. efficiency of the gas engine and coefficient of performance of the chillers).

3.1 Liquid Air Energy Storage component model

The LAES component model has been developed taking into consideration the operating parameters such as the Round Trip Efficiency (η_{RTE}), the LN_2 Specific Consumption (SC) and the cold energy utilization ratio. Such parameters are helpful because they allow to characterize the LAES performance for the given power/energy of charge, P_L^-. The authors have presented details on the LAES modelling in previous works [12,13] and as a result the global quantities such as recoverable cooling and heating power, LAES storage capacity and generated power have been established by means of global correlations. The LAES capacity (expressed by its storage volume) is established by (eq.1), with ρ_{LN2} as the liquid nitrogen density.

$$V_{LAES} = \frac{P_L \cdot \Delta t}{SC \cdot \rho_{LN_2}} \tag{1}$$

By means of energy conservation equations it is possible to establish the amount of cold energy generated and the electric work produced by the turbine during the discharge phase as expressed by the functional correlation given in (eq.2), being COP_{ABCH}^{LT} the low temperature loop absorption chiller coefficient of performance.

$$f(P_L^-, P_L^+, \eta_{RTE}, SC, CP_{LAES}, Q_{LHT}, V_{LAES}, COP_{ABCH}^{LT}) \tag{2}$$

Taking the LAES capacity expressed in kWh or in m^3 into account, during the ODP solving the evaluation of the LAES capacity has to be performed for ensuring the feasibility of the numerical solution and the capability of the system of storage energy during the off-peak operations and release it during peak ones. The LAES capacity (similar approach of the state of charge in EES) at the next interval (t+1) is established by (eq.3) and it is done during the 48 intervals of the day operation.

$$V_{LAES}(t+1) = V_{LAES}(t) + \frac{P_L^- \cdot \Delta t}{SC \cdot \rho_{LN_2}} - \frac{P_L^+ \cdot \Delta t}{\eta_{RTE} \cdot SC \cdot \rho_{LN_2}} \tag{3}$$

Adoption of inequality constraints for checking that the LAES volume – at the instant $t+1$ - is in the range between the minimum volume and the maximum volume has been introduced (eq.4).

$$V_{LAES}^{min} \leq V_{LAES}(t+1) \leq V_{LAES}^{MAX} \tag{4}$$

The binary variable (the mixed integer one 1/0), representing a logic operator, ensures that during each Δt interval the LAES system can only be in charge, storage or discharge mode.

It has been implemented in the code the

3.2 Objective function definition and constraints structure

The solution of an ODP consists of two main steps such as the minimization or maximization of the objective function (ObF) and the satisfaction of the equality constraints, namely power flows (electricity and cooling bus load demands). From a numerical perspective, the adopted solver is based on simultaneous solutions; this means that concurrently to the equality constraints satisfactory also the *ObF* is optimized. In the current work, the *ObF* to be maximized has been set to be the Net Present Value (NPV), expressed by (eq.5).

$$ObF - Search\ MAX\ of:\ NPV = \sum_{k=1}^{N} \frac{CF}{(1+i)^k} - C_{APEX} \tag{5}$$

being C_{APEX} the overall polygeneration plant capital expenditure, expressed as the sum of the various components investment costs, and the Cash Flow (CF) defined as the difference - integrated over the year - between the cost of the generation of the proposed polygeneration system (cost of fuel plus electricity) versus the cost of the generation in the case that all the electricity (also used for feeding the vapour compression chiller for cooling power generation) is purchased at the CTO contracted electric price p_G from the Singaporean national grid, as given in (eq. 6).

$$CF = \int m_F(t) \cdot p_F(t) \cdot dt + \int P_G(t) \cdot p_G(t) \cdot dt - \int P_G^R(t) \cdot p_G(t) \cdot dt \tag{6}$$

The satisfaction of the energy flows (operational constraints) for the ODP both on the electric and cooling buses is expressed by (eq.7) and (eq.8), respectively.

$$P_{EL} \cdot \Delta t = P_{ENG} \cdot \Delta t + P_{PV} \cdot \Delta t + P_G^+ \cdot \Delta t + P_L^+ \cdot \Delta t - P_L^- \cdot \Delta t \quad (7)$$

$$CP \cdot \Delta t = CP_{ABCH} \cdot \Delta t + CP_{VCCH} \cdot \Delta t + CP_{LAES} \cdot \Delta t \quad (8)$$

Under this conditions the ODP has been fully stated and in the next section the test case and the analysis of the results is presented.

4. Test Case and Results

The capability of the proposed polygeneration system has been explored for both the cases in which either LAES or EES is being considered. As stated in the previous sections, the electric and cooling power profile have been set as constraints to be satisfied, with the CTO consumptions known. The assessment has been carried out taking into consideration the following component specifications, in terms of sizes and costs. The internal combustion engine is a 1MW gas engine; the waste heat is recovered through an absorption chiller generating 1.2 MWc of cooling power. The capex of the cogeneration plant has been established by factorized methods and estimated to be equal to 1.6MS$. The solar PV surface is of 2000 m2 and the corresponding nominal power is of 230 kWe for an investment cost of 0.6 MS$. The vapour compression chiller shows a nominal plate cooling power of 2000 kWc and the capital cost has not been included because it is already installed at CTO. The sensitivity analysis has been performed varying the LAES and EES capacity in the range 300 kWh to 2000kWh. For these storage capacities, the specific cost of LAES is of 320S$/kWh [6,14] while for Lithium (Li-on) EES is 560 S$/kWh [15]. The evaluations have been performed taking a typical day profile of electricity consumption into consideration (Singapore does not have huge seasonal weather changes) and assuming an interest rate *i* of 6% and a lifetime of the power plant of 20 years. The price of the fuel, on the basis of the natural gas trade price, has been assumed to be 0.45 S$/kg for a low heating value of 48MJ/kg.

The optimized solution of the ODP is reported in figure 3. The electric load (continuous red line on the left) and the cooling load (dashed blue lines on the right) are data available and they have been set as constraints for solving the ODP. The black line - in both the charts - represents the price of the electricity purchased from the national grid. With the fuel cost assumed to be constant (as in the typical case of *take or pay* contract for the natural gas), the p_G plays a key role in the optimal control strategy definition, as clearly shown in the figure 3. Accordingly, during night hours, when the price of the electricity is minimum, the gas engine is turned off and the whole amount of the electric load is satisfied by the electric work purchased by the grid (red area on the left). As a consequence, the cooling load demand is fully satisfied by running the vapour compression chiller, being the absorption chiller turned off as well. The control strategy of the whole systems manages to avoid purchasing the electricity from the grid during the peak hours (13.00 to 15.00) thus the LAES is charged in the first hours of the morning, when also the solar PVs contribute to generate electric work (yellow area) for matching the electricity demand. Indeed, it could be seen that the green bars (representing the level of the LAES storage capacity, similarly to the state of charge of the EES) increase during the relatively low p_G hours and decrease until the minimum allowed value (eq. 4) in which the electricity demand is high. It should be remarked that the LAES is charged before the spike on the cooling demands that takes place between 08.30 and 10.00 in the morning. A small contribution to the cooling bus is given by the LAES (orange area on the right) during the discharge phase, when some cold energy is released. In figure 4, the ODP solved for the polygeneration system equipped with EES is presented. As a consequence of the EES having a higher round trip efficiency than the LAES, the EES are used also during the night hours. EES is fully charged by the cogeneration till 01.30 and then, it is used for reducing the amount of electric work purchased by the grid during the night hours, when the cogeneration is turned off because of the reduction of the cooling demand. Also during day time (16.00-17.30), the adoption of EES allows to reduce the electric work purchased from the grid, as shown by the comparison of the figures 3 and 4 (left charts). In both the scenario, with EES and LAES, the control strategy substantially searches for the minimum operational cost along the reference period of operation.

For understanding the techno-economic feasibility of the two solutions, the cost benefit analysis of the proposed layout, both equipped with EES (continuous line) and LAES (dashed line), has been carried out. Results of this analysis are summarized in figure 4. The *NPV* and *ROI* for the two energy storage technologies and for two different storage capacities 300kWh (red lines) and 2000kWh (blue lines) have been presented. For the smaller capacity, the ROI of the two solution is practically the same, about 7 years. For the 300kWh storage capacity, a NPV of 2.3 MS$ is achieved. Increasing the capacity of the storage systems, the weight of C_{APEX} of the EES becomes more significant in the overall capital expenditure of the polygeneration plant if compared with the LAES plant layout. As a consequence, the ROI of 2000kWh EES is about 11 years, while the LAES ROI is of 9 years. NPVs in this configuration are lower. It is worthy of note that typical lifetime of EES is less than 10 years. It means that in the 300kWh case, after 20 years, the EES NPV should be lower because of the need to replace the battery component in the 10th year.

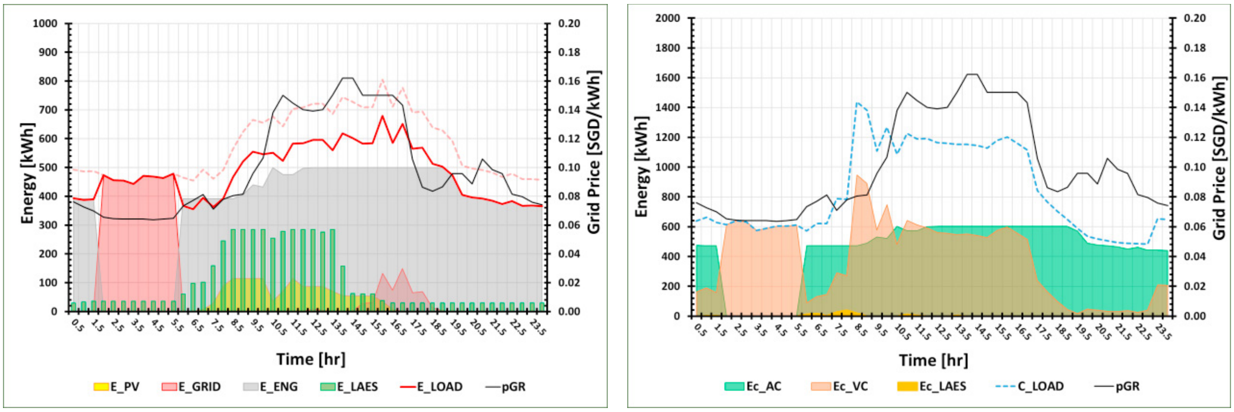

Figure 3: 300kWh LAES arrangement - Optimal Dispatch (electric Load – Left) – (Cooling Load – Right)

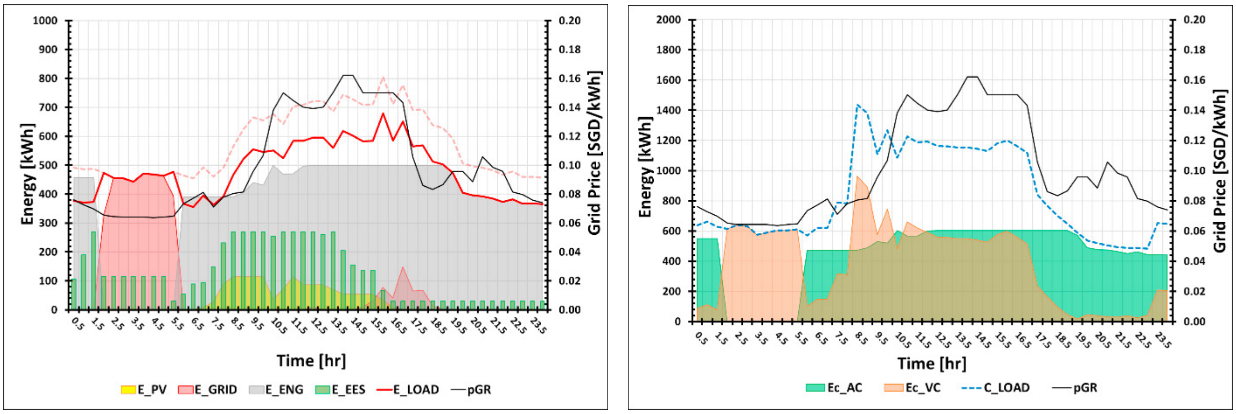

Figure 4: 300kWh EES arrangement - Optimal Dispatch (electric Load – Left) – (Cooling Load – Right)

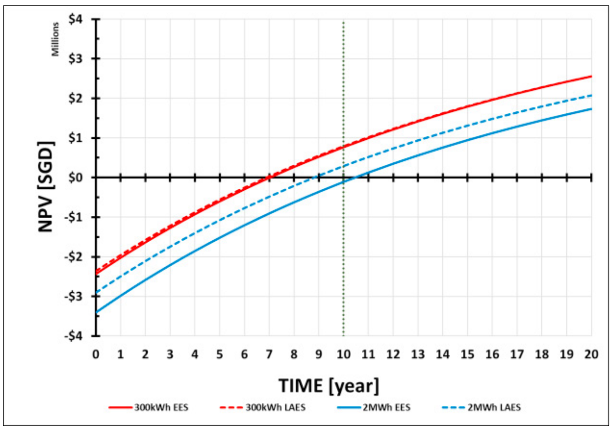

Figure 4: Net Present Values and ROI for EES and LAES capacities of 300kWh and 2000kWh

5. Concluding Remarks

The paper deals with the adoption of polygeneration power plants in the smart energy scenarios as a valid alternative to the traditional generation systems for cost savings, pollutant emissions mitigation and for overall increase in performance efficiency. Due to the renewable energy source fluctuations and to the high variability of the electricity price during the polygeneration system operations, the adoption of the most suitable energy storage between LAES and EES has been investigated. According to the present state of the art, LAES are becoming valid alternatives to EES because of the significantly lower capital cost and a longer lifetime in the region of 25 years. The penetration of small scale LAES into smart grid energy system, which has not been widely explored, has been analysed in the present paper using a polygeneration power plant layout equipped with the LAES in the building estate applications. In order to better understanding the best control strategy of this highly integrated system, the resolution of an optimal dispatch problem coupled with a cost benefit analysis has been performed. The authors have adopted a mixed integer quadratic programming solver for ensuring robustness and low computational cost to the system. As a result, the optimal dispatch for the electricity and cooling buses demands have been presented, highlighting the more convenient time to operate the LAES. For the same demands, the EES polygeneration plant layout has also been evaluated, showing how the EES higher round trip efficiency plays a key role in the management of the energy storage system duty cycle. Indeed, from an energy perspective, the minimum electric work purchased by the grid is achieved by the utilization of EES rather than LAES in the polygeneration system. Looking instead at the techno-economic feasibility of the solution, taking the real lifetime of 20 years of the plant, LAES becomes a competitive alternative because its capital cost is almost half that of EES and because LAES performance are not significantly affected by duty cycles.

The paper has demonstrated that by adopting the current state of the art of LAES, characterized by almost 50% round trip efficiency, the ROI of a 300kWh capacity LAES is shorter than 7 years and the NPV exceeds 2.0 million Singapore dollars after 20 years of operations. This result has been achieved taking into consideration that the LAES prioritizes electrical power output over heating and cooling power output during the discharge phase.

In the future, by optimal control of the recirculation factor, it will be possible to select the best LAES heating and cooling recovery fraction for matching the end-user demands and increasing the overall polygeneration system efficiency. However, a higher recirculation factor results in a lower round trip efficiency. Thus, efforts to increase LAES round trip efficiency would provide the opportunity to better integrate LAES in various polygeneration scenarios, where cryogenic cold energy is potentially required.

Acknowledgments

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