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Applications of micro-CAES systems: energy and economic analysis

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Abstract

The present study concerns the development of a micro-CAES system for thermal and electrical energy storage for residential and non-residential users (shelter/remote users including), in order to reduce energy costs and increase the reliability of energy supply from renewable sources. The micro-CAES system allows you to store the electricity generated from renewable and conventional sources to pressure energy. Further thermal energy can be recovered from conversion process, stored and used for space heating or hot water. The micro-CAES allows you to reduce peak energy demand by utilities (peak shaving), decrease the size of the power generation devices (downsizing), reduce the power of the contract with the grid operator, size the system on the load curve power users in order to increase energy efficiency and economic sustainability reducing management costs with the advantage to reduce operating costs, use of non-toxic materials, zeroing of GHG emissions (zero emission). The innovative technology is based on high-efficiency energy storage process via storage of compressed air at high pressure, quasi-isothermal compression of a mixture air-liquid for heat storage and supply of electrical power constant during the expansion. The air-liquid mixture with excellent ratio between the phases allows you to obtain quasi-isothermal compression, with maximum compression efficiency and high thermal exchange, it enables to have a constant electrical power during the expansion, at a constant pressure during discharge. A dedicated software enables to manage the micro-CAES system to adapt its operation as a function of external conditions and user requirements. An energetic and economic analysis has been performed identifying the optimal size reference. The power supply system provides for the integration of small wind and photovoltaic with a storage system based on micro-CAES. The technological challenge is to be able to ensure a constant power level selected throughout the day.

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Keywords: Energy storage; Renewable sources; performance analysis; Integrated energy system;

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1. Introduction

The micro-CAES is a technology for electrical and thermal energy storage, which uses as a vector fluid the pressurized air collected in special vessels to improve energy efficiency and optimizing operating efficiency while safeguarding the environment. The aim is to reduce energy consumption and increase the reliability of electrical and thermal energy supply from renewable and conventional sources using small size energy production systems also with a view to economic and environmental sustainability overcoming the limitations of toxic or difficult to dispose solutions. This system complements generation plants from RES allowing an optimized selection in relation to daily electricity demand and substantial savings. It is crucial in case of high electrical powers are needed for low time intervals (fast charging of electric vehicles). The main advantages are: storing electricity from RES and conventional sources; storing electrical energy into pressure energy and return it when necessary. This process can recover thermal energy, which can also be stored and later used for heating or hot domestic water; *peak shaving*; buying electricity from the grid when it is more convenient by reducing power generation system size (*downsizing*); reducing contract size with the grid operator to avoid network congestion; improving the penetration of RES and revive markets of technologies that are causing the decline in sales due to the reduction of incentives. The Benefits are: management cost reduction of energy flows, use of non-toxic materials which no special procedures for disposal, no GHG emissions. The target market includes: residential complexes, hotel facilities, hospitals, industrial districts, shopping malls and outlets, sports centres and gyms, prisons, farms, electric vehicle charging, parking & parking areas, small electricity auto-producers. This study focuses primarily on the residential market and the hotel as they are characterized by a number contingent of potential customers.

Nomenclature

CAES	Compressed Air Energy Storage	AEEGSI	Agency for Electricity,Gas and Water
PV	Solar Photovoltaic	RES	Renewable Energy Sources
GHG	Greenhouse Gas	SSPC	Simple System of Production And Consumption
PB	Pay-back time	EROI	Energy Return On Energy Investment
P	Power	ESOI	Energy Stored On Electrical Energy Invested
V	Storage volume	p	pressure

2. Market analysis

The electric storage market has a high potential even in the face of any government incentives (as in Germany). The predominant technology is electrochemical storage, although a recent study released by Stanford University, has highlighted the convenience of using storage technologies like CAES against electrochemical storage, as have an index of energy cost (ESOI) much higher [1]. The target market is to decrease the amount related to electrochemical storage encouraging market entry of the CAES system focusing on the beneficial aspects of these systems, namely: zero environmental impact; possibility to have the same declared efficiency for a number of years higher than electrochemical storage systems suffering from performance deterioration; recovering thermal energy from the conversion process. Through the preliminary analysis performed was estimated turnover for the CAES, of EUR 88.6 million with a penetration rate of 2% on the market; while considering a penetration of the storage system of 10% the potential is around EUR 443 million. Table 1 contains individual items of potential customers.

Table 1 - Market structure in Italy for a CAES product penetration level of 2% and 10% respectively. No distinction between the two CAES models studied. (Source: Federalberghi, Istat, Autostrade for Italy and Eurostat)

Category	Total costumers number	Penetration 2%		Penetration 10%	
		Customers	Incomes (€)	Customers	Incomes (€)
Residential complexes	40,500	810	12,150,000	4,500	60,750,000
Hotel facilities	34,000	680	10,200,000	3,400	51,000,000
Industrial districts	101	2	30,300	10	151,500
Shopping malls & outlets	58,000	1,160	17,400,000	5,800	87,000,000
Sports centers & gyms	2,000	40	600,000	200	3,000,000
Prisons	231	5	69,300	23	346,500
Services areas (motorways)	425	9	127,500	43	637,500
Farms	160,000	3,200	48,000,000	16,000	240,000,000
TOTAL			88,577,100		442,885,500

Market structure: the characteristics that customers must have, for solution CAES+PV, depend on the possibility of installing a PV system and power levels sufficient to have an economic benefit. Since the CAES inherently versatile and customizable there are no stringent constraints for installation and use. Potential clients must meet the following requirements: requirements on electric power required to have economic benefit; availability of space for PV and CAES. The CAES market has a turnover about EUR 15 million in Italy with a penetration of 2%, while with a penetration of 10% the potential is around EUR 74 million. Table 2 shows the breakdown of potential market in Italy.

Table 2 - Market structure in Italy for a CAES product penetration level of 2% and 10% respectively. No distinction between the two CAES models studied. (Source: Federalberghi, Istat, Autostrade for Italy and Eurostat)

Category	Costumers	Customers with power requirements only	Customers with space /power requirements	Penetration 2%		Penetration 2%	
				Customers	Incomes (€)	Customers	Incomes (€)
Residential complexes	40,500	40,500	10,125	203	3,037,500	4,500	15,187,500
Hotel facilities	34,000	23,000	20,400	408	6,120,000	3,400	30,600,000
Industrial districts	101	101	81	2	24,240	10	121,200
Shopping malls & outlet	58,000	17,400	8,700	174	2,610,000	5,800	13,050,000
Sports centers & gyms	2,000	2,000	1,200	24	360,000	200	1,800,000
Prisons	231	231	219	4	65,835	23	329,175
Services areas (motorways)	425	425	425	9	127,500	43	637,500
Farms	160,000	32,000	8,000	160	2,400,000	16,000	12,000,000
TOTAL					14,745,075		73,725,375

The target market extends from residential complexes to nod-residential users in which it can be install power generation plants from RES. For example the hotel industry is developing more and more towards an environmental management of buildings encouraging RES penetration: some Italian regions are moving to sensitize the industry to the use of clean energy resources. There are 101 industrial districts potentially interested in Italy. The tertiary sector as well as the entire industry can have an economic benefit from CAES, especially industries using compressed air within their process. A further application is the charging of electric vehicles, being the CAES versatile and adaptable to different configurations. All isolated users not supplied from national electricity grid which require a storage system. The analysis given is directed to Italian market but can be extended to European market. The use of storage systems is however being tested and the evolution of this market is tied mainly to government incentives. In Germany they have been allocated funds for installation of storage devices (about EUR 67 million) [2].

3. Scenario Analysis

The energy and economic analysis was carried out without considering the incentives provided to increase in energy efficiency, sustainable energy production and storage systems exploitation. The evolution of the market, in fact, is mainly due to governmental incentives to increase electric storage utilization. The competition is linked to the development of electrochemical systems and in particular to the reduction of purchase cost. The possible scenarios are related to increase in electricity costs and any increases in the cost differential between day and night kWh. The forecasts indicate an increase of electric cars from the current 0.02% to 3% for 2020. It can be stated with certainty that the charging systems of electric vehicles will follow the same growth trend. A further scenario is attributable to the development of the SSPC (Simple Systems of Production and Consumption). With Decision 578/2013/R/EEL of 12 December 2013, the AEEGSI gives clear rules on home for plants above 200 kW and the ways in which a manufacturer can install a RES cogeneration power plant on the user property and directly sell to him the produced electricity. The market for storage systems will experience significant benefits, in order to ensure continuity of electricity supply. The competitive advantage of CAES compared to electrochemical batteries are concerns the follow aspects: no decrease in performance in charge/discharge; use of different form of energy than electricity (heat); zero environmental impact (not using toxic and difficult to dispose materials); reliability. The environmentally sustainable cutting-edge technology is suitable for development of RES. Also from a financial perspective the proposal, based on components widely available on the market, has low investment costs in the face of high benefits for manufacturers, consumers and environment. In a recent study the ESOI parameter quantifying the energy cost of a storage system is determined [1]. From the comparison of ESOI of different storage technologies, it is clear that the physical storage methods have energy performance of an order of magnitude higher than those of the electrochemical storage (Figure 1). For these reasons the CAES has significant advantages compared to electrochemical storage. Figure 1 also shows two graphs on use of different storage systems integrated in a PV plant and a wind farm: the excellent integration between CAES and RES systems, in particular, with regard to wind power plants, batteries cannot be used because they have ESOI too low.

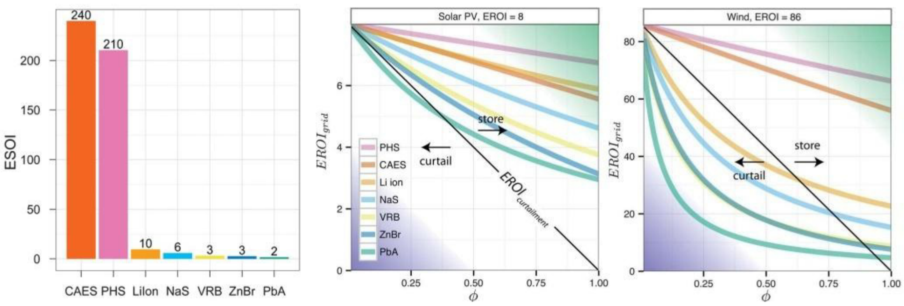

Figure 1: ESOI for various storage technologies (left) [3]. Applicability of the energy storage systems as a function of the energy source (right) [1].

4. Methodology

The target market is Italian market due to easier data determination. The micro-CAES system can be applied to all residential customers P>14 kW and non-residential users (e.g. hotels) P>60 kW. The main characteristics of users are availability of space for integration of a RES plant and CAES: for industry the CAES will be placed in open spaces and for residential users in function of availability of space according to safety and maintenance requirements. The solution may find applications wherever RES are used and storage systems encouraged. Table 3 shows the hotels with electric power requirements. Considering uncertainties in estimating volumes and issues in terms of space, not all exercises are potential customers. In case of low penetration (2%), potential customers are about 1,400. In case of strong penetration (10%) about 7,000. Table 3 shows analysis on turnover in Italy, Spain, Germany, France.

Table 3 - Economic analysis on the turnover attributable to hotels, shopping centers and farms, in Italy, Spain, Germany and France.

Category	Total number of costumers	Penetration 2%		Penetration 10%	
		Customers	Incomes (EUR)	Customers	Incomes (EUR)
Hotel facilities	69,980	1,400	20,994,000	6,998	104,970,000
Shopping centers	13,710	274	4,113,000	1,371	20,565,000
Farms	60,250	1,205	18,075,000	6,025	90,375,000
TOTAL			43,182,000		215,910,000

5. System description: micro-CAES technology

The technology allows to realize a quasi-isothermal compression, so as to ensure highest compression efficiency and adequate heat level to power a thermal user. Innovative technology allows to obtain a constant electrical power during expansion by maintaining constant pressure throughout discharge. The micro-CAES is instructed by a dedicated software and adjusts its operation according to external conditions and requirements. By controlling operating flow rates it can possible to achieve a high-efficient quasi-isothermal compression: during compression, gaseous phase exchanges heat with liquid in order to supply a thermal user also cooling compressed air through an air/liquid exchanger. This heat is exploited to feed the thermal user with two advantages: highly efficient compression, increase in performance by CAES/thermal user integration. Downstream of the compression, air is stored in a vessel to maintain a constant pressure in the inlet to expander. The CAES is optimized according to electrical load and energy production by a dedicated software that optimizing the management of energy flows during the device’s activity and minimize operating costs. The software automatically instruct a control unit which determines: energy from grid, charge/discharge levels in function of the power available from RES/conventional sources, energy required and operating costs. The basic components can be purchased directly on the market. From market research it is observed that the higher costs are related to storage systems purchase, namely the storage cylinders air representing ca. 45% of total cost (Figure 2).

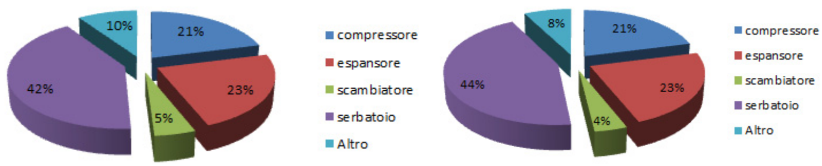

Figure 2 - Graph of percentage incidence of individual components on total cost of CAES for the Model 1 (left) and 2 (right).

CAES not involves toxic and noxious substances and has no environmental risks during disposal or in case of malfunctioning and particular risks being equipped with safety valves with considerable environmental advantage compared to electrochemical storage. Selling price is based on component cost and the profit margin for the buyer on the initial and on annual revenues compared to a solution without CAES. Errors and uncertainties on selling price are due to no taking into account benefits from economies of scale and incentives, in order to determine costs and earnings. We estimated that the construction cost may also decrease by 50%. The large number of manufacturers of basic components provides a significant advantage as non-dependence on the materials and possibility of negotiation. It has been estimated for CAES model 1 (residential users: $V=1m^3$; p=300 bar; P=3 kW) a total cost of 10,000 EUR.

Table 4 – Financial planning.

Model	Selling price (EUR)	User	PBP (years)	Investment saving (EUR)	Annual return (EUR)	Cash flows (25 years)	Production cost (EUR)
CAES 1+PV	27,000	14 kW (minimum)	6	500	3,805	40,618	10,000
	(CAES 1 only)	33 kW (optimal)	5	17,000	7,213	76,998	
CAES 2+PV	45,000	35 kW (minimum)	8	750	8,174	87,257	15,000
	(CAES 2 only)	100 kW (optimal)	7	30,000	21,365	228,000	

For residential users with maximum power demand of 33 kW – in the case of investment including this CAES model and 15 kW of PV – the benefit amounts to EUR 17,000 compared to PV plant 33 kW. The same analysis repeated for CAES model 2 (non-residential users: $V=2m^3$; p=300 bar; P=6 kW), for which a cost of EUR 15,000 was estimated. The benefit for non-residential user (e.g. hotel) 100 kW amounts to 30,000 EUR. So selling price for both models depend on the construction cost and market strategies. The maximum selling price as sum of manufacturing cost and saving for the optimal solution. For the production of prototypes CAES 1 and CAES 2 (about 9 weeks) we estimated an initial capital of EUR 35,000 considering: cost of materials, purchase and installation of measuring instruments.

6. Results and discussion

Residential users and hotel users were chosen making use of models and tools for numerical simulation on the impact of technologies based on renewable energy sources [10], [11], [12]. Optimal size for residential and non-residential has been identified. For residential users the model CAES 1 (3 kW for about 3 hours), for non-residential users the model CAES 2 (6 kW for about 2 hours) was considered. The optimal size for economic benefit is: 33kW for residential users, 100kW for non-residential. Residential users: the first solution is PV system dimensioned on peak demand, the second one is a complex system in which the micro-CAES is integrated to PV (CAES+PV), the latter reduced by 50% compared to the previous year. The residential complex with a peak demand of 14 kW represent the minimum size for which it is economically advantageous to use an integrated system (CAES+PV) [4]. So, considering a residential complex with power demand of 33 kW, the energy analysis were performed. For the solutions proposed (CAES+PV; PV only) in Figure 3 daily load curves and CAES charge/discharge status are shown. An integrated CAES+PV allows to optimize electrical energy use during the day thereby reducing demand from electric grid, but especially as a complex system to be automatically managed.

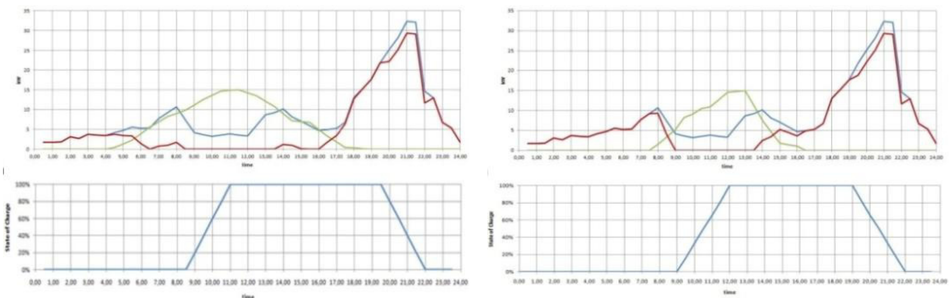

Fig. 3 – (a) typical summer (left) and winter (right) daily load curve (electric power demand, in blue; available power from PV, green, power input from grid in case of CAES + PV, in red); (b) the micro CAES charge status.

The PB for CAES+PV is 5 years. The results of economic and energy analysis are listed in Table 5. The investment saving of the CAES+PV (PV size 15 kW) compared to only PV system (PV size 33 kW) amounts to EUR 17,000. Non-residential users (hotels): starting from electrical load taking into account a power demand of 100 kW will have the trends shown in Figure 4 related to a summer and a winter day. The PB for CAES+PV is 7 years. The results of economic and energy analysis are listed in Table 6. The investment saving of CAES+PV (PV 70 kW) compared to only PV (100 kW) amounts to EUR 30,000.

Table 5 – Comparative economic and energy analysis between the PV solution and CAES+PV solution for residential users.

Solution	Electrical saving		Thermal saving	
	kWh/y	€/y	kWh/y	€/y
PV	18,666	4,229	-	-
CAES+PV	21,572	6,788	5,765	425

Table 6 – Comparative economic and energy analysis between the PV solution and PV + CAES for non-residential users.

Solution	Electrical saving		Thermal saving	
	kWh/y	€/y	kWh/y	€/y
PV	125,742	21,352	-	-
CAES+PV	122,760	20,845	6,939	511

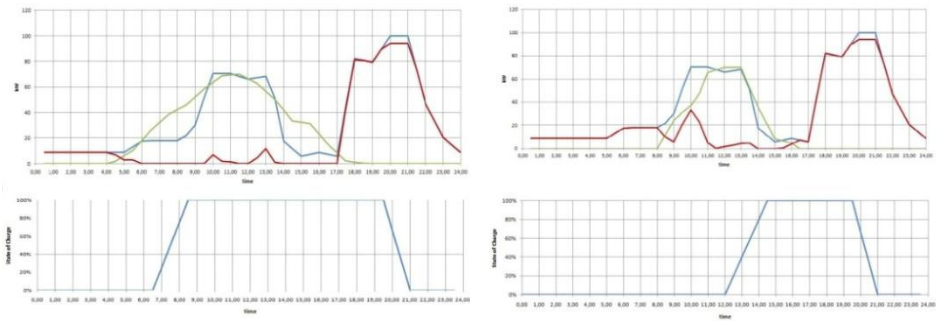

Fig. 4 – (a) typical summer (left) and winter (right) daily load curve (electric power demand, in blue; available power from PV, green, power input from grid in case of CAES + PV, in red); (b) the micro CAES charge status.

Hotel with peak demand of 100 kW (about 65 rooms) are optimal size (Figure 6) that is cost effective to use an integrated system (CAES+PV). Finally, Figure 5 shows the trends in impact of annual saving on annual costs of CAES+PV; impact of saving in investment between PV only and CAES+PV; payback time of CAES+PV solution. Optimal size is located at the intersection of the two curves of impact.

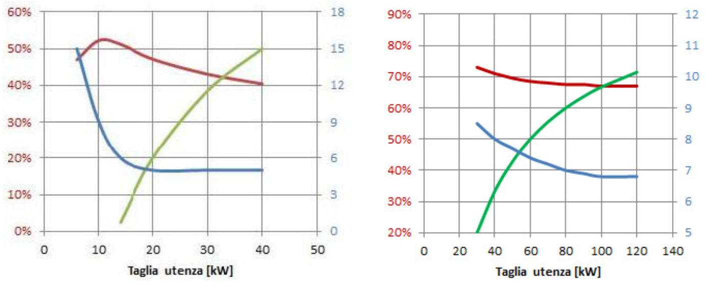

Figure 5 – Residential users (left) and non-residential users (right): impact of annual savings on annual costs of CAES + PV solution (red line); the impact of saving in investment between only PV and CAES+PV solution (green line); the payback time of the micro CAES+PV solution (blue line). The optimal size was determined by the intersection of the two curves of impact.

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Biography

Alessandro Tallini, Ph. D. in Energetics, is an expert in energy efficiency sector, in this areas has been involved in energy auditing and feasibility studies for public and private sector. He is involved in R&D projects on energy efficiency and environmental sustainability at Faculty of Engineering, Sapienza University of Rome.