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CONCEPT AND APPLICATION OF DISTRIBUTED COMPRESSED AIR ENERGY STORAGE SYSTEMS INTEGRATED IN UTILITY NETWORKS

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ABSTRACT

Distributed energy storage has been recognized as a valuable and often indispensable complement to small-scale power generation based on renewable energy sources. Small-scale energy storage positioned at the demand side would open the possibility for enhanced predictability of power output and easier integration of small-scale intermittent generators into functioning electricity markets, as well as offering inherent peak shaving abilities for mitigating contingencies and blackouts, for reducing transmission losses in local networks, profit optimization and generally allowing tighter utility control on renewable energy generation. Distributed energy storage at affordable costs and of low environmental footprint is a necessary prerequisite for the wider deployment of renewable energy and its deeper penetration into local networks. Thermodynamic energy storage in the form of compressed air is an alternative to electrochemical energy storage in batteries and has been evaluated in various studies and tested commercially on a large scale.

Small-scale distributed compressed air energy storage (DCAES) systems in combination with renewable energy generators installed at residential homes or small businesses are a viable alternative to large-scale energy storage, moreover promising lower specific investment than batteries. Flexible control methods can be applied to DCAES units, resulting in a complex system running either independently for home power supply, or as a unified and centrally controlled utility-scale energy storage entity.

This study aims at conceptualizing the plausible distributed compressed-air energy storage units, examining the feasibility for their practical implementation and analyzing their behavior, as well as devising the possible control strategies for optimal utilization of grid-integrated renewable energy sources at small scales. Results show that overall energy storage efficiency of around 70% can be achieved with comparatively simple solutions, offering less technical challenges and lower specific costs than comparable electrical battery systems. Furthermore, smart load management for improving the dispatchability can bring additional benefits by profit optimization and decrease the payback time substantially.

1. INTRODUCTION

Enhanced utilization of intermittent renewable energy sources for power generation, such as wind and solar, requires the application of various types of energy storage solutions. For stand-alone systems, energy storage is inevitable in cases when stable and reliable power output is desired, unless balancing power is provided by conventional methods, usually by additional fossil fuel fired equipment.

For grid-tied systems, energy storage is generally not considered necessary as the grid is presumed to always be able to provide balancing power. However, the increased penetration of intermittent renewable energy in electrical grids is a serious challenge. Possible solutions involve a wider utilization of energy storage systems, together with smart management of the electricity supply and demand chain. In the best case, energy storage could convert intermittent sources of energy into perfectly dispatchable power generators.

Modern electricity production and demand management in functioning electricity markets should be able to cope with the larger deployment of intermittent renewable energy resources without the need to make them perfectly dispatchable. Better prediction of their output is often enough to provide for better grid integration strategies and cater for optimal operation and control of balancing power generation. This applies to both large nation-wide electricity markets (Independent System Operators) and also to utility-scale or distribution network management solutions.

Diverting the produced power through an energy storage system, regardless of the type and size of the system, would always introduce additional losses as the energy storage can never be 100% efficient. An optimal solution would therefore attempt to utilize a maximum possible amount of energy for covering loads, while sending to storage only the amount that cannot be absorbed at a specific moment. Furthermore, storing energy would have the most positive effect on the overall system if it provides for peak shaving and load leveling. Such partially- or quasi-dispatchable distributed energy resources would present a major contribution to its greater acceptability by local electricity networks.

Established electricity markets are using the day-ahead forecasting of generation and consumption often together with a floating price of electricity that varies each hour or shorter intervals (such as LMP price). All power producers are required to announce their envisaged generation a day ahead within a 24-hour time frame, and forced to keep up to it strictly. For wind and solar power generators, better weather forecasts are crucial in this respect. Forecasting has been largely improved recently, however, it can never provide enough precision. Moreover, forecasting can be particularly incorrect and often impossible, and is therefore not required, for micro generators such as rooftop PVs and small wind turbines.

Distributed Energy Storage (DES) technologies are usually located near customers. They mostly are connected to the secondary side of distribution transformers. DES applications in distribution networks bring a number of advantages for both utilities and customers. Supply and demand balancing, back-up power, power quality and reliability improvement are among these. In this paper, distributed compressed air energy storage (DCAES) is considered. In addition to the mentioned DES and specifically DCAES advantages, the authors aim to present the optimal operational approach based on the Discrete Ascent Optimal Programming (DAOP) algorithm [23, 24] to realize higher profits for the utility and distribution network operator.

2. COMPRESSED AIR ENERGY STORAGE – PRINCIPLES, PROS AND CONS

Large-scale energy storage systems in the form of Pumped Hydro Energy Storage (PHES) and also Compressed Air Energy Storage (CAES), can be regarded as conventional technology. The CAES has been recognized as a reasonable alternative, having certain environmental advantages and offering a larger number of potential sites if compared to the PHES. Nowadays there are two multi-MW CAES systems in operation in the world – one in Germany and one in Alabama, USA. The performance and advantages of large CAES systems have been previously reviewed by various authors, for example in [1-5], among others. Comparisons with other storage alternatives and specific CAES applications in different locations serving different electricity markets have been examined in [6-10].

Numerous CAES components and configurations have been developed and patented by researchers through the last 30 years, see e.g. in [3]. A figurative representation of a typical large-scale CAES system using an underground air cavern is shown in Figure 1.

Mid-scale CAES systems have been extensively evaluated in [11-13], among others. Lund et al. [11] devise an algorithm and compare different strategies for the optimal operation of a local mid-scale CAES system in a region of Denmark characterized by very high penetration of wind power while the balancing power is delivered by thermal plants primarily operating in cogeneration mode and limited in load levelling by their heating loads. Zafirakis and Kaldellis [12] propose and scrutinize a system featuring 15 MWh storage capacity to allow for both increased wind energy contribution and better utilization of existing thermal power plants within the autonomous grid of the island of Crete.

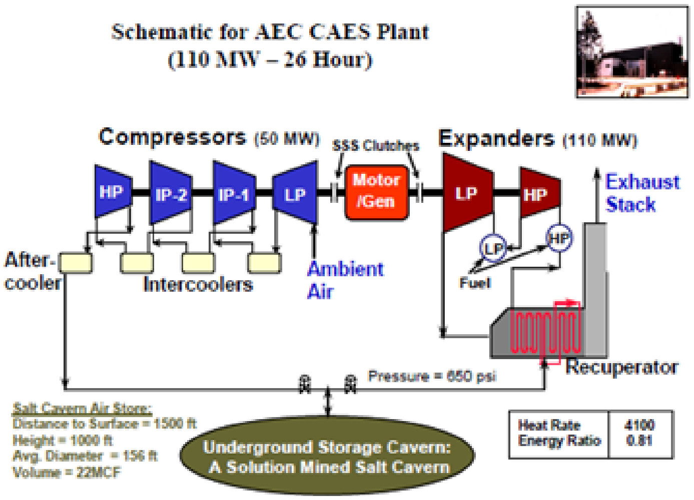

Fig. 1: *Conventional large-scale CAES concept using an underground cavern, intercooling of the compressed air and a fossil fuel for heating the air before expansion. This is the existing plant in Alabama, USA (Alabama Electric Cooperative), commissioned in 1992 at a capital cost of $600/kW [2].*

M. Nakhamkin, being one of the most active proponents of CAES solutions in the USA and the driving person behind the large-scale CAES shown in Fig.1, has also proposed a midscale CAES system of 15 MW net power output [13], utilizing above-ground air storage unit, i.e. a pressurized vessel. While the pressure vessel can be erroneously thought to be the bottleneck of the system in terms of reliability and economy, the study shows that it essentially covers only 28% of the expected total capital cost for such a plant. Whereas the power extraction equipment (compressors, expanders, combustors, heat exchangers, el. machinery) together with instrumentation and balance of plant, represent 37% of the capital cost [13]. The specific investment for the 15 MW energy storage system would sum up to $ 1200–1300 per kW, i.e. twice higher than that of the old large-scale CAES plant. If the storage capacity of such a plant would be assumed sufficient for 10 hours of full load operation, the specific investment costs per unit storage capacity for the total plant would hence be $ 120 – 130/kWh, whereas just the pressurized air vessel would cost around $35/kWh capacity, a very promising value.

The abovementioned investment cost presumptions are confirmed in recent review studies by Beaudin et al. [6], Diaz-

Gonzalez et al. [7] and by Mason & Archer [8], who summarize others' work on cost comparisons of various storage solutions and conclude that the air storage cavern or vessel would cost from $ 5/kWh up to $100/kWh, while the total installed power of the CAES plant is expected to show specific costs in the order of $1100–1600/kW. These are several times lower than the established investment costs of electrical battery systems, as presented in the same studies cited above.

Small- and micro-scale DCAES systems would be placed at the end-user side or at least close to the power generator and would use pressure vessels for storing the compressed air. The layout of a DCAES system, considered in this study, is presented in Figure 2. Some DCAES solutions have previously been proposed and evaluated in a few referenced studies, among which most notably: the 500kW system described by Grazzini & Milazzo [14]; the tri-generation micro DCAES able to serve both as an independent energy storage and also provide heating and cooling, presented by Li et al. [15]; the exergy analysis of a micro tri-generation DCAES system featuring a $1m^3$ ($27ft^3$) storage vessel at 50 bar pressure (725 psi), performed by Kim and Favrat [16]; the innovative wind-diesel hybrid DCAES system in which the diesel engine is modified to serve as an expander for the pressurized air during storage discharge, described by Ibrahim et al. [17]; the study of a small wind turbine coupled to a micro DCAES through a variable planetary transmission gearbox aimed at optimizing the wind turbine output and the air storage operational characteristics, performed by Shaw et al. [18]; the attempt by Paloheimo and Omidiora [19] to define pico-DCAES systems for remote mobile network masts or for handheld electronic devices.

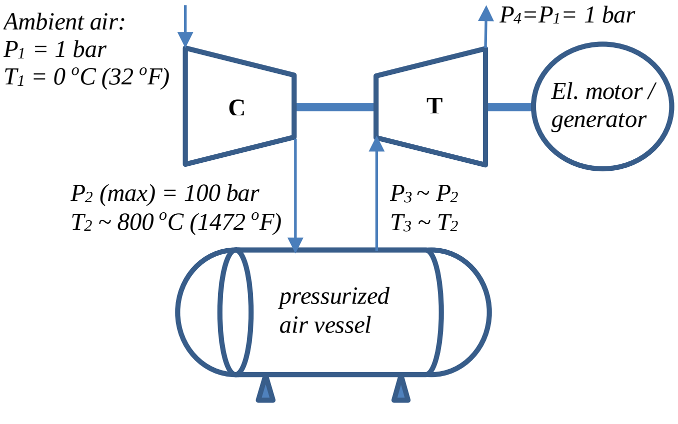

Fig. 2: *Simplified layout of the suggested DCAES system, utilizing a purely adiabatic cycle without heat exchange.*

Proczka et al. [20] recognize the importance of the pressure vessel as a critical component of the DCAES system, and discuss the governing regulations and stress analysis tools for the design and manufacturing of purpose-maid steel pressure vessels suitable for DCAES applications.

Small DCAES solutions would be competing against the established electrochemical energy storage method in batteries. DCAES offer some serious advantages, particularly notable in micro applications, such as:

- DCAES units using pressure vessels are universally appropriate for any location, if compared with large underground reservoirs or with PHES systems;
- DCAES units promise much longer life span than electrical batteries, without deterioration;
- DCAES units do not need high-tech production lines and do not use rare or toxic materials, the hardware is easily recyclable, therefore can be considered as having a much smaller environmental footprint than electrical batteries;
- Pressure vessels for small DCAES systems can be manufactured, installed and maintained entirely by local businesses, in contrast to batteries;
- Control methods or management strategies developed for batteries are directly transferable to CAES systems.

The expected disadvantages of small CAES units can be summarized as follows:

- Not proven yet, costs may be high initially;
- Require larger space than batteries;
- Has lower overall energy efficiency than advanced battery systems;
- The power extraction and ancillary equipment introduces losses, may require extended maintenance or may show low reliability;
- Storage pressure varies during the charge/discharge cycle, therefore the compression & expansion devices should operate at variable conditions and may lose efficiency in deep off-design modes.

3. THERMODYNAMIC CONSIDERATIONS FOR DCAES

CAES systems are accumulators utilizing the potential energy of reversible air compression and expansion processes. Their performance is described with thermodynamic relations, simplified by the fact that for the governing parameters air can be approximated to ideal gas (perfect gas), where the idealized equation of state can be used. A representative summary of the major thermodynamic considerations valid for CAES systems has been published by Grazzini & Milazzo [14], among others.

The size or type of the storage tank would not be of any importance for the general performance of the CAES system, unless thermal losses from tank walls to/from surroundings would be taken into account. On the other hand, the storage capacity of the CAES unit is a direct function of the tank size (tank volume), as well as of the air temperature in the tank. The compression process raises the temperature of the air considerably, whereas the stored mass of air in a given volume decreases with rising temperature together with the decrease of its density. Equations 1 through 3 represent the simplified relations used for the analysis of idealized CAES performance, where $\eta_{C,T}$ is the isentropic efficiency of the compressor or turbine, C_P and C_V are the average specific heats for clean air at the relevant temperature range, and $P_{C,T}$ is the power demand or power yield of compressor or expander respectively. Figure 3 shows the function of rising temperature of the air charge with varying isentropic efficiency and increasing pressure ratio for the purely adiabatic compression process. Adiabatic compression is practically applicable only to devices with reasonably high isentropic efficiency, therefore it is critical for micro DCAES units to use properly optimized compressor and expander devices.

$$T_2 - T_1 = \Delta T_C = \frac{T_1}{\eta_C} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{(Cp/Cv)-1}{Cp/Cv}} - 1 \right] \tag{1}$$

$$T_3 - T_4 = \Delta T_T = T_3 \cdot \eta_T \cdot \left[1 - 1 / \left(\frac{p_3}{p_4} \right)^{\frac{(Cp/Cv)-1}{Cp/Cv}} \right] \tag{2}$$

$$P_{C,T} = \dot{m}_{air} \cdot \bar{c}_P \cdot \Delta T_{C,T} \tag{3}$$

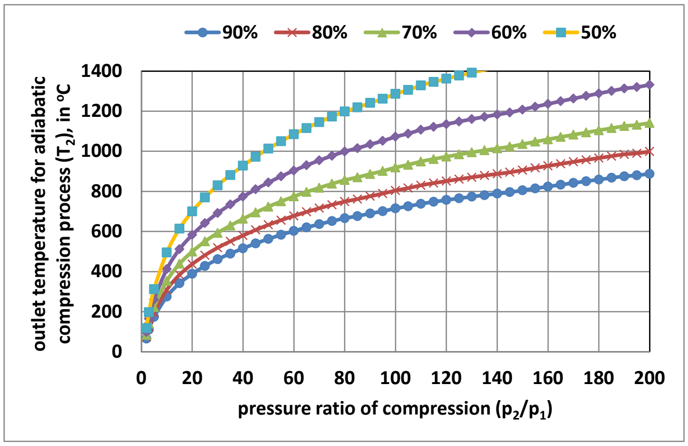

Fig. 3: *Temperature of compressed air into storage, as a function of pressure ratio and isentropic efficiency for the ideal adiabatic compression process.*

Intercooling and aftercooling can be applied within the compression process for increasing the storage capacity and decreasing the power demand for compression. However, this involves additional components and increases the complexity and costs, therefore deemed impractical for very small DCAES units. A large part of the potential energy of the compressed air lies in its temperature, thus reheating of the air before and during the expansion process needs to be applied in order to deliver a reasonable amount of power output at discharge, confer with Fig. 1. Reheating is done by additional fuel, usually by natural gas, which decreases the energy efficiency (increases the heat rate) of the overall energy storage process. The heat rejected during intercooling can also be stored in an external thermal storage and returned to the air before expansion, such arrangements have been proposed for example in [14] & [16].

For the DCAES system studied herein, a purely adiabatic approach without any heat exchange is suggested, aiming at lowest possible complexity and simplest possible configuration, where lower costs and ease of maintenance are of primary importance. Furthermore, free space for additional heat storage or access to fuel supply for air reheat may not be available. The compressed air is charged into the storage vessel without intercooling, and expanded directly during discharge without external reheat. Figure 2 shows the proposed configuration with its main parameters. The pressurized air tank is thermally insulated, in the ideal case preserving all the heat of the stored air until the expansion process starts.

Figure 4 shows the specific power demand for compression without intercooling (per unit mass flow of air), and the power yield at the expander shaft from discharging of the same air without additional heat input. The compressor and expander units are coupled to and driven by a convertible motor-generator electrical machine. The specific type of the power components is not a focus of this study. The air storage vessel is assumed without any heat losses, perfectly insulated.

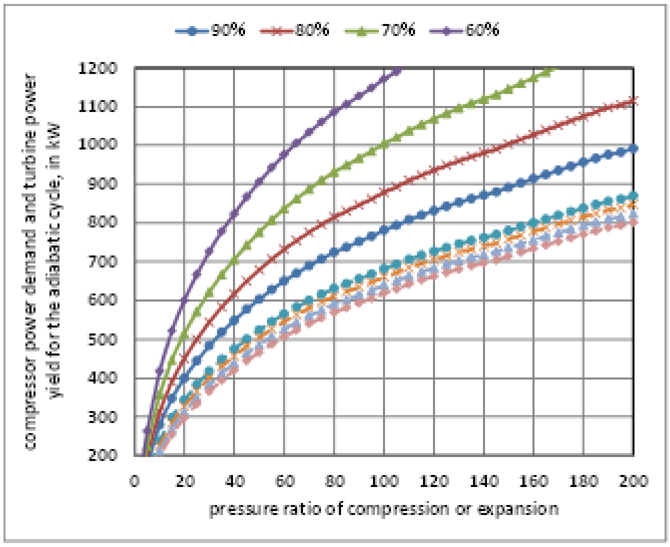

Fig. 4: *Specific power demand for compression (charge, solid lines) and possible power yield from expansion (discharge, dashed lines), for the ideal adiabatic cycle without heat exchanger, at varying isentropic efficiencies of compressor and expander.*

The pressure in the air storage vessel is a variable parameter, which may be detrimental to the efficiency of the expansion device. In practice, the expander is designed to work with a steady input pressure, which is usually chosen close to the lowest pressure of the fully discharged system. The air is throttled from the higher pressure of the storage at any given moment down to the input pressure of the expander. The throttling process represents a loss, however, it is small due to the fact that the air is a perfect gas and the isoenthalpic throttling maintains the temperature of the air almost constant.

The insignificant extent of the throttling loss has been calculated and discussed for example in [15] and [17]. The depth of discharge is limited down to the design input pressure of the expander, below which further expansion is either not possible or would simply operate at very low efficiency. The specific power island arrangement and compressor/expander configuration for the chosen pressure ratio, including throttling and other related losses, are not the focus of this work and will be addressed in subsequent studies.

In the ideal case when no thermal losses and no pressure losses are considered, the rate of utilization of storage volume decreases with rising pressure, through the increase of the temperature T_2 after compression. If the compressed air is intercooled and/or aftercooled, i.e. sent to storage at close-to-ambient temperature, the mass of stored air per unit volume of storage space (here called "cold storage") for the given maximum pressure, would be considerably higher than that of the purely adiabatic "hot storage" considered herein. This difference is quantified in Figure 5, which shows the specific energy storage capacity ratio as a function of the air pressure in the storage tank for "cold" and "hot" alternatives, where in both cases the power yield from air expansion assumes either additional reheat or idealized preservation of the adiabatic temperature after compression. The isentropic efficiency of both compression and expansion is taken as 80%.

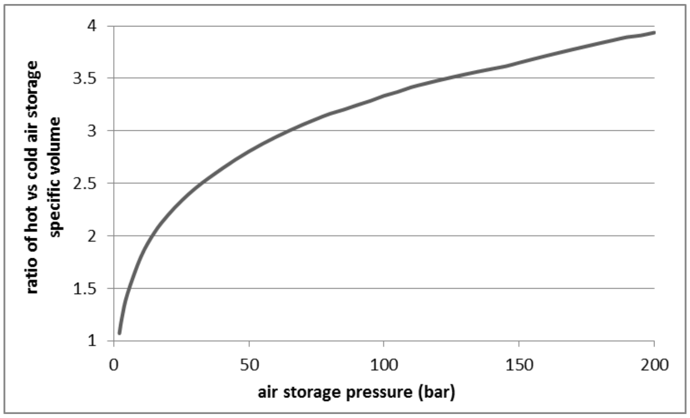

Fig. 5: *Relation between the specific storage volume of the CAES pressurized vessel for "hot" and "cold" options: "cold storage" assumes aftercooling to a temperature of 50 °C (122 °F), while "hot storage" refers to ideal adiabatic temperature in the vessel. In both cases the expansion starts from the hot adiabatic temperature.*

Table 1 presents the overall energy efficiencies of idealized purely adiabatic CAES systems, as a function of varying storage pressure and for different isentropic efficiencies of the compressor and expander devices.

A maximum storage pressure of 100 bar (1470 psi) is chosen for the proposed DCAES system in this study, believed to offer an optimum trade-off between a high rate of storage volume utilization and a low complexity (easier manufacture and maintenance) of the pressure vessel and power island. The isentropic efficiency for both the compressor and expander is assumed at 80%, similar to the values expected of small piston machines or turbochargers, which presumably will be used for air charge and discharge. The idealized efficiency of the overall energy storage process, for the chosen parameters, is 75.2 %, comparable to the efficiency of low-tech battery systems. Of course, in real conditions this value will be lower.

Table 1: *Overall energy efficiency (%) for small DCAES with ideal adiabatic cycle, disregarding any thermal losses, pressure losses and throttling losses.*

Pressure ratio	$\eta_C = 80\%$ $\eta_T = 80\ \%$	$\eta_C = 70\%$ $\eta_T = 80\ \%$	$\eta_C = 60\%$ $\eta_T = 70\ \%$
5	69.8	61.1	48.5
10	71.6	62.7	50.6
30	73.6	64.4	52.9
50	74.4	65.1	53.7
75	74.9	65.6	54.3
100	75.2	65.8	54.6
150	75.6	66.2	55.1
200	75.9	66.4	55.4

4. OPTIMAL OPERATION OF DCAES SYSTEMS IN DISTRIBUTION NETWORKS

The distributed compressed air energy storage systems help distribution networks in different ways. In this section, the market based optimal control approach is applied to achieve higher profits from a DCAES unit in addition to the inherent advantages of DCAES for utility applications as described in the sections above.

An example for a small DCAES application is considered and assessed herein. The energy storage unit may either operate as a load leveling system without local power generation, or it can be charged by local renewable power, either a small wind turbine or a series of rooftop PV panels, and help with their integration into the local utility grid. A group of family houses or a single commercial or public building in the country of Denmark, connected to a distribution transformer, is used as a representative case.

A private household in Denmark has the right to apply net metering on an annual basis for up to 6 kW of renewable power generation installed on the premises, regardless of the type and source of renewable energy [21]. This allowance was limited severely at the end of 2012, but driven by the sharp decrease of PV prices, Danish households managed to install about 220 MW of PV panels during year 2012, almost all of them as 6 kW rooftop single-house systems, in a country of hardly 5.6 million inhabitants [22]. This gives around 40 W of newly installed PVs per capita, clearly among the highest annual per capita PV growth rates in the world.

Net metering on an annual basis is very lucrative for the Danish households as it constitutes a kind of a tax credit system, in a country where taxes and duties take a 70% share of the price of electricity for residential end users. This is though bound to change, as the legislation is being altered to sharply curtail the net metering from an annual down to an hourly basis for installations commissioned during 2013 and onwards. Local energy storage systems would help the households to continue utilizing net metering in an optimal way even if the hourly time interval applies in the future for both old and new installations.

At the same time, local utilities are forced to accept the explosion of intermittent demand-side produced power and to operate in a highly fluctuating spot market where pricing may vary from 0 up to $ 0.2/kWh within a day. A properly managed energy storage system would clearly provide a profit.

A DCAES system serving a small group of houses or a public building and defined with the parameters selected above would aim at storing 25 kWh of electrical energy – equal to the total consumption for the summed buildings in a few hours. The community would be able to avail of net metering on a hourly basis, plus that the utility will be able to properly plan for both the hour-ahead and the day-ahead spot pricing. The proposed DCAES unit of 25 kWh output capacity with the parameters selected above, would need a pressurized storage vessel of about 6.85 m^3 (242 ft^3) net volume.

Proper utilization of the energy storage would require an optimal operational strategy where the storage may be charged with grid electricity if prices are low and if no local energy is being generated, or may discharge regardless of the local load if prices are high. One prospective method for such optimization algorithm is presented and elaborated by Broadwater et al. [23], called the Discrete Ascent Optimal Programming (DAOP). Arghandeh and Broadwater [24] have recently adapted the DAOP algorithm and successfully applied it for the optimal management of community-based utility-owned battery storage systems in the USA.

The DAOP optimization approach is applied here for the streamlining of the 25 kWh DCAES system serving a group of houses connected to a distribution network and subjected to the Nord Pool spot market electricity price fluctuations typical for a selected region in Denmark.

The DAOP method uses an iterative algorithm which attempts to maximize the profit by controlling the storage as a function of the momentary (hourly) price of grid electricity. Such behavior is beneficial for both the distribution network operation and for the customers. The distribution network operator or local utility should be able to directly monitor and control the energy storage. Furthermore, the utility may also be the owner of the energy storage unit. The DCAES system could completely support local loads for a period of some hours to manage outages and eliminate the effects of temporary faults.

The DAOP optimization algorithm searches for the charge or discharge energy quantities for each of the next 24 hours. Mathematically, the power output values at each hour are independent variables for the objective function. The profit for each hour is the dependent variable inside the objective function. The discrete ascent optimal programming code first identifies the schedule with minimum charging and discharging that satisfies the various constraints at each hour. Then, starting from the initial schedule, the algorithm proceeds to add equal amounts (kWh) of charge or discharge activity in each iteration, moving toward an “optimal” schedule. The DAOP does not scale back in any iteration once a certain schedule has been planned for that hour. This “greedy” characteristic of the DAOP algorithm ensures that it surely converges in a finite number of steps [24].

For DCAES optimization, the day ahead and intraday hourly market prices from the “Nord Pool Spot” market for the year of 2012 are applied [25]. The spot prices belong to the Southern Danish exchange region (DK2). Figure 6 depicts the DK2 electricity prices for the first week of each month in 2012.

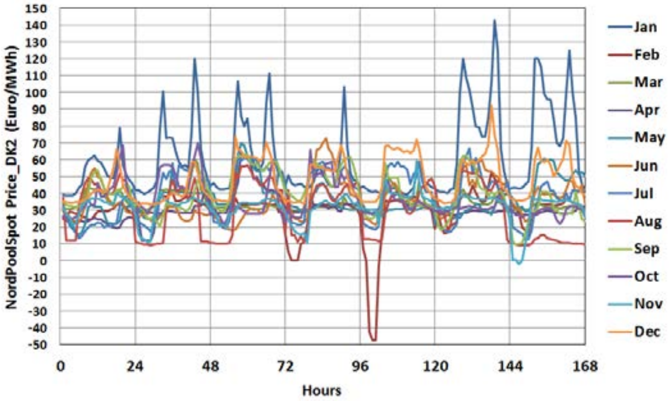

Fig. 6: *Nord Pool Spot electricity prices for Denmark DK-2 section for the first week of each month in 2012 [25]***.**

Figure 7 illustrates the DAOP results for the operational monthly benefit from a DCAES unit coupled to a distribution transformer. The maximum profit is achieved during January. Other months with comparatively high profits are February, July and December.

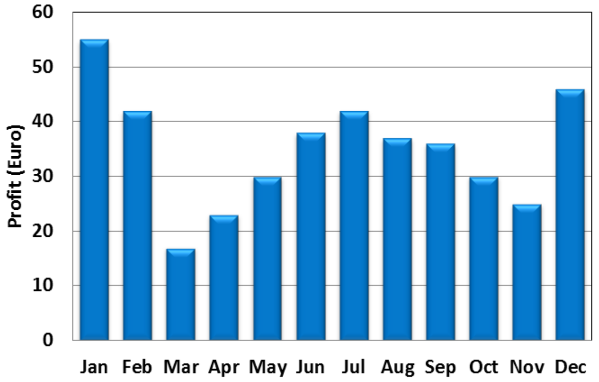

Fig. 7: *DCAES Unit Operational Profit for 2012 considering Nord Pool Spot for Denmark DK-2 prices.*

Figure 8 shows the distribution transformer loading with and without a DCAES unit for a day in June 2012. The locational marginal price (LMP) for the electricity spot market is illustrated by dashed green line. The main control strategy for the energy storage unit is to charge during hours of low electricity price and discharge during hours of high such, thus optimizing the internal consumption and altering the loads on the distribution transformer. The storage management system would need to properly predict the electricity price fluctuations and optimally operate the charge/discharge cycles within each consecutive hour for each 24-hour period.

As a result, the profit for the customer is maximized especially in the hour-based net metering environment, while the prediction of loads and the supply of balancing power by the utility network operator are being eased out.

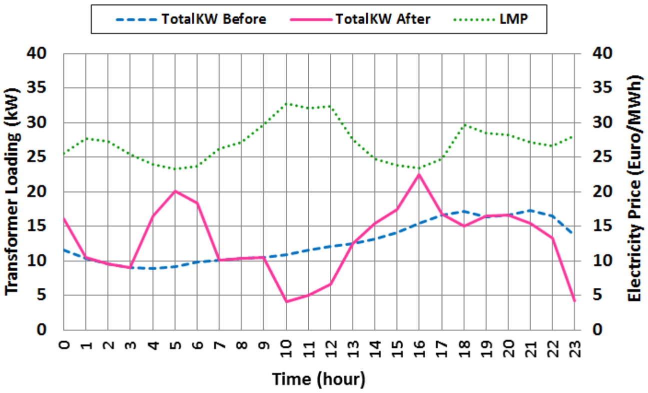

Fig. 8: *Transformer loading without DCAES (blue dashed line) and with DCAES (red solid line). The locational marginal price (LMP) of electricity for the chosen day is the green dashed line.*

During low electricity prices (3 AM to 6 AM), the DCAES charges to store energy for higher price hours. There is a peak price at 10 AM to 12 AM, therefore the storage discharges to reduce the load and to make a profit. During later low price hours (2 PM - 5 PM), the DCAES again charges up storing energy to compensate its depletion and to have enough capacity for late evening discharging when the price goes up.

A quick economy analysis for the simple payback of the proposed DCAES unit of 25 kWh, using average specific costs as presented in chapter 2 above, would result in expected investment of around $8,000 for the pressurized air vessel and the power equipment. If the storage system is utilized for the application described in this chapter, serving the grid by hourly charge/discharge cycles without the presence of local power generation, for the electricity market conditions shown in Fig. 6 and profit results given in Fig. 7, the annual profit would sum up to an average of $550/year (at exchange rate of 1.31 $/€). This gives a simple payback time of 15 years. The DCAES unit can supposedly be owned and operated by the utility, while the actual benefits from its utilization should also include any other positive effect that the storage unit has on the local grid and on the utility planning burden, plus the ability to increase profits further if local power generation is installed.

5. CONCLUSIONS

Increased utilization of renewable energy sources with intermittent nature for distributed power generation requires the application of various types of energy storage solutions. In the general case, cost-effective energy storage even without local power generation can largely improve the behavior of local grids and lessen the burden on operators and utilities by providing planned peak capacity and improved predictability in the hour-ahead and day-ahead electricity markets. Compressed air energy storage at small scales is applicable to distributed systems, can be used to replace electrical batteries and promises better economy and lesser environmental impact than batteries, as well as the ability to be designed, manufactured, installed and maintained entirely by small local businesses.

DCAES of simplified construction utilizing an adiabatic cycle has been investigated with certain simplifications and generalizations in the study presented herein. The results show that the chosen system format is plausible and presents no technical challenges. Proper dimensioning and practical design of the system has not been the focus of this study, but rather the application of a DCAES of similar architecture integrated with the local electricity distribution grid at the secondary (low voltage) transformer side and serving directly a small group of several houses or a commercial or public building.

A DCAES unit storing 25 kWh of net electrical energy and serving a small neighborhood or a public building would not incur large footprints or expenses and is certainly feasible in terms of structural design, manufacturing and maintenance. It could even be inbuilt and concealed into the utility transformer structure itself or placed in a backyard or basement, in a much similar way as electrical battery systems. Its optimal integration into the low-voltage side of utility grids, even at the absence of local power generation, could provide gross annual profits of $550 just by acting as a load balancing unit for the conditions assessed above and typical for Northern Europe, leading to a simple payback time of around 15 years.

It is suggested that the DCAES system could be installed, owned and operated by the utility, where its proper valorization would include far more positive effects related to decreased transmission losses for the local network and back-up tasks, enhanced peak shaving, improved utility planning, etc.

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