CONTROL STRATEGY FOR DISTRIBUTED COMPRESSED-AIR ENERGY STORAGE IN GRID-TIED SMALL-SCALE RENEWABLE ENERGY SYSTEMS

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ABSTRACT

Small-scale energy storage solutions for distributed applications, with or without connection to the grid, have been recognized as a valuable and sometimes indispensable complement to local energy production based on renewable energy sources. In the case of grid-tied energy storage units, the possibility to operate in peak shaving mode, mitigating contingencies and providing backup power, reducing transmission losses, and generally giving larger utility control on renewable energy generation makes distributed energy storage a necessary prerequisite for the wider deployment of renewable energy systems and their deeper penetration into utilities' portfolios. Thermodynamic energy storage in the form of compressed air can be applied at small scales as an alternative to electrical batteries.

Distributed compressed air energy storage (DCAES) units combined with small-scale solar or wind energy converters installed at residential homes or small commercial buildings do not present any major technical challenges, and promise lower specific investment than batteries if mass produced. Flexible control methods can be applied for optimizing the behavior of the energy storage system and maximizing the benefits from its utilization.

This study aims at presenting a devised operational control strategy applied to distributed compressed air energy storage systems, as well as assessing the best scenario for optimal utilization of grid-integrated renewable energy sources at small scales in dynamic electricity markets. Profit maximization for the end consumer is the major goal.

Results show that profits can be achieved even without integration of local power generation, if optimal charge and discharge strategy is found as a function of electricity price and various restrictions. A monthly benefit of \$ 77 is expected during times of generally high consumption levels for an aggregated group of several residential houses, growing to \$ 82.5 /month if a 15 kW renewable energy capacity is installed in the locality. Smart load management approximating a quasi-dispatchable behavior of the energy storage can bring additional benefits to the transmission system operator, leading to improved grid stability.

1. INTRODUCTION AND BACKGROUND

Environmental concerns and rising fuel prices together with decreasing costs for renewable energy production, especially in the form of photovoltaic (PV) installations, are paving the way towards a larger and constantly increasing penetration of renewable energy sources into utility grids. However, the inability to control the output of renewable energy sources results in operational challenges for local and regional electricity grids.

Enhanced utilization of intermittent renewable energy for power generation requires the application of various types of energy storage solutions, in order to provide a means for dealing with the imposed operational challenges. Furthermore, energy storage systems can be used for ancillary services, peak load reduction, and mitigating brownouts in distribution and transmission networks [1].

The adoption of distributed PV rooftop panels as well as small wind turbines into local grids can create problems for the distribution networks. In addition, utility companies have to handle different prices of electricity during different times of the day due to the dynamic and fluctuating electricity market. Therefore, an optimized operational strategy for small intermittent grid-integrated generators should be found, with the purpose to provide smart control based on real-time electricity price and actual load profiles. Established electricity markets are using the day-ahead bidding of generation and consumption often together with a floating price of electricity that varies each hour. 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. The growing number of such local renewable energy producers is adding a growing strain on the local utilities forced to provide load leveling and back-up power. Energy storage presents a way to alleviate this problem.

Facing these challenges, this study presents a possible application of an operational optimization algorithm for a Distributed Compressed Air Energy Storage (DCAES) systems integrated in utility grids. The DCAES system represents either neighborhood based solution serving a range of private houses or a large commercial building, or a fleet of micro-scale units situated at single residential or small commercial or public buildings. In all cases, the energy storage units are being fed by locally installed PV or wind energy generators and connected to the secondary side (low-voltage side) of distribution transformers. Withholding locally generated power in storage and feeding it to the grid only when the electricity costs are optimally high represents a gaming method aiming at realizing higher revenues due to the time variable cost of electricity [2].

Diverting locally 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 local 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 transmission grid if it provides for peak reduction and load leveling, which would be the major goal for any energy storage method even without the presence of local power generation.

2. OBJECTIVES AND METHODOLOGY

The objective of this study is to present an optimized solution for economically profitable control strategy to improve the adoption of locally generated distributed renewable power (rooftop PVs or small wind turbines) into utility distribution networks. The control system decisions and the imposed actions depend on the consumer load profiles and on the real-time Locational Marginal Price (LMP) of electricity. Economic operation of the energy storage unit is a complex problem because of the time dependency of the storage capacity where sufficient energy reserves must be maintained in case of grid loss, the solar irradiation or wind speed uncertainty at the location, and the real-time LMP variability throughout the day.

A possible application of optimally controlled DCAES system is therefore attempted. The DCAES system represents either neighborhood based solution serving a range of private houses or a large commercial building, or a fleet of micro-scale units situated at single residential or small commercial or public buildings. In all cases, the energy storage units are being fed by locally installed PV or wind energy generators and connected to the secondary side (low-voltage side) of distribution transformers. The DCAES behavior can be assumed similar to electrical batteries, thus methods developed for and applied to battery systems can successfully be transferred and applied to DCAES units.

The mathematical approach used is the Discrete Ascent Optimal Programming (DAOP) algorithm. An advantage of the DAOP method is its assurance of convergence after a finite number of computational iterations [26, 27]. The final result involves an optimal sequence for storage charge & discharge cycles throughout a given day, where the difference between low and high electricity price peaks is utilized for maximizing the profit from storage operation. The input parameters for the simulation process are the variable LMP of electricity during a 24-hour period, the variable power output from the local renewable energy production unit, and the starting level of energy storage charge. The output is in the form of an optimum profile of the charge/discharge cycle throughout the given time period and the profit made by selling electricity primarily at high-price hours instead of directly feeding it out to the grid whenever it has been generated.

3. COMPRESSED AIR ENERGY STORAGE SYSTEMS

Large-scale compressed air energy storage (CAES) systems can be regarded as conventional technology. They have certain environmental advantages if compared to pumped hydro energy storage and allow for a much larger number of potential sites. 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 [3 - 7], among others. Comparisons with other storage alternatives and specific applications in different locations around the world, serving different electricity markets, have been examined in [8 - 12].

Various CAES configurations have been proposed through the years, see e.g. in [5]. A figurative representation of an existing large-scale CAES system using an underground air cavern is shown in Figure 1.

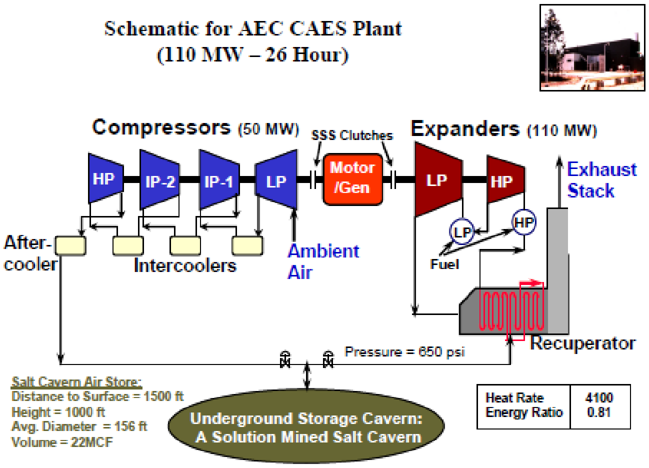

Fig. 1: Conventional large-scale CAES concept using an underground cavern, intercooling of the compressed air and a fossil fuel for heating the air before expansion. This is the existing plant in Alabama, USA (Alabama Electric Cooperative), commissioned in 1992 at a capital cost of $600/kW [4].

Mid-scale CAES systems have been extensively evaluated in [13-15], among others. Lund et al. [13] 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 [14] 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 island grid of Crete.

M. Nakhamkin, being 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 [15], 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 together with instrumentation and balance of plant, represent 37% of the capital cost [15]. The specific investment for the 15 MW energy storage system would sum up to $ 1200–1300 / 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. [8], Diaz-Gonzalez et al. [9] and by Mason & Archer [10], who 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 would have specific costs in the order of $1100–1600/kW. These are several times lower than the established investment costs of electrical batteries, as cited in the same studies above.

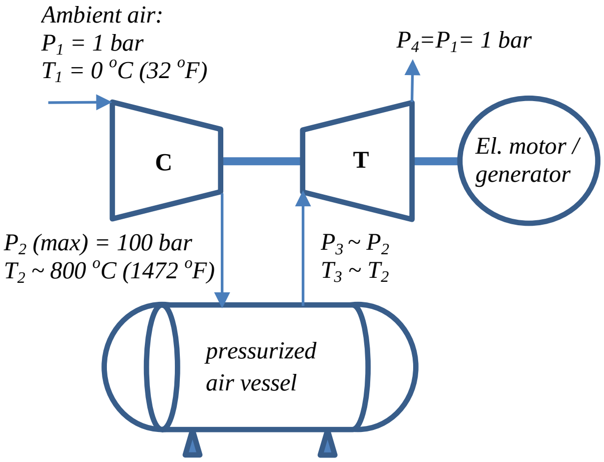

Fig. 2: Simplified layout of the proposed idealized DCAES unit, utilizing a purely adiabatic cycle without heat exchange.

Small- and micro-scale DCAES systems 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 500 kW system described by Grazzini & Milazzo [16]; 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. [17]; the exergy analysis of a micro tri-generation DCAES system featuring a 1 m^3 (35 ft^3) storage vessel at 50 bar pressure (725 psi), performed by Kim and Favrat [18]; 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. [19]; 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. [20]; the attempt by Paloheimo and Omidiora [21] to define pico-CAES systems for remote mobile network masts or for handheld electronic devices. Proczka et al. [22] 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 storage in batteries. DCAES units offer some serious advantages, such as:

- DCAES units using pressure vessels are universally appropriate for any location;
- DCAES units promise longer life span than electrical batteries, without deterioration of performance;
- DCAES units do not require high-tech production and do not use rare or toxic materials, the hardware is easily recyclable, therefore 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 DCAES units can be summarized as follows:

- Not proven yet, costs may be high initially;
- Require larger space than batteries;
- Have 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 operate at variable conditions and lose efficiency in deep off-design modes.

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 the air can be approximated to ideal gas (perfect gas) and idealized equations can be used. A summary of the thermodynamic considerations valid for CAES systems can be found in [16] and others. A closer thermodynamic analysis and design characteristics for the hereby proposed and evaluated DCAES system is not the focus of this study.

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. The larger part of the potential energy of 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, if done by additional fuel, decreases the energy efficiency (increases the heat rate) of the overall energy storage process. The heat rejected by intercooling can also be stored in external thermal storage and returned to the air before expansion, as proposed for example in [5], [16], [18].

For the DCAES system studied herein, a purely adiabatic approach without heat exchange is suggested as of Fig. 2, aiming at lowest possible complexity and simplest configuration, where lower costs and ease of maintenance are of primary importance. The compressed air is charged into the storage vessel without intercooling, and expanded directly during discharge without external reheat. The pressurized air tank is thermally insulated, in the ideal case preserving all the heat of the stored air until the expansion process starts [23].

4. PARAMETERS AND ASSUMPTIONS

The purely adiabatic DCAES system proposed here is being evaluated by the present authors in terms of design and thermodynamic performance in other studies [23]. It aims at simplicity and straightforward architecture with minimum complexity and low number of components. It also compromises performance for achieving low costs, durability and ease of maintenance. The size or type of the air storage vessel would not be of any importance for the general performance of the DCAES system, unless thermal losses to surroundings would be taken into account. The actual design and dimensioning of the DCAES unit are not the focus of this study.

The energy storage system considered herein consists of one or more DCAES units of total capacity of 50 kWh, situated by a transformer serving a neighborhood of several houses. The used model of time varying loads is based on customer billing information, load research data and measurements from the primary sides of distribution transformers for a chosen locality in the state of New York [28].

Figure 3 shows the typical load profiles for a day with the highest load (July 5) and a day with the lowest load (October 11) in the chosen neighborhood for year 2011.
To analyze the energy storage behavior, a 25 KVA single phase distribution transformer is considered. The total

aggregated renewable energy installed capacity at the location is assumed in the range of 0 to 15 kW. These could be a series of PV panels spread on one or several house rooftops, or one or more small windmills somewhere in the vicinity. The specific distribution of the load and the generation capacity among the houses are not important for the final results.

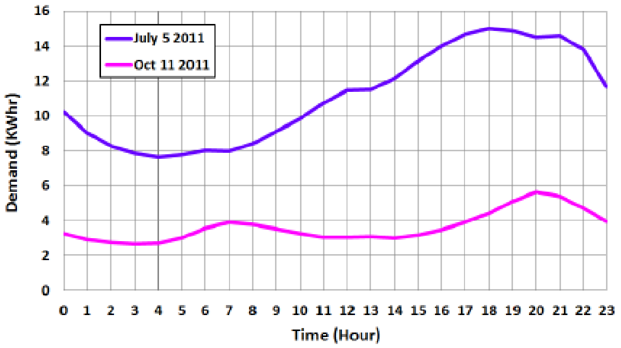

Fig. 3: Distribution transformer loading (hourly load profiles) during maximum and minimum load days in the chosen location.

Table 1 summarizes the important electrical system parameters for the energy storage unit. The discharge cycle is able to provide 25 kW power output and exhaust the storage within 2 hours for fully covering the possible peak loads of the local consumers. The charging cycle is more restricted and the storage unit would need 4 hours to charge fully if starting from empty.

<u>TABLE 1: A SUMMARY OF MAJOR ELECTRICAL PARAMETERS FOR THE PROPOSED DCAES SYSTEM</u>

Parameter	*Value*	*Unit*
Total capacity	50	kWh
Max power output	25	kW
Max charging rate	12.5	kWh/h
Max discharging rate	25	kWh/h

In order to quantify the expected power delivery by the distributed generators, a PV array is considered. The PV power output is based on the National Renewable Energy Laboratory (NREL) data from “In My Backyard” (IMBY) [24] and the “PVWatts” online tools [25]. These online PV power calculation tools use solar irradiation, meteorological data and PV performance parameters to produce hourly power output values for any location in the United States. For the analysis in this study, four levels of local power generation capacity are considered in four case scenarios, assuming PV panels of respectively 0 or of 5 kWp, 10 kWp and 15 kWp installed on rooftops in the neighborhood. Their predicted power output for the typical high-load day of July 5, is presented in Figure 4.

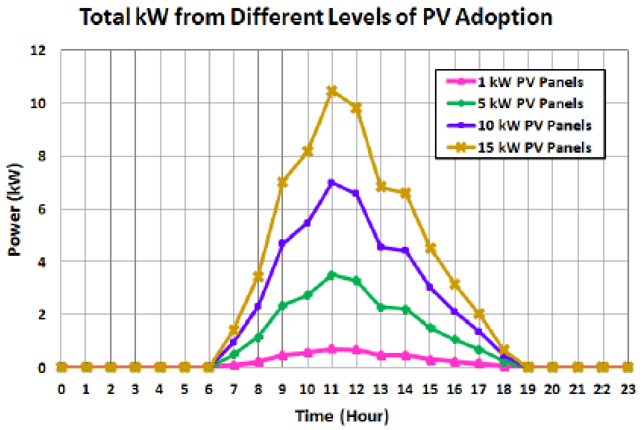

Fig. 4: Expected power output from different PV capacities installed in the selected location: 1 kWp, 5 kWp, 10 kWp, 15 kWp, for the day of July 5, 2011 [27].

The optimal control strategy aims at using locally produced electricity as much as possible. Such behavior is beneficial for both the consumers and for the distribution network operator. From the utilities perspective, the load factor improvement can lead to decreased operational costs. At the peak hour when the LMP is high, the utility can relieve part of the network congestion by partly supplying customers’ needs by locally generated renewable power. The energy storage unit can also support loads for a period of some hours to manage outages and eliminate the effects of temporary faults. From consumers’ point of view, the optimal control of the DCAES system can decrease electricity bills by eliminating the purchase of electricity at the most expensive hours.

In order to determine what the storage should do at the current time, the optimization algorithm defines an estimated schedule for the next 24 hours. Knowledge of the load forecast, the day-ahead electricity LMP, and weather data allows the control system to plan an optimal charging and discharging cycles in advance. Figure 5 shows the data flow of the storage management system. Load profile, momentary energy storage capacity, PV output, and market price of electricity form the main data components of the optimization algorithm.

Conceptually, the optimization algorithm works as follows: if the current LMP is lower than expected in the near future, the battery will charge, subject to both rate (kW) and capacity (kWh) constraints; similarly, if the current LMP is higher than expected in the near future, the battery will discharge, subject to the same constraints.

Considering the market price, the optimal energy storage operation schedule is composed of 24 hour-slots within each day. Internal losses as a function of the storage state of charge can also be integrated in the calculations, relevant to both battery systems where voltage is a function of charge level, and to CAES systems where the pressure in the air vessel varies greatly throughout the charge/discharge cycle and affects the performance of the power equipment.

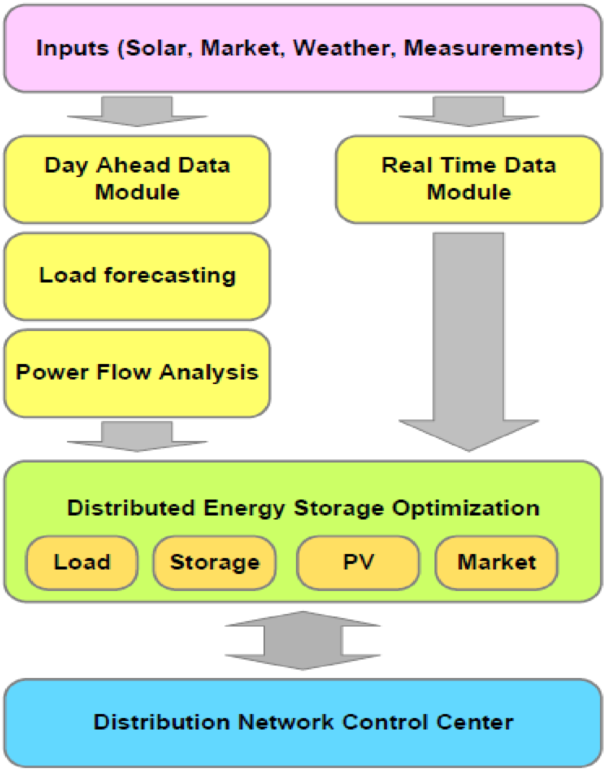

Fig. 5: Schematic architecture of distributed energy storage control system for optimum operation and profit maximization [27].

The profit maximization is limited by physical and functional characteristics of the energy storage. Firstly, a minimum charge has to remain in the storage in order to meet the demand in case of grid faults. Secondly, the supply of renewable energy is limited to what is available at each hour. The transfer of electricity to and from the power grid is also dependent upon the real-time LMP price and the forecasted LMP price. Therefore, the following constraints are imposed on the storage unit: charge and discharge rate constraints, minimum capacity constraint, necessary reserve capacity requirement at each hour, and transformer loading constraint at each hour. The detailed description of the calculation procedure is presented by Arghandeh and Broadwater in [27].

The discrete ascent optimal programming (DAOP) [26] algorithm 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 of energy (kWh) of charging or discharging activities during each iteration, moving toward an “optimal” schedule. The DAOP does not scale back in any hour during any iteration once a certain amount of charge or discharge has been scheduled for that hour. This “greedy” characteristic of the DAOP algorithm ensures that it can converge in a finite number of steps.

5. SIMULATION RESULTS AND DISCUSSION

The results from the DAOP calculation runs are presented in the figures below. Figure 6 shows the results of PV integration with aggregated residential loads of the considered neighborhood, for the peak day of July 5, 2011. The yellow line on top represents the aggregated load profile for the same group of houses without any local power generation, confer with Fig. 3 above.

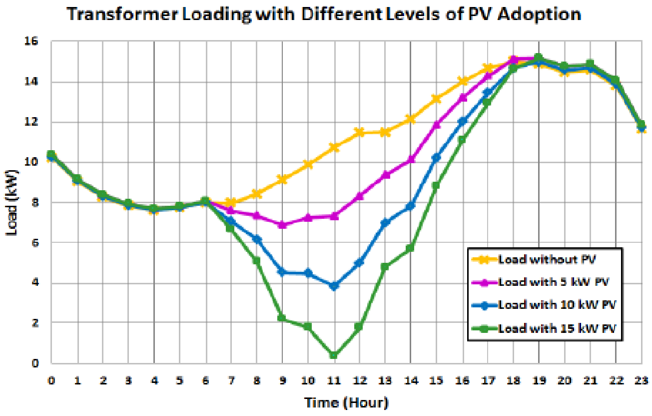

Fig. 6: Aggregated load for the considered neighborhood at different capacities installed of PV panels, for the day of July 5.

The load profiles for different PV adoption levels are presented in Figure 7, with and without energy storage, where the storage behavior has been optimized for customer benefit. From 5 AM to 9 AM the LMP price is low and demand is not high, therefore the energy storage charges to its maximum capacity. From 9 AM to 6 PM, the storage maintains its capacity as high as possible to be ready for the peak hours, 6 PM to 9 PM. During the peak hours the storage starts to discharge to serve loads and to avoid buying expensive electricity. At 9 PM the LMP has reached its highest level and is bound to start decreasing. Therefore, at 9 PM the storage unit covers the entire load and sells power to the grid. The negative load sign at 9 PM shows the reverse power flow from the DCAES unit to the grid. It should be pointed out that the energy storage control system prioritizes customer benefit in terms of price savings and not load leveling. The storage does not discharge when the electricity price is low even if the load is close to peak values (morning), while it discharges sharply at the time when the price is highest and both the price and the load are bound to start decreasing (late evening).

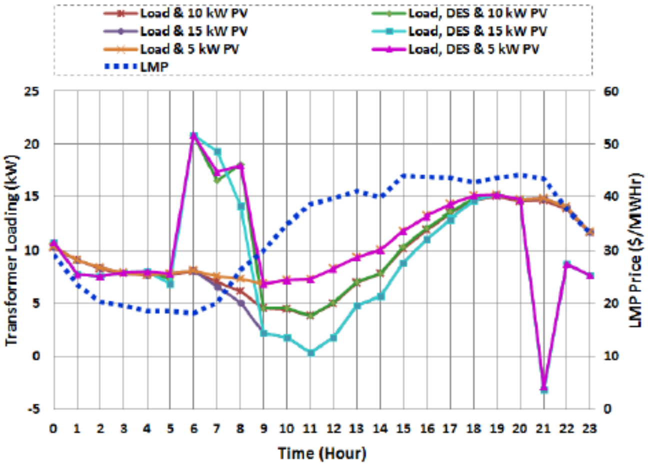

Fig. 7: Load profiles with and without energy storage, and optimal storage behavior for different PV capacities in the locality, maximizing the benefit for the customer. The dashed line represents the LMP variation throughout the same day.

Figure 8 presents the economy results for the considered case scenarios. As the local generation capacity (PV size) increases at distribution transformers downstream, higher benefits are achieved by energy storage. In the case without local power generation, the energy storage unit can still deliver a net benefit of nearly $ 77 over the month of July 2011 by utilizing its ability to store cheap electricity and sell it back when the price is highest. When 15 kWp PV capacity is present, the benefit rises to $ 82.5 /month.

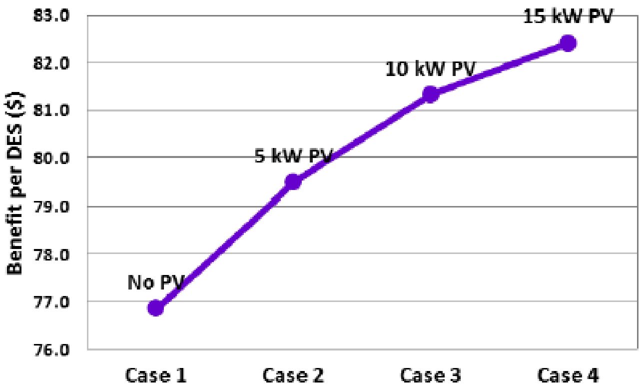

Fig. 8: Economic benefits due to optimized control strategy of the distributed energy storage unit.

While the PV panels (or any local power generators) are usually owned by the electricity customers, the energy storage solution would impose a large investment burden and could primarily be constructed, owned and operated by the utility. In that case, the operational strategy may change somewhat to prioritize utility benefit and load leveling rather than customer benefit. However, in all cases both the utility and the customers would profit from energy storage deployment. Careful economy analysis is further necessary for assessing payback times and return on investments.

6. CONCLUSIONS

Adoption of energy storage at the customer side integrated in local utility electrical grids is feasible and would provide operational and economy benefits. Distributed small-scale compressed air energy storage systems are possible to build and apply in ways similar to electrical batteries.

An iterative algorithm has been used, which attempts to maximize profits by properly managing the stored energy. The discrete ascent optimal programming algorithm can be utilized to optimally coordinate the energy storage behavior with or without the presence of local renewable power generation. At growing levels of local power production, the optimal storage management maximizes the profits by properly selecting charge/discharge strategies as a function of electricity price and storage parameters. The optimal control strategy considers device and grid constraints in addition to the real-time market prices and load profiles.

The simulation results show that the control system provides economic benefits via dynamic response to fluctuating electricity market price and renewable energy harvesting levels.

It is suggested that the energy storage 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, blackout mitigation and back-up tasks, enhanced peak shaving, improved utility planning, etc.

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