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ELECTRICITY STORAGE AND DEMAND-SIDE MANAGEMENT: IS THEIR CO-EXISTENCE POSSIBLE?

Lazaros Exarchakos Matthew Leach
Imperial College London, Centre for Energy Policy and Technology
Prince Consort Road, London SW7 2BP
United Kingdom
lazaros.exarchakos@imperial.ac.uk m.leach@imperial.ac.uk

ABSTRACT
Electricity market opening tends to cause actual generation costs to be reflected in prices, which become more variable and tend to follow the patterns of load peaks. Generating electricity at peak times is costly and in this occasion there might be an opportunity for electricity storage systems to contribute both technically and financially for relieving grid congestion. But while storage operation is based on exploiting demand and thus price peaks, Demand-Side Management (DSM), when being simultaneously in action, aims at their reduction. These two peak-load management mechanisms might therefore be in conflict, giving rise to concerns for the economic success of storage. We approach the implications for storage profits by such a co-existence, simulating the technical optimization of three main storage technologies, used for energy arbitrage services only, under DSM scenarios. It is revealed by this analysis that under the assumptions made and conditions posed, a substantial amount of DSM had only a small effect on storage profits for all technologies, as the maximization of the electricity discharged was achieved by all. The paper is based on the first stages of a larger research effort in this field, and describes the initial model formulation.

KEY WORDS
Load Management, Modelling, Electricity Storage, Cash-flow.

1. Introduction

Electricity storage has already been a practice followed by utilities for load leveling, power quality and security enhancement. In the environment emerging under the gradual liberalization of electricity markets, the cost of generation is receiving increased attention and simultaneously environmental concerns resulting from the sector's energy intensiveness has lead to rethinking of advanced electricity storage systems as alternatives to peaking power plants. Storage, when used for arbitrage services, is taking advantage of the peak energy prices by charging at low prices and selling electricity at the peaks in order to generate value [1].

As known, in a fairly open electricity market, where the wholesale prices reflect the variable marginal cost of generation, the peak prices go alongside in time with the extremes of load. The Greek situation at present is an Electricity Pool where the available power by producers is bid by the previous day, and the wholesale electricity price, very simplistically, corresponds to the intersection point of the general equation of electricity offer and the general equation of electricity demand. It is obligatory for the producers to incorporate the marginal variable cost of electricity generation into their offers to the Pool, and their offer has to be higher than, or equal to that cost [2]. Consequently, price reflects the variable cost of generation. However, the dominant position of the Public Power Corporation (PPC) in the market, holding over 95% of the electricity production, apart from creating distortions to the further opening of the market, also binds the electricity price into practically one producer's actions and management. In this specific case, no one can exclude the possibility of the state's intervention for social welfare reasons.

While storage is valuable for the reasons mentioned, another technique to relieve the grid's congestion is DSM. The target of DSM measures is to "shave" the load peaks and shift that load to off-peak times of the day. Thus whilst sharing objectives for peak load management, storage and DSM opportunities may be in conflict, with the former made viable by high demand peaks, and the latter intending to reduce them.

The aim of this research is to explore the financial, and technical (energy) performance of electricity storage when DSM measures are in action at the same time. The analysis is based on scenarios for DSM implementation in the current level of the Greek market opening to competition. Three major storage technologies have been chosen to participate in the analysis for comparison. The initial load and wholesale price data sets are derived from the Greek Transmission System Operator (TSO), referring to the years 2004 and 2005 and are in the form of hourly values.

2. Storage systems to compare

Storage systems can serve load leveling and power quality duties. Depending on the scope of investment, profitability or power quality and safety, it is required high energy capacity or high power output respectively. In this research, managing load is of interest and the technologies which correspond to these needs are those with high energy storage capacity and low to high power output.

Their characteristics necessary for the cash-flow analysis and their ability to capture energy, are their round trip efficiencies adding the losses of storage media. Losses due to transmission are not taken into account as they are fairly common also for other technologies such as thermal plants. The energy/power ratio chosen for all three technologies is 8h. That is their ability to deliver energy at full load for a period of 8 hours in a 24h day [3].

The technologies fulfilling the requirements for load leveling (especially for medium-scale applications in the range of 5-40 MW of installed capacity) and considered here are:

- *Pumped Hydro Storage (PHS).* PHS is a technology characterized by low energy requirements and low carbon emissions, both for operation. The efficiency used for this technology includes the round trip efficiency of electricity conversion and the losses in storage media (evaporation and seepage) and is 78% [3].
- *Compressed Air Energy Storage (CAES).* For CAES the evaluation of efficiency is more complicated as this technology includes gas use for delivering electricity. Consequently, for calculating the electrical efficiency it needs to subtract the amount of energy corresponding to gas from the electrical energy finally generated. This gives an efficiency of 71% [3].
- *Flow Batteries.* In this technology are included types of batteries also known as regenerative fuel cells, like the Vanadium-redox and Regenesys batteries, suitable for small to large scale applications. The efficiencies estimated include losses due to battery pumps, cooling systems and AC-DC-AC converters, which finally are 75% and 65% respectively [3].

3. Methodology

The methodology has been structured in a sequence of interlinked actions as shown in Figure 1. At a first step, DSM is applied on load data to 'shave' peaks and shift load. Statistical analysis is then necessary to evaluate the elasticity of price with respect to load. At a next step, the operation of the three technologies is simulated under the load and price conditions created from the first step. The intention is to come up with estimates of the cash-flow for the private investor of the storage system and energy gains for the electricity system.

3.1 DSM Scenarios

DSM is implemented under two scenarios; the baseline 'Scenario 1', which assumes no effects on load and prices and the alternative 'Scenario 2' where load reduction and shifting are applied.

Scenario 2 sets various levels of peak load reduction, displayed in Table 1, along with load shifting to off-peak times. The logic behind the way these reductions were applied is examined in paragraph 3.1.1. The officially reported DSM actions (from the TSO) for load reduction in the second half of 2005 reveal the system's weak points where air-conditioning during summer and limited water reserves in dams for load leveling in late summer, autumn and early winter trigger load leveling needs and are achieved through bilateral agreements between the TSO and Selected Big Consumers [4].

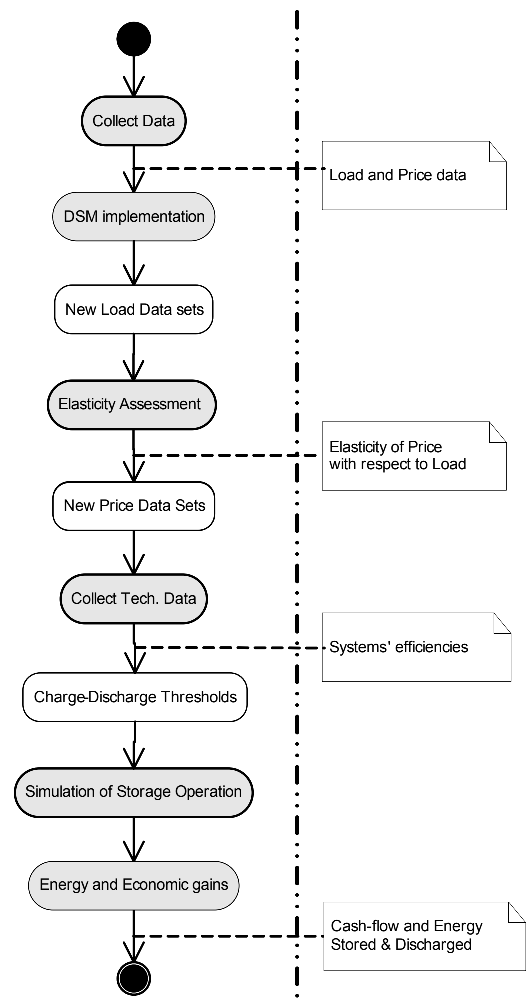

Figure 1. Actions and States of the model

3.1.1 Peak "Shaving"

Each year has been divided into three time periods, corresponding to a set of similar level of load peaks. Simulation in Matlab calculated the peak load reduction and shifting. The percentages shown in Table 1 are almost double of those used by the TSO, assuming a more intensive implementation of DSM measures. So, for both years those figures are as follows:

Table 1. Cases of load reduction applying DSM

Time Period	Cases: If load is (in MW):	Then reduce peak by
Jan-Mid.May	6500≤load<7000	1.5 %
	7000≤load<7500	2.0 %
	load≥7500	2.5 %
Mid.May-Sep	7500≤load<8000	3.5 %
	8000≤load<8500	4.5 %
	8500≤load<9000	5.0 %
	load≥9000	6.0 %
Oct-Dec	7000≤load<7500	2.5 %
	7500≤load<8000	3.0 %
	load≥8000	3.5 %

3.1.2 Load Shifting

The load shifting in this analysis follows the guideline of 'no energy missed'. That is, the amount of energy reduced is completely shifted. It is assumed that the consumers' behaviour in allocating their consumption at off-peak times is not known. The method used for load shifting is by uniformly distributing the energy corresponding to load reduction into off-peak hours of the day. In this way a smooth allocation throughout the whole off-peak periods is achieved. The final shape of the load curve at off-peak times should not exceed in any occasion the load in peak times after DSM implementation.

3.2 Load change impacts on Prices

DSM has direct impacts on load and through load, indirect impacts on prices. The method followed to track the changes in prices is to evaluate the elasticity of price with respect to load through statistical assessment by non-linear regression between the two variables. The data sets used for this are the initial ones. The complexity of the non-linear regression was diverted through log transformation of both variables into a linear regression equation. The equation expressing the relation between the price and load is:

$$P = \alpha L^{\beta}$$

where P for Price and L for Load, α the constant value and β the slope of the linear regression.

This equation is log-transformed as follows:

$$\ln(P) = \alpha + \beta \ln(L) + e$$

where e corresponds to the error.

The relationship determined using the statistical software package SPSS is:

$$\ln(P) = (-7.369) + (1.257)\ln(L) + 0.095$$

From this relationship the elasticity of Price with respect to Load shows that for 1% of Load change the Price changes by 1.257% in the same direction (positive changes in load trigger positive changes in prices). That figure reflects the actual market liberalization level and market response. This analysis assessing the load changes impacts on prices gives a new data set for wholesale electricity prices under the current environment of liberalization.

3.3 Set of Storage Charge-Discharge Thresholds

Simulating the storage operation for assessment of the energy gains and cash-flow, it is necessary to set the Charge and Discharge thresholds (P1 and P2 respectively). Those correspond to two electricity price values within the day which will be different each day as the price patterns also differ. The technical and economic optimization of storage systems require different conditions to be fulfilled. In this analysis which focuses on the technical optimization under arbitrage services only, those are:

a) the amount of energy captured in a day equals the energy discharged plus the efficiency losses and
b) the maximum time the system can discharge electricity at full capacity is 8 hours per day.

The operating strategy that needs to be followed for that approach is to discharge electricity at full load for prices above the Discharge threshold and to buy electricity at full capacity for prices bellow the Charge threshold, always considering the conditions mentioned. For price values between the thresholds the storage system should remain idle, as the ancillary services are not of interest [1]. The selection of this energy/power ratio is done for reasons of simplicity as the research is in initial steps and because economic constraints in designing such systems require ratios of 8h and 16h [3].

4. Results

The results of the analysis refer to the energy stored and discharged and the cash-flow produced by the three different technologies in the environments of DSM and no-DSM. The calculation of those figures was made under several assumptions:

a) the level of storage systems integration in the system (capacity installed) is not affecting wholesale electricity prices,
b) the installed nominal capacity of storage systems assumed in the interconnected electricity system of the Greek mainland (islands are excluded) is 100 MW representing 1.1 % of the overall

generation capacity (which is almost 11 GW) and

c) the storage systems have the ability to charge at full capacity and also to discharge at full capacity with a maximum time limit of 8 hours per day.

4.1 Load reduction and Shifting

The implementation of DSM on load patterns resulted in energy reduction during peak times equal to 654 015 MWh which corresponds to almost 0.63% of the total energy consumed in years 2004 and 2005, even though the peak "shaving" was significant. The patterns of load alterations of a typical day are shown in Figure 2. The 'Shifted Load' curve is more flat than that of the 'Initial Load' one, as expected.

4.2 DSM effects on Prices

The load reduction due to DSM did not have significant impact on prices; however, the thresholds were quite distant in the DSM and No-DSM cases. Figure 3 is indicative of those differences between P1 and P2 which is almost 11.4 € when DSM is applied and almost 4.5 € when it is not.

For reference only, it has to be noted that Figures 2 and 3 correspond to the same day and the values refer to PHS technology which was chosen for purposes of discussion. Similar price behaviour is noticed for the other technologies.

4.3 Technical Gains and Cash-flow

4.3.1 Energy Stored and Discharged

Nominal capacity of the storage system (here accumulated for the whole electricity system and equal to 100 MW) affects the amount of energy that can be stored and discharged. An initial presumption might be that those amounts of energy will be affected also by the set of thresholds P1 and P2. However, the analysis revealed that P1 and P2 are always best allocated; the conditions mentioned in paragraph 3.3, *optimize* the technical operation of the storage system, thus the amount of discharged energy is always the maximum possible which corresponds to nominal capacity times the maximum hours of discharging capability. It is also the fact that the price patterns are not extremely variable in the Greek market (there are many equal price values for many sequential hours) so it is easy for the simulator to achieve the maximum discharging capability. Those are the reasons why for all technologies the model gives the same discharged energy, either with or without DSM, equal to 800 MWh per day.

The energy stored by each technology separately, is the same for both DSM and no-DSM cases. Further, the discharged energy is identical for all technologies and under all cases. This is because the simulator reaches the highest technical limitations of the storage systems.

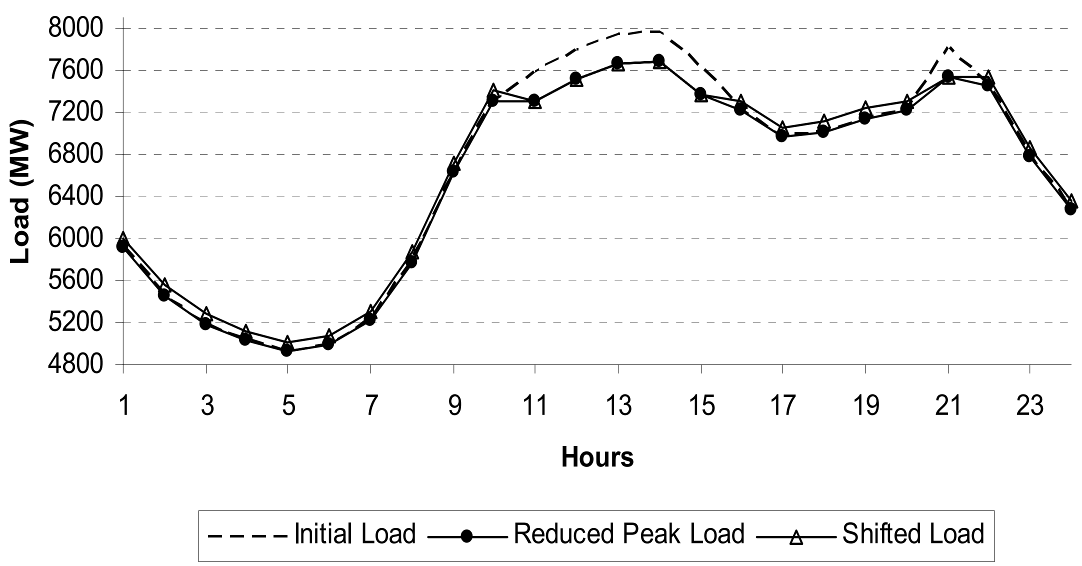

Figure 2. Load pattern modifications for a typical day

With the approach followed, the 8h energy/power ratio was easy to meet, but if the ratio was set to 16h it might wasn't the case for every technology and every day to achieve it. This would possibly give different energy discharge values. The difference in stored energy appearing between the technologies derives from the different efficiency loss factor of each one. The smaller this value the higher the energy stored to achieve the optimum of 8 hour discharge at full capacity. The relevant results are found in Table 2. The initial stage of this analysis required the simplistic use of the efficiencies without considering more detailed and accurate technical issues of the technologies which may be affecting the final performance.

Table 2. Accumulative table for all technologies' achieved figures

	Cases	Energy Stored (MWh)	Energy Discharged (MWh)	Cash-flow (€)
Pumped Hydro	DSM	804 099	584 799	25 651 591.1
	No-DSM	804 099	584 799	25 736 160.0
	Difference	0	0	84 568.9
CAES	DSM	877 199	584 799	25 651 455.0
	No-DSM	877 199	584 799	25 736 160.0
	Difference	0	0	84 705.0
Vanadium-redox Batteries	DSM	804 099	584 799	25 651 534.0
	No-DSM	804 099	584 799	25 736 160.0
	Difference	0	0	84 626.0
Regenesys Batteries	DSM	950 299	584 799	25 651 534.0
	No-DSM	950 299	584 799	25 736 160.0
	Difference	0	0	84 626.0

4.3.2 Cash-flow

The economics involved at this stage of analysis are relative to the private investor's cash-flow earnings through selling electricity to the network and it does not assess the achievable net revenue. An analysis aiming the economic optimization would require consideration of at least energy generation and operation & maintenance (O&M) costs of the storage systems and a different set of thresholds. The cash-flow corresponds to the energy discharged times the price of each MWh sold. Since all technologies in this analysis manage to reach their technical limit of 8h of discharge per day, the cash-flow is maximized and is the same for all technologies as the figures in Table 2 indicate. The fact that the cash-flow is slightly different between technologies for the DSM case is clearly related to the available data and the simulation. The data are in a discrete form and are not expressed by equation. Therefore, in the simulation the set of thresholds is not sequential but follows steps. This makes both the set of thresholds and the outcomes of the simulation to develop in steps and to differ.

As noted, the energy discharged in all cases is the same. But as the prices in DSM and no-DSM cases do not fully coincide, the amount of money gained also differs and is higher for no-DSM case by around 0.33%. This figure is quite small if compared with the load reduction achieved with DSM.

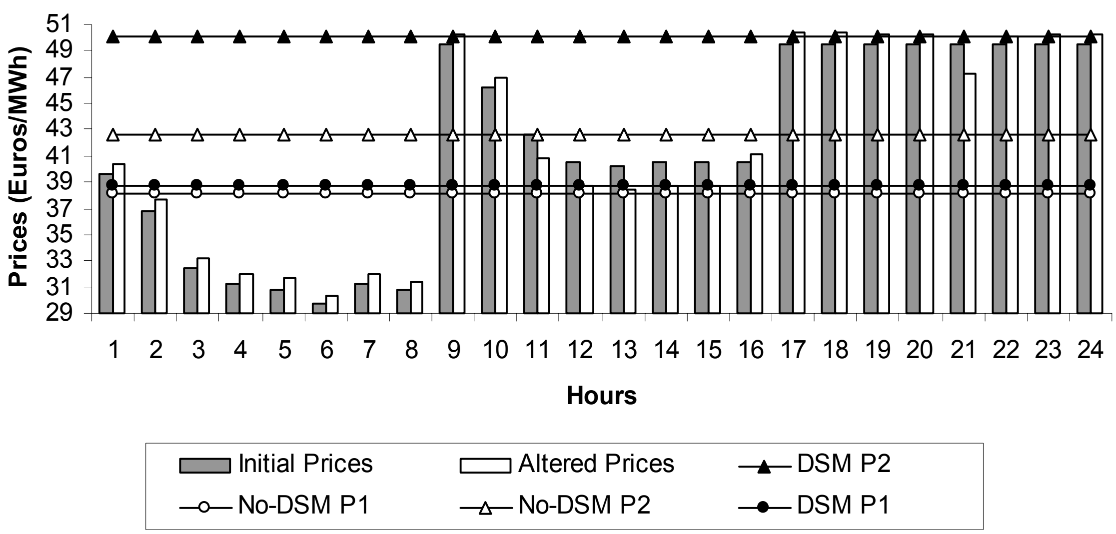

Figure 3. Price modifications and Charge-Discharge Thresholds

5. Conclusion

The analysis revealed that with the given assumptions and market conditions, DSM is not practically influential on the cash-flow the electricity storage system can achieve. No-DSM case is just 0.33% more economically beneficial than the DSM case during the two years considered. This result is largely affected by the technical optimization strategy followed for energy arbitrage services. Since this strategy tends to maximise the energy delivered by storage systems and make it similar for all technologies (and thus the value gained is almost identical for all technologies), the overall profitability of each technology and the comparison in DSM and no-DSM states will strongly depend on the electricity generation and storage system O&M costs, whose assessment is outside the scope of this paper. Technically, the Charge and Discharge thresholds are virtually not playing any role in the maximum amount of energy stored in all the technologies tested since the strategy best allocates them for maximization of electricity discharge.

Whilst these initial results suggest only a limited influence of DSM on storage, several aspects of the analysis require extension and refinement. Further development of this research will include analysis of the effect of the electricity storage on electricity prices, creating interaction in the system between storage and prices. The assumptions and conditions set for the analysis will also be revised and developed. The technique used to shift the load will be revised to link to socioeconomic parameters affecting the consumers' behaviour for a more realistic approach to DSM. Finally, the selection of the energy/power ratio for the storage devices, a significant parameter in the analysis, needs to reflect the reality more closely by incorporating the technical constraints of each technology.

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