Techno-economic analysis of the deployment potential of energy storage for grid connected applications

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Abstract—**Electric energy storage can provide several services and is used in a variety of applications today. New and improved technologies and decreasing cost of batteries make electric energy storage already competitive in certain applications and with increasing share of renewable energy resources the need for energy storage increases.**

This paper presents services that can be provided by grid connected energy storage as well as applications in which these services can be deployed. Five current and potential future markets have been studied and the deployment potential for grid connected energy storage in these markets has been analyzed. Metrics for measuring the benefits of deployment cases of energy storage have been developed from the combination of services, applications, and markets.

Deployment cases have been defined for frequency regulation in the eastern United States and peak limiting in California and examined in cost-benefit and sensitivity analyses. The results show that energy storage is cost-efficient for these deployment cases even if frequency regulation market prices and subsidies drop below today's level.

From the analyses conducted in this thesis it can be concluded that energy storage offers valuable alternatives to current grid resources and can help integrate fluctuating generation and demand if market structures are in place that treat energy storage and the services it offers in a fair way.

Key Words—**energy storage, battery, cost-benefit analysis, market analysis, frequency regulation, peak limiting**

I. INTRODUCTION

ELECTRIC energy storage has been deployed for well over two centuries since Volta built the first electrochemical battery in 1800 and has always been a part of the electricity system [1], [2]. Due to their limited power and energy capacities though, until recently batteries have been used mainly in small scale and mobile applications.

The need for energy storage has been in existence since the start of the first locally isolated grids a century ago to today's internationally interconnected grids. This need is a result of the variable demand from the consumer side in the electrical grid and an increasing deployment of fluctuating renewable energy sources.

With increasing deployment of renewable energy resources such as wind and solar photovoltaic adding variability at the generation side, the need for flexible grid resources like electric energy storage is increasing. Depending on the application, energy storage systems (ESSs) are capable of providing different valuable services.

In this context it is important to note that the definitions of the terms "service" and "application" vary among the reviewed literature and are sometimes used interchangeably. Within this paper the term "service" describes the electrical operation that is fulfilled by the energy storage system including its power conversion system. The term "application" describes the location within the grid and the connection and functionality of the ESS in relation to its surrounding infrastructure as well as its technical characteristics. The term "benefit", which in the literature also often describes a service, is used in this paper exclusively for financial benefits. While the term "energy storage" can generally refer to the storage of all forms of energy, here only storage technologies for storage and discharge of electricity are considered, i.e. mainly electrochemical batteries.

II. BACKGROUND

There is a great variety of services provided by energy storage systems in a wide range of applications. These applications cover the whole energy supply chain from generation through the transmission and distribution network to the end-consumers. In some markets, services are recognized as market products which can be traded between market participants, whereas in other markets most of the possible services that ESSs can offer are internalized in the existing electricity system and cannot be valuated. In this chapter, different services provided by ESSs are identified, energy storage applications are introduced, and potential markets for ESSs in the USA, Germany, Australia and Japan are presented.

A. Services

Depending on the application, an ESS can provide multiple services, although it is important to consider whether or not these services can be called upon at the same time.

The definitions for services vary throughout the literature and can be somewhat arbitrary since each service is derived from the simple storage operations of energy charging (power absorption) or energy discharging (power injection) over a certain period of time. In this paper the services presented in Table 1 are considered and roughly grouped according to their most common applications. It is important to note that the services as they are defined here do not always match market products.

Table 1 Energy storage services and their application groups

Application Group	Service	Description
Generation Side	(Large scale) Energy time-shift	• transfer of electric energy from one time period to another • participation in the wholesale market: charging during low load periods (off-peak), discharging during high load periods (peak)
	Electric supply capacity	• charging during off-peak periods, discharging during peak periods, reducing the overall system peak • replacement of peak power plants
	Reserves	• inject power into the grid in order to cover unexpected deviations in generation and demand • ESS for short term reserves which require fast reaction times (spinning reserve, primary control reserve)
	Frequency regulation	• balancing expected short term deviations of generation and loads • ESS follows regulation signals very closely →reduction of the need for frequency regulation
	Black-start capability	• re-energizing the grid after a major power outage has occurred • providing power for restarting other generation resources
	Load following	• maintaining the balance in the system by reacting to fluctuations in generation and demand • following the load in the so called “shoulder hours” in the morning when demand increases and in the evening when demand decreases
T&D System	Load leveling	• smoothing or leveling the load curve of the area served by the ESS • charging during low demand periods and discharging during high demand periods
	T&D Congestion relief and upgrade deferral	• ESS installed electrically downstream of the congested or overloaded part of the T&D system • reducing high loads on existing equipment and thus extending its lifetime • discharging during high load periods reducing the electrical strain on the T&D equipment, charging during low load periods
	Voltage support	• managing reactance caused by grid equipment and consumers that display characteristics of inductors or capacitors • injecting or absorbing reactive power into or from the grid
	Power quality	• monitoring the grid power • discharging with smooth power output to balance variations in voltage magnitude, variations in the primary frequency, low power factors, harmonics, interruptions in service and other phenomena
End-Consumer	Electric service reliability	• ensuring uninterrupted power supply to the load in case of a complete power outage • protecting must-run equipment and ensure flawless operation • operating in islanding mode and resynchronizing to the grid once it is re-energized
	Peak limiting	• limiting the maximum power draw from the grid • discharging during load peaks
	Time-of-use shifting	• storing energy during low demand for discharge during high demand • saving money by charging during off-peak periods at low energy prices and consuming the stored energy during expensive peak periods
Renewables Integration	RE Capacity firming	• producing a nearly constant power output by absorbing peaks and suppressing valleys in generation • avoid the need for curtailing by buffering unexpected peaks
	RE Ramp rate control	• controlling the change of power output over time • charging during fast ramp up, discharging during fast ramp down to limit the change in overall power output
	RE Time-shift	• storing RE when it is abundantly available at low prices and discharging it when it is needed and at high prices • avoid curtailment, increase self-consumption, increase profit

B. Applications

An application is a use case of one or multiple services and specifies the location of the ESS within the grid and the connection and its functionality in relation to its surrounding infrastructure as well as its technical characteristics. Here only grid connected applications are considered, which are subdivided into applications located at the generation site, in the transmission grid, in the distribution grid, and behind the meter at the customer site.

1. At Generation Site

ESSs can be applied to provide services in support of or instead of other generation resources like thermal power plants or RE power plants. Supporting power plants with services like reserves, frequency regulation and load following increases their efficiency and lifetime, resulting in less fuel consumption and less emissions per generated kWh. ESSs offering electric supply capacity can replace thermal power plants. ESSs located close to large RE resources providing RE capacity firming, RE ramp rate control, RE time-shift, and possibly frequency regulation, help integrating RE and ensure system stability.

2. In the Transmission Grid

ESSs located in the transmission grid can reduce transmission congestion and support transmission infrastructure to extend equipment lifetime and defer investments. Similar to applications at the generation site, ESSs in the transmission grid are able to provide ancillary services such as reserves, frequency regulation, load following, black start capability, and voltage support. This enhances system reliability and reduces the need for additional generation resources or existing generation to operate in part load.

3. In the Distribution Grid

Energy storage in the distribution grid close to the demand side can provide important ancillary services like load leveling, voltage support, and power quality and is able to relieve distribution equipment and defer investments. If placed closely to a renewable energy source it can additionally support RE integration by RE capacity firming, RE ramp rate control, and RE time-shift.

4. Behind the Meter

ESSs installed at the consumer behind the meter can help to reduce the electricity bill by peak limiting and thus reducing demand charges, or by time-of-use shifting to shift the power draw from the grid to cheaper time periods. ESSs are also used to ensure electric service reliability and power quality for sensitive equipment, for example in data centers, hospitals or airports. In combination with renewable energy sources, behind the meter ESSs can increase the self-consumption of the generated energy or feed the energy into the grid at the economically best time.

C. Markets

When analyzing markets for energy storage it is important to understand that energy markets, and electricity markets in specific, have always been heavily regulated with regulatory rules historically grown according to traditional generation and transmission infrastructure. These regulatory rules often created artificial markets that made the profitability of projects strongly rely on the currently applicable legislation.

1. USA

In the US there exist several markets which are separated according to states and transmission zones. On a national level they are under supervision of the Federal Energy Regulatory Commission (FERC) while each state has its own Public Utilities Commission (PUC) regulating the energy market within its competences on a state level.

In order to understand the creation of new market rules it is important to recognize that the initial phase of rule development is a highly political process. For a new a law to be established or an existing law to be changed, a member of parliament or a political party needs to introduce a bill which has to be approved by committees, chambers, and the president or governor. The new law is then enforced by the FERC or PUC which give orders that are interpreted by the stakeholders that are affected.

The current energy storage market in the US is constantly growing, with growth rates of 40% in 2014 and an expected growth of 250% in 2015 according to GTM Research [3]. However, most of the growth takes place in two regional markets, namely PJM Interconnection and California, where 79% or 99 MW out of 115 MW of installations since 2013 have been deployed [3]. Reasons for this lie in the market rules for frequency regulation in PJM and mandates and utility tariffs in California which will be explained in more detail in the following sections.

2. PJM Interconnection (Eastern United States)

The PJM Interconnection, LLC (PJM = Pennsylvania - New Jersey - Maryland) is a regional transmission organization (RTO) in the eastern United States.

The energy storage market in PJM is mainly based on providing frequency regulation. PJM was the first RTO or ISO to implement FERC Order 755, which requires compensation for capability *and* performance of frequency regulation, into its market rules.

There are two signals for frequency regulation in PJM, a slow moving signal (RegA) derived from the low-pass filtered area control error (ACE) which is sent to traditional regulating resources like combined cycle or coal power plants, and a fast moving, dynamic signal (RegD) derived from the high-pass filtered ACE which is sent to dynamic resources such as energy storage or demand response resources. These two signals are differentiated by the ramp rate they request from the resource and by the mileage they travel as depicted in Figure 1. Mileage in this context is defined as the accumulated change of the signal within one hour and shows how much a resource ramps up and down per assigned MW. Its unit is ΔMW/MW.

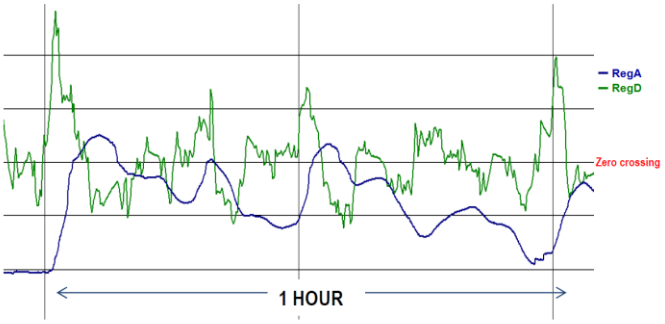

Figure 1 Frequency regulation signals RegA (blue) and RegD (green) in PJM [4]

Following FERC Order 755 which separates capability and performance of a resource, there is a two-part bidding and a two-part payment process. From the costs of the marginal resource, the regulation requirement (about 0.7% of expected peak load), and historical performance data a regulation market capability clearing price (RMCCP) and a regulation market performance clearing price (RMPCP) is calculated [5].

In 2014 the average RMCCP was about 39 $/MW and the average RMPCP 4$/MW with an average mileage ratio of 2.9 ΔMW/ΔMW [6].

Another important point to consider is the limited market size of the frequency regulation market which comprised an average of 663 MW in 2014 [7]. With increasing deployment of ESSs for frequency regulation the market size and also the compensation prices may decrease as provision of frequency regulation becomes more efficient.

3. California

In California most of the ESSs are deployed behind the meter at the end-consumer side of the grid. This is due to favorable electricity tariffs with large differences between peak and off-peak prices as well as subsidies by the state.

The Self-Generation Incentive Program (SGIP) subsidizes the installation of distributed generation resources which also includes energy storage. The current incentive for an ESS is 1.46 $/W [8].

Electricity tariffs for commercial and industrial customers in California usually consist of time-of-use energy charges and relatively high demand charges for the peak power drawn from the grid in a month. ESSs that are supported by the SGIP incentive and reduce demand charges by peak limiting offer an interesting value proposition. Additional savings can be earned by exploiting the TOU tariff by shifting consumption to the cheaper off-peak hours.

The energy storage market is projected to grow rapidly in the next few years due to state law from 2010, Assembly Bill 2514. Following this law CPUC developed a mandate which requires the three biggest utilities to procure 1325 MW of energy storage until 2020. In another order, CPUC requires time-of-use tariffs for retail customers to be implemented by 2019. Depending on the difference between peak and off-peak prices, these tariffs may open a new market for ESSs at residential customers [9].

California is also one of the most progressive states regarding renewable energy integration requiring that by 2020 at least 33 percent of its electricity will be generated by renewable energies. Despite the large amount of residential rooftop solar installations, this has not benefited ESS deployment since there is a net-metering policy in place leaving no financial incentive for energy storage. Besides California, net-metering exists in 43 other states of the US [10].

4. Germany

The energy storage market in Germany is mainly based on RE time-shifting for increased self-consumption of solar energy from residential rooftops. Until 2012 there had not been any financial incentive for storing excess energy from PV systems as the feed-in tariff had been higher than the retail prices for electricity [11]. In 2013 the feed-in tariff fell below the retail rates and is currently at about 0.12 €/kWh, while the retail price has been constantly growing to an average of 0.29 €/kWh today [12]. This price difference offers a value proposition for storing excess energy for later use.

The German government developed a market incentive program for decentralized energy storage for small PV systems (< 30 $\mathrm{kW_{PV}}$) to increase self-consumption and contribute to grid stabilization. The incentive program offers low-interest loans and a repayment bonus.

In order to be eligible for participation in the incentive program, the feed-in power must be limited to 60% of the PV peak power. This is to ensure that ESSs are installed in a beneficial way for the grid, reducing strain on grid equipment during peak generation.

Installing an ESS in combination with a PV system offers substantial savings to end-consumers. Additional returns for the ESS owner are offered by some storage suppliers who operate many behind-the-meter ESSs and aggregate them to a virtual power plant which participates in the wholesale market [13].

Except for storing solar energy for self-consumption, it is difficult to find a profitable business model for ESSs in Germany. There is the possibility to participate in the primary control reserve providing frequency regulation, but this is only cost effective for integrated utilities that are able to stack several services of the ESS to benefit from multiple revenue streams [14].

5. Australia

The Australian energy storage market is currently in a phase of uncertainty. Most of the ESS deployment in the past has been focused on smart grid research projects or off-grid applications.

The most promising market, however, is the residential rooftop solar sector. With increasing electricity retail prices and decreasing costs for solar PV, residential rooftop solar installations have become more and more common which in turn has caused fixed network costs to increase the average electricity price even further. With very low feed-in tariffs for solar energy at 0.06 AU$/kWh and peak period prices for households at 0.525 AU$/kWh energy storage offers an appealing value proposition. Households can reduce their electricity bill significantly by utilizing ESSs for RE time-shifting to increase self-consumption of their generated solar energy [15].

Unlike in Germany though, there is no incentive program for residential ESSs in place. In order to become a business case, the costs for ESSs must be low enough to be covered by the savings that potential operators can achieve. According to various analyses this is the case now in many regions of Australia or will be the case in the near future.

One point among others to be considered is the expiry of solar feed-in tariffs for 250 000 households in 2016 and another 400 000 households in 2020 [16]. There is a serious market for ESSs emerging in Australia which might take off fully once prices for ESSs in Australia approach those in the United States. Currently, costs of comparable ESSs are two to four times higher in Australia than in the US [17].

6. Japan

Japan's electricity market is currently undergoing big changes as it is facing impactful deregulation measures. Besides these changes Japan has quite a unique electrical system with two different frequency zones, consisting of many islands which are connected by transmission lines with limited capacity and a strong growth of renewable energy deployment, especially since the Fukushima nuclear accident in 2011 [18].

The energy storage market in Japan is just starting to grow, mainly due to large subsidy programs. In 2014 the Japanese government announced a program supporting homeowners and businesses willing to install lithium-ion batteries with a total of 10 billion yen (74 million €) [19]. Furthermore, there is an additional support package for ESSs announced in 2015 providing a total of 81 billion yen (600 million €) for ESS funding [20].

III. METRICS DEVELOPMENT

In order to assess the economic value of the benefits of energy storage in an application, appropriate metrics are necessary, which need to be selected according to the individual case. It is important to choose a metric that takes into account the value proposition of the respective ESS. Therefore, good knowledge of the service provided, of the market in which the ESS participates, and of the application in which the ESS is installed is required for the development process of metrics which has been designed here, as shown in Figure 2.

Once the service, the market, and the application are identified, a value proposition can be derived, which is either a market product, which can be traded and has a market price, or it is valued as a system support, supporting the operation of the system in which it is installed.

A. ESS Based Metrics

ESS based metrics measure the monetary value of the benefits generated directly by the ESS. The services that the ESS provides can be translated directly into one or several market products which can be traded on the wholesale market and are priced according to the market.

ESS based metrics can be divided into power based and energy based metrics, depending on the discharge duration necessary for the respective service or market product.

Energy based metrics can be used, e.g. to measure the benefits generated by participation in the wholesale energy market by providing large scale time shifting. The benefits are derived from the difference of the energy price, thus the unit is [\$/kWh].

Power based metrics may measure the benefit gained from availability or the benefit gained from performance and actual operation. Availability describes the offer of keeping a certain amount of power capacity at stand-by for a period of time during which it can be called upon and is valued by [\$/kW/h]. The benefit gained from performance and actual operation is generated by charging and discharging with the required power at the requested time and measured in [\$/ΔkW/h].

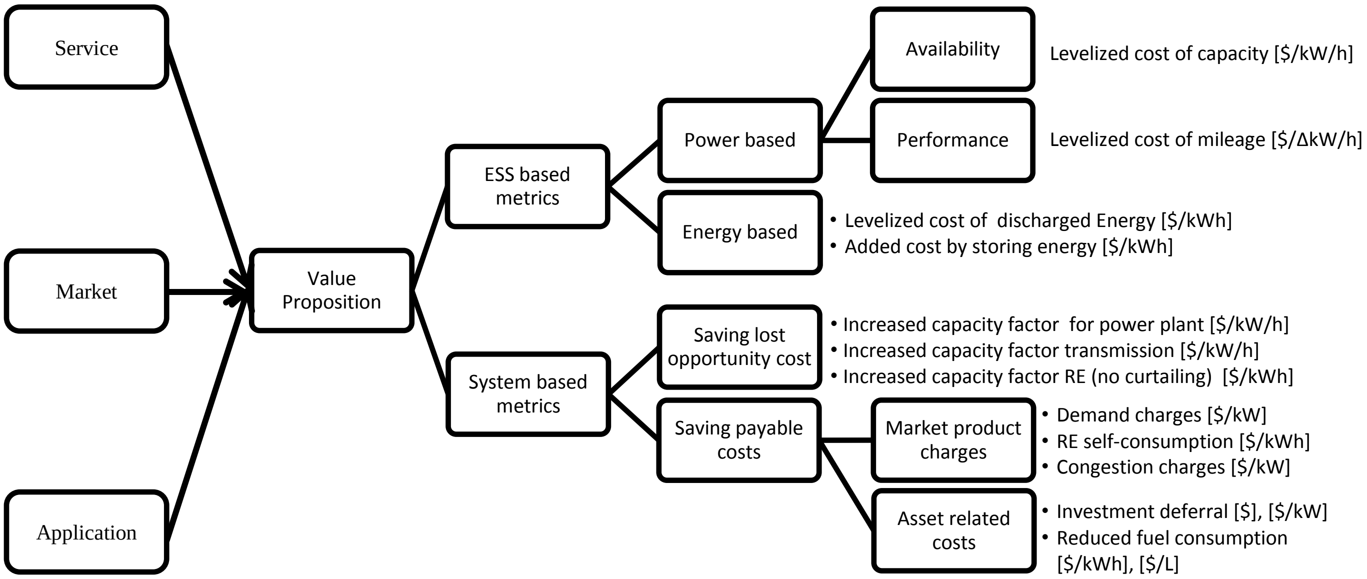

Figure 2 Metrics development process with the input parameters service, market and application

B. System Based Metrics

If the value proposition of the ESS is regarded as system support, i.e. the ESS supports the operation of the system in which it is installed, system based metrics can be applied.

System based metrics refer to the added value to the system regardless of the system size. The revenue stream described by system based metrics results from saved costs, which are either payable costs or lost opportunity costs.

Payable costs can be market product charges or asset related costs. Market product charges are costs that usually accrue on the consumer side, e.g. the costs that appear on the electricity bill like demand charges [$/kW], energy charges [$/kWh] or VAR charges for reactive power [$/kVAr].

Asset related costs are derived from investments in permanent or consumable elements of the system. Investments in permanent elements such as T&D infrastructure can be deferred or avoided using an ESS and can be measured in [$] or [$/kW]. Consumable elements of the system include fuel such as gas, diesel, or coal. Fuel costs can be reduced by a steadier operation of a power plant or avoiding operation at all and can be measured in [$/kWh] or [$/L].

Lost opportunity costs accrue when an element of the system is not allowed to generate the value that it would be capable of generating in optimal conditions. This is usually related to a reduced capacity factor of the element.

An ESS can increase the capacity factor of equipment like power plants, RE sources, and transmission and distribution facilities by providing several services. The benefits from an increased capacity factor and the reduced lost opportunity costs can be measured using the metric of the respective product value, usually either [$/kW/h] or [$/kWh].

IV. METHODOLOGY

A generic methodology for defining clear deployment cases of ESS as well as for analyzing these cases regarding costs and benefits, and their sensitivity to certain parameters is developed. The modeled ESS consists of a power conversion system (PCS) and a storage section and is illustrated in Figure 3.. Both sections have inherent efficiencies which are taken into account in the overall system efficiency η_{Sys}.

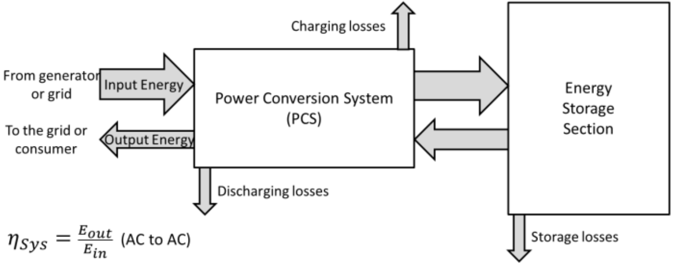

Figure 3 Main section of ESS and energy losses [21]

A. Case Definition

The process of developing a clear deployment case for an ESS in terms of market, application, services, and metrics is divided into four steps which are shown in Figure 4.

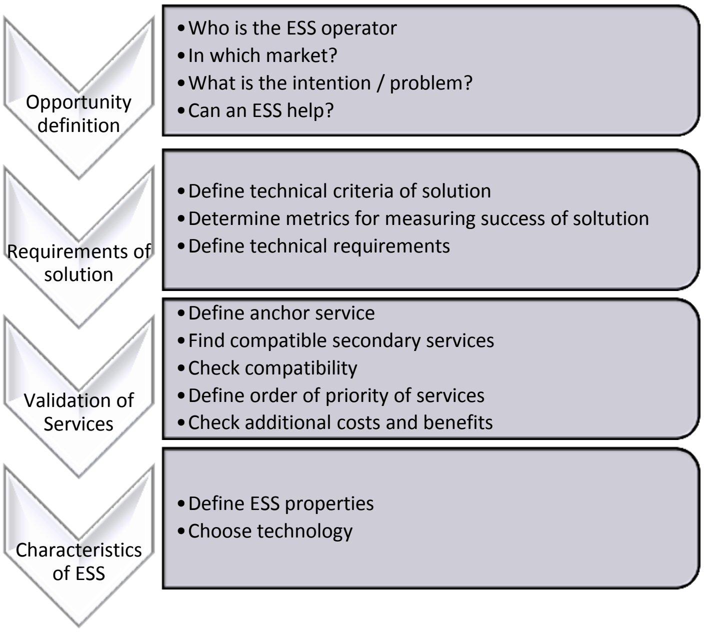

Figure 4 Process of developing an ESS deployment case (adapted from [22])

B. Cost-Benefit Analysis

As the CBA in this thesis is performed from the ESS operator's and owner's point of view, only the monetary effects of investment and operating costs, as well as the benefits generated by the ESS and the system in its immediate surrounding are considered.

After the deployment case for the ESS has been clearly defined, the CBA can be carried out following the steps presented in Figure 5.

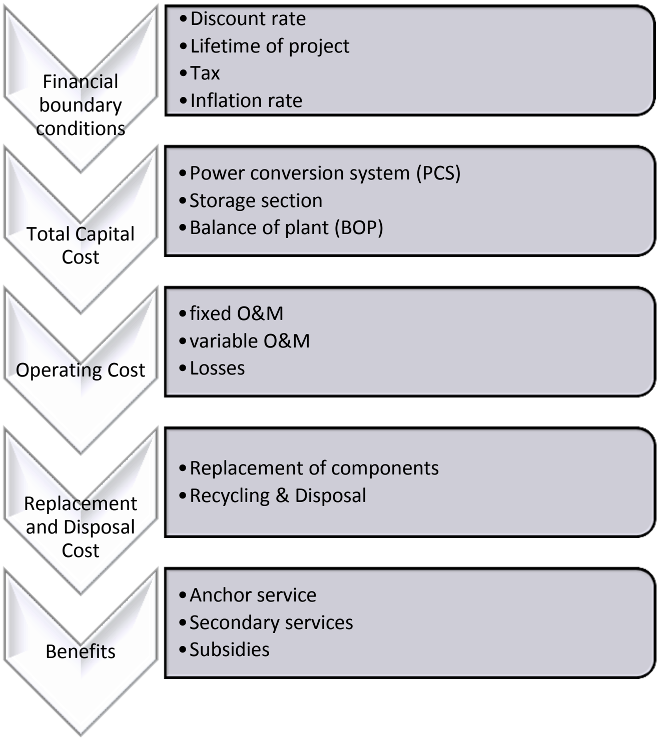

Figure 5 Calculation flow for Cost-Benefit Analysis

C. Sensitivity Analysis

While the cost-benefit analysis is a good tool to measure the profitability of a project, it is limited to one specific deployment case. In order to take uncertainties into account and to test the dependencies of the deployment case on certain input parameters, a sensitivity analysis must be performed.
The selection of sensitivity parameters depends on the deployment case, especially regarding the generation of benefits.

V. Results and Discussion

Two deployment cases have been defined and analyzed in cost-benefit analysis and a sensitivity analysis: frequency regulation in PJM and peak limiting in California. The results of the sensitivity analyses are presented and discussed in the following sections.

A. Frequency Regulation in PJM

The anchor service in this deployment case is frequency regulation. Only few secondary services can be provided in combination together with frequency regulation, which requires sophisticated control software. Large scale time-shifting has been chosen as secondary service, which requires only two short term interruptions of frequency regulation per day. Because the services are provided separately from each other there is no problem regarding compatibility, while frequency regulation has the highest priority. Added costs may accrue if the energy capacity is increased for large scale time-shifting. This is analyzed in the sensitivity analysis as well as the question whether or not there are additional benefits from providing large scale time-shifting while stopping frequency regulation. The input values for this case are shown in Table 2.

Table 2 Input values: Deployment case 1 - Frequency regulation

Input parameter	Value	Unit
Power capacity	32	MW
Energy capacity	8	MWh
Yearly equivalent full cycles	330	-
System efficiency	90.25	%
Discount rate	10	%
Weighted average cost of capital	8	%
Inflation rate	2	%
Tax rate	42	%
Project lifetime	20	years
PCS lifetime	10	years
Storage section lifetime	10	years
PCS cost	150	$/kW
Storage section costs	300	$/kWh
BOP cost	85	$/kW
Fixed O&M cost	7.5	$/kW
Variable O&M Cost	2.3	$/kWh
Disposal & Recycling cost (PCS)	5.5	$/kW
Disposal & Recycling cost (storage section)	5.5	$/kWh

The benefits in this case result from the regulation market clearing price (RMCP) credits and from participation in the wholesale market. The metrics of the benefits are levelized cost of capacity [$/kW] and levelized cost of mileage [$/ΔkW] for frequency regulation and added value by storing energy [$/kWh] for large scale time-shifting. These metrics are converted into pure monetary terms [$] during the calculation.

In each sensitivity case only the respective parameters are varied while all other input parameters are kept constant. The graphs are marked with a yellow star to indicate the base case scenario.

1. Available Energy Capacity for time-shifting

The available energy capacity for time-shifting is the portion of the overall energy capacity that generates benefits from participation in the wholesale market. This energy capacity has been varied between 0-55% of the overall energy capacity. The development of the NPV for the varying available energy capacity for time-shifting is shown in the graph in Figure 6.

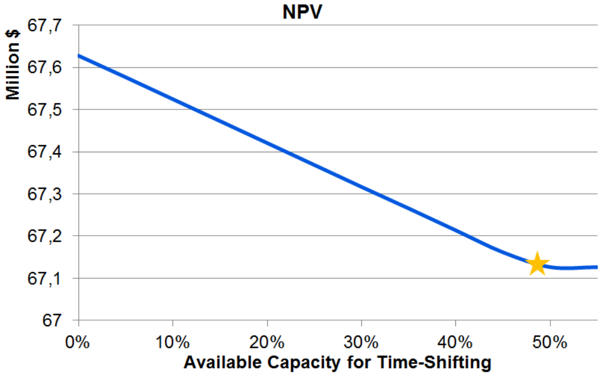

Figure 6 NPV in dependence on the available energy capacity for time-shifting

The decreasing NPV indicates that the profitability decreases with increasing available energy capacity for time-shifting until a certain point. This means, that the more energy is traded at the wholesale market, the less profit is generated, even though the differences are not very large. This seems remarkable since the ESS is expected to produce additional benefits by providing a secondary service. However, the important point to consider here is that the ESS requires time for charging and discharging during which it cannot provide frequency regulation. Therefore, it loses the opportunity to generate benefits from frequency regulation during this time. These lost opportunity costs are larger than the additional benefits gained from large scale time-shifting and they grow with the time that the ESS is not able to provide frequency regulation, which is proportional to the available energy capacity for time-shifting.
The available energy capacity for time-shifting above which the profitability stays constant is 48.4%, which is the maximum energy capacity that still allows the ESS to operate within the limits required for frequency regulation.

2. Regulation Market Clearing Prices (RMCPs)

The provision of frequency regulation is the main source of benefits for the ESS. These benefits are calculated from the RMCCP and the RMPCP, thus their values have a major influence on the profitability of the ESS which is tested by varying them between 10-150% of their original values. The mean of the original RMCCP is 39.63 $/MW and the mean of the original RMPCP is 4.07 $/MW. The dependency of the profitability on the RMCPs is shown by the NPV in Figure 7.

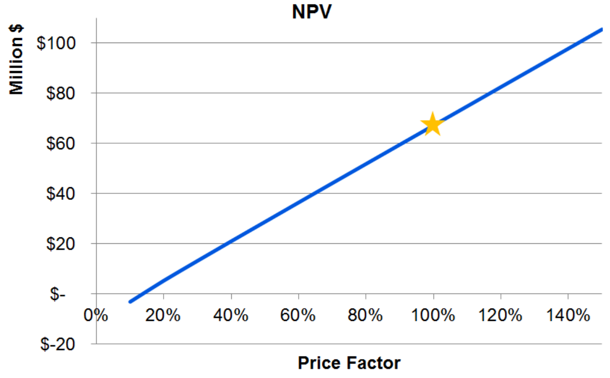

Figure 7 NPV in dependence on the RMCP

It is obvious that the profitability increases with increasing price factor, i.e. the factor that the RMCPs have been multiplied by. The zero-crossing of the NPV represents the price factor that makes the project profitable and is found to be 13.7%. The equivalent mean values of the RMCCP and the RMPCP are 5.44 $/MW and 0.56 $/MW respectively.

Below certain RMCPs, participation in the wholesale market by large scale time-shifting becomes more valuable than providing frequency regulation during the time of charging and discharging. This has been analyzed by comparing the profitability metrics of the base case, which provides the maximum possible amount of large scale time shifting, with a case without any large scale time-shifting. The graph in Figure 8 shows the difference in NPV (ΔNPV) of the two cases as shown in the following equation.

$$\Delta NPV = NPV_{with\,TS} - NPV_{without\,TS}$$

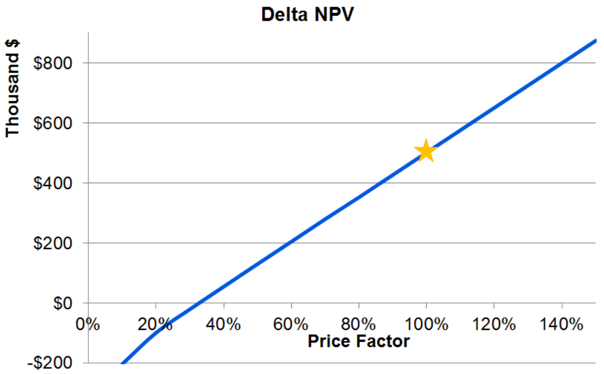

Figure 8 Difference of NPVs without and with time-shifting in dependence on the RMCP

In this case the zero-crossing of the ΔNPV represents the price factor, below which participation in the wholesale market is more profitable than providing frequency regulation during the time of charging and discharging. By linear interpolation this point is found to be 32.8% of the original RMCPs. The equivalent mean values of the RMCCP and the RMPCP are 12.99 $/MW and 1.33 $/MW respectively.

B. Peak Limiting in California

This deployment case addresses behind-the-meter ESSs at a commercial or industrial (C&I) site providing peak limiting for demand charge reduction. The load data of an original site has been used.

As the intention is to reduce demand charges, the anchor service has been defined to be peak limiting with active power injection in the order of 25% of the monthly peak load for the time of the respective peak. TOU shifting has been considered as a secondary service, but is only performed for the energy that needs to be charged or discharged for peak limiting. That means that, if possible, the ESS charges during off-peak hours and not during peak hours.

In California, energy storage is subsidized by the state. For this case the subsidies are assumed to be 1000 $/kW of power capacity which is less than the actual subsidies of 1460 $/kW. Here, these subsidies are subject to the following two conditions: they are only applicable to the minimal, required power capacity and they may not exceed 75% of the total capital cost. However, they may also be applied to possible replacements at the end of the component lifetime.

Table 3 Input values: Deployment case 2 - Peak Limiting in California

Input parameter	Value	Unit
Power capacity	100	kW
Energy capacity	270	kWh
Yearly equivalent full cycles	406	-
System efficiency η_{Sys}	90	%
Discount rate	10	%
Inflation rate	2	%
Subsidies	1000	$/kW
Demand charge summer	25	$/kW
Demand charge winter	13	$/kW
Project lifetime	20	years
PCS lifetime	10	years
Storage section lifetime	10	years
PCS cost	150	$/kW
Storage section costs	300	$/kWh
Balance of plant cost	85	$/kW
Fixed O&M cost	7.5	$/kW
Variable O&M Cost	2.3	$/kWh
Disposal & Recycling cost (PCS)	5.5	$/kW
Disposal & Recycling cost (storage section)	5.5	$/kWh

The benefits result from savings on the electricity bill and thus depend on the electricity tariff and can be measured in [$/kW] and [$/kWh].

1. Reduction of Peak Load

The dependence of the profitability on the reduction of the peak load has been examined by varying the reduction of the peak load between 5-50% of the monthly peak value. It is shown by the NPV in Figure 9.

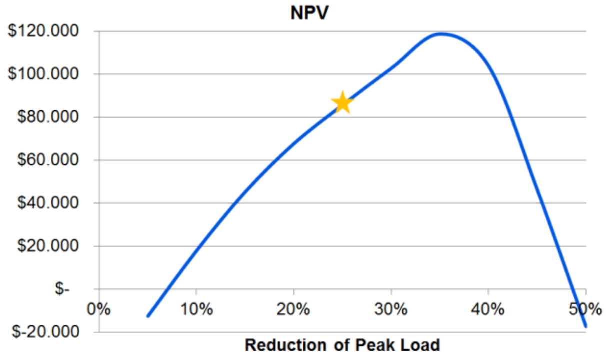

Figure 9 NPV in dependence on peak load reduction

The NPV illustrates that there is a maximum of profitability at 35% reduction of the peak load. Thus, the assumed base case with 25% reduction of peak load is not the most profitable. The project becomes unprofitable for peak load reduction of less than 7.1% and more than 48.6% of the monthly peak load. The maximum of the profitability exists, because savings on the electricity bill increase with increasing reduction of the peak load, however, with increasing reduction of peak load the required power and energy capacity of the ESS increases, which leads to higher initial costs, and thus to a lower NPV.

2. Subsidies

Subsidies reduce the initial investment costs and the replacement costs and thus influence the overall profitability of the project. The subsidies have been varied between 0-1600 $/kW to assess this influence. This is shown by the NPV in Figure 10.

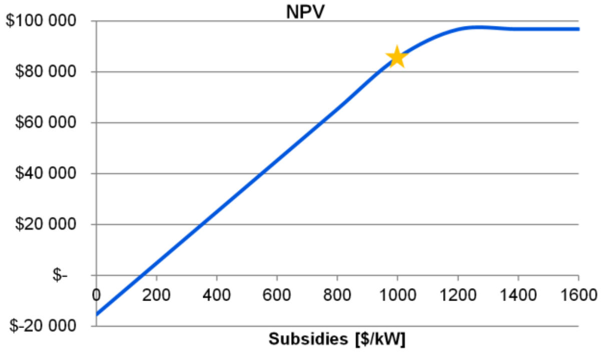

Figure 10 NPV in dependence on the subsidies

The NPV shows that the profitability increases with increasing subsidies until the subsidies reach the limit of 75% of the investment cost at 1075 $/kW. The project becomes unprofitable if the subsidies fall below 152 $/kW.

These results show that the current subsidies in California at 1460 $/kW are at a level that is much higher than needed for many projects to operate profitably. Although there is still a need for subsidies in many cases for a profitable deployment of ESS for peak limiting, this need is decreasing with further technological development and further price reduction of the components of ESSs, especially of batteries. Therefore current and future subsidies, not only in California, but in any market, should take into account the ongoing development of technology and prices. Thus, they should be adapted to a minimum level that is required in order to ensure fair support of a technology.

VI. CONCLUSION

It has been shown that ESSs can be deployed profitably in certain applications, such as providing frequency regulation in the PJM market in the US or reducing the electricity bill for C&I customers, by limiting their peak, load in California. The cost-benefit and sensitivity analysis of these two applications demonstrated that ESS deployment can be profitable even with less beneficial market structures.

Energy storage can be a cost effective solution in many applications already today. Additional benefits may be generated by ESSs by offering secondary services, which create new revenue streams.

Further decreasing prices, especially for batteries as observed in recent years, will result in an increase of the profitability of existing applications of ESSs and open up new opportunities for other services and applications.

With the analysis of present and possible future markets for ESSs it has become obvious that current market rules and regulations across markets are not consistent and have a strong influence on whether or not ESS deployment is economically feasible. The case of PJM in the US shows that if regulating orders, which are applicable for the whole US, are transferred into market rules considering energy storage, ESSs are able to participate competitively in the open market and improve the overall system stability.

It can further be concluded that markets and market rules around the world are changing in favor of energy storage. However, since electricity markets are highly regulated and rule making is a very political process, changes are happening slowly and require a change of mindset of policy makers. ESSs can provide several valuable services, which are not recognized and compensated in the current market. Also, current market structures are often not clear about how to treat energy storage, as a load or as a generation resource.

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