UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
CORSO DI LAUREA MAGISTRALE IN INGEGNERIA ENERGETICA

ECONOMIC AND TECHNICAL STUDY OF INTEGRATION FOR AN ENERGY STORAGE SYSTEM WITH PHOTOVOLTAIC PLANT AS A POWER CURTAILMENT SOLUTION

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ANNO ACCADEMICO 2017-2018

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List of Abbreviations

AC	Alternative Current
ANM	Active Network Management
BESS	Battery Energy Storage Systems
$\mathrm{Benefit}_{\mathrm{PVCt}}$	Economic Benefit of PV Energy Time shift
$\mathrm{Benefit}_{\mathrm{T\&D}}$	Economic Benefit Transformer Upgrading Evidence
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CE	Columbic efficiency
CF	Capacity Factor
CF_k	Cash Flow of year K
DC	Direct Current
DG	Distributed Generation
DLC	Double Layer Capacitor
DOD	Debt of Discharge [%]
DSOs	Distribution System Operators
EDLC	Electric Double-Layer Capacitors
EES	Electrical Energy Storage
EPC	Engineering, Procurement, and Construction
ESS	Energy Storage System
FES	Flywheel Energy Storage
FIT	Feed in Tariff
HBF	Hybrid Flow Battery
HE	High Energy
HP	High Power
HVRT	High Voltage Ride-through

IEC	International Electro Technical Commission
LA	Lithium Acid battery
LCOE	Levelized Cost of Energy [ϵ/ kWh]
LCOES	Levelized Cost of Energy Storage [ϵ/ kWh]
LCOS	Levelized Cost of Storage [ϵ/ kWh]
LIFO	Last In First Off
LVOES	Levelized Value of Energy Storage [ϵ/ kWh]
LVRT	Low Voltage Ride-Through
Me-air	Metal air battery
MPPT	Maximum Power Point Tracking
NaNiCl	Sodium Nickel Chloride battery
NaS	Sodium Sulfur battery
NFG	Non-Firm Generator unit
NiCd	Nickel–Cadmium battery
NiMH	A nickel–metal hydride battery
NPV	Net Present Value
OCV	Open Circuit Voltage
PHS	Pump Hydro System
POI	Point of Interconnection
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
SOC	State of the Charge [%]
SOC_i	Stat of charge of the i-th battery.
T&D	Transmission and Distribution of Electricity
TSOs	Transmission System Operators
RPC	Reactive Power Control
VG	Variable Generation
VRG	Various Renewable Energy

V-redox	vanadium redox battery
UPS	Uninterruptible Power Supply
Zn-air	Zinc–air battery

List of symbols

$\mathrm{C_{bat}}$	capacity of the battery
$\mathrm{C_E}$	Cost of the energy capacity [unit cost per MWh]
$\mathrm{C_s}$	Cost of apparent power rating [unit cost per MVA]
d	Degradation Rate of Solar Panel [%]
E_{curt}	Total curtailed energy
$\mathrm{E_p}$	Generation profile defined
$\mathrm{E_t}$	Energy Generate in a given year t
F_t	Interest Rate of Expenditure
H_2	Hydrogen
k	Number of profile
M_t	Cost of Maintenance at year t
O_t	Cost of Operation at year t
$\mathrm{P_{LV}}$	Demand profile
P_n	Total active power of the controllable DG plants,
p_n^+	Maximum value of power, restricted by the available resource,
PG	Power flow to the transformers
PV_{ts}	Energy time-shift
Q_{i-max}	Maximum Capacity of the battery
r	Interest rate [%]
V	Rated Battery Voltage
ϵ	Price Scaling Factor
η_{st}^{dis}	Discharging Efficiency
η_{st}^{char}	Charging Efficiency
η	Total Efficiency
$\lambda_{\mathrm{cur}}^{actual}$	Actual curtailment level
$\lambda_{\mathrm{cur}}^{desired}$	Desired curtailment level

π_{export}	Retail Price Supply by Utility
π_{import}	Price of Purchasing Electricity During Energy Import
$\bar{\pi}_t$	Average Price in 24 hours

Abstract

A challenge of high penetration of renewable energy is periods when system demand is low and there is too much electricity generation. When this occurs, it can be necessary to turn down or curtail energy. Curtailing renewables can help to relieve over-generation and potentially provide ancillary service. The integration of Electrical Energy Storage and solar plant systems can fulfill the required storage for the curtailed energy of the power plant to reduce energy wastage. Besides, it is expected to solve problems such as peak shaving, power fluctuation, ramping control and power supply.

This thesis presents a review and classification of existing EESs and their application, furthermore it provides a planning framework of techno-economic aspect of EES integration during curtailment of photovoltaic power plants and the way in which renewable energy might move towards EES integration. It is necessary to determine principles of curtailment and grid constrain. The capacity required to meet curtailment and system flexibility and its impact on VRE deployment are presented. Furthermore, different case studies are discussed in detail.

Introduction

With the rising price of the electricity and the decreasing FIT, EES is becoming more important. Although lots of scenarios have been applied in the EES system integrated with renewable energy, there is no standardized assessment of EES. Different types of EES can be integrated by renewable energy in terms of various application of EES.

The study evaluates techno-economic aspects of storing energy during curtailment of photovoltaic power plants. The purpose of the thesis is to provide insight into the consequences of saving energy in different scenarios from end-users or the main grid, single dwelling or substation. This master thesis is structured as follows.

The first chapter introduces the concepts of electrical energy storage and its main role in renewable energy systems. EES applications and technologies are presented in the second chapter. Battery and its standardization is provided in second chapter. The required data for techno-economic study of electrical energy system operation is discussed in chapter three. Marketing price and indicators to address economic benefit of EES systems and its effect on charging and discharge of energy storage are widely explained. Chapter four addresses case study of PV plants which are integrated with energy storage system, the data and conclusion of each study is summarized to evaluate EES role during curtailment. Different scenarios are presented to compare EES technology versus PV curtailment from a cost and value perspective. The case studies analyzed EES integration from a techno-economic perspective, during curtailment. Furthermore, PV curtailment and the restriction of the grid or load demand, duration storage and load patterns at the presence of EES integration in compared to the case without storage are discussed widely.

1 Chapter 1: Electrical Energy storage

In this chapter a main concept of the Electrical Energy Storage (EES) is introduced. Electrical energy storage is one of the technologies in the areas covered by IEC which makes it possible to manage and optimize energy.

In order to solve global environmental problems, renewable energies such as solar and wind will be widely used and this means the future of energy supply will be influenced by fluctuating renewable energy sources and electricity production will follow weather condition and the surplus and deficit in energy need to be balanced [1]. Any deficit must be compensated to satisfy the grid requirement and the energy demand. These compensations could be achieved by fossil sources. But fossils are not the only way to compensate the deficit. Improvement of energy storage system can lead to use less fossil. Also, any surplus power may be thrown away when it is not needed on the demand side. Therefore, valuable energy can be effectively used by storing surplus electricity in EES. Besides, due to the fast growing of renewable energy, marketing of renewable energy is becoming more and more important, that means a forecast of the variation of the supply and demand of the energy will be required.

1.1 Role of EES

Historically, EES has played three main roles in renewable energy field which are briefly explained in following sections.

1.1.1 EES and Electricity Load

Long distance between generation and consumption of the energy can cause the instability in power supply of the grid which must be balanced. The forecast of the demand variation and balance it with the storage energy can help to guarantee stability of the grid. According to [1] EES system can be used in order to improve the reliability and the quality of the power supply, frequency and voltage. EES systems can support also when power network failures occur due to natural disasters. Advances to the electric grid must maintain a robust and resilient electricity delivery system, and energy storage can play a significant role in meeting these challenges by improving the operating capabilities of the grid, lowering cost and ensuring high reliability, as well as deferring and reducing infrastructure investments.

Finally, energy storage can be instrumental for emergency preparedness because of its ability to provide backup power as well as grid stabilization services [2].

1.1.2 EES and Marketing

Power demand and price for the electricity vary time to time, the marketing of renewable energy is highly influenced by the demand of energy. A surplus of electricity can be stored with low off-peak prices and sold in peak hours or can be saved for the self-consumption in the absence of daylight in large scale power plants.

EES reduces electricity obtained at off-peak times when its price is lower. The utility company is presented with a uniform demand or as minimizing consumption costs by storing energy during off-peak time periods when prices are lower and use the stored energy during peak time periods when prices are higher [1]. In large scale solar system, electrical energy storage can be used to save energy where there is a curtailment on the grid connection point, this energy can be used later or can be sold back to the grid.

1.1.3 EES and Environment

Electrical power generation is changing dramatically across the world because of the need to reduce greenhouse gas emissions and to introduce mixed energy sources. The power network faces great challenges in transmission and distribution to meet demand with unpredictable daily and seasonal variations. Electrical Energy Storage (EES) is recognized as underpinning technology to have great potential in meeting these challenges, whereby energy is stored in a certain state, according to the technology used, and is converted to electrical energy when needed [3].In the near future energy storage will become indispensable in emerging IEC- relevant markets in the use of more renewable energy, to achieve CO_2 reduction and for Smart Grids[1]. The battery itself runs clean and stays reasonably cool. Most sealed cells have no vents, run quietly and do not vibrate. This is in sharp contrast with the ICE and large fuel cells that require compressors and cooling fans [4].

1.2 EES Systems and Classification

Electrical energy cannot be stored directly, but it can be stored in other forms and then converted back to electricity when it is needed [5].

EES systems can be divided into five main groups, electrical, thermal, chemical, electrochemical and mechanical. The different EESs are mentioned below. The characteristic of the EES have already been widely attempted in other researches and it is not the purpose here. According to [6] different types of EES are listed in the Table 1.1.

Table 1-1 Types of energy storage system

Mechanical	
PHS	Pump Hydro Systems
FES	Flywheel Energy Storage
CAES	ComprEESed Air Energy Storage
Electrical	
LA	Lithium Acid battery
Nicd, NiMH	Nickel Cadmium
Li _ion	Lithium ion
Me_air	Metal Air battery
NaS	Sodium Sulphur battery
NaNiCl	Sodium Nickel Chloride battery
	Flow battery
HFB	Hybrid Flow Battery
Chemical	
H2	Hydrogen
SNG	Synthetic Natural Gas
Electrochimical	
DLC	Double Layer Capacitors
SMES	Superconducting Magnetic Energy Storage

There is different classifications for the EES system. The most important characteristics of EES technologies are presented in Table 1.2 and Table 1.3 Several factors must be considered in order to EES integration. The selection of the most preferable technology for a specific application depends on the size of the system, the specific service, the electricity sources and the marginal cost of peak electricity [7]. Various inputs are listed in the following tables.

Table 1-2 Characteristics of EES Technologies, Part 1 [6]

		PHS	CAES	Hydrogen	Flywheels	SMES	EDLC	Pb-acid
Power Rating	MW	100-5000	100-300	<50	<20	0.01-10	0.001-10	100-10^5
Energy rating	kWh	2×10^5-5×10^5	2×10^5-10^5	>10^4	10-5000	0.1-100	0.001-10	100-10^5
Specific power	W/kg	Not appl.	Not appl.	>500	400-1600	500-2000	0.1-10	75-300
Specific energy	wh/kg	0.5-1.5	30-60	33.33	5-130	0.5-5	0.1-15	30-50
Round Trip Efficiency	%	75-85	<55	24-49	85-95	>95	85-98	80-90
Critical voltage	V	Not appl.	Not appl.	Not appl.	Not appl.	Not appl.	0.5	1.75
Discharge time		h-days	h-days	s-days	15s-15min	ms-5min	ms-1h	s-3h
Response time		s-min	1-15min	ms-min	ms-s	ms	ms	ms
Lifetime	years	50-100	25-40	5-15	>20	>20	>20	3_15
Lifetime	cycles	>50000	No limit	>1000	10^5-10^6	10000	>500000	2000
Operating temp.	°C	Ambient	Ambient	80 to 100	-20to 40	-27 to-140	-40 to85	25
Self-discharge	%/day	0	0	0.5-2	20-100	15	2-40	0.1-0.3
Recharge time		min-h	min-h	Instant	<15min	min	s-min	8h-16h

Table 1-3 Characteristics of EES Technologies, Part 2[6]

		NiMH	Li-ion	NaS	NaNiCl	V-Redex	ZnBr	Zn_air	NiCd
Power Rating	MW	0.000001_0.2	0.1-5	0.5-50	<1	0.03-7	0.05-2	several	<40
Energy rating	kWh	0.01-500	0.01-10^5	6000-6×10^5	120-5000	10-10^4	50-4000	1000	0.01-1500
Specific power	W/kg	700-756	230-340	90-230	130-160	N/A	50-150	1350	150-300
Specific energy	Wh/kg	60-120	100-250	150-240	125	75	60-80	400	45-80
Round trip efficiency	%	70-75	90-98	85-90	90	75	70-75	60	70-75
Critical voltage	V	1	3	1.75-1.9	1.8-2.5	0.7-0.8	0.17-0.3	0.9	1
Discharge time		h	min-h	s-h	min-h	s-10h	s-10h	6h	s-h
Response time		ms	ms-s	ms	ms	<1 ms	<ms	ms	ms
Lifetime	years	5_10	8_15	12_20	12_20	10_20	5_10	30	15_20
Lifetime	cycles	300-500	>4000	2000-4500	1000-2500	>13000	>2000	>10000	1500
Operating temp.	°C	-20 to45	-10 to45	300	270 to 350	0 to 40	20 to 50	0 to 50	-40 to45
Self-discharge		0.4-1.2	0.1-0.3	20	15	0_10	0-1	N/A	0.2-0.6
Recharge time		2h-4h	min-h	9h	6h-8h	min	3h-4h	N/A	1h

1.3 Energy versus power and discharge time

EES technologies can be separated into two categories "high power and "high energy" storage systems. Electrochemical EES systems can be used either in high power (HP) or high energy (HE) applications [6].

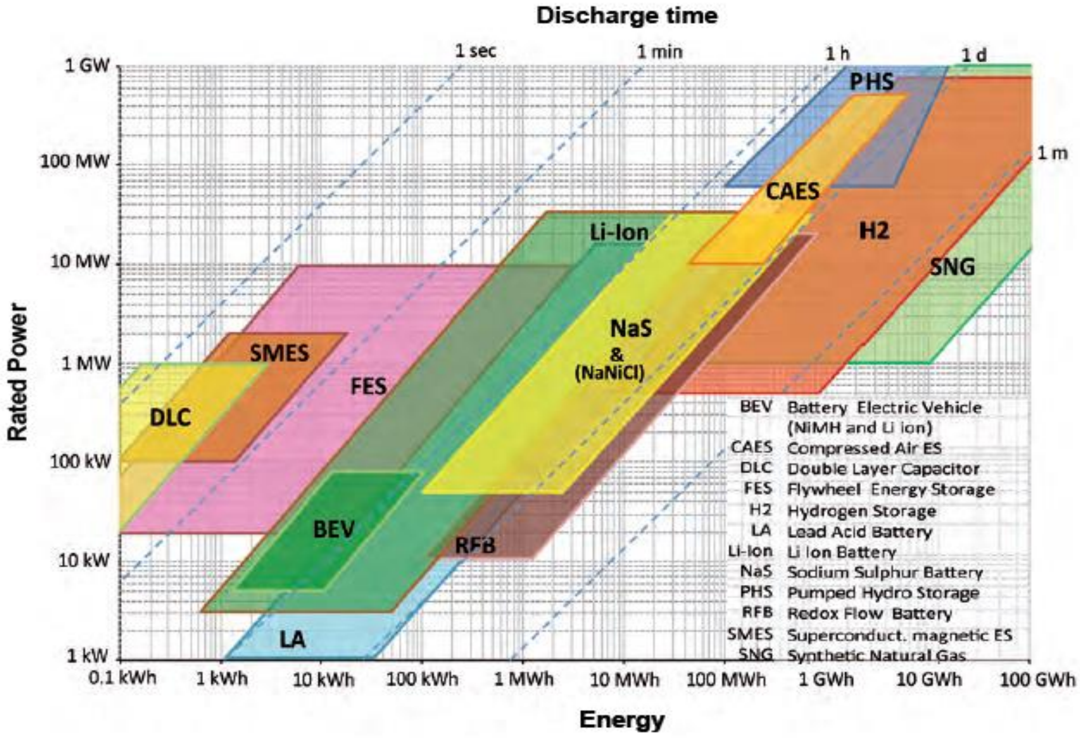


Figure 1-1 Rated power, energy content and discharge time of EES technologies

The rated power is plotted against energy of EES systems. Highly compact EES technologies can be found at top right. Large volume and volume consuming storage system are located at the bottom left [8].

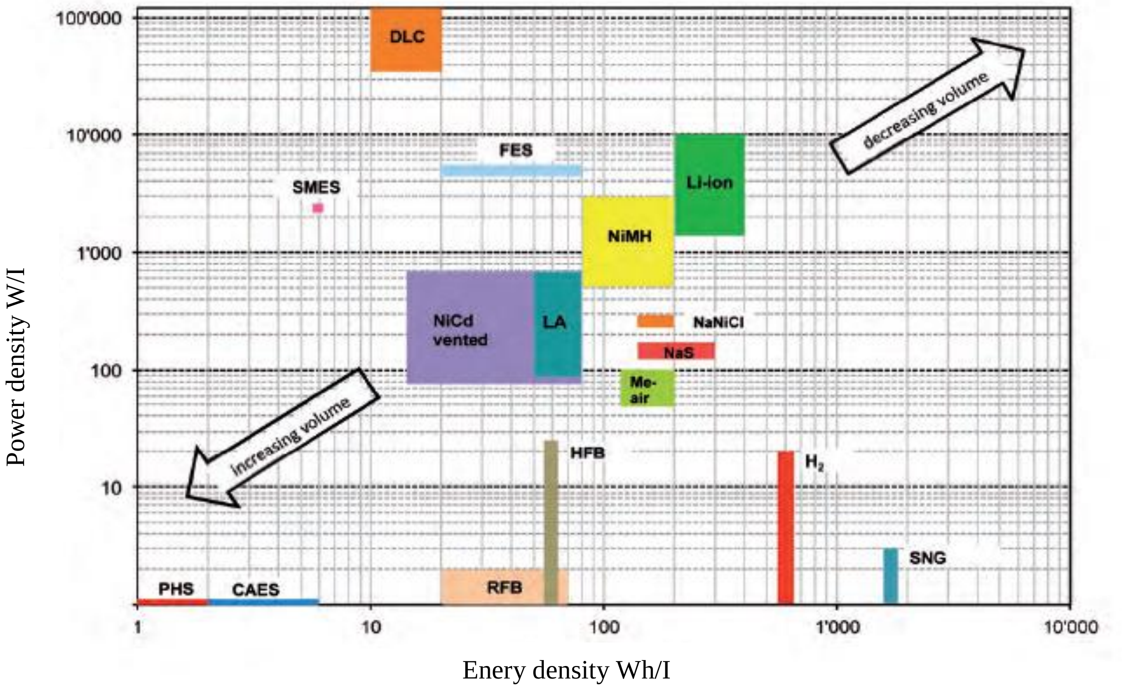


Figure 1-2 Power Density against Energy Density of Different Energy Storage Systems

Energy density, power density and discharge time are important factors to choose different EES in order to storage energy according various uses. For primary control choosing an EES with quick time respond and high-power density is necessary. While when it is necessary to prolong discharge period the EES with higher discharge time is required. The main outcome of the table above includes the most important characteristics of EES technologies. PHS, CAES and flow batteries have a low energy density and volume consuming energy storage. On the contrary Li-ion has both high energy density and high-power density. Zinc-air has higher energy density in compare to Li-ion but less power density. PHES and CAES have high energy rating and power rating as well. Flow batteries have high financial potential [8].

1.4 The state of Art

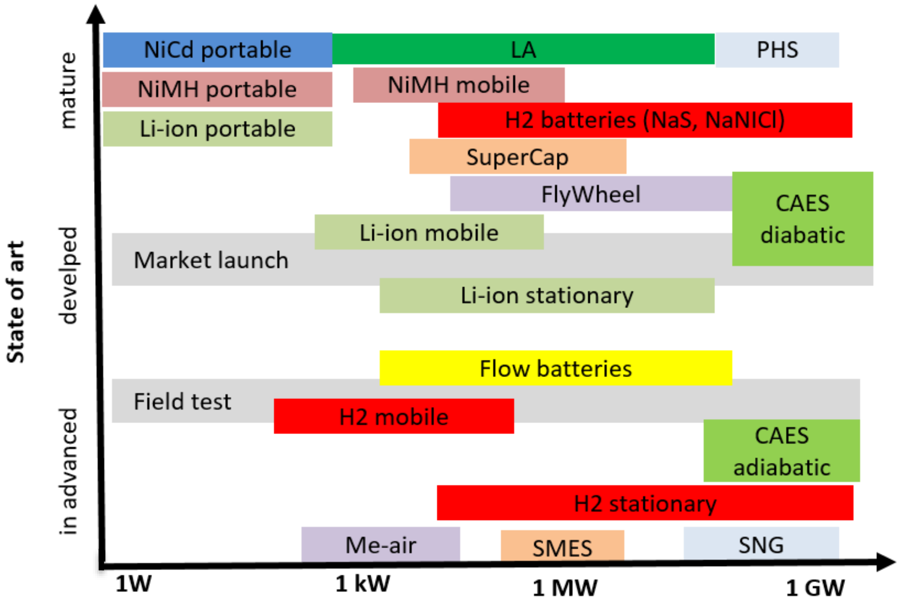


Figure 1-3 The state of art of Different Energy Storage Technologies

According to [9] not all the technologies are enough mature yet. The electrochemical battery has the advantage over other energy storage devices that the energy stays high during most of the charge and then drops rapidly as the charge depletes.

1.5 Hybrid Storage

Each storage system has its own pros and cons. Different necessities and requirement of the solar plant can lead us to choose hybrid storage system. Hybrid storage systems are expected to provide increased operational safety, greater efficiencies, improved life time and reduced costs, so the use of multifunctional hybrid EES is considered to be a favorable option in the future [6].

For large scale-solar technologies lithium–ion, sodium sulfur, lead acid, fly wheels and flow batteries, hydrogen storage, synthetic natural gas, pumped hydro storage due to the high rated energy and power are all viable candidate.

1.6 Application of EES

EES integration with renewable energy make the grid more dynamic and reliable on the supply-side. According to [10] both photovoltaic and energy storage systems will play a major role in the future system. As we mentioned in previous section the EES can be used widely for different applications. In the following section each application is briefly discussed.

1.6.1 Frequency and Voltage Regulation

A Basic service must be provided by power utilities to keep supply power voltage and frequency within tolerance. Frequency is controlled by adjusting the output of power generators [1].

EES can provide frequency control functions by charging and discharging in response to an increase or decrease, respectively of grid frequency. According to [11]the advantage of supplying reserve power by means of storage is that BEES allows more accurate active power response to frequency perturbation. This approach to frequency regulation is a particularly attractive option due to its rapid response time and emission-free operation [12].

1.6.2 EES and Ramp control

Sunny days produce a smooth arc of power production that peaks at midday. In this case power production changes relatively slowly and within utility power ramp rate specification. On cloudy days, power production is not smooth and can change rapidly, so that power ramp rates exceed utility specifications [13].Rapid fluctuations in the active power output of a PV plant caused by traveling, opaque and compact clouds can generate fluctuations of the grid voltage, the local impact and magnitude of which depends on parameters such as the relative size of the PV plant to the distribution feeder capacity and the distance between the point of interconnection (POI) and the substation [6].

Large and fast changes in power result in voltage and frequency regulation issues. The impact from these power irregularities is greater with larger plants or high penetration of PV with relation to the grid size. When the cloud power roles away, adjusting power ramp rate of the PV inverter can control the power surge, but this will not help shortfall in power when the clouds roll in [14]. Grid operators generally attempt to limit the ramp rates. Manifesting at the POI via curtailment and energy storage assisted smoothing [15].

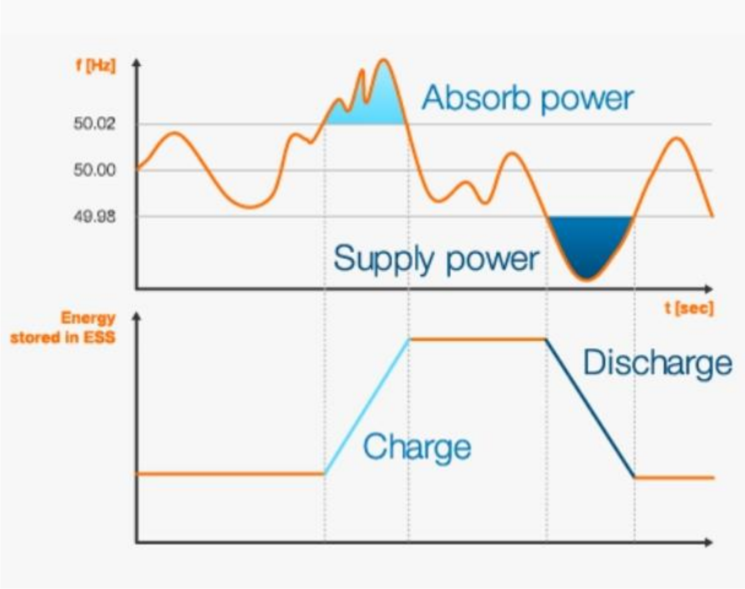


Figure 1-4 Frequency regulation through the Storage System

According to [16] relatively a small power and energy are needed to provide voltage support and securing voltage quality.

1.6.3 Load leveling

Load leveling usually involves storing power during periods of light loading on the system and delivering it during periods of high demand. During these periods of high demand the energy storage system supplies power, reducing the load on EES economical peak-generating facilities [12].

The consumer cost of electricity consists of a demand charge (kW) and an energy charge (kWh). Load leveling by EES can suppress the peak demand, however charge/discharge loss will simultaneously increase the amount of electricity consumed [1].

Figure 1-5 Discharging EES for Load Leveling

By installing EES the utility can supply stable power to consumers. A reliable power supply for protection and control is very important in power utilities [1].

In a load leveling scenario, an electrical energy storage device would be charged during low-power demand periods and would-discharge during high power demand periods, thus utilities would need less overall power generation capability, and could delay the installation of extra generating capacity [17].

1.6.4 Peak Shaving

High PV penetration can cause an overproduction of power, especially during clear summer days around midday. Those production peaks are detrimental for electric grid stability. These peaks can be lowered so called peak-shaving, by shifting loads to those periods so called load shifting [18].

Peak shaving is like load leveling, but the purpose is reducing peak demand rather than for economy of operation. The goal is to avoid the installation of capacity to supply the peaks of a highly variable load. Peak shaving installations are often owned by the electricity consumer, rather than by the utility. Commercial and industrial customers save on their electricity bills by reducing peak demand. Utilities reduce the operational cost of generating power during peak periods - reducing the need for peaking units. Investment in infrastructure is delayed due to the flatter loads with smaller peaks [12].

Storing PV power that is generated during the early and midday periods and releasing it later in the day, during peak demand. Energy storage systems can be deployed to limit the power delivery input to the grid. By curtailing PV generation, power delivery is stretched out longer during the day [14].

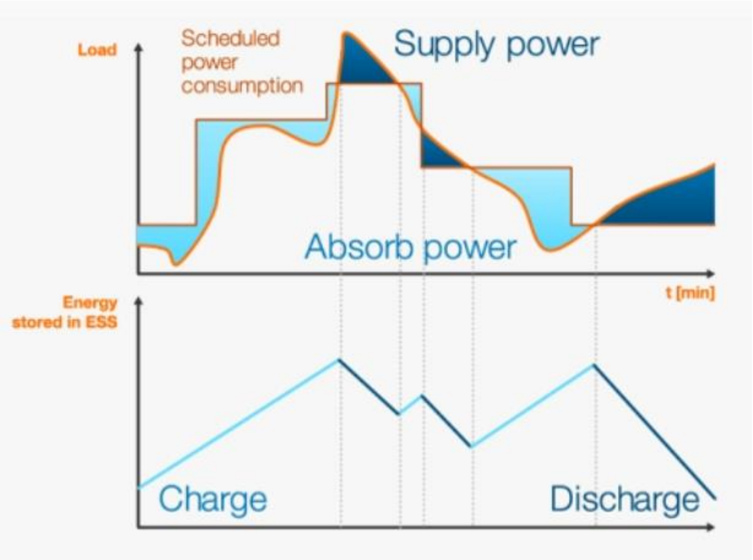


Figure 1-6 Discharging EES for Peak Shaving

During high demand periods of the year, demand can be managed through load shifting, load reduction or another demand side response. Peak shaving is literally the removal of the tops of peak energy demand, conventionally considered to be applied at a bulk distribution point in the distribution network [19].

1.6.5 Capacity Firming

As the energy storage systems (EES) are highly utilized in the micro-grids where renewable energy resources are interconnected with EES in the distribution level, PV/wind power capacity firming application becomes very important issue to be achieved as it will further allow the renewable energy resources to be one hour dispatchable electric power resource [20].

1.6.6 Utility and Congestion

Network congestion occurs when electricity is unable to flow where it is needed due to physical (e.g. not enough capacity) or contractual (all available capacity has been reserved) issues[21].The congestion is a shortage of transmission capacity to supply a waiting market, and the condition is marked by systems running at full capacity and proper efficiency which cannot serve all waiting customers. When congestion occurs in a competitive market, there is a risk of price gouging from utilities that control transmission services. The grid operators are aware of this risk, and most jurisdictions have built safeguards into their free-market regulations to insure that abusive pricing does not occur, and that congestion-related energy cost increases reasonably reflect the extra costs incurred in alleviating the condition [22].

Utility companies try to predict future congestion and avoid overload, for example by dispatching generators´ output or ultimately by building new transmission routes. The only way to tune the system is to increase its capacity. So, the congestion can be alleviated. EES can mitigate congestion by storing electricity as substations where loads cannot be transmitted, so transmission lines can maintain enough capacity. Saved energy be used where lines are not available due to congestion. This approach also helps utilities to postpone or suspend the reinforcement of power networks [1].

The variable, intermittent power output from a renewable power plant can be maintained at a committed (firm) level for a period. The energy storage system smooths the output and controls the ramp rate (MW/min) to eliminate rapid voltage and power swings on the electrical grid [12].

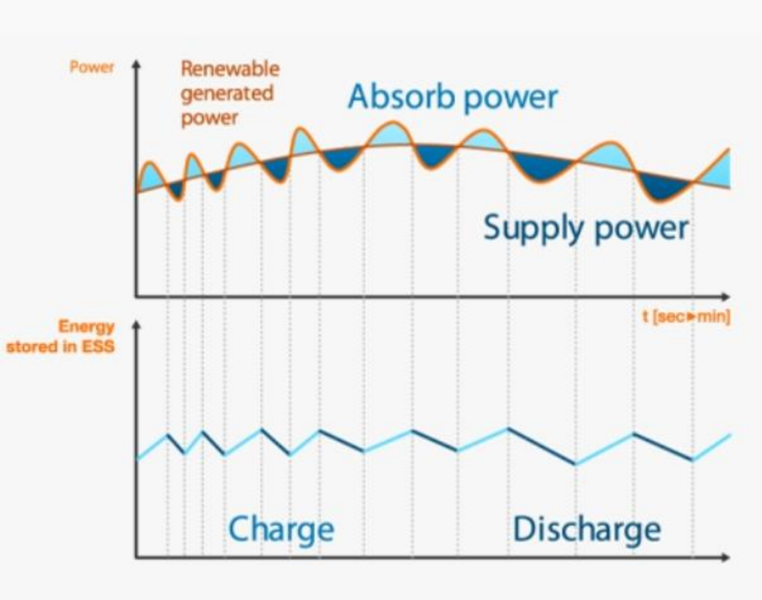


Figure 1-7 Charging and discharging EES based on generated power

1.6.7 Power Quality

In power quality applications, an energy storage system helps protect downstream loads against short-duration events that affect the quality of power delivered [12].

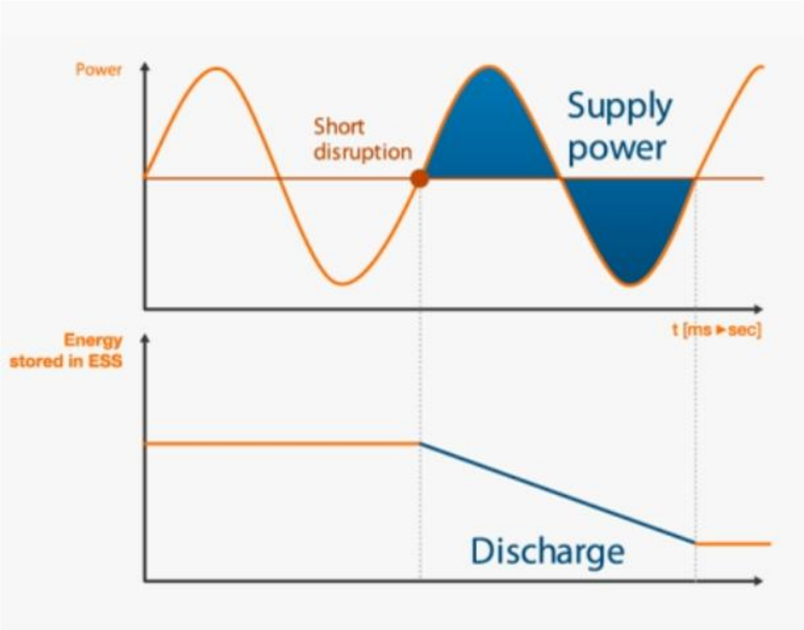


Figure 1-8 Discharging EES in Case of Short Disruption Generation

According [23] the controllability of power plants connected to the medium voltage system is regulated in technical directives. These directives include:

- Static voltage control for limiting slow voltage variations.
- Dynamic support of grid operation in case of voltage dips.
- Limitation of active power output e.g. in case of “potential risks for secure system operation” or in case of frequency rise
- Provision of reactive power

In large-scale power, plant the owner will receive payment for its full output capacity by selling directly to the electricity grid. It is important for the grid operator to have balance system. Batteries can help the system operator manage fluctuations on demand, delivering frequency regulation in a less expensive manner than transmission line upgrades [1].

1.6.8 Spinning Reserve

The spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. A utility or a group of utilities must be able to accommodate the loss of the largest generator in the system with limited power flow and frequency variation. This generally means that all generators on the system must have a few percent of immediate reserve capacity associated with their rotational inertia and their primary energy [24].

To provide effective spinning reserve, the energy storage system is maintained at a level of charge ready to respond to a generation or transmission outage. Depending on the application, the system can respond within milliseconds or minutes and supply power to maintain network continuity while the back-up generator is started and brought on line. This enables generators to work at optimum power output without the need to keep idle capacity for spinning reserves. It can also eliminate the need to have back-up generators running idle [12].

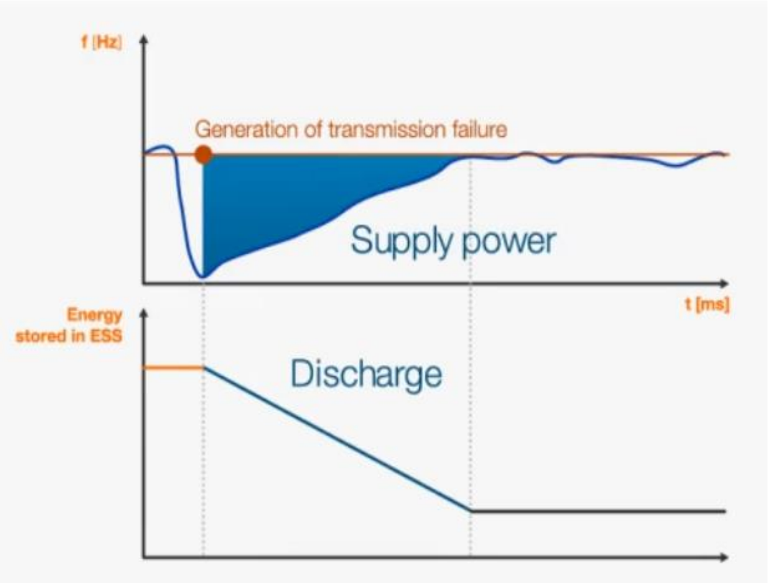


Figure 1-9 Discharging EES in Case of Transmission Failure

1.6.9 Self-consumption of the power plant

The self-consumption option applies to each kilowatt hour of solar energy that is consumed in the immediate vicinity of the PV plant that generates that power [25]. The PV electricity production in kWh/kW_p is the function of available global horizontal solar irradiation. During the summer time by increasing the day light duration of import active power is decreasing and this fact must be considered during charging and discharging of the battery.

The self-consumption directly depends on the size of the PV system and losses due the cabling and other components. Electricity consumption required for providing self-consumption of the power plant must be purchased from the grid during the absence of day light. Otherwise energy can be stored by charging EES during the day time and discharging during the night to provide self-consumption of power plant and he energy is taken from grid to self -consumption can be taken from the storage system.

1.6.10 Curtailment

According to [26] curtailment predominantly occurs due to oversupply and ramping constraints, transmission limitations. As a result, an operator or utility directs a generator to reduce output. The common metric to measure curtailment is as a percent of what a generator could have produced.

Curtailment is widely expected to increase as more variable renewables come online. Many studies have shown that EES is indispensable for the introduction of large amount of renewable energy. The necessary volume and timescale of EES is strongly dependent on renewable energy development. There are many different definitions of curtailment and there is no standardized way to measure it. The operators consider curtailment as downward dispatch. On one hand, curtailment can be problematic because it decreases the capacity factor of renewable energy projects and can thereby reduce project revenues. On the other hand, curtailment can be a valuable resource, helping stabilize the grid and improve system flexibility. Due to the speed in which renewables can be ramped up or down, curtailing renewables can help to relieve over-generation and potentially provide ancillary services [26].

1.6.11 Time Shifting

Time shifting is a function of energy storage to match the supply and demand of energy. Utilities constantly need to prepare supply capacity and transmission/distribution lines to cope with annually increasing peak demand, and consequently develop generation stations line to produce electricity from primary energy. For some utilities generation cost can be reduced by storing electricity at off-peak times, for example at night, and discharging it at peak times. If the gap in demand between peak and off-peak is large, the benefit of storing electricity becomes even larger. Using storage to decrease the gap between daytime and night time may allow generation output to become flatter, which leads in an improvement in operating efficiency and cost reduction in fuel [1].

When a power network cannot meet increasing power demand an installed large-scale battery mitigates the congestion and help the utilities to postpone or suspend the reinforcement of the network.

According to [1] and [14] large scale technologies including lithium-ion, sodium sulfur, lead acid, flywheels and flow batteries are better in order to ramp control due to shorter time of response. Technologies with a higher time rate are better suited to firming, shaping and curtailment application.

1.6.12 EES and Inverters

The two main choices available are battery-specific inverters and so-called ‘hybrid’ or multi-mode inverters [27]. Battery-specific inverters manage the charging and discharging of a battery bank. Just as with other inverters, their job is to convert DC electricity into AC electricity, but they also do the reverse – converting AC electricity into DC in order to charge a battery bank during cheap off-peak grid electricity. They have modular nature lends to greater system design flexibility and can be relatively easily retrofitted onto existing solar PV systems for addition of battery storage [27].

Frequency regulation requires quick response by the EES, generally within seconds of utility SCADA command or a frequency change event. In the event of the frequency drop, the EES can be used to assist with frequency changes, by pushing or pulling power into the grid to accommodate for frequency drops or surges. An inverter- based EES can deliver this kind of support because of its inherent step response capabilities. A similar benefit of grid-tied inverters is the ability to deliver lagging or leading reactive power or volt-ampere (VAR) for voltage control. Additional VAR support can be provided in conjunction with existing PV inverters. However, an inverter base EES can deliver full 360-degree power and reactive power support with fast response. The EES can help provide grid healing with both low voltages ride-through (LVRT) and high voltage ride-through (HVRT) capabilities [3].

Voltage is generally controlled by taps of transformers, and reactive power with phase modifiers. EES located at the end of heavily loaded line may improve voltage drops by discharging electricity and reduce voltage rises by charging electricity [1].

1.7 Conclusion

So far, we have briefly overviewed the relative strength and weakness of different EES technologies and their applications. EES will play a significant role in the early future due to achieving high penetration of renewable energy. Summarizing Figures 1.1 provides an overview of EES and its application.

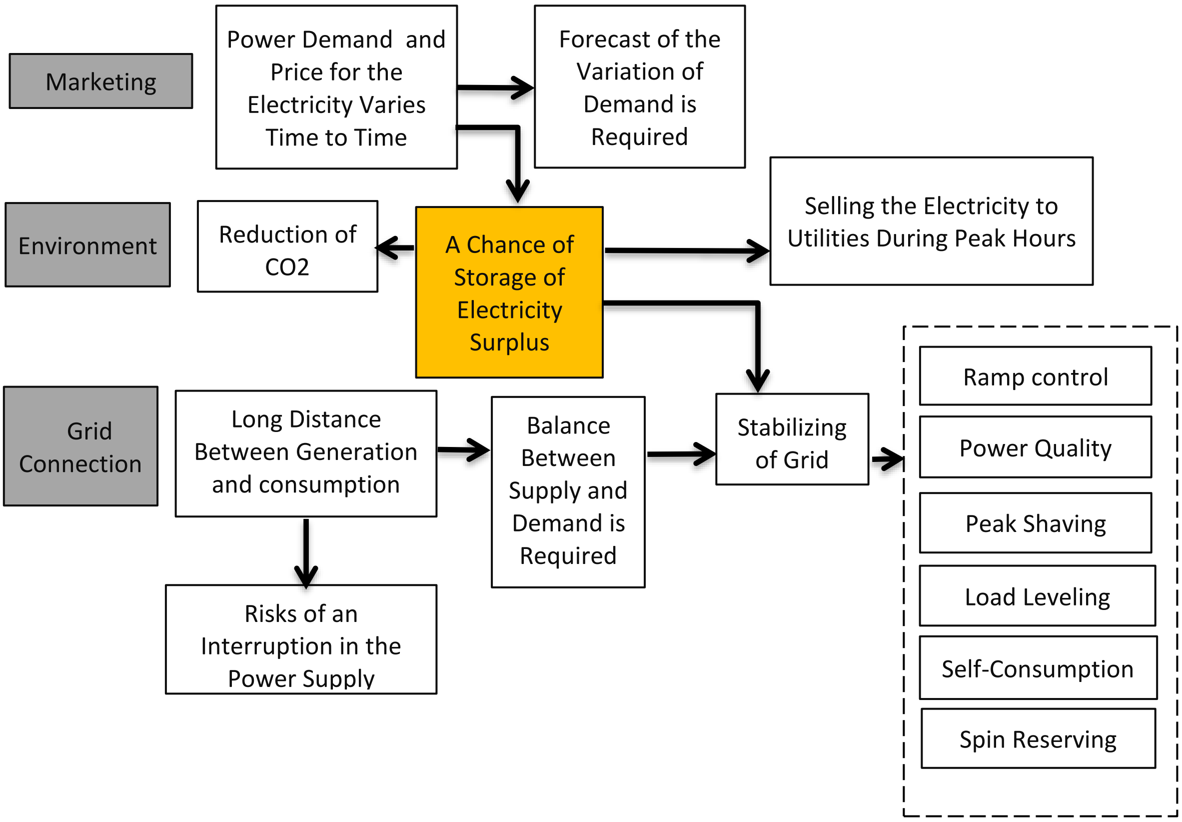


Figure 1-10 EES Main Application in Renewable Energy

Choosing EES technology depends on what is required on each site. Different application with different requirement can lead us to use different EES. As we have seen there is a wide range of different technologies to store electrical energy.

2 Chapter 2: Battery and standardization

The electrical energy storage system standardization is important, because it covers terminology technical features, testing and system integration [1]. In this chapter standardization of batteries includes basic characteristics of components and systems such as capacity, power, charging and discharging, lifetimes and standardization of EES are discussed. According to [1], [4], [14], [19] and [27] for choosing a suitable ESS, all major factors need to be taken into consideration in order to choose an appropriate technology.

2.1 DC versus AC Storage

Most batteries are composed of several cells. In stand-alone power systems, the battery bank voltages commonly used are 12V, 24V, 48V or 120V [28]. Based on this the appropriate inverter must be used. Energy can be stored on DC side directly. In this case, since the battery works with different voltage, DC-DC inverter is required. Subsequently energy which is stored in the battery will be transferred on AC side with an DC-AC inverter. While the battery which is used on AC side needs to be equipped with an AC-DC inverter directly. In figure below the solar PV system with both AC and DC battery storage is shown.

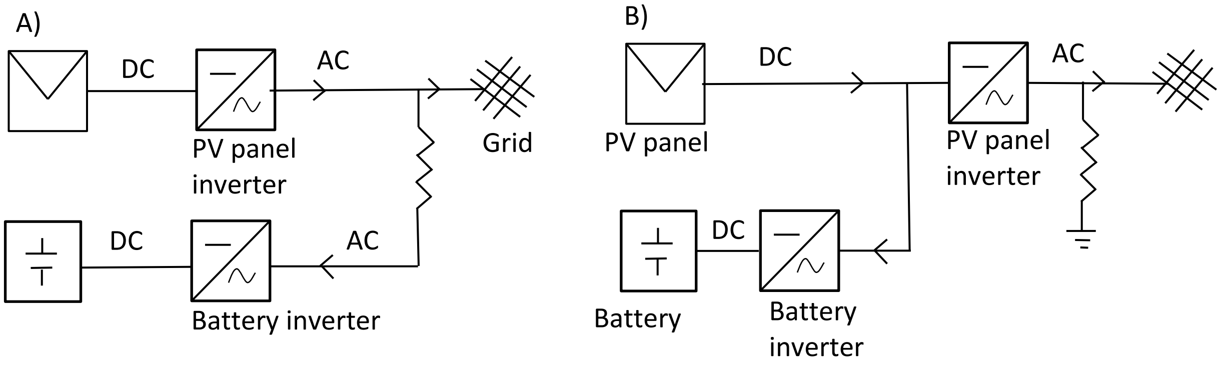


Figure 2-1 A) Solar PV System with AC Battery Storage, B) Solar PV System with DC Battery Storage.

2.1.1 DC Storage

Batteries likewise require an inverter to render their stored energy usable. DC-coupled storage can only store energy from the solar panels. DC storage is lower cost because they can share the inverter with the solar panels, and to the output of the solar panels and stores DC power directly from the panels. They are not able to storage grid power. DC storage systems are most useful when the primary aim is to store excess solar energy gathered during the daytime and use it during the peak load time in the evening when the sun is setting. This would be most appropriate in cases where the customers do not consume much electricity during the daytime [29].

2.1.2 AC Storage

If batteries are AC-coupled, they will require a separated inverter of their own and they can store energy from solar generation as well as grid. AC-coupled storage is bi-directional and can store grid power. They provide greater flexibility through off-grid uninterruptible power supply (UPS) modes, which means the end-user has power even when the grid is down, grid charging and network support capabilities, such as power factor correction. They can also take advantage of energy trading schemes on the wider network to earn extra income for the operator [29].

An AC system usually also includes a UPS mode, which can also provide backup AC power from the batteries when the grid has failed or is disconnected. DC systems, on the other hand, require the grid to be available always to export AC power, as is the case with a typical PV inverter, when the grid goes down, the system must also shut down for safety reasons.

According to [23] the bi-directional inverter controls power flow between the different units can be used which has to DC ports which are connected to the PV panel and battery storage and two AC ports to the utility. Regardless of the output of the solar panels, the power output will be cut-off by the inverter, as a result power does not exceed the inverter’s rated capacity.

According to [30] the batteries can be operated either connected to the grid or stand-alone. Batteries can optimize self-consumption when they are connected to the grid.

2.2 Capacity

The term capacity of batteries refers to the amount of charge that the battery can deliver at the rated voltage, the capacity is directly proportional to the amount of electrode materials in the battery. The capacity C_{bat} is measured in ampere-hour(Ah).

The available capacity of the battery consists of the depth of the discharge (DOD), the maximum charge and the efficiency of the battery [4]. The unit in which capacity is measured is the ampere-hour. The quantity C is defined as the current that discharges the battery in 1 hour, so that the battery capacity can be expressed by C- Ampere-hours. But in the field of electricity is measured in watt-hours. The energy capacity of a battery is simply given by multiplying the rated battery voltage measured in volt by the battery capacity measured in ampere-hours.

$$E_{bat} = C_{bat}\mathrm{V}$$

Peukert Law relates battery capacity to discharge rate. The Peukert Law expresses the efficiency factor of a battery on discharge [31].

$$\mathrm{Cp} = e^{k}t$$

where Cp is the amp-hour capacity at a 1 A discharge rate, t is the discharge time, in hours, k is the Peukert coefficient, typically is between 1.1 to 1.3.

2.3 Efficiency

Due to storage mechanism, the efficiency of a PV storage cannot be measured at an instance in time as “power efficiency”. But instead has to be measured as “energy efficiency per day” by comparing input and output energy delivered during the battery cycle [30].

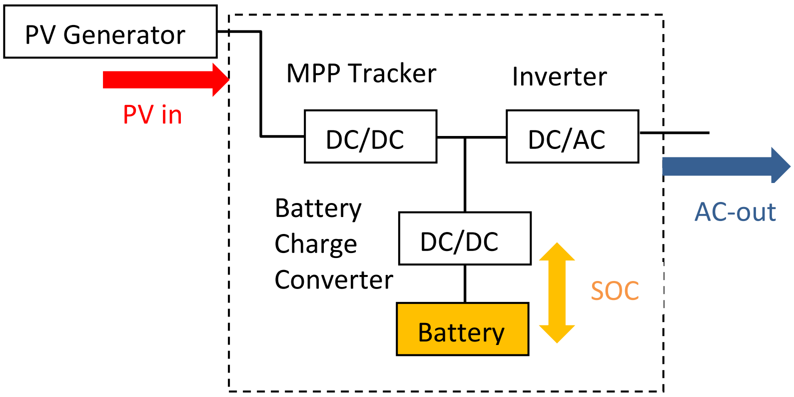


Figure 2-2 schematic depiction of PV inverter and PV storage system, with DC-coupled battery as part of the inverter system

In the figure above E_{PV-in} is input flow and E_{AC-out} is output flow. The electricity generated by the PV system can be either inverted and transmitted to an AC and transmitted to the loads of the grid or stored into the storage. Since the battery works with DC current, the load must be converted to DC. When the power plant needs to access electricity from the storage, the DC power is trapped from DC bus and converted to AC. The efficiency of energy conversion must be taken into account in total efficiency of the battery.

MPPT connect DC-DC converter between PV array and battery and control this converter with a maximum power point tracker.

PV inverters can be characterized by the efficiency of the inverter, which is calculated from the ratio of input to output power $\frac{P_{pv\_in}}{p_{AC\_out}}$. Due to the possibility to store energy in the battery, the output power is not strictly following the input power. During one battery cycle the energy efficiency is expressed by $\frac{E_{pv}}{E_{AC_{out}}}$, where DC/DC conversion is considered. The efficiency of the inverter of power plant can be found of data sheet of power plant.

2.3.1 Roundtrip Efficiency

The ratio of energy put in to energy retrieved from storage is the round-trip efficiency (also called AC/AC efficiency), expressed in percent. According to [4] and [32] round trip efficiency can be considered as the amount of energy that can be extracted from a battery as a percentage of the amount of input energy it took to store it. For example, if 1kWh of electricity is fed into a battery and the amount of energy which can be extracted from that input is only 800Wh then the efficiency of the battery is 80%. The loss in energy is caused by heat or other inefficiencies within the system. Round trip efficiency is highly dependent on the battery's DOD. The round-trip efficiency is given as the ratio of the total storage output to the total storage input.

$$\eta_{bat} = =\frac{\mathrm{E}_{out}}{E_{\mathrm{in}}}$$

The battery round trip efficiency is defined as the product of these two efficiencies.

$$\eta_{bat} = \eta_{\mathrm{V}} \times \eta_{\mathrm{C}} = \frac{\mathrm{V}_{\mathrm{discharge}}}{V_{\mathrm{charge}}} \times \frac{\mathrm{I}_{\mathrm{discharge}}}{I_{\mathrm{charge}}}$$

Where η_{V} the voltaic efficiency, which is the ratio of the average discharging voltage to the average charging voltage and η_{C} is defined as the ratio of the total charge extracted from the battery to the total charge put into the battery over a full charge cycle.

2.3.2 Columbic Efficiency

Columbic efficiency (CE), also called faradaic efficiency or current efficiency, describes the charge efficiency by which electrons are transferred in batteries. CE is the ratio of the total charge extracted from the battery to the total charge put into the battery over a full cycle [9].

2.3.3 Total Efficiency

To provide energy with the battery storage the loss and the efficiency of each component must be considered. This is important during charging and discharging of the battery. $\eta_{\mathrm{DC-AC}}$ and $\eta_{\mathrm{AC-DC}}$ are related to the efficiency of inverter of the battery. Total efficiency can be defined by the following formula [33].

$$\eta = \eta_{\mathrm{AC-DC}} \times \eta_{st}^{char} \times \eta_{st}^{dis} \times \eta_{\mathrm{DC-AC}}$$

Where η_{st}^{char} and η_{st}^{dis} are charging and discharging efficiency of the storage system. The energy efficiency per day depends on total throughput, relation of throughput to local load and on the battery cycling during that day [30].

2.4 Debt of cycle and State of Charge

State of Charge (SoC), which is defined as the percentage of the battery capacity available for discharge. There is a maximum capacity of battery is expressed by SoC_{max} and usually is calculated using current integration to determine charge in battery capacity over time.[34] The debt of cycle (DOC) describes the amplitude between the peak and the minimum state of-charge within a cycle and determines the cycle-aging [35]**.** DoD is defined as following formula.

SoC= $\frac{E_{bat}}{C_{bat}V}$

2.5 Depth of discharge

The depth of discharge specifies what percentage of the battery capacity has been discharged. For example, if a 10kWh nominal capacity battery has 5kWh stored in then its current DOD is 50%, if it has 2kWh left in storage then its DOD is 80%. Most batteries simply cannot be drained of all their stored energy. In most cases, doing this would cause irreversible damage to their components. DoD is defined as following formula.

DoD= $\frac{C_{bat}\,V- E_{bat}}{C_{bat}\,V}$

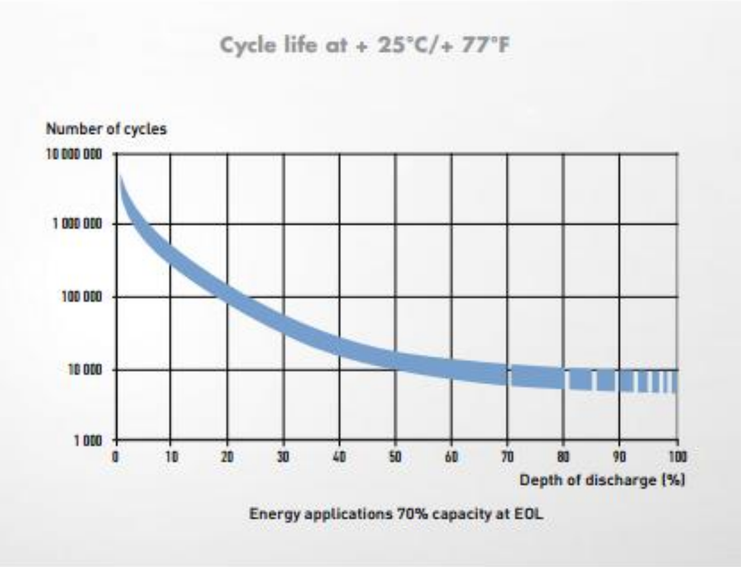


Figure 2-3 Number of Cycles against depth of discharge for lithium-ion battery

Batteries are typically specified by recommended maximum DOD for their nominal cycle lifetime and the expected cycle life of a battery tends to decrease as the DOD is increased. Cycle life as function of discharge can be different [32].

Depth of Discharge	Lithium-ion Discharge Cycles
100% DOD	300/600
80% DOD	400/900
60% DOD	600/1500
40% DOD	1500/3000
20% DOD	1500/9000
10% DOD	10000/15000

Table 2-1 Lithium-ion Discharge Cycles and Depth of Discharge

Number of cycles for a unique battery is notably different in different literatures. It is important to consider a realistic number of cycles. A partial discharge reduces stress and prolongs battery life, so does a partial charge. Elevated temperature and high currents also affect cycle life.100% DOD is a full cycle; 10% is very brief. Cycling in mid-state-of-charge would have best longevity [36].

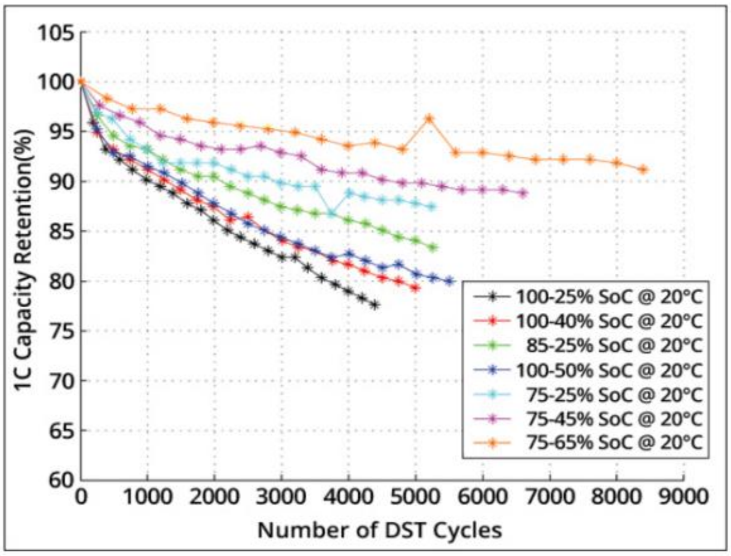


Figure 2-4 Capacity loss of Li-ion within given charge and discharge bandwidths

Evaluating battery life on counting cycles is not conclusive because a discharge may vary in depth and there are no clearly defined standards of what constitutes a cycle. A battery may fail within the allotted time due to heavy use or unfavorable temperature conditions [32].

Batteries charging to 85% have a longer life span than enabling full charge. Although longer lasting, a less than full cycle does not fully utilize -a battery. 75–65% SOC offers longest cycle life. 100–25% SOC gives long runtime, makes best use of battery, but reduces battery life [36].

Li-ion does not need to be fully charged as is the case with lead acid, nor is it desirable to do so. A partial charge is better. In fact, it is better not to fully charge because a high voltage stresses the battery. Choosing a lower voltage threshold or eliminating the saturation charge altogether, prolongs battery life but this reduces the runtime. Chargers for consumer products go for maximum capacity and cannot be adjusted. Estimating SOC by reading the voltage of a charging battery is impractical; measuring the open circuit voltage (OCV) after the battery has rested for a few hours is a better indicator[37].

Li-ion has minimal losses during charge and the columbic efficiency is better than 99 percent. At 1C, the battery charges to 70 percent state-of-charge in less than an hour; the extra time is devoted to the saturation charge. Li-ion does not require the saturation charge as lead acid does; in fact, it is better not to fully charge Li-ion — the batteries will last longer but the runtime will be a little less. Of all chargers, Li-ion is the simplest. No trickery applies that promises to improve battery performance as is often claimed by makers of chargers for lead- and nickel-based batteries. Only the rudimentary CC/CV method works.

Lead acid cannot be fast charged and the term “fast-charge” is a misnomer. Most lead acid chargers charge the battery in 14–16 hours; anything slower is a compromise. Lead acid can be charged to 70 percent in about 8 hours; the all-important saturation charge takes up the remaining time. A partial charge is fine provided the lead acid occasionally receives a fully saturated charge to prevent sulfation [38].

In general the future perspective seems to be promising for Li-ion batteries in grid scale application as the final price is declining and the functionality is over improving by optimizing manufacture costs, extending the life time, using new materials, and improving the safety parameters [39].

2.6 Lifetime

According to [4] and [40] battery lifetime is greatly affected by the number of discharge or recharge cycles and the depth of discharge in terms of percentage of total discharge. Beside the lifespan of a deep cycle battery will vary considerably with how it is used, how it is maintained and charged and temperature [41]. If the battery only lasts one cycle then the price of each kWh you extract from the battery would be astronomically high [32].

2.7 Charge and Discharge Time

According to [1]charge and discharge time can be classified in three groups:

1. Short discharge time (seconds to minutes), suitable for the plants with power-to-energy ratio less than one. EES systems for short discharge times cover wide range of rated power and energy density. Several mature EES technologies, specially battery systems can be used in this range.

2. Medium discharge time: minutes to hours, suitable for the plants with power-to-energy ratio between 1 and 10.

3. For long discharge time (days to months), suitable for the plants with power-to-energy ratio greater than 1 (with power range of GWh- TWh). New EES technologies such as H2 and SNG must be developed. [4] PHS is the only currently feasible large capacity EES for medium discharge time.

The discharge duration calculated by energy can be store in EES divided by power rating of the same EES.

Some energy storage technologies can discharge at a relatively high rate for relatively short periods of time. It is often referred to as “emergency” rating [18].The storage system must not be empty when needed to discharge or full when needed to charge.[5].Parameters relating to the discharge power or current of the battery are “maximum power demand” and “surge demand” [42].

At the shortest timescale, significant storage has been deployed for providing operating reserves including frequency regulation, which responds to small random variations in small random in normal demand. This fact discussed widely in section of frequency regulation[43]. Any longer timescales, up to several hours, storage has been deployed to provide peaking capacity and to shift energy from off/peak to peak periods. Some storage systems enable the plants perform daily shifting and provide additional arbitrage between weekday and weekend price difference [44].

The photovoltaic yield depending on the location and the efficiency of the inverters and Batteries with lower DoD could last more. That means in case of lower DoD, the capacity of each battery is smaller, and more batteries are needed to fulfill the same task.

2.8 Types of Charge Controllers

There are essentially two types of controllers which are called shunt and series.

According to [45] a shunt controller bypasses current around fully charged batteries and through a power transistor or resistance heater where excess power is converted into heat. Shunt controllers are simple but are only designed for very small systems. Series controllers stop the flow of current by opening the circuit between the battery and the PV array. Series controllers may be single-stage or pulse type. Single-stage controllers have a greater load-handling capacity than shunt-type controllers. Pulse controllers and a type of shunt controller referred to as a multi-stage controller have routines that optimize battery charging rates to extend battery life. Most charge controllers are now three-stage controllers. These chargers have dramatically improved battery life.

- PV array voltage: The controller’s DC voltage input must match the nominal voltage of the solar array.
- PV array current: The controller must be sized to handle the maximum current produced by the PV array

2.9 Conclusion

In this chapter the most important feature of the EES and its standardization are discussed. Based on different application the battery can be placed on AC or DC side. Debt of Discharge, temperature and voltage variation, Charge and discharge time are important factors which must be considered in order to choose battery. Battery size must be chosen properly to avoid over-sizing or under-sizing. Relationships between electricity flows and the storage capacity, which is not linear become an important design criterion. The most important features of each technology are mentioned in the table below. However, there are still room for each technologies' properties.

Short response time	Zn-air, NiCd, $\boldsymbol{H_2}$, NiMH, Li-ion and NiNlCl.
Short discharge time and short respond time	SMEs, EDLCs and flywheels
High energy	PHS, CAES
High power	SMEs, EDLCs and flywheels

Figure 2-5 The most important features of each EES technology

Each technology has its own pros and cons. It is impractical to choose an EES that can provide a solution to all events all time. The main trade-off in battery development is between power and energy. batteries can be either high-power or high-energy. Since the study is concentrated on providing storage during curtailment of power during the high peak shaving technologies in the higher time range are better choice. Different ESSs with the same size have different discharge and respond time which depend on technology of ESS and its inverter. technologies with higher power rate are suitable for sudden interruption of electricity distribution.

Techno- economic criteria must be evaluated to choose a proper storage system. Overview of the model of EES integration is summarized in the figure below. The outputs of the model are discussed in further details in the next chapter.

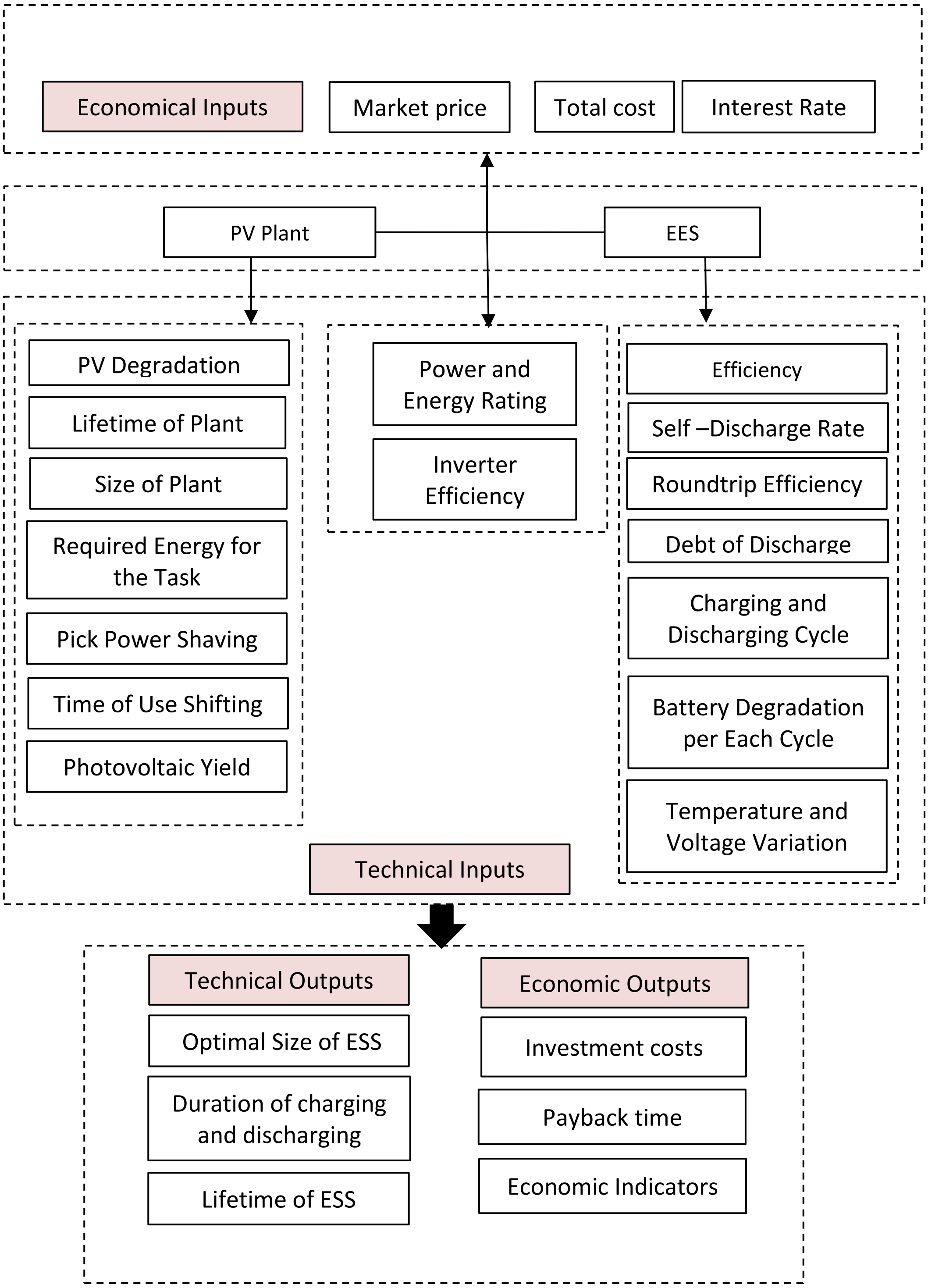


Figure 2-6 Overview of the model of EES integration

3 Chapter 3: Techno-Economic Aspect of EES Integration During Curtailment

Solar photovoltaic technology is becoming mature electricity supply option from techno- economic perspective. The curtailment PV installed capacity has grown at an average rate of 49% for the last decade[46]. Reduction of feed in tariff and PV deployment can introduce more additional economic risk in the future. While dynamic curtailment happens due to fluctuating nature of renewable energy and its unpredictable market, EES integration of the renewable energy is becoming more interesting. In this chapter curtailment constraint and its diversity, EES operation during curtailment, charging and discharging strategy and its effect on battery degradation are discussed. Furthermore, operational policy of EESs and insight through the economic indicators to evaluate EES and its cost efficiency are widely presented.

3.1 Operational policy of curtailment

This section provides the initial assessment of EESs for PV plants. A challenge of integration high penetration of renewable energy is managing periods when system demand is low and there is too much electricity generation. When this occurs, it can be necessary to turn down or curtail energy. This can happen due to local network congestion which is called “constraint”. collectively, curtailment and constraints are known as “dispatch down” of power.

According to [19] with the rising price of the retail electricity and the decreasing cost of the PV technology, grid parity with commercial electricity will become a reality in Europe. This fact, together with less attractive PV feed-in-tariffs and incentive to promote self-consumption suggest.

Communication between components, interconnection requirements, Power quality, voltage tolerances, frequency and synchronization are required to invest the battery integration during curtailment.

3.2 Curtailment Classification

The possible contribution to total curtailment in renewable energy source can be divided into involuntary and voluntary curtailment. Avoiding curtailment requires investing capacity including international interconnection and storage solutions [47]. According to[48] and [49] in certain situations, curtailment to a limit extent is an optimal solution with regard to total costs of providing electricity. In case of involuntary curtailment there are two possibilities.

A) lower connection charges than those under the mandatory regime if the RES unit agrees to connect at a different network node with possibly higher curtailment

B) connection to a point with less expected curtailment than in the mandatory benchmark situation. Different curtailment situation is summarized in the table 3-1 [47].

Table 3-1 Categories of Curtailment Situation [47]

Reason	Voluntary	Involuntary	Rational	Possible Compensation
Network Constraints	Accepted in contracts, at time of connection	Short term DSO-controlled generation reduction	Avoid overinvestment in transmission and distribution capacity, extension delays	DSO and TSO compensate based on market price and/or subsidy
Security	Specialized market	Max generation limits for a number of consecutive hour, mainly enforced by TSO	Reduce reserve Capacity costs/dynamic reserve dependent on variable generation	Separate market or compensation from TSO/grid users based on legislation
Excess generation relative to load levels	Low or negative power market prices induced	Generation limits enforced by TSO	Highest marginal costs generators should be curtailed if market failed	Compensation by TSO based on subsidy to provide incentive or voluntary curtailment, no compensation for involuntary curtailment
Strategic bidding	Manipulate prices	--	Profit from exercise of market power	

There are stimulus and incentive to develop renewables, but there are three set of issues which can sometimes restrict the connection of renewable generation to power system. According to [50] these include:

1. Network issues which focus on local issues such as lack of capacity on the network to enable new connections and control voltage and reactive power levels on the network.
2. System issues which can include security of supply, back up reserve and system balancing. System which re overloaded with new generation may have difficulty in balancing generation and demand.
3. Market issues such as subsidies, compensation and electricity pricing.

In several of the existing early deployed active network management (ANM), the method of curtailment is Last in first off (LIFO). This means that the first non-firm generator unit(NFG) to sign a contract is always the last NFG to be curtailed [51].

3.2.1 Curtailment Method

Historically curtailment has been driven largely by transmission constraints because of limited transmission capacity for delivering electricity from the point of generation to load centers[52].Besides market rules might influence on the curtailment implication. According to [50] the curtailment method could be divided in to eight methods.

1. **Non-market arrangements:** Non- market arrangements use predetermined rules to curtail NFG. These rules are decided by the DNO and NFG must to adhere these rules in order to connect to the network. Non-market arrangements are simple for DNO to implement as no charges to current rules and regulations are required.
2. **Last in First out**: Last in first out (LIFO) is method under which, the first NFG to be curtailed under a constraint event is the chronologically last NFG to connect to the network or added to an AM scheme. In this method since the lowest priority generator maybe located furthest from the constraint which would be result in a higher volume of curtailment required when compared with generator located closer to the point of congestion, would not necessarily be the best way of fully utilizing the available network capacity or the available

renewable generation. Besides as the number of NFG increase, the capacity factor (CF) for those at the bottom of the priority list may begin to approach unacceptable levels and discourage any new NFG connections.

3. **Pro Rata:** The pro rata method divides the required curtailment equally between all NFG contributing to a network constraint. The total amount of curtailment would be shared by each NFG output to total required curtailment implementing this method would grant equitable access for multiple NFG. However, it is difficult for the DNO to calculate the long-term volumes of curtailment of this method since, as more NFG connected, the level of curtailment of each NFG will increase.
4. **Shedding rata:** The method curtails NFG based on the order specified in a predetermined Rota. This Rota could be changed on a daily, weekly or monthly basis using the network operator’s discretion. As the level of generation connected under a Rota increases, the level of curtailment may increase.
5. **Technical best:** this PA curtails the NFG in order of size of contribution to the prevailing constraint or based on which generators are most effective in relieving constraint. This approach would ensure the minimization of the volume of energy curtailed and the most efficient operation network. This approach may discriminate against certain NFG based on their location and their capacity.
6. **Greatest Carbon Benefit**: This method aims to minimize carbon emission associated with the activity managed networks by curtailing NFG which out of purpose in PV plant management.
7. **Most Convenient:** This method allows the system operator to curtail the generator they know to be the most convenient i.e. easiest to implement and most effective for relieving network constrains. This may be unfair discrimination against certain type of generator.
8. **Generator size:** This method curtails the largest generator that is contributing to a constraint first, where size refers to output at time of constraint. This method has the advantage of easing network congestion quickly by regulating or removing the largest NFG first. This PoA could be deemed unfair, and may discourage efficient investments from developers e.g., reluctance to install larger generating units.

In order to compare the impact of different PoA, a quantitative analysis was carried out using a power flow constraint ANM technique. This method applies the PoA within the constraint analysis to compare the impact of LIFO, pro rata and rata arrangements on NFGCFs. Relevant demand and generation data for the case study network is used to identify periods of constraints. The Constraint Analysis Process is shown in figure below [50]

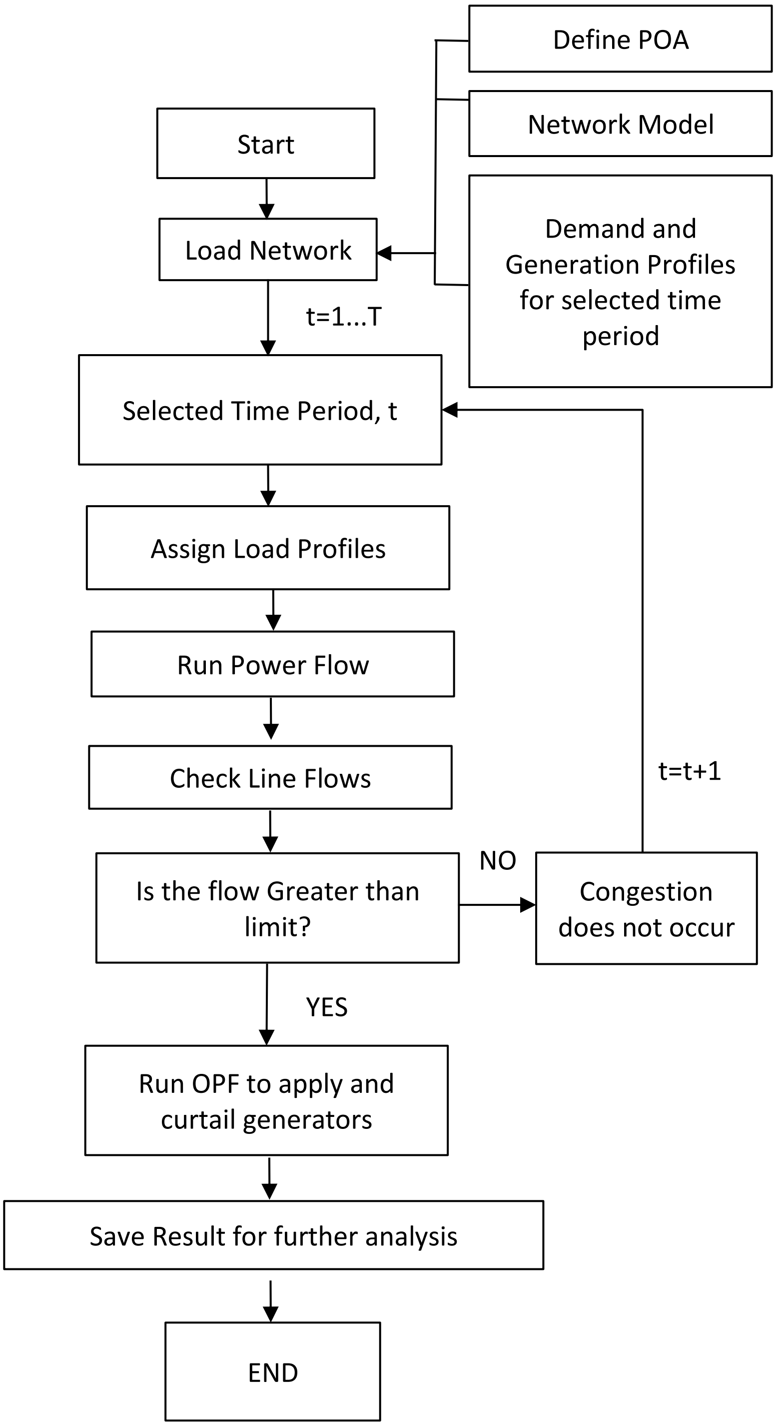


Figure 3-1 Constraint Analysis Modeling Process

Although individual renewable generators can demonstrate rapid, short/term fluctuations in output, grid integration studies have found little inherent need for storage to address the problems, largely because diverse renewable generator locations minimize rapid fluctuations of aggregate renewable output [53].

3.3 Storage Operation During Curtailment

As wind and solar plants rapidly grow, grid operators are raising concerns about periods of over-generation. A host of supply-side and demand-side measures can keep curtailment to minimal levels, but policy reforms also are needed to make curtailment a viable tool [26]. Increasing export capacity will largely depend on creating new mechanism to buy and sell energy on a day-ahead and real-time basis. The increased demand response cases depend on greater adoption of time-of-use or real-time pricing across a large fraction of electricity consumers [54]. When high penetration of DG capacity exists, some DG network could be subject to significant levels of curtailment [18]. Network issues could be actively managed in real-time by storing of excess of DG and releasing it later when constraints are not binding [55].

Integrating large amount of variable e generation (VG) solar into a region's power grid without causing significant VG curtailment and thus preserving VG's environmental and economic value will likely require increasing system flexibility through a combination of changes to grid operation and deployment of enabling technologies. Yet questions remain about the amount and configuration of storage needed to reduce VG curtailment as well as how to value the multiple benefits storage can offer VG integration and grid operation [44].

Battery management ensures efficient battery utilization. Discharging battery at peak prices when possible give a battery with a shorter payback time [33].

3.3.1 Charging and Discharging Policy

In particular, the storage is charged or discharged depending on the price in hour t(π_t) , and the 24 hour price. The relationship between the price and price scaling factor along they-axis is illustrated in figure below [56].

Scaled factor is a number which scales or multiplies in price and it is shown by $\in$, where $\in_2 < \in_1$. $\bar{\pi}_t$ is the 24-hour average price which is compared to average price of $\bar{\pi}_t$ over future i number of hours ($\bar{\pi}_{t+i}$). $\bar{\pi}_{t+i}$ is defined in formula below.

$$\bar{\pi}_{t+i}=\frac{\sum_n^i \bar{\pi}_t}{i}$$

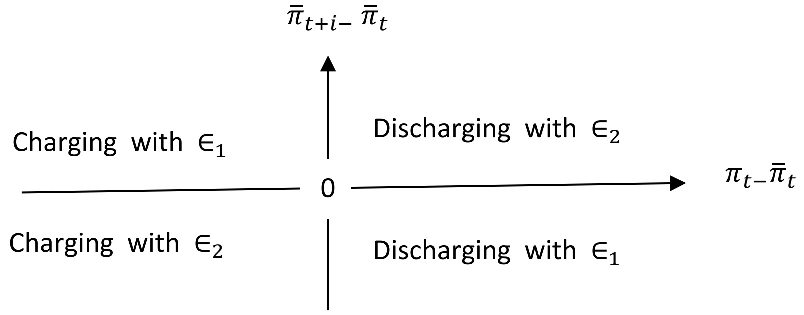


Figure 3-2 Relation Between Price, Decision to Charge and Discharge Price and Price Scaling Factor

When $\bar{\pi}_{t+i} > \bar{\pi}_t$ discharging is scaled down and charging scaled up. When $\bar{\pi}_{t+i} < \bar{\pi}_t$ discharging is scaled up and charging scaled down.

The rate of charge or discharge (P_{stored}) depends on its rated power electricity (P_{rated}), discharge efficiency ($\eta_{\text{Discharge}}$), a price scaling factor ($\in_{price}$) and storage state of charge scaling factor ($\in_{SoC}$). The minimum and maximum stored power are defined by following formula.

$$P_{stored} = \begin{cases} \min\left(P_{rated}, P_{rated} \in_{SoC} \in_{price}\right) & if\ \pi_t < \bar{\pi}_t \\ \max\left(-\eta_{\text{Discharge}} P_{rated}, -P_{rated} \in_{SoC} \in_{price}\right) & if\ \pi_t > \bar{\pi}_t \end{cases}$$

The wholesale electricity price Π is estimated depending on merit-order position. If the energy will be curtailed Π can be calculated as a following procedure [56].

$$\Pi = \dot{\pi}_g \times [1 + k \times e^{-\alpha\left(\frac{P_w - P_{curtailed}}{P_w}\right)}]$$

Else if peaking plant generating the wholesale price can be calculated by following formulas.

$$\Pi = \dot{\pi}_g \times [1 + k \times e^{-\alpha\left(\frac{C_g - C_{curtailed}}{C_g}\right)}]$$

Otherwise:

$$\Pi = \dot{\pi}_g \times [1 + ke^{-\alpha\left(\frac{\dot{\pi}_{g+1} - \dot{\pi}_g}{\dot{\pi}_g} \times \frac{P_g}{C_g}\right)}]$$

Where $\dot{\pi}_g, \dot{\pi}_g$ and P_g are the marginal cost of generation, installed capacity and power output in the specific current order. K and α for scaling up and down respectively and is the number of hours. P_w is power plant output.

Note that Wholesale price is a gross profit which consists of material costs, labor invested, rent and fixed costs and profit margin. It is needed to cover business over a head and irregular expenses. While most of the time we end up using retail price multiplied by a factor less that one to calculate wholesale price, retailers earn profit and the mark up the price [57].

Within the market, the decision to generate is based on the economics of dispatches. If a plant bids higher than the market clearing price, which for renewable energy could occur if prices are negative, the plants is not dispatched and does not generate revenue [58].This surplus of energy can be saved in to the storage.

3.3.2 Electricity services and Curtailment

According to [59] the benefit of BEES integration during curtailment of power can be calculated by following formula.

$$\mathrm{BEES_{value}} = \mathrm{Benefit_{PVts}} + \mathrm{Benefit_{PVCt}} + \mathrm{Benefit_{T\&D}}$$

Where $\mathrm{Benefit_{PVts}}$ is PV energy time-shift ($\mathrm{PV_{ts}}$) with an economic benefit referred to the avoided costs associated with the energy losses of PV curtailment for the consumer, $\mathrm{Benefit_{PVCt}}$ referred to the avoid cost associated with the energy losses of PV curtailment for the consumer and $\mathrm{Benefit_{T\&D}}$ is T&D upgrading deferral and potential evidence of transformer upgrading which is relevant for DSO.

The surpluses of energy will be stored, to supply it later if this an economic driver, the electricity price associated with the discharge is higher that then the electricity price associated with the instantaneous export of PV electricity.

If π_{export} is the retail price (supplied by a utility company) in case of single home, while for a BEES installed at a distribution substation refers to electricity wholesale price at the discharge time and π_{import} is the price of purchase electricity during energy import $\mathrm{Benefit_{PVts}}$, is calculated by following formulas.

$$\text{Benefit}_{\text{PVts}} = \text{E}_{\text{discharging}} \times \pi_{\text{import}} - \text{E}_{\text{charging}} \times \pi_{\text{export}}$$

$$\text{Benefit}_{\text{PVts}} = \text{E}_{\text{charging}} \times \pi_{\text{import}} \times (\eta - \frac{\pi_{\text{export}}}{\pi_{\text{import}}})$$

$$\text{Benefit}_{\text{PVCt}} = \text{E}_{\text{PVCt}} \times \eta \times \pi_{\text{import}}$$

The energy available from the renewable energy source will vary from day to day during year. That means choosing EES system requires a profound analysis of how to charge and discharge batteries during different months of the year [60].

Regarding PV curtailment, the studies show that the marginal costs of lost PV production are much lower than the marginal costs of a distribution transformer [59].

3.4 EES system Model and Input Data of Curtailed Power

The avoidance of PV Curtailment: An electricity demand profile described as PL ϵ $R^{n\times k}$, and PV generation profile defined E_p ϵ $R^{1\times k}$, where n is the number of profile and k is the number of measurement. The difference between generation(PV) and consumption(PL) at each bus is calculated as follows [59].

P_{LV}(i,k)=PL(i,k) –PV(i,k),   i=1,2,…,n

And the power flow to the transformers PG ϵ $R^{1\times k}$ is equal to:

$$PG = \sum_{i=1}^{n} P_{LV}(i,k)$$

$$\begin{cases} PG > 0 \quad When\ grid\ is\ providing\ electricity\ to\ demand\ loads \\ PG < 0 \quad When\ the\ excess\ powers\ fed\ in\ to\ the\ grid \end{cases}$$

3.4.1 PV Energy Time Shift and Avoidance of PV curtailment

If Q_{i-max} is the maximum capacity of the battery and SOC_i is the state of charge of the i-th battery. When there is free capacity in EES, the extra energy will be stored in the EES, inversely the battery discharges when the demand is higher than the production and SOC_i(k) >0. A positive value of power generation, PG(k) represents a power flow from the medium voltage side towards the low voltage side i.e. the grid is providing electricity to the demand loads. A negative value PG(k) represents a reverse flow in the transformers i.e. the excess power from the distribution system fed back to the main grid [59]. Three scenarios are considered.

1. In this case battery located next to the distribution transformer performing PV energy time-shift and the avoidance of PV curtailment. The scenario is summarized in the following equation.

```
If  $PG(k) < 0$   &   $SOC_i(k) < Q_{i-max}$
        $P_{charging(k)} = PG(k),\ P_{discharging(k)} = 0$
else    $P_{charging(k)} = 0, P_{discharging(k)} = 0$
If  $PG(k) > 0$   &   $SOC_i(k) > 0$
        $P_{charging(k)} = 0, P_{discharging(k)} = SOC_i(k)$
else    $P_{charging(k)} = 0,\ P_{discharging(k)} = 0$
```

2. In this case, EES located next to distribution transformer performing PV energy time-shift, avoidance of PV curtailment and T&D upgrade deferral. The capacity of the BEES is fixed to store any reverse power flow larger than the transformers capacity which is predefined as power limit (P_{lim}). The difference between the reverse power flow and the limit is used to charge a BEES as described below.

```
If      $-PG(k) < P_{lim}$
        $P_{charging(k)} = PG(k), P_{discharging(k)} = 0$
else
        $P_{charging(k)} = 0, P_{discharging(k)} = 0$
end
```

A BESS discharges only when the price of the electricity market surpasses a predefined price during the days, which is defined by $\pi^{max}(k)$) in EUR/MWh.

```
If  $SoC(k) \geq 0$ &  $\pi(k) < \pi^{max}(k)$
        $P_{charging(k)} = 0, P_{discharging}(k) = P_{LV}(k)$
```

```
        else
$P_{charging(k)} = 0, P_{discharging}(k) = \min(P_{LV}, SoC(k)\eta)$
End
```

It is important to consider that discharging is limited to the storage capacity.

3. Battery at each individual dwelling, performing PV energy time-shift- these BESS follows a similar scheduling in part 1.A BESS charges as soon as there is reverse flow at each consumer $P_{LV}(i,k) < 0$ there is free capacity in the battery $SOC_i(k) < Q_{i-max}$. inversely a BESSs discharges when the electricity demand is higher than the PV production $P_{LV}(i,k) > 0$ and the battery has energy stored $SOC_i(k) > 0$.

```
If $P_{LV}(i,k) < 0$  &  $SOC_i(k) < Q_{i-max}$
        $P_{charging(k)} = P_{LV}(i,k),\ P_{discharging(k)} = 0$
else    $P_{charging(k)} = 0, P_{discharging(k)} = 0$
If $P_{LV}(i,k))>0$  &  $SOC_i(k) > 0$
        $P_{charging(k)} = 0, P_{discharging(k)} = SOC_i(k)$
else    $P_{charging(k)} = 0,\ P_{discharging(k)} = 0$
```

In further step state of charge of a storage system is calculated integrated the power charge and discharge in every interval predefined by the model.

3.4.2 Minimizing Storage Size

Storage size may vary, however, depending on the particular needs of a facility and the length of power outages expected. According to [61] it is reasonable to find the minimum storage size to reduce curtailment. By minimizing the total cost of storage, optimal power flow (OPF) find the minimum sizes (power and energy) able to reduce curtailment. For this purpose, an iterative process must be adopted in the frame work. Active network management (ANM) has the potential to facilitate the integration of large volume of renewable distribution generation (DG).

Network issue could be actively managed in real-time by storing the excess of DG capacity exist within the same distribution network. The OPF also embeds ANM schemes that provide further flexibility to manage congestion and voltage constraints, potentially allowing the use of smaller storage sizes.

Two stages are considered in order to fulfill this objective. The first stage considers only hourly time-series data between the scale of problem and the high granularity representation of the operational aspects. however, this granularity might result in over or undersized storage facilities given that intra-hourly fluctuation has been neglected. The storage requirements for a congestion issue due to a 60-min average generation can be significantly different from those resulting from 15 or 1-minute values where sudden curtailments occur. Consequently, a second stage is introduced by which the optimal control is applied adopting a high granularity. The second stage examines the actual curtailment level to be achieved by the storage sizes determined in the first stage. This is done by considering 1-minute control cycles.

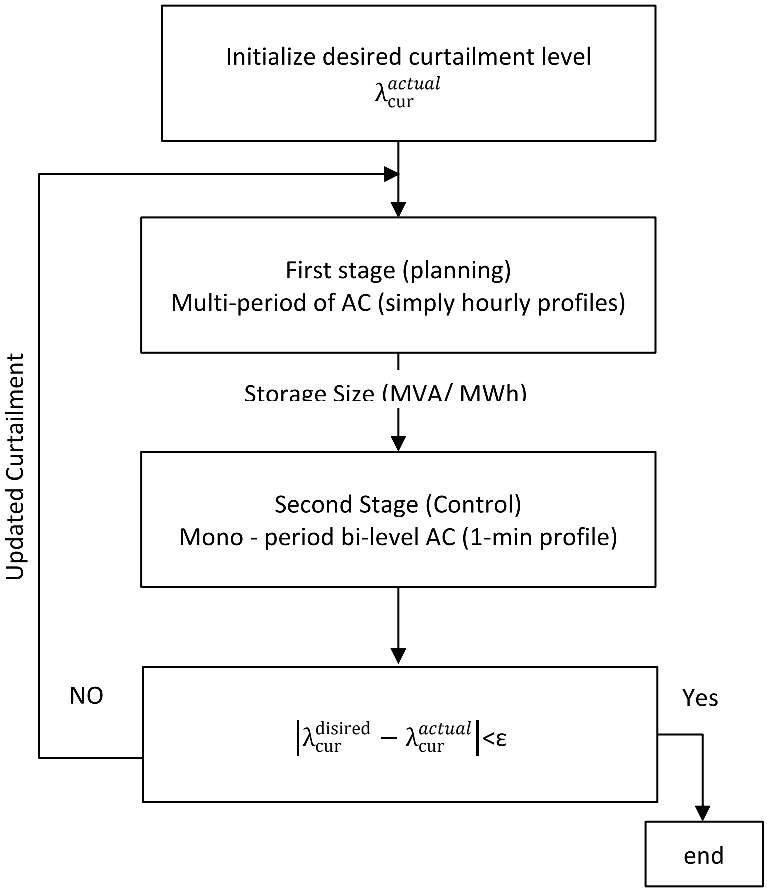


Figure 3-3 Two storage sizing framework

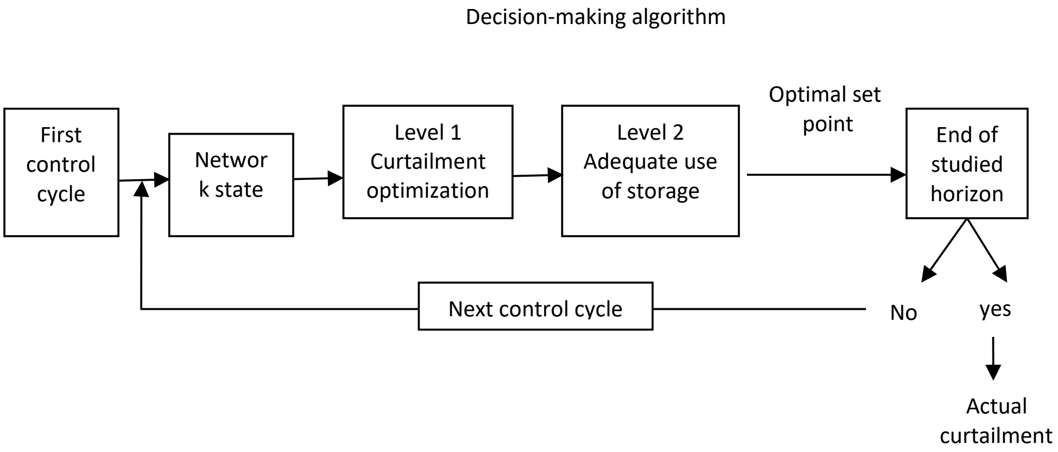


Figure 3-4 Control framework of curtilment

The figure above shows the second stage examination, where the actual curtailment level to be achieved by the storage sizes determined in the first stage. This is done by considering 1-minute control cycles.at the start of each control cycle, the state's load, generation, storage devices are sent to the decision-making algorithm to find the best set points of controllable elements that allow minimizing generation curtailment (level 1).to guarantee that the storage devices only store the excess of generation determined in level 1, level 2 is introduced. In addition, for those control cycles where there is no need of curtailment, level 2 also determines the adequate level of discharge. After level 2, the final optimal set points for all controllable elements are issued.

If the difference between the actual curtailment level, $\lambda_{\mathrm{cur}}^{actual}$ is obtained at the second stage and the desired curtailment level , $\lambda_{\mathrm{cur}}^{desired}$ is outside the tolerance is defined by ε. The first stage is given an updated curtailment level which is calculated by adjusting the previous curtailment level up or down according to the binding tolerance and a defined step. The optimization carried out in Level 1 maximizes the total active power of the controllable DG plants, p_n^+, whose maximum values are restricted by the available resource, P_n, at that control cycle. By maximizing the harvesting of DG plants, the minimum volume of curtailment is ensured for the corresponding control cycle [61].

$$Max \sum\nolimits_{n \epsilon N} \mathrm{P}_n$$

$$\mathrm{P}_n < \mathrm{p}_n^+$$

where the available power resource p_n^+ is product of the DG power rating, $\mathrm{p}_n^{rated}$for that control cycle. Once the maximum active power of controllable DG is identified, the volume of curtailment E_{curt} can be determined.

$$\mathrm{E}_{curt} = \sum_{n\epsilon N} (\mathrm{p}_n^+ - \mathrm{P}_n) \ \Delta\mathrm{T}_c$$

where $\Delta\mathrm{T}_c$ is 1/60 hour (1-min control cycle)

To determine the minimum size of storage facilities, for both energy and power, the objective function is formulated to minimize a proxy of the overall capital cost. This allows realistically relating energy capacities and power ratings in a single equation, as shown in following formula [61].

$$min \sum_{\mathrm{st} \in \mathrm{ST}} \mathrm{C_E} \ E_{st}^{rated} + \mathrm{C_s} \, S_{st}^{rated}$$

The minimum energy capacity represented by E_{st}^{rated} (MWh) and apparent power rating represented by S_{st}^{rated} (MVA). The weighting coefficients $\mathrm{C_E}$ and $\mathrm{C_s}$ are the relative costs of the energy capacity and the apparent power rating, respectively.

Storage facilities are controlled to discharge (inject) or charge (absorb) active power, $\mathrm{P_{st,t}}$, at each time step within the converter apparent power rating, S_{st}^{rated}. Positive values of $\mathrm{P_{st,t}}$, correspond to injection of power (discharging) [61].

$$-S_{st}^{rated} \le \mathrm{P_{st,t}} \le S_{st}^{rated}; \ \forall \ \mathrm{st,t}$$

The energy losses that result from energy and power conversion must be accounted for during charging and discharging. Therefore, the change in the stored energy, $\Delta E_{st,t}^{stored}$ at each time step and the corresponding stored energy, $E_{st,t}^{stored}$ can be represented by following formula.

$$\Delta E_{st,t}^{stored} = \begin{cases} \frac{\mathrm{P_{st,t}}\,\Delta \mathrm{t}}{\eta_{st}^{dis}}, & \mathrm{P_{st,t}} \ge 0 \\ -\ \mathrm{P_{st,t}}\, \eta_{st}^{char} \Delta \mathrm{t}, & \mathrm{P_{st,t}} < 0 \end{cases} \quad \forall \ \mathrm{st,t}$$

$$E_{st,t}^{stored} = E_{st}^{(0)} + \sum_{\mathrm{t=t}}^{\mathrm{t}} \Delta E_{st,t}^{stored} \quad \forall \ \mathrm{st,t}$$

where η_{st}^{char} and η_{st}^{dis} are the charging and discharging efficiencies, respectively. Δt is 1 hour and $E_{st}^{(0)}$ is the initial stored energy at the beginning of the planning horizon.

Based on [11] charging and discharging the state of charge of the battery at each t can be calculated by the following formula.

$$\mathrm{SoC_t} = \mathrm{SoC_{t-1}} - \frac{\eta\, \mathrm{P_{st,t}}\, \Delta \mathrm{t}}{E_{st}^{rated}}$$

$$\eta = \frac{1}{\eta_{st}^{dis}} \text{ in discharging phase } \quad \mathrm{P_{st,t}} \geq 0$$

$$\eta = \eta_{st}^{char} \text{ in charging phase } \quad \mathrm{P_{st,t}} < 0$$

As the battery storage is considered, it is important to ensure battery is discharging appropriately, otherwise discharging could lead to the huge loss. Broadly, the objective of the storage control strategy is that the rate of charge or discharge of the storage depends on its state of charge, as well as the relative prices in the wholesale electricity market [56].The stored energy is controlled between a minimum level and its rated capacity and it is shown by following formula.

$$1 - DoD^{max}(1 - \mathrm{DoDmax})\, E_{st}^{rated} \leq E_{st}^{rstored} \leq E_{st}^{rated};\ \forall\ \mathrm{st, t}$$

3.5 Implication of Marketing During Curtailment

To some extent energy demand is predictable, and fossil fuel plants can be scheduled to start and stop, at times of anticipated demand change. Additional plants that start and stop quickly (e.g. gas turbines) can be held in reserve for unanticipated demand changes. On the renewable side, solar and wind power do not have this character at all and energy output simply cannot be increased on demand [62]. It is still not clear under which condition storage system integration with renewable energy can be profitable and to which extent economic optimization of PV system and storage size affects the profitability of storage over time in large scale power plants. Besides in the course of time the subsidies for customers have been decreasing and the costs for electricity per kWh have been continuously rising.

According to [8] marketing incentive program for the storage of the government improves the financial results clearly. Furthermore, the comprehensive market experience is required in order to forecast guaranteed return. Technical reduction for unavailability of sunlight, seasonal variation of solar radiation, seasonal variation of the load shutdown of plant due to the permit conditions, cable losses, investment cost of EES investment prices, manufacturing tolerance of modules, the effective cell temperature financing parameters must be considered. Germany supports storage through financial incentives for prosumers, which has led to a significant share of new residential PV installations with storage units. In Australia, several thousands of units were installed in 2016, mainly in the residential segment. In other surveyed countries, such developments haven't been reported at the same level [46].

In order to progress the discussion further, we need to introduce a more appropriate metric, the cost of stored energy (COS). This is a much closer approximation to the true cost of battery storage[4]. An individual technical economical optimization is highly recommended, especially concerning the storage size. High efficiency, low operating and high capacity loss can lead to higher profitability [8].

How the storage markets are expected to develop has direct implications for which technologies will be most needed, which technology will need what type of further development, what considerations will influence roll out and penetration and what implementation problems may be expected [1].

Capital cost is certainly an important economic factor, but the total ownership cost must be calculated. For example, the capital cost of lead-acid batteries is relatively low yet may not be the least expensive option for ramp control because of their relatively short lifespan for this type of cycling application. It will be critical to adjust policies, incentives, and operations to accommodate higher levels of variable energy generation from wind and solar power and reduce generation from natural gas.

3.6 Curtailment Market

According to [50] Curtailment market might take the form of generators submitting bids on annual, quarterly, monthly or daily basis in which they indicate their willingness to curtail. In a perfect market, this bid would be equal to the price the NFG would have received had they been allowed to generate during the constraint period. The system operator will always aim to clear the constraint with minimum cost to the system i.e. the lowest bids will be curtailed first compensation might be paid as bid, reflect the curtailment market cleaning price, or be a fixed price e.g., a percentage of a price of wholesale electricity during some period.

3.6.1 Order of Curtailment

Curtailment order can be influenced by market design, contracts, and plant economics, as well as whether the curtailment relates to local transmission congestion or is caused by balancing-related challenges. Real-time pricing which is tariffed retail charges for delivered electricity power varies hour-to-hour and they are determined from wholesale market prices. A number of utilities and operators base curtailment on contracts. If there are transmission constraints, the most expensive energy is curtailed. So the order of curtailment is based on the cost of generators as well as contractual issue [58].

3.6.2 Marginal Cost

The cost added by producing one additional unit of a product or service is called marginal cost. In electricity marketing marginal cost is defined as the cost to serve the next increment of load in a system that is economically operated [63]. Marginal cost plays a key role in the economic theory that proves a competitive market is efficient, but there are also two practical use of marginal cost increase its importance in a power market. Firstly, many markets rely on a central day- ahead auction in which generators submit individual supply curves and the system operator uses these to determine the market price. Because price should equal marginal cost in an efficient market, the auction rules should be informed by a coherent theory of marginal cost. Secondly, many power markets suffer from potential market-power problems which cause the market price to diverge from marginal cost [64]. At the same time, increasing value of storage at high PV penetration could make batteries, at project future cost, competitive with combustion turbines [65].

From a theoretical perspective, curtailment should take place up to the point where the marginal cost of avoiding this curtailment equals the marginal value of spilled energy. For an adequate economic evaluation however, the use of curtailment has to compared to other options for balancing the feed-in of VRG [66].

Increased penetration of renewable generation into distribution networks is presenting number of challenges to distribution network operators, including the provision of network access in capacity constrained networks. Since the distribution networks operate is moving from a passive system to a more active system, is necessary to determine the curtailment arrangements or principle access [50].

Electricity storage is used not only can be used to store excess of energy that would otherwise be curtailed, but is also a primary technology for providing system flexibility in the carbon tax scenario [67].

3.7 Market Indicators of Energy Storage System

There are numerous studies determined the cost effectiveness of EESs where there are used different indicators which are discussed in this chapter. The following chapter is concentrated on levelized cost of energy, since it is the most common indicators to evaluate storage system. LCOE and NPV can be calculated as an output of the model to compare different case of curtailment to see what our best overall option might be.

3.7.1 Levelized Cost of Energy

Levelized cost of energy is a measure of costs which attempts to compare different methods of electricity generation. It is an economic assessment of the average total cost to build and operate a power generating asset over its life time divided by the total energy output. In case of EES integration besides PV degradation, battery degradation over life time of power plant must be taken into consideration. According to [68] levelized cost of energy can be obtained by following formula.

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{(I_t + M_t + O_t + F_t)}{(1+r)^t}}{\sum_{t=o}^{n} \frac{E_t}{(1-r)^t}}$$

Where $E_t = S_t(1-d)^t$

The LCOE for PV systems given by the author also considers the degradation factor of PV modules. The energy generated in a given year E_t is the rated energy output per year S_t which discounted back with discounted rate r, is multiplied by the degradation factor (1-d) which decrease the energy with time. Interest rate is shown by r. The maintenance costs, operation costs and interest expenditures for time year t are donated as M_t,O_t and F_t respectively. It should be noted that the initial investment It is one-off payment. I_t as an investment cost should not be discounted and it should be taken out of the summation [39].

The energy storage installation potential depends on various factors such as surplus PV generation and cost of the storage battery system [59].

3.7.2 Levelized Cost of Storage

According to[69] levelized cost of storage can be defined as following formula.

$$\mathrm{LCOS} = \frac{\mathrm{I_0} + \sum_{\mathrm{t=1}}^{\mathrm{n}} \frac{\mathrm{C_{EES_t}}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum_{\mathrm{t=o}}^{\mathrm{n}} \frac{\mathrm{E_{EES_t}}}{(1+\mathrm{r})^{\mathrm{t}}}}$$

Due the various application of storage system, LCOS can be widely change. Besides, the storage levelized cost estimations are incomplete, since they do not cover the required business models and its characteristics for storage [39].

According to [59] the levelized cost of BEES, LCOES is the ratio between the total cost of a BEES and the life cycle discharge throughout the project considering the value of money time.

$$\mathrm{LCOES} = \frac{\mathrm{CAPEX} + \frac{\mathrm{OPEX}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum_{\mathrm{t=o}}^{\mathrm{n}} \frac{\mathrm{E_{dis}}}{(1+\mathrm{r})^{\mathrm{t}}}}$$

3.7.3 Levelized Cost of System

The economic feasibility of an energy generation project can be evaluated using various metrics, but the levelized cost of electricity generation is most often used when comparing electricity generation technologies or considering grid parity for emerging technologies or considering grid parity for emerging technologies such a PV [70].

Subsequently levelized cost associated to the storage itself, based on the value of the PV generation which is curtailed and considering whole sale price is defined as Levelized Cost of Storage and it is given in equation below [68].

$$\mathbf{LCOE_{system}} = \frac{\sum_{t=0}^{n} \frac{C_{system_t}}{(1+r)^t}}{\sum_{t=o}^{n} \frac{E_{system\ t}}{(1+r)^t}}$$

LCOE is also not perfect indicator. LCOE does not measure the reliability of a battery, or the impact of the sourcing of its components on the environment and while it looks at the cost side of the equation, it fails to look at the other side revenue.

According to [70] the LCOE calculations are assumption were clarified. It was found that lack of clarity in assumption and justifications in some LCOE estimates could lead to the wrong outcomes. therefore, sensitive analysis is required.

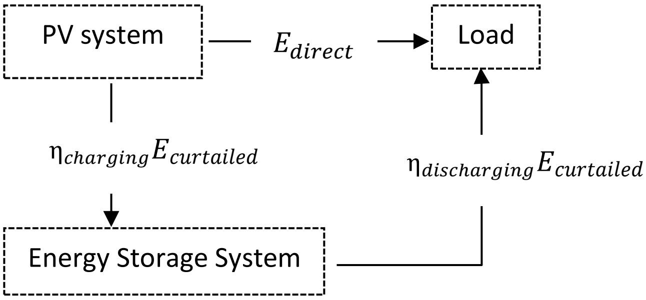
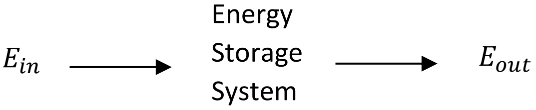


Figure 3-5 Energy Flow Diagram PV System Integrated with EES

The figure above shows the energy flow diagram of the PV system integrated with storage system. In the figure below the direction of energy flow of EES has been shown.



Consequently in order to proceed cost calculation the following formulas are given [39].

$$\mathrm{LCOE}(\mathrm{E}_{in}) = \frac{\sum_{t=0}^{n} \frac{C_{in\ t}}{(1+r)^t}}{\sum_{t=o}^{n} \frac{E_{in\ t}}{(1+r)^t}}$$

$$\mathrm{LCOE}(\mathrm{E}_{out}) = \frac{\sum_{t=0}^{n} \frac{C_{in_t}}{(1+r)^t}}{\eta \sum_{t=o}^{n} \frac{E_{in\ t}}{(1+r)^t}} + \frac{\sum_{t=0}^{n} \frac{C_{ESS_t}}{(1+r)^t}}{\eta \sum_{t=o}^{n} \frac{E_{in_t}}{(1+r)^t}}$$

C_{in_t} is the total cost for delivering the PV energy into EES at year t. E_{in_t} is the input energy to the EES at year t. the LCOE for EES in a renewable energy system is more complicated to comprehended.

C_{system_t} and $E_{system_t}$are the total cost and total energy production from the system at time t respectively. The total cost of the renewable system is the sum of PV generation and storage costs. The total energy produced is the energy output of EES and the energy directly delivered to the PV load by PV, therefore, the LCOE for the system is given in following formula [71].

$$\mathrm{LCOE(E}_{in}) = \frac{C_{pv_{direct}} + C_{pv_{curtailed}} + C_{ESS}}{E_{ESS} + E_{pv_{direct}}}$$

3.7.4 LCOES Versus LVOES, Total Revenue

Levelized cost of energy storage, measures the total revenue and the levelized value of energy storage are obtained by:

$$\mathrm{LCOES} = \frac{CAPEX + \dfrac{OPEX_{Ct}}{(1+r)^k}}{\sum_{k=0}^{n} \dfrac{E_{dis}}{(1+r)^k}}$$

$$\mathrm{LVOES} = \frac{\sum_{k=1}^{n} \dfrac{BESS_{value}}{(1+r)^k}}{\sum_{k=1}^{n} \dfrac{E_{dis}}{(1+r)^k}}$$

3.7.5 LCOES Versus LVOES, Benefit of Energy Time-Shift

According to [59] the levelized cost of energy is calculated individually for economic benefit of energy time shift stored into the EES. The levelized cost of a BEES is the ratio between the total cost of a BEES and the life cycle discharge time, considering the value of money time can be summarized in following formula.

$$\mathrm{LCOCt} = \frac{\dfrac{OPEX_{Ct}}{(1+r)^k}}{\sum_{k=0}^{n} \dfrac{E_{dis}}{(1+r)^k}}$$

Likewise, the levelized value of energy storage, LVOES, measured the total revenues (avoided cost) the benefit is given by T&D upgraded deferral value is given by following formula.

$$\mathrm{LVOCt} = \frac{\sum_{k=1}^{n} \frac{BESS_{T\&D}}{(1+r)^k}}{\sum_{k=1}^{n} \frac{E_{PVCt}}{(1+r)^k}}$$

3.7.6 NPV

Finally, Net Present Value per unit of CAPEX to balance cost and value of batteries is given by following formula. Where CF_k refers to cash flow of year K considering economic benefit.

$$NPV_{CAPEx} = \frac{\sum_{n}^{K=0} \frac{CF_k}{(1+r)^k}}{\mathrm{CAPEX}}$$

3.8 Conclusion

So far overall cost of EES integration considering specific parameters must be presented are discussed. This chapter investigated the battery integration of photovoltaic power plants during curtailment. To quantify the ability of storage to mitigate curtailment the input such as duration, energy, power and both daily and seasonal hours of curtailment of the system is required. To reduce energy curtailment iterative process with real-time control aspects to achieve more accurately size is required. This can be realized in two steps. The first-stage provides initial storage size for planning and the second stage provides the effective controlling. This two-stage iterative process allowed the refinement of multiple storage sizes for a more accurate curtailment minimization.

The ability to avoid curtailment is a function of both the power and energy capacities of the energy storage system. The simulation with varying energy storage size to examine curtailment reduction is suggested. To investigate the performance of different battery technologies, key parameters should be further investigated. This includes technical parameters, such as battery efficiency, maximum depth of discharge, etc. as well as non-technical, such as the power-energy cost relationship. Furthermore, the proposed planning framework can be extended to incorporate the effects of charging and discharging cycles on the lifetime of the storage facilities, either as constraints based on the battery characteristics or as a cost embedded in the objective function

As it is discussed market price effect on charging and discharging EESs and losses during charging and discharging. The following sections describe how the values are processed in the model to generate our results in different studies. Battery lifetime is greatly affected by the number of discharge or recharge cycles and the depth of discharge in terms of percentage of total discharge. LCOE is a crucial factor as an output of the model to compare different case of usage of the batteries to see what best overall option might be. Other economic optimality and incentive are discussed, furthermore, indicators such a $LCOE_{system}$, LVOES and LCOS are defined in different studies. In the next chapter, different scenarios are discussed to demonstrate the marginal LCOE due to the constraint in solar energy. The following table introduces the most important indicators in EES integration system with renewable energy.

Table 3-2 Economic indicators of storage system integration with PV plant

Net Present Value	$\mathbf{NPV_{CAPEx}} = \frac{\sum_{\mathbf{n}}^{\mathbf{K=0}} \frac{\mathbf{CF_k}}{\mathbf{(1+r)^k}}}{\mathbf{CAPEX}}$
Levelized value of energy storage considering the benefit is given by T&D upgraded deferral	$\mathrm{LVOCt} = \frac{\sum_{k=1}^{n} \frac{BESS_{T\&D}}{(1+r)^k}}{\sum_{k=1}^{n} \frac{E_{PVCt}}{(1+r)^k}}$
Levelized cost of energy considering the benefit of energy time shift stored into the EES	$\mathrm{LCOCt} = \frac{\frac{OPEX_{Ct}}{(1+r)^k}}{\sum_{k=0}^{n} \frac{E_{dis}}{(1+r)^k}}$
Total levelized cost of storage	$\mathrm{LCOS} = \frac{\mathrm{I_0} + \sum_{\mathrm{t=1}}^{\mathrm{n}} \frac{\mathrm{C_{EES_t}}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum_{\mathrm{t=o}}^{\mathrm{n}} \frac{\mathrm{E_{EES_t}}}{(1+\mathrm{r})^{\mathrm{t}}}}$

Total levelized cost of system (power plant and storage)	$\mathrm{LCOE}_{\mathrm{system}} = \frac{\sum_{t=0}^{n} \frac{C_{system_t}}{(1+r)^t}}{\sum_{t=o}^{n} \frac{E_{system\ t}}{(1+r)^t}}$

4 Chapter 4: Case Studies

In this chapter the different techno-economic studies are summarized in case of EESs integration with PV plants during curtailment. The following studies address different scenarios from end-users or the main grid, single dwelling or substation.

4.1 Case study1: Dwelling versus main Grid, Zurich

In this study (et al. Felix Rafael;2018) battery storage, PV curtailment and grid reinforcement are compared for residential area in Zurich with large PV penetration from a techno-economic perspective. The analysis focuses on the implication of the location and related size of the battery storage and the type of curtailment control (fix versus dynamic) for relevant stakeholders such as consumer and the distribution network operator. In the base line scenario, PV curtailment is used to reduce the reverse power flow (electricity feed-in) at the medium to low voltage transfer. The reactive power control (RPC) and on-load tap changers (OLTC) are excluded. The results are used to discuss trade-offs between storage system and PV curtailment control by consumers and DSOs.

Lithium-ion battery is used, and battery life time is considered without including the lifetime of existing power plant planned by 2035. Twice level of current price of 0.5 CHF/kWh (.42 cents/kWh) was used as an input data. From the cost perspective, a BEES comprises four components, namely cell stack (storage medium), inverter cost, balance-of-plant (BoP) and maintenance. The following input considered in order to provide cost and revenue study of battery integration.

Table 4-1 Technical and economic characteristics of Li-ion battery for lithium-ion battery energy storage system

EES type	Li-ion battery
Round Trip Efficiency [%]	90
Maximum SOC	0.8
Minimum SOC	0.1
Power Rating [kW]	Q
Cell Cost [€/kWh]	285
Battery Inverter rating [kW]	Q

Battery Inverter Cost [€/kW]	285
Balance-of- Plant Cost [€/kW]	8.5
Maintenance Cost	8.5
Maximum Cycle Life	3000
Maximum Calendar life [years]	22
Calendar losses [%/month]	0.07
Discount Rate [%]	4

Table 4-2 PV generation and electricity demand characteristics of the dwelling selected for the study of the residential battery system

PV installed capacity	Peak Electricity Demand	Annual PV Generation	Annul Demand
4.9 kW	5.9 kW	5550 kWh	2900 kWh

The cost of storage could be different for various batteries. The battery cost per kWh means the total capacity of the battery is expressed in Watt hour, which is found by multiplying voltage per ampere hour. The price per kWh is considered by dividing the price for a battery by the capacity of the battery. Scenarios which are considered are defined and summarized in table below to compare EES technology versus PV curtailment from a cost and value perspective.

Table 4-3 Various scenarios to compare EES technology versus PV curtailment

scenario	B_1	B_2	B_3	C_1	C_2
Solution	BEES	BEES	BEES	Curtailment	Curtailment
Location	Substation	Substation	Dwellings	Dwellings	Dwellings
Owner/Operator	DSO	DSO	Consumer	DSO	Consumer
Electricity Price	Wholesale	Wholesale	Retail	Wholesale	Wholesale
Size/ Control	Optimized	Fixed	Optimized	Dynamic	Fixed
Service benefits	PVts & PVct	PVts & PVct & T&D	PVts & PVct & T&D	T&D	T&D

Economic Benefits	PVts & PVct	PVts & PVct & T&D	PVts & PVct & T&D	T&D	T&D

Note that in scenario B1, BEES shift any surplus of energy across the distribution network, but it does not assure the maximum reverse flow is always smaller than the physical capacity of the transformer. In case B2 the size of 1.65 MWh of EES are chosen to store any reverse flow power larger than the nominal size of the transformer.

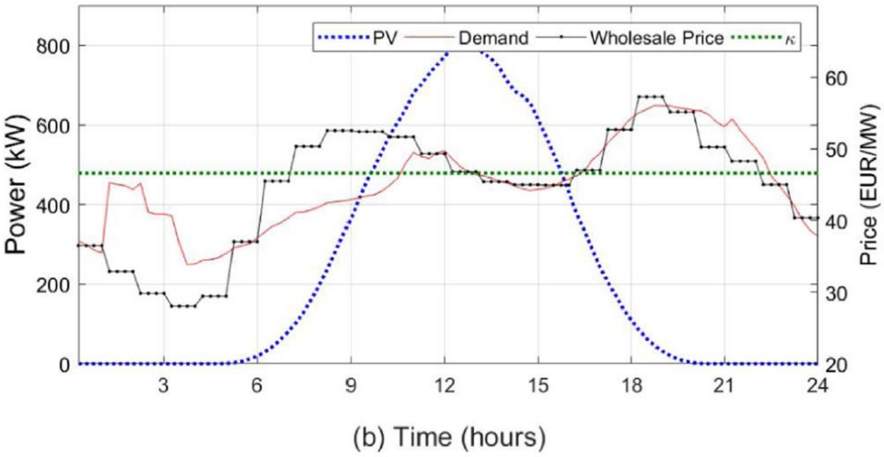


Figure 4-1 Average PV Electricity Demand, Electricity Price Limit per Day

The figure above shows that how the whole sale price is changing over 24 hours by the demand. LCOE and LVOE of EES capacity for the various scenarios are calculated and presented in figure below.

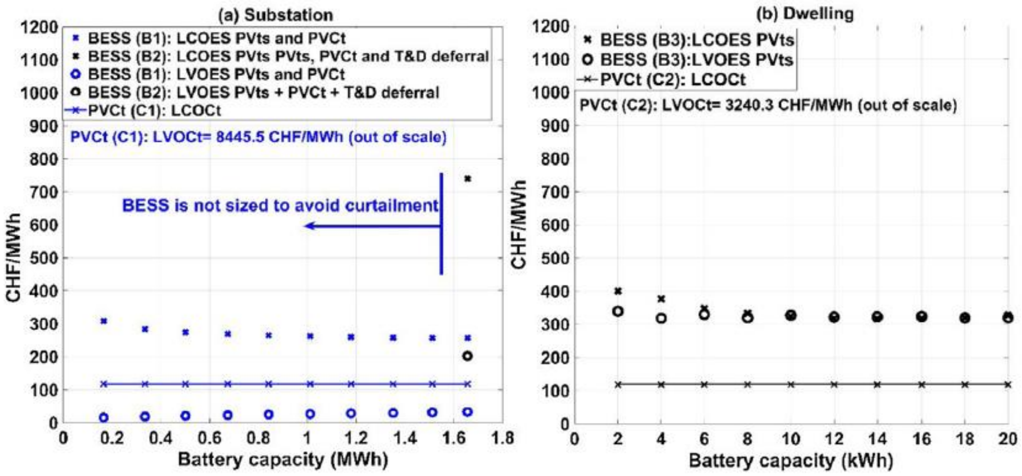


Figure 4-1 a) Substation: LCOES and LVOES for the scenarios corresponding to solution implemented in the substation namely B_1 , B_2 and C_1; b) Dwelling: Scenarios corresponding to solution located in an individual dwelling, namely $,B_3\ and\ C_2$, for the scenario B_1 results are presented by the function of the battery capacity.

Table 4-4 LCOE and LVEOS Substation Scenarios:

Battery capacity [MWh]	LCOE [CHF/MWh]	LVOES [CHF/MWh]
0.2	308.1	15.7
1.5	357.1	33.3

The LCOE of the residential EES is always higher than for the EES connected to the distribution transformer. Also, the value associated with the discharge is higher than its cost. Note that LCOE is related to the cost of EES integration, while LVOES is benefit achieved from the battery.

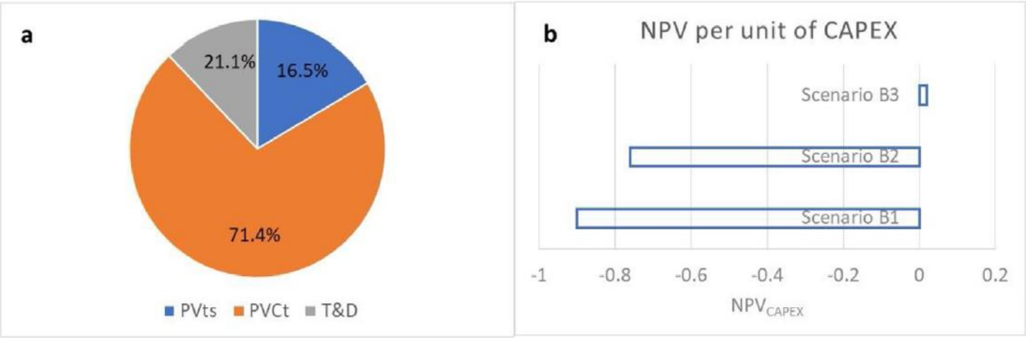


Figure 4-2 a) Break down a value creation as percentage of the 1.6 MWh battery is the scenario B namely PV energy time shift and avoidance PV curtailment and upgrade deferral b) NPV per unit of capex for the three different battery scenarios (optimal EES in scenario).

As a result, there is slight positive NPV per unit of CAPEX in case of residential batteries. Managing PV energy with a BEES at the residential increases both levelized value and levelized cost of stored PV electricity compared to a centralized management by the DSO. Consumers should pay 23% more for the battery discharge from a life-cycle perspective but residential batteries allow them to replace retail electricity and this fact increases the value of the battery discharge markedly. This helps to create marginal economic cases for residential batteries with positive NPV results since LVOES is slightly larger than LCOS values. Regarding DSOs avoidance of PV curtailment and distribution upgrading bring some benefit but LVOES is still less than LCOS.

4.2 Case study 2: 50% PV Penetration, California

In this study (et al. Paul Denholm ;2016) the amount of storage that may be required to satisfy up to 50% of California's electricity demand with solar photovoltaic technology and the amount of storage required to achieve high penetration of PV in a set of low, mid and high grid flexibility has been discussed. Solar penetration in California in 2014 was 16,148 GWh which contains 6% of total annual generation of energy. Before evaluating the storage, the impact of increased generator flexibility, demand response, exports and electric vehicle are considered. However, even a very flexible power system will likely need additional storage to enable 50% penetration of PV. In this study PV Penetration is the ratio of peak PV power to peak load apparent power. Assuming a target year of 2030, plausible pathway exists for PV to achieve a levelized cost of electricity as low as 3 cents/kWh. This would allow PV to have very high curtailment rates and still achieve a net-LCOE goal of 7 cents/kWh. The net-LCOE is defined as the cost of energy that can be used by the grid after considering curtailment and storage losses.

It is essential to consider power of storage system in order to save energy in a short time. In this study the storage capacity is determined by power. Three scenarios have been defined. For each scenario the marginal curtailment and LCOE for different level of PV penetration with additional storage are calculated. Add storage has eight hours of usable capacity, which would allow the added storage to replace new peaking capacity.

Table 4-5 the values represent the peak and average shiftable load during months of highest curtailment

	Low Flexibility	Mid Flexibility	High Flexibility
Minimum Generation Level [GW]	10	8.75	7.5
Export Capacity [GW]	2.5	5	10
Demand Respond Availability [GW peak/avg. daily GWh]	0.4/22	2/10	4/21
EV Penetration	5%	15%	25%

Fraction of EVs Optimally charged	33%	50%	75%

The storage is assumed to have 8 hours' capacity with an 80% round-trip efficiency.

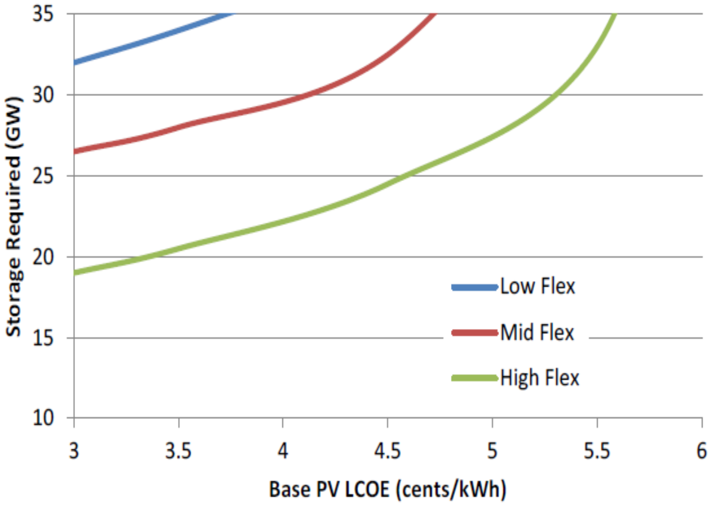


Figure 4-3 Energy Storage Required to achieve a marginal net PV LCOE of 7 cent/kWh as a function of base PV LCOE at 50% PV penetration and two levels of grid flexibility

Net LCOE is defined as:

$$\mathbf{LCOE_{Net}} = \frac{\text{LCOE}}{(1 - \text{curtailment rate})}$$

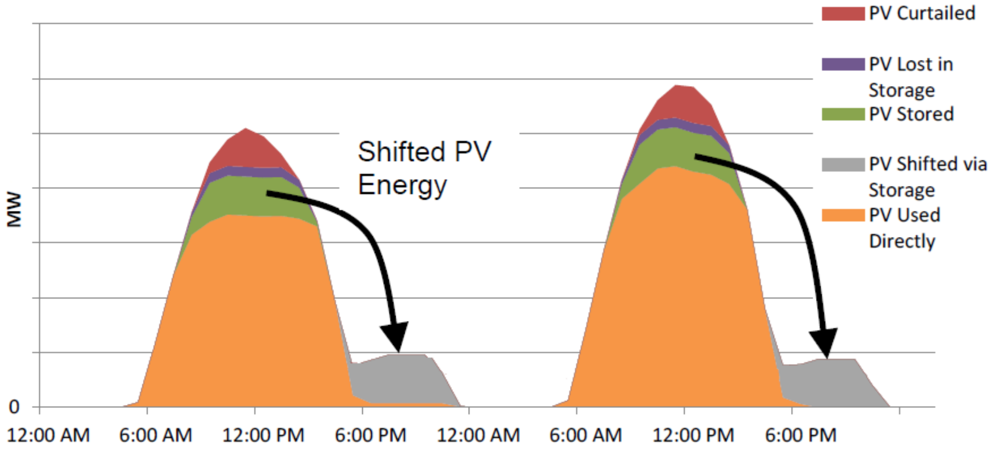


Figure 4-4 System Dispatch in 48 hours with 20% Potential Annual Solar, California

With 20% potential annual solar 4.6% of energy will be curtailed. The figure below shows the marginal and average curtailment rates of PV as a function of annual energy.

The marginal and average curtailment rates of PV as a function of annual energy contribution from PV has been illustrated.

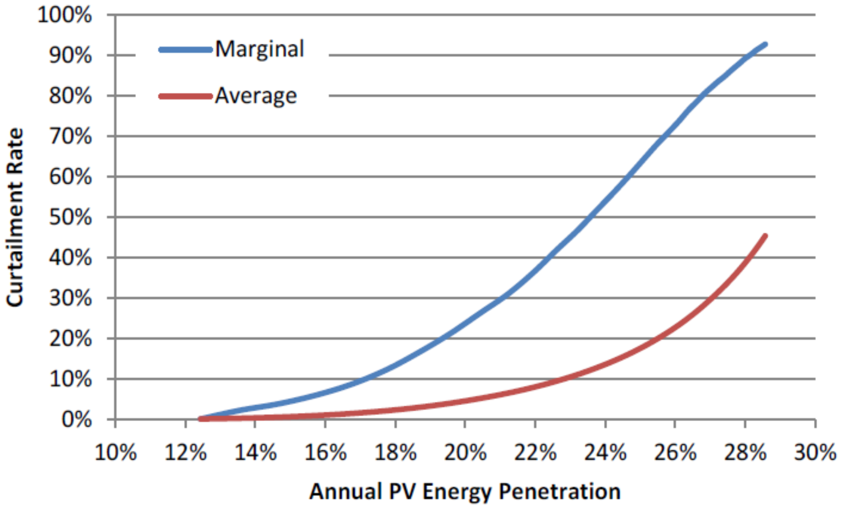


Figure 4-5 Curtailment Rate for Annul PV Energy Penetration

The marginal and net LCOE of PV assuming a base LCOE of 6 cents/kWh are shown in figure below. As curtailment increases as the net LCOE increases. The marginal curtailment rate increases rapidly once PV penetration rise above 20%.

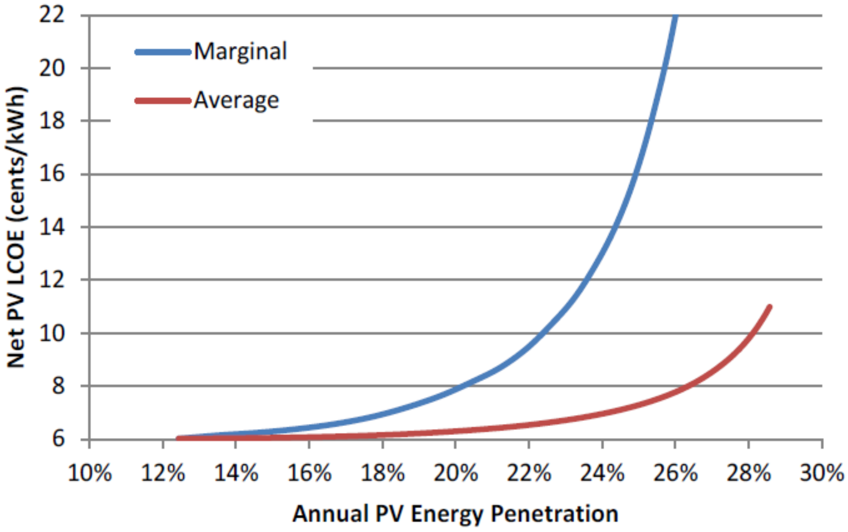


Figure 4-6 Net LCOE base PV cost of 6 cents/kWh

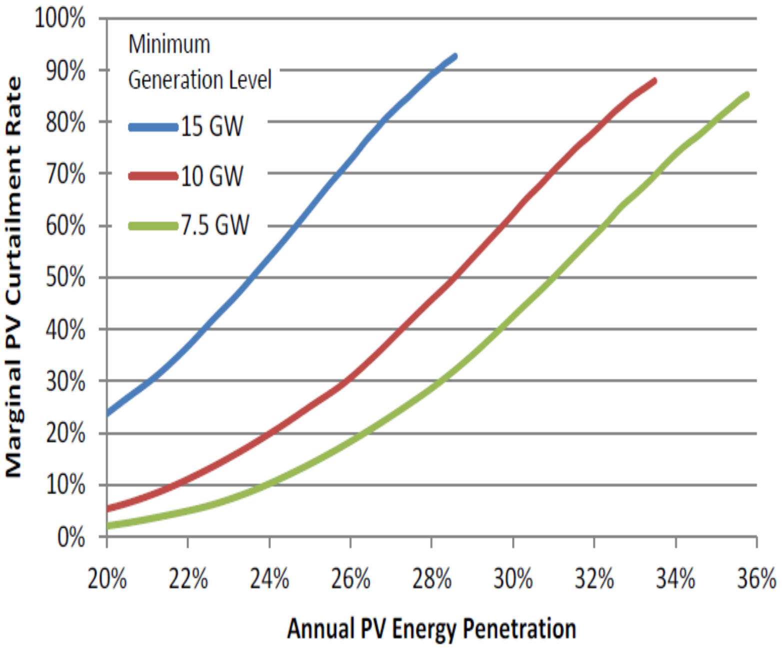
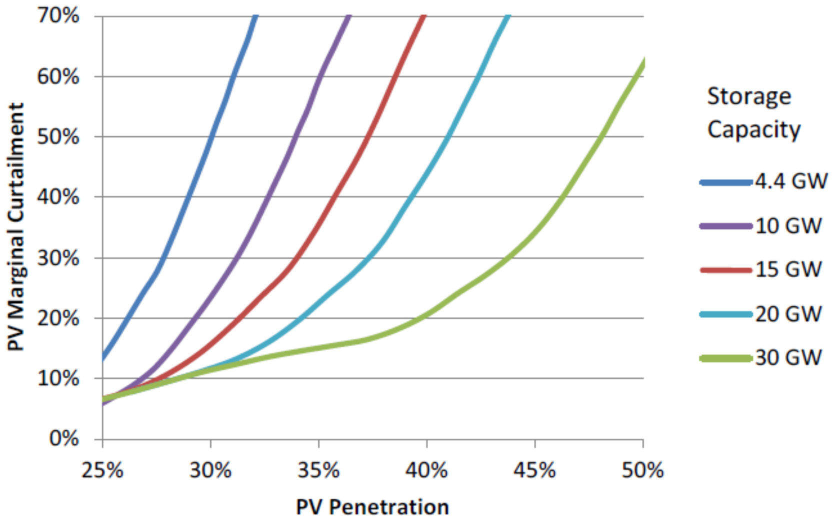
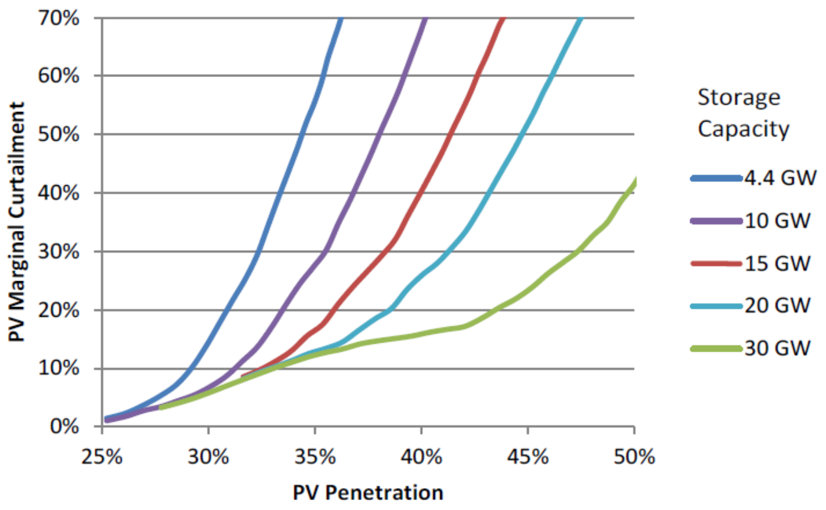


Figure 4-7 Impact of System Minimum Generation Level on Curtailment with Increasing PV Penetration

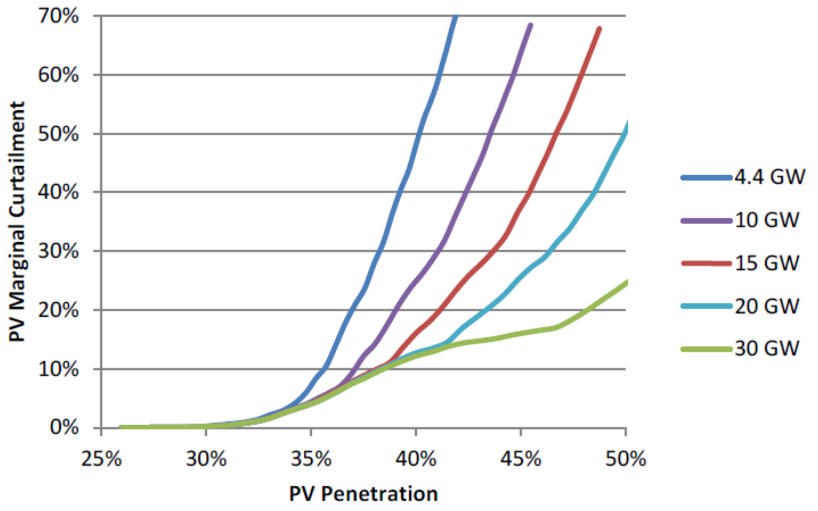
The figure above shows curtailment as a function of PV penetration at three different generation levels. The 10 GW case could be achieved from a 50% reduction in minimum generation level from cogeneration plants and the elimination of must-take contract with out of state generation. The7.5 GW case represents a further 50%reduction in minimum generation levels.



(a) Low flexibility



(b) Mid flexibility



(c) High flexibility

Figure 4-8 Relationship Between System Flexibility, Storage Capacity and Curtailment for low, mid and high flexibility

Figures above summarize marginal curtailment as a function of PV for each flexibility scenario. Each curve within the separate scenarios represents a different amount of storage ranging from the base storage capacity of 4.4 GW to 30 GW. Figure a demonstrate that 30 GW of storage and low flexibility result in marginal curtailment exceeding 60% at 50% PV. Curtailment decreases substantially as flexibility and storage increase. Each curve shows lower limit to marginal curtailment independent of the amount of storage added, because storage losses are counted as curtailment. At lower levels of flexibility, more PV energy must be cycled through storage. In the low-flexibility scenario, for example, when PV reaches 30% penetration, about 60% of the incremental PV is placed into storage and 40% is used directly. As flexibility increases, less PV energy must be cycled through storage, which lowers the minimum curtailment rate. The figure below translates the results in into marginal LCOEs as a function of storage capacity for each flexibility scenario as well as wo base PV costs: 6 cents /kWh and 3 cents/kWh (the net LCOE is multiplied by 1/(1-marginal curtailment rate).

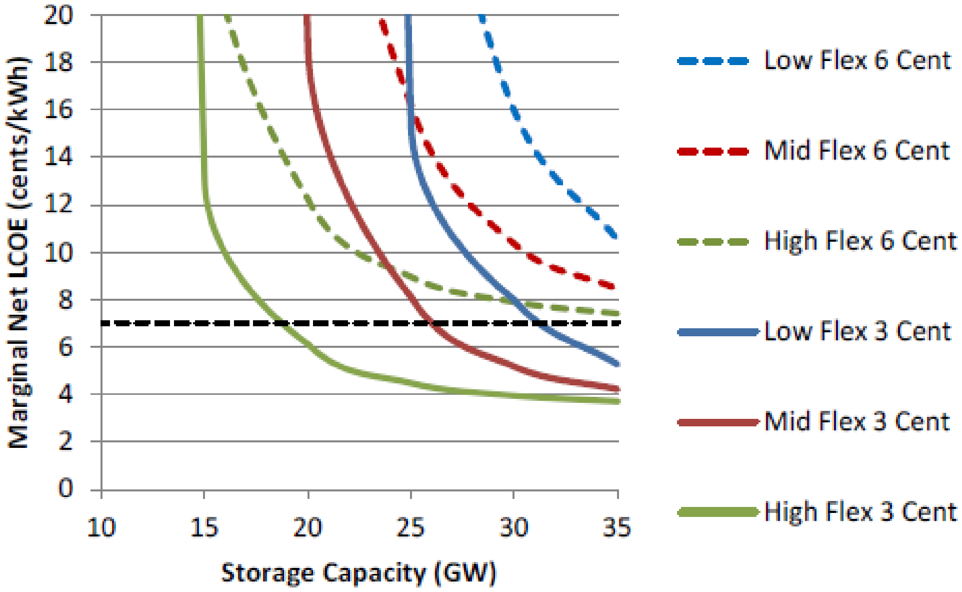


Figure 4-9 Marginal net LCOE as a function of energy storage capacity at 50% PV penetration for each flexibility scenario and two base PV costs 3 cents/kWh and 6 cents/kWh

In the figure below the amount of storage needed is examined as function of base PV LCOE using the target of 7 cents/kWh for the net LCOE.

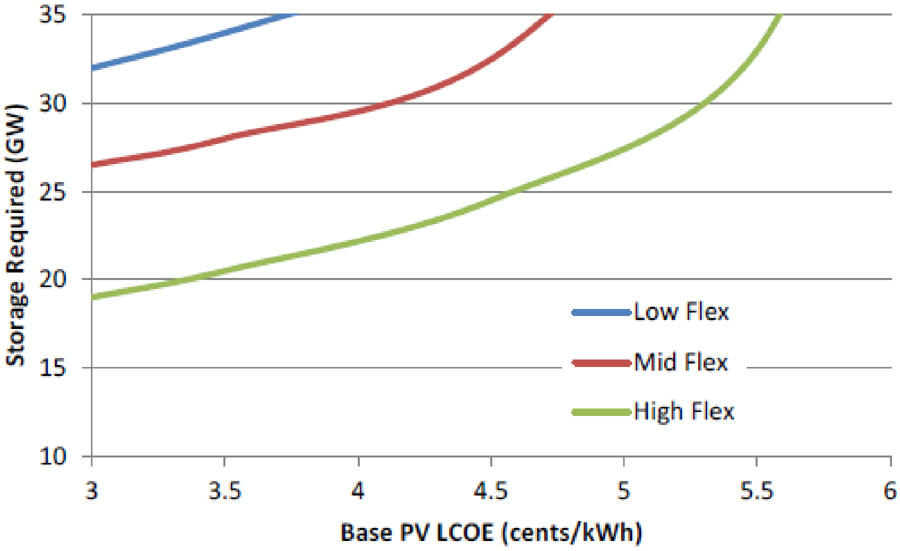


Figure 4-10 energy storage required to achieve a marginal net PV LCOE of 7 cents/kWh as a function of base LCOE at 50% PV penetration and three levels of flexibility

Consequently, 30 GW of storage and low flexibility result in marginal curtailment exceeding 60% at 50% PV penetration. In mid-flexibility scenario, with 50% PV penetration the marginal curtailment rate drops below 40%.

	low flexibility	**mid flexibility**	**High flexibility**
Maximum curtailment	60%	40%	20%

Figure 4-11 PV marginal Curtailment for low, mid and high flexibility with the storage capacity of 4,4 GW to 30GW

As a result:

- Reducing the base LCOE of PV would help to have some benefit, but the shape of marginal curve means even very low-cost PV would require addition grid-flexibility measures to achieve penetration beyond 25% of PV technology.
- The significant increase in storage requirements when moving to lower grid flexibility or higher PV costs

- Curtailment’s impact on PV economics can also be measured as increased cost, here translated net LCOE which is defined as the cost.
- Curtailment decreased subsequently as flexibility and storage increase
- As flexibility increases, less PV energy must be cycles through storage, which lowers this minimum curtailment.
- It estimated that with very low-cost PV with a base-LCOE at 3 cents/kWh 19 GW of storage would be required.
- The study shows that both grid flexibility and low-cost PV appear critical to reducing storage requirements.

4.3 Case study 3: Rate of Curtailment, Biehla

The study is executed for 2.66 MW-p existing power plant Biehla, Germany. The selected parameters are relevant to needed EES which must be integrated by the power plants. The power load of with considered. The optimizing power plant itself is not objective here. The following inputs are considered to calculate economy indicators of EES integration. The installation and O&M cost and installation cost of EES are not considered here.

System Size [kW-p-DC]	2664
Specific Yield [kWh/ kW-p]	968
1st-Year Production [kWh]	2578752
Annual Degradation [kWh]	0.5
EES Type	Li-ion BEESs
Round Trip Efficiency (%)	85
Round Trip Efficiency (%)	85
Maximum SoC	0.8
Minimum SoC	0.2
Battery cost (€/kWh)	300
Battery Inverter Cost(€/kW)	4000
Balance-of- Plant Cost (€/kW)	8.5
Interest rate	2%
Feed in Tariff [€/kWh]	0.07
PPA Escalator [%]	2
Cost of EPC with No Battery System [€/Wp]	87

Table 4-6 Cost and Technical Specification of the System Components of 2.65 MWp power plant

In the first step the import and export of energy during one year with no battery storage has been analyzed. In the second step the study has been carried out with battery integration. Furthermore, curtailment impacts on the system and the energy lost during curtailment have been discussed. The battery storage has been considered to analyze different cases of energy consumption. The charging and discharging model has been analyzed and simulated based on the load profile of the active power import from the grid and the efficiency of the power plant component. The approach provides the optimization of power plant management for charging and discharging EES by applying history data of energy import per day.

The amount of energy which must be saved into the battery is the extra energy which will be wasted, when there is not curtailment the energy charged into the battery is not the extra energy and the profitability is decreasing subsequently, but it is still has more revenue in compare to the case without battery. The profitability of battery storage increases notably when curtailment takes place more often.

In the figure below the active energy export is plotted over one year. Subsequently the Different curtailment level is applied to the export power.

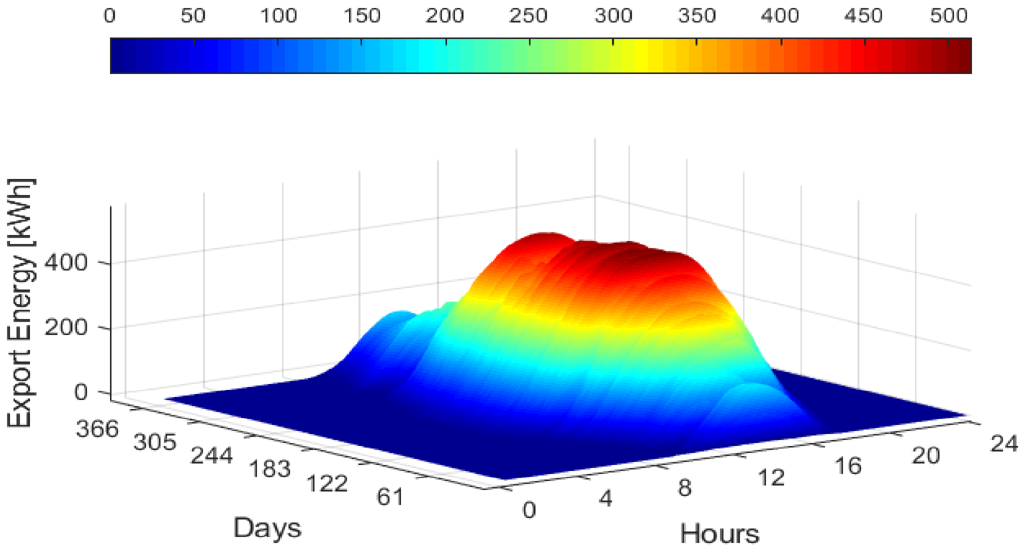


Figure 4-12 Annual Exported Energy with 15 Minutes Interval Measurement
of 2.66 MWp power plant in one year

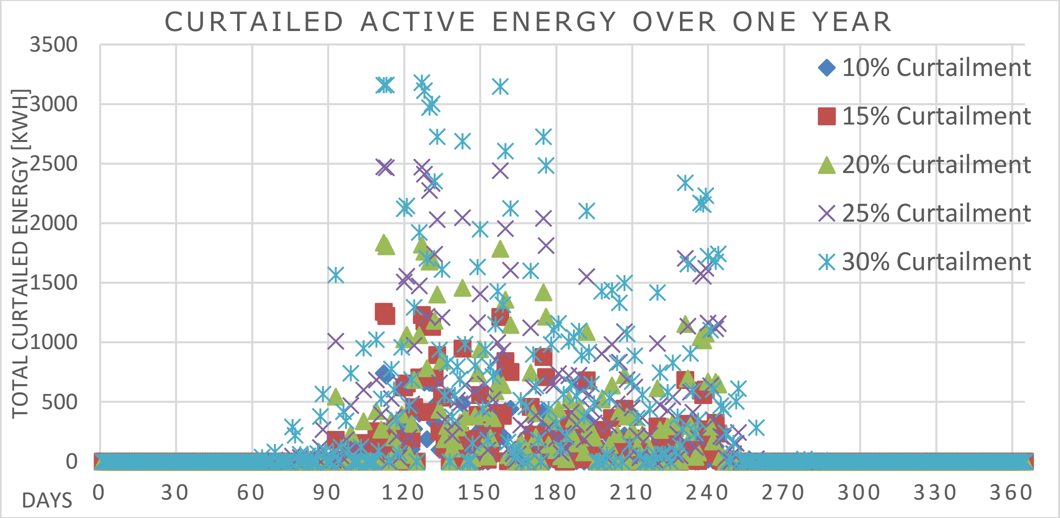


Figura 4-2 Total Curtailed Active power for A 2.66 MWp Power Plant plotted for different rate of Curtailment, Biehla

The results show that by increasing curtailment power rate from 10% to 30%, number of days without curtailment decreases from 66% to 52%. The following values show the energy regarding to different level of curtailment. C_n is defined as the ratio of curtailed power to the total power

Table 4-7 10%, 15%, 20%, 25%, 30% Annual Curtailed Energy of Different Level of Curtailment.

The level of power curtailment	**The curtailed Energy**	**The rate of Curtailment**	**Days without Curtailment**
[%]	[kWh]	Cn	
10%	15667	0,6%	66%
15%	33560	1,4%	60%
20%	59132	2,4%	57%
25%	93314	3,8%	55%
30%	136.803	5,6%	52%

In addition, levelized cost of energy of the PV system and the one which is integrated with EES are compared to different level of curtailment applied to the power rate.

Table 4-8 LCOE for Lithium-ion in Case of the system with Storage and no Storage Integrated for 2.66 MWp Power Plant in Biehla

Curtailment Rate	LCOE No storage [€/kWh]	LCOE with Storage [€/kWh]
0	0.059	0.058
10%	0.059	0.058
15%	0.059	0.059
20%	0.060	0.059

As a result, there is small benefit for the system integrated with the storage system with the 30% level of curtailment. Lower level of curtailment there has smaller benefit. Therefore, Market price can influence on storage system integration during curtailment.

4.4 Case study 4: Study on power plant of 5 MW_p in Kenya and Surplus of Energy

For a 5 MWp power plant in Kenya (et al. McCullagh) three cases are considered:

Case 1: the solar power meat the restriction of the grid or load demand and no curtailment happen,

Case 2: If the solar panel production could not meet the load demand the surplus of energy will be curtailed and discarded due to no storage existence and in case 3 the surplus of energy can be stored in the storage system. [39]. Case one is not objective here. The input data are summarized in the following table.

Table 4-9 Parameters Used for LCOS Study for PV Integration

EES ty	Li-ion BEESs and VRX
Project life time	20
Discount Rate [%]	2
Storage Power Capacity [MW]	2
Storage Energy Capacity [MWh]	4
Cycle Per Day	1.25
DoD	100
Days of Operation per Year	350

Annual Energy Production [MWh]	1750
System’s Total Generate Energy [GWh]	35
Maximum Cycle Life	3000
Maximum Calendar life(years)	22

Table 4-10 Cost and Technical Specification of the System Components

	PV	**Vanadium Redox(VRB)**	**Lithium-ion Battery**
Capital Cost	120 $/kWh	760-1600 $/kWh	715-1648 $/kWh
Installation Cost	108 $/kWh	100-140$/kWh	80-95 $/kWh
System Lifetime	N/A	20 years	20 years
Roundtrip Efficiency		70%	90%

Table 4-11 LCOE for VRB in Case of the system with Storage and no Storage Integrated for 5MWp Power Plant in Kenya.

r (%)	**LCOE ($/KWh) NO Storage**	**LCOE ($/KWh) With Storage**
2	0.168	0.186
5	0.212	0.223
8	0.259	0.262
10	0.291	0.289
15	0.374	0.355

Table 4-12 LCOE for Lithium-ion in Case of the system with Storage and no Storage Integrated for 5MWp Power Plant in Kenya

r(%)	LCOE ($/KWh) NO Storage	LCOE ($/KWh) With Storage
2	0.153	0.183
5	0.182	0.212
8	0.214	0.242
10	0.235	0.263
15	0.291	0.315

As a result:

System without storage attracts a smaller LCOE but naturally at a higher risk of security supply.

From marginal cost can be seen that energy waste will lead to a higher LCOE, so it would be important to add a storage system to minimize the storage wasted and to potentially reduce the LCOE.

It is important to add a storage system as component of the system rather than adding in a later stage. The earlier addition can lead to a smaller LCOE.

4.5 Case study 5: Times scales of EES Needed for Reduction Energy Curtailment

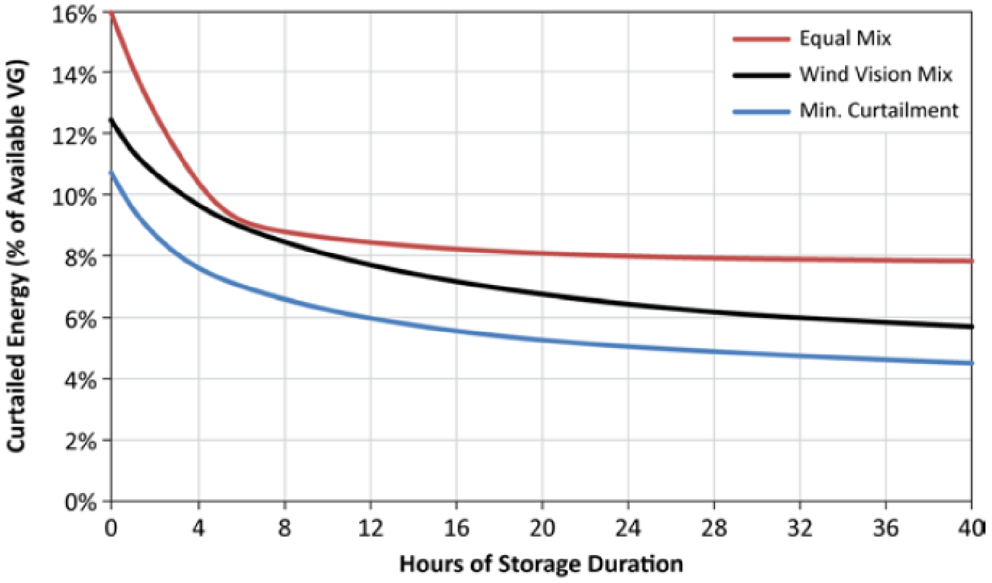
This study is provided by et.al P. Denholm [44]. In this study simulation are performed using 6 years load patterns and corresponding wind and solar generation data (2007-20112) based on hourly load data. The wind and solar energy deployment to 470 TWh is scaled based on historical load profile. The penetration of PV in 2016 is MW. The report analyzes the storage duration required to reduce VG curtailment under high VG scenarios. Further information is not provided in the article.

Effectiveness of EES integration is evaluated by considering two case, with and without the use of storage. The case study examines a scenario where VG provides 55% of the electricity demand in largely isolated electricity reliability council of Texas grid system in 2050. In 2016 met about 15% of its annual electricity demand with wind or solar. There are three primary scenarios:

Wind vision :11% PV and 44% Wind

Minimum Curtailment: 18% PV and37% Wind

Equal mix 27.5% wind ad 27.5% PV



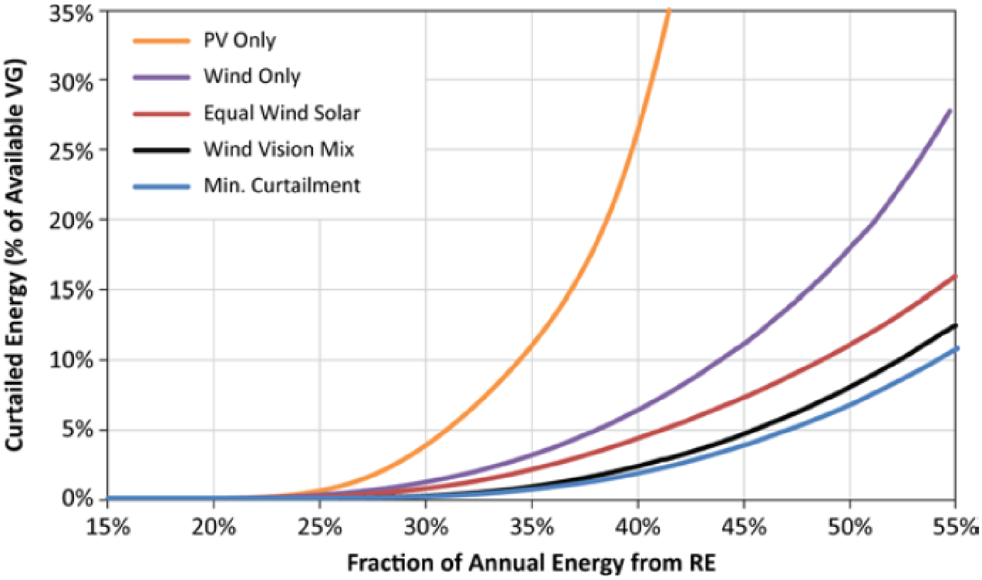
b) Fixed storage capacity (8.5 GW)

Figure 4-13 Total Curtailment as a Function of Storage Power Capacity a) and duration b) at a fixed 55% VG Penetration

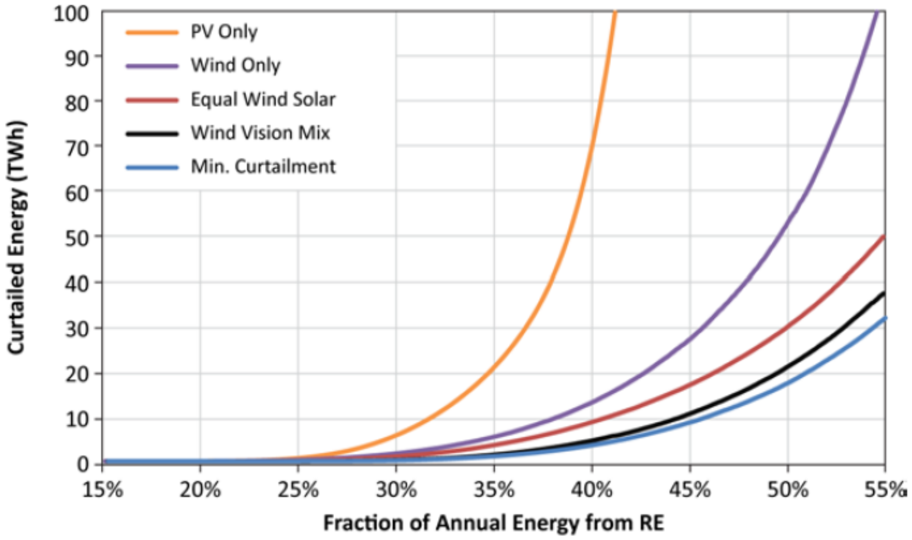
The figure above shows the case where the storage capacity added with 4 hours of duration and the second case where we fixed storage capacity at 8.5 GW of storage capacity (equivalent to about one-third of peaking capacity in 2050) but vary duration. The case with 8.5 GW of capacity with 4 hours of duration reduced total curtailment by 24%-38% (resulting in a total VG curtailment rate between 8% and 10%). Figure b shows that adding additional storage duration further reduces curtailment but with diminishing return. The value of 8.5 GW storage was based on EES required by 2050.

It performs chronological dispatch of energy storage. The model is used to dispatch the power system with increasing levels of wind and solar to examine resulting curtailment patterns and the ability to avoid curtailment via energy storage.

Figure below shows curtailment over arrange of VG penetration with no storage.in figure a) the percentage of VG which is curtailed is demonstrated as a function of penetration for three scenarios mentioned before, as well as the extreme cases of only wind and only solar. Figure b shows the absolute amount of VG curtailment. This and subsequent figures show the results using data from all size years.



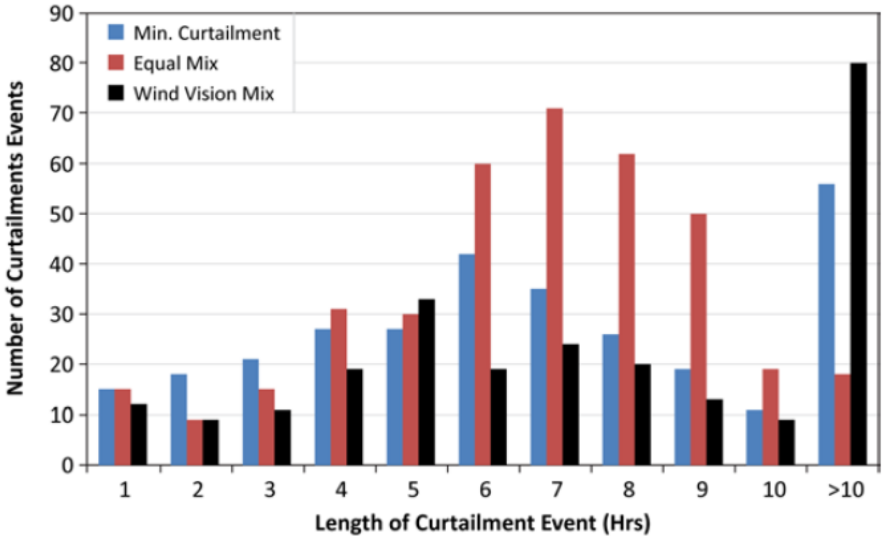
a) Total curtailment rate (%)



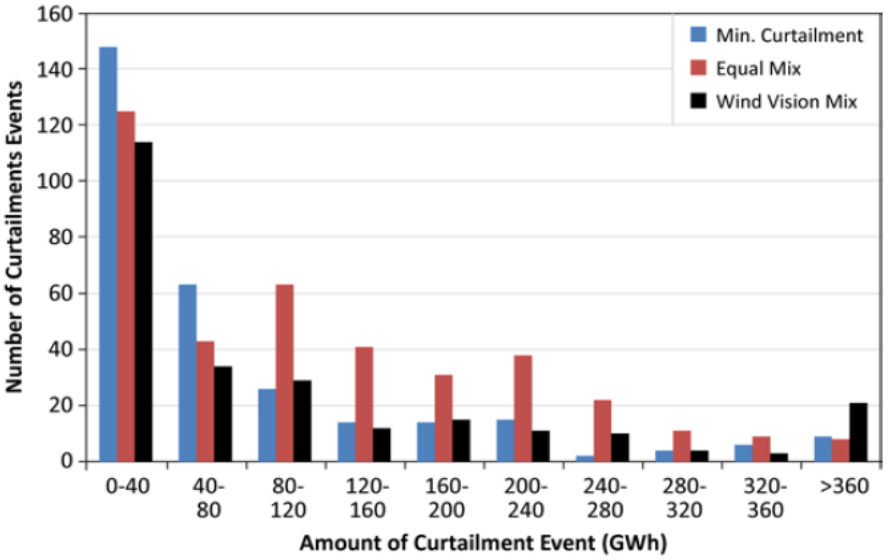
b) Total curtailment (energy)

Figure 4-14 a) Total VG Curtailment Rate and Energy Curtailed b) Energy Curtailment Rate under in with Different Mixes of Wind and Solar and No Energy

Figure below shows the distribution of curtailment-event duration and energy at 55% VG in each scenario with no storage using 2012 wind, solar and patterns. Long curtailment events are most common in the wind vision scenario., with 32% of events occurring over at least 10 hours. in contrast, the equal-mix scenario has shorter curtailment events with higher average power and often with greater total energy than in the wind vision scenario.



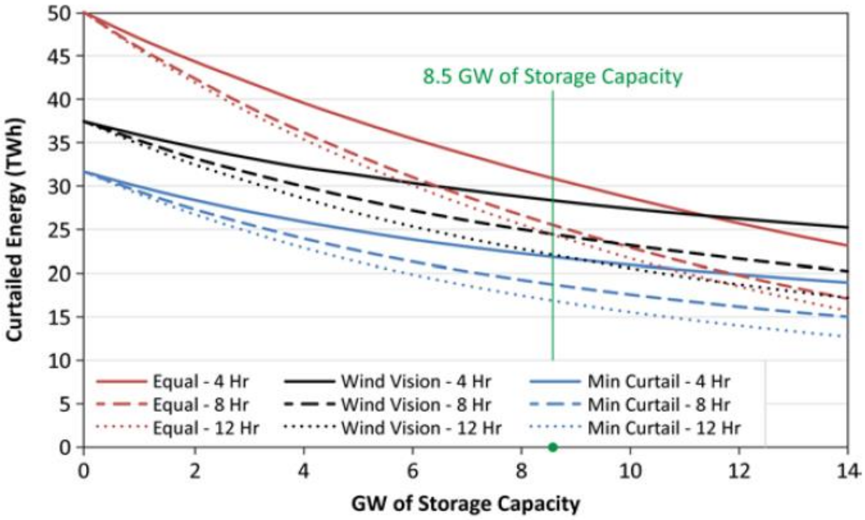
a) Distribution of duration



b) Distribution of energy

Figure 4-15 Distribution of duration (a) and energy (b) of curtailment events with no storage using 2012 solar, wind and load patterns.

The next figure illustrates the substantial curtailment reduction possible with relatively short-duration storage. It shows the total VG curtailment and fraction of potential VG curtailed at 55% VG for increasing quantities of storage power capacity with 4,8. Or 12 hours of storage duration. Without any storage about 11% -16% of VG energy is curtailed. At this level of power capacity adding the first 4 hours of storage reduces the curtailment rate by 3-5 percentage points to 11% or less across all scenarios. With 8 hours of storage, curtailment is 9% or less across all scenarios.



a) Total curtailment

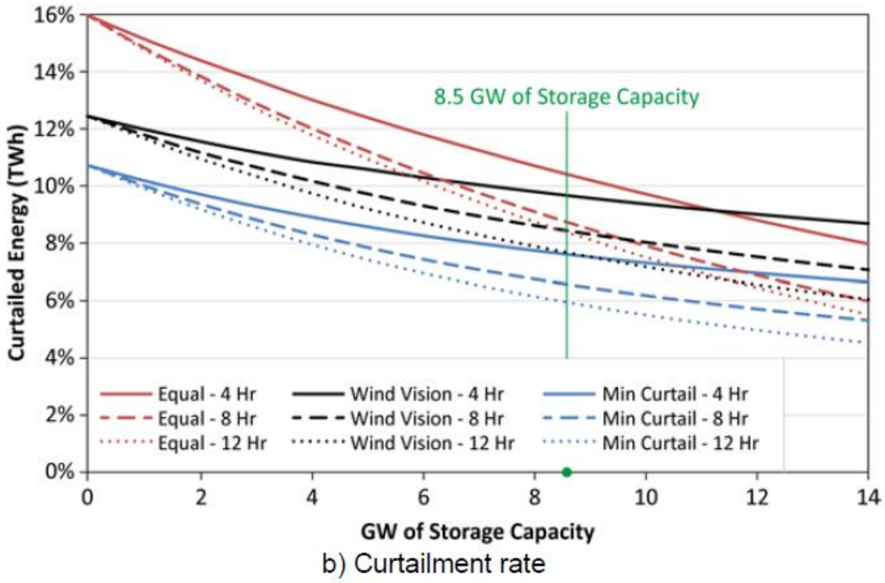


Figure 4-16 Total Curtailment a) and Curtailment rate (b) at 55% VG as a function of storage power capacity for the three study scenarios at varying storage durations

As a result:

- completely eliminating curtailment is not practical as it would require significant increase in storage power capacity as well as very long durations.
- The results suggest that relatively short-duration energy storage might offer an effective path to reduce VG curtailments at partnership up to 55%. Across all mixes of wind and solar resources analyzed, at least half of the potential avoided-curtailment benefits are realized with 8 hours of storage, and to be little increment benefit in deploying very-ling duration or seasonal storage.
- A key element of increasing energy storage uses to integrate renewable energy and reduce curtailment is identifying timescales for storage needed, that is, the duration of energy storage capacity per unit of power capacity [44].

4.6 Conclusion

In this chapter several scenarios from different literatures are presented and EES technology versus PV curtailment from a cost and value perspective are compared. The increase in curtailment can substantially reduce the value of VG and decrease its cost-competitiveness. By increasing the PV penetration well-understood changes to grid operation, regional cooperation and demand response can lead to economic integration of enabling EES technologies. Based on different usage EES can be installed next to the distribution transformer or next to the buses where PV systems are installed. The main results obtained from this chapter are listed below.

Short-duration energy storage might offer an effective path to reduce VG curtailments at partnership up to 55%.

The duration of the curtailment is an important factor which must be considered. A key element of increasing energy storage uses to integrate renewable energy and reduce curtailment is identifying timescales for storage needed. Short-duration energy storage might offer an effective path to reduce VG curtailments

Complete eliminating curtailment is not practical as it would require significant increase in storage power capacity as well as very long durations.

Using EES in residential due to the higher retail price is the most promising integration option in to obtain higher revenue.

When the batteries simply get too large and the investment cannot always be justified. Size of the EES is the one of the main keys in cost efficiency.

Conclusion

An overview of past studies shows that how different parameters, such as PV system and storage size, affect specific economic output parameter such as the cost of electricity or the profitability of the integrated PV and storage system. The main results obtained from this thesis are listed below.

- System without storage can attracts a smaller or bigger LCOE, this fact depends on several factors which are widely discussed in the third chapter. Besides, technical evaluation and market price could highly influence on EES integration. The duration of the curtailment is an important factor which must be considered.

- Other key element of increasing energy storage uses to integrate renewable energy and reduce curtailment is identifying timescales for storage needed. The case where the storage capacity added with 4 hours of duration and the other case where the storage capacity at 8.5 GW is fixed, but duration varies, are compared. As a result, the case with 8.5 GW of capacity with 4 hours of duration reduced total curtailment by 24%-38%. Therefore, short-duration energy storage might offer an effective path to reduce VG curtailments. The ability to avoid curtailment is a function of both the power and energy capacities of the energy storage system.

- There is slight positive NPV per unit of CAPEX in case of residential batteries in compare to main grid. This is because the retail price of electricity is high, and this fact increases the value of the battery discharge adequately.

- It is important to add a storage system as component of the system rather than adding in a later stage. The earlier addition can lead to a smaller LCOE.

- The simulation with varying energy storage size to examine curtailment reduction is suggested. Complete eliminating curtailment is not practical as it would require significant increase in storage power capacity as well as very long durations. The reason is that the batteries simply get too large and the investment cannot always be justified. Using EES in residential due to the higher retail price is the most promising integration option in order to obtain higher revenue.

Reference

[1] IEC, “Executive summary.,” *Electr. Energy Storage White Pap.*, vol. 39, pp. 11–12, 2009.

[2] “Grid Energy Storage,”. December, 2013.

[3] X. Luo, J. Wang, M. Dooner, and J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation q,” *Appl. Energy*, vol. 137, pp. 511–536, 2015.

[4] T. Wohlmuth, J. Researcher, F. Jetzinger, S. Researcher, and J. Schmid, “Optimizing self-consumption of grid-connected PV / storage systems,”. February, pp. 37–40, 2014.

[5] “http://new.abb.com/grid/stronger-smarter-greener/digital-grid,” *ABB*.

[6] Chatzivasileiadi,Aikaterini, Eleni;Ampatzi, and I. Knight, “Characteristics of electrical energy storage technologies and their applications in buildings ,” *Chatzivasileiadi, Aikaterini Ampatzi, Eleni Kn. Ian*, vol. 25, 2013.

[7] Droege P, “Urban energy transition: from fossil fuel to renewable power,” *Elsevier*.

[8] M. Bruch and M. Müller, “Calculation of the Cost-Effectiveness of a PV Battery System,” vol. 46, pp. 262–270, 2014.

[9] “http://batteryuniversity.com/learn/article/discharge_methods.”

[10] I. Ranaweera, “Modelling of Photovoltaic Modules with Battery Energy Storage in Simulink / Matlab Håvard Breisnes Vika,” . June, 2014.

[11] C. Reserve, “Integration of Lithium-Ion Battery Storage Systems in Control Reserve,” pp. 1–22, 2017.

[12] ABB, “http://www.abb-energystoragesolutions.com/.” .

[13] K. Panagiotou, C. Klumpner, and M. Sumner, “The effect of including power converter losses when modelling energy storage systems : a UK Domestic Study . Keywords « Battery Management Systems (BMS) », « Energy system management », « Energy storage ». Abstract The Energy Storage System and Data Sou.”

[14] B. V. Scaini, “Grid support stability for reliable , renewable power,”. December, 2012.

[15] C. J. Barnhart, M. Dale, R. Brandt, and S. M. Benson, “Environmental Science,” pp. 2804–2810, 2013.

[16] F. Marra, Y. T. Fawzy, T. Bülo, and B. Blažič, “Energy Storage Options for Voltage Support in Low-Voltage Grids with High Penetration of Photovoltaic,” pp. 1–7, 2012.

[17] B. M. S. Whittingham, “History , Evolution , and Future Status of Energy Storage,” vol. 100,

2012.

[18] C. Lu, H. Xu, X. Pan, and J. Song, “Optimal Sizing and Control of Battery Energy Storage System for Peak Load Shaving,” pp. 8396–8410, 2014.

[19] E. Matallanas and D. Masa-bote, “PV self-consumption optimization with storage and Active DSM for the residential sector,” vol. 85. 2011, pp. 2338–2348, 2014.

[20] M. Ahmed, “Energy Storage PV Capacity Firming with Forecasted Power Reference and Optimal Error Minimization,” 2015.

[21] “https://www.entsoe.eu/about-entso-e/market/market-integration-and-congestion-management/Pages/default.aspx.”

[22] “https://www.energyvortex.com/energydictionary/transmission_congestion.html.”

[23] A. Burke, H. Kdr, and Q. Xunh, “An Intelligent Solar-Powered Battery-Buffered EV Charging Station with Solar Electricity Forecasting and EV Charging Load Projection Functions” no. December, 2014.

[24] “http://energystorage.org/energy-storage/technology-applications/spinning-reserve.”

[25] “https://www.sma.de/en/partners/knowledgebase/the-self-consumption-bonus.html.”

[26] R. Golden and B. Paulos, “Energy in California and,” *Electr. J.*, vol. 28. 6, pp. 36–50, 2015.

[27] J. Martin, “https://www.solarchoice.net.au/blog/hybrid-inverters-battery-inverters-home-energy-storage,” 2015. .

[28] “http://www.yourhome.gov.au/energy/batteries-and-inverters.” .

[29] “http://www.solarchoice.net.au/blog/ac-vs-dc-solar-battery-storage-explained.” .

[30] F. Iwes, I. R. Aachen, L. T. De Salvagny, and S. Batteries, “Sol-Ion PV Storage System: Field Trial Results, Spread of Operating Conditions and Performance Evaluation Based on Field Data,”. September, pp. 24–28, 2012.

[31]“http://batteryuniversity.com/learn/article/bu_503_how_to_calculate_battery_runtimehttp://batteryuniversity.com/learn/article/bu_503_how_to_calculate_battery_runtime.” .

[32] “https://www.solarchoice.net.au/blog/levelised-cost-of-storage-compare-battery-value,.”

[33] A. Purvins and M. Sumner, “Optimal management of stationary lithium-ion battery system in electricity distribution grids,” *J. Power Sources*, vol. 242, pp. 742–755, 2013.

[34] B. Zhang, Z. Lu, and M. Chen, “A High Efficiency DC / AC Inverter for Energy Balancing of Battery Modules,” pp. 1609–1614, 2014.

[35] C. N. Truong, M. Naumann, R. C. Karl, M. Müller, A. Jossen, and H. C. Hesse, "Economics of Residential Photovoltaic Battery Systems in Germany : The Case of Tesla ' s Powerwall," 2016.

[36] "http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries."

[37] "http://batteryuniversity.com/learn/article/charging_lithium_ion_batteries."

[38] "http://batteryuniversity.com/learn/article/all_about_chargers."

[39] C. S. Lai, M. D. Mcculloch, and P. Group, "Levelized Cost of Energy for PV and Grid Scale Energy Storage Systems," pp. 1–11.

[40] S. Hench, "How is the cost for batteries per kWh calculated Energy storage/battery companies get prices of $800 per kWh for their cells and Tesla says their Powerwall costs about $350 per kWh. How are these figures calculated with grid electricity prices around $0."

[41] "https://www.solar-electric.com/learning-center/batteries-and-charging/deep-cycle-battery-faq.html."

[42] T. D. G. Off-grid, *Palau Workshop*. .

[43] B. Xu, Y. Dvorkin, D. S. Kirschen, C. A. Silva-Monroy, and J. P. Watson, "A comparison of policies on the participation of storage in U.S. frequency regulation markets," *IEEE Power Energy Soc. Gen. Meet.*, vol. 2016–Novem, 2016.

[44] P. Denholm, T. Mai, P. Denholm, and T. Mai, "Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment," no. September, 2017.

[45] "http://www.energy.wsu.edu/Documents/SolarPVforBuildersOct2009.pdf." .

[46] International Energy Agency (IEA), "Snapshot of global photovoltaic markets," *Photovolt. power Syst. Program.*, no. T1–31:2017, pp. 1–16, 2017.

[47] H. Klinge Jacobsen and S. T. Schröder, "Curtailment of renewable generation: Economic optimality and incentives," *Energy Policy*, vol. 49, pp. 663–675, 2012.

[48] E. Ela, "Using Economics to Determine the Efficient Curtailment of Wind Energy Using Economics to Determine the Efficient Curtailment of Wind Energy," . February, 2009.

[49] N. Acharya, C. Ching liu, and B. Djukanovic, "Wind generation curtailment to relieve line overlod in an on-line environment," *Electr. Comput. Eng. Ames,IAUSA.*

[50] L. Kane and G. Ault, "A review and analysis of renewable energy curtailment schemes and Principles of Access: Transitioning towards business as usual," *Energy Policy*, vol. 72, pp. 67–77, 2014.

[51] R. A. F. e. al Currie, "Smarter Ways to Provide Grid Connexions for Renewable Generators,"

IEEE, pp. 1–6, 2010.

[52] D. Lew *et al.*, “Wind and Solar Curtailment: International Experience and Practices,” *Int. Work. Large-Scale Integr. Wind Power into Power Syst. as well as Transm. Networks Offshore Wind Farms*, pp. 1–7, 2013.

[53] A. D. Mills and R. H. Wiser, “Changes in the economic value of photovoltaic generation at high penetration levels: A pilot case study of California,” *2012 IEEE 38th Photovolt. Spec. Conf. PART 2*, June, pp. 1–9, 2012.

[54] P. Denholm and R. Margolis, “Energy Storage Requirements for Achieving 50 % Solar Photovoltaic Energy Penetration in California,” *Nrel*, . August, 2016.

[55] J.P.Brton and D.G., “Energy storage and its use with intermittent renewable energy,” *IEEE Trans. Energy Convers.*, pp. 441–448, 2004.

[56] J. McKenna and M. Thomson, “Impact of wind curtailment and storage on the Irish power system 2020 renewable electricity targets: a free open-source electricity system balancing and market (ESBM) model,” *3rd Renew. Power Gener. Conf. (RPG 2014)*, p. 3.2.3-3.2.3, 2014.

[57] “https://bizfluent.com/facts-5923577-difference-wholesale-price-retail-price-.html.” .

[58] L. Bird, J. Cochran, and X. Wang, “Wind and solar energy curtailment : experience and practices in the United States,” *Natl. Renew. Energy Lab.*, March, p. 58, 2014.

[59] F. R. Segundo Sevilla, D. Parra, N. Wyrsch, M. K. Patel, F. Kienzle, and P. Korba, “Techno-economic analysis of battery storage and curtailment in a distribution grid with high PV penetration,” *J. Energy Storage*, vol. 17, pp. 73–83, 2018.

[60] X. Xiu and B. Li, “STUDY ON ENERGY STORAGE SYSTEM INVESTMENT DECISION BASED ON REAL OPTION THEORY,” 2011.

[61] S. W. Alnaser, “Optimal Sizing and Control of Energy Storage in Wind Power-Rich Distribution Networks,” pp. 1–10, 2014.

[62] D. Timmons, J. M. Harris, and B. Roach, “The Economics of Renewable Energy,” *Renew. Energy*, vol. No. 15081, pp. 1341–1356, 2009.

[63] R. Khatami, M. Parvania, and P. Khargonekar, “Scheduling and Pricing of Energy Generation and Storage in Power Systems,” *IEEE Trans. Power Syst.*, vol. 8950, no. c, pp. 1–14, 2017.

[64] S. Stoft, “Reviewed Work: Power System Economics: Designing Markets f or Electricity,” *Int. Assoc. Energy Econ.*, vol. 23, pp. 112–114, 2002.

[65] P. Denholm, V. Diakov, and R. Margolis, “The Relative Economic Merits of Storage and Combustion Turbines for Meeting Peak Capacity Requirements under Increased Penetration of Solar Photovoltaics,” *Nrel*, September, 2015.

[66] M. Steurer, U. Fahl, and A. Voß, “Chapter 15 – Curtailment: An Option for Cost-Efficient Integration of Variable Renewable Generation?,” *Eur. Energy Transit. - Insights Policy Mak.*, vol. 49, October, pp. 97–104, 2017.

[67] N. Johnson, M. Strubegger, M. McPherson, S. C. Parkinson, V. Krey, and P. Sullivan, “A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system,” *Energy Econ.*, vol. 64, no. 3, pp. 651–664, 2017.

[68] K. Branker, M. J. M. Pathak, and J. M. Pearce, “A review of solar photovoltaic levelized cost of electricity,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 4470–4482, 2011.

[69] World Energy Council, “E-storage: Shifting from cost to valueWind and solar applications 2016,” 2016.

[70] K. Branker, M. Pathak, J. M. Pearce, M. J. M. Pathak, and J. M. Pearce, “A Review of Solar Photovoltaic Levelized Cost of Electricity A Review of Solar Photovoltaic Levelized Cost of Electricity,” *Renew. Sustain. Energy Rev.*, vol. 15, pp. 4470–4482, 2011.

[71] K. Branker, M. J. M. Patgak, and J. . Pearce, “Levelized costs of wave and tidal energy in the UK: Cost compeititiveness and the impotance of banded Renewables Obligation Certificates, Energy Policy,” *Renew. Sustain. Energy Rev.*, 2011.