KTH Industrial Engineering and Management

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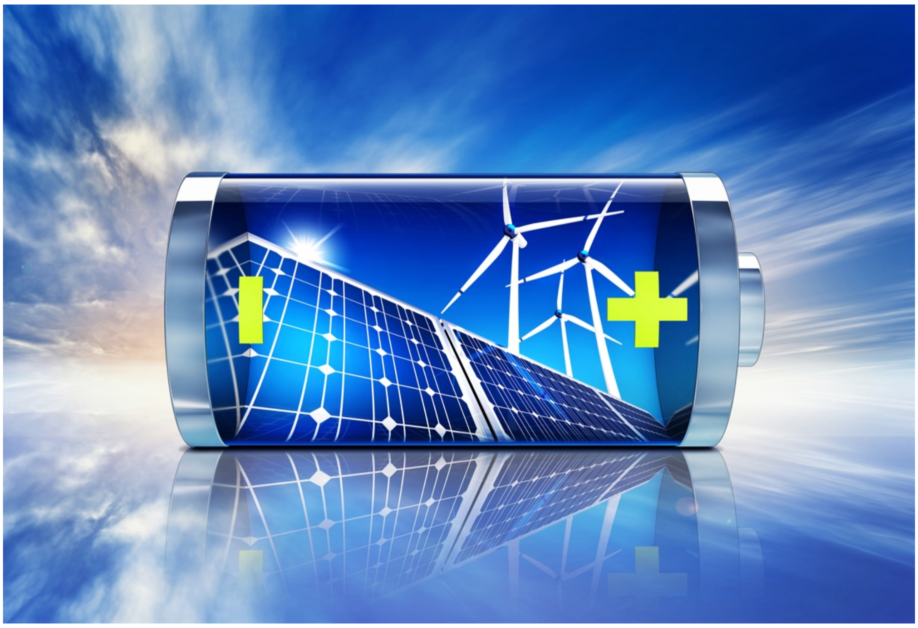

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Abstract

The aim of this study is to identify existing models for estimating costs of battery energy storage systems(BESS) for both behind the meter and in-front of the meter applications. The study will, from available literature, analyse and project future BESS cost development. The study presents mean values on the levelized cost of storage (LCOS) metric based on several existing cost estimations and market data on energy storage regarding three different battery technologies: lithium ion, lead-acid and vanadium flow. These values are intended to serve as benchmarks for BESS costs of today. The results show that for in-front of the meter applications, the LCOS for a lithium ion battery is 30 USDc/kWh and 34 USDc/kWh for a vanadium flow battery. For behind the meter applications, the LCOS for a lithium ion battery is 43 USD/kWh and 41 USD/kWh for a lead-acid battery. A sensitivity analysis is conducted on the LCOS in order to identify key factors to cost development of battery storage. The mean values and the results from the sensitivity analysis, combined with data on future cost development of battery storage, are then used to project a LCOS for year 2030. The results from the sensitivity analysis show that capex, cycles and discount rate have the biggest impact on the LCOS formula. The projection conducted in this study indicates that LCOS will decrease significantly by 2030. The results show that for in-front of the meter applications, the LCOS for a lithium ion battery will drop 60 % and 68 % for a vanadium flow battery. For behind the meter applications, the LCOS for a lithium ion battery will drop 60 % and 49 % for a lead-acid battery.

Sammanfattning

Denna studie syftar till att identifiera befintliga modeller för att estimera kostnader för batterilagringssystem för både små och storskaliga applikationer samt att från tillgänglig litteratur, analysera och estimera framtida kostnader för batterilagringsystem. Studien presenterar medelvärden på ”levelized cost of storage (LCOS)” baserat på befintliga kostnadsberäkningar och marknadsdata för tre olika batteriteknologier: litiumjon, bly och vanadin-flödesbatteri. Dessa medelvärden kan ses som riktmärken för kostnader av batterilagringssystem idag. Resultaten visar att LCOS för ett litiumjonbatteri är 30 USDc/kWh och att LCOS för ett vanadin-flödesbatteri i storskaliga applikationer är 34 USDc/kWh. För småskaliga applikationer visar resultaten att LCOS för ett litiumjonbatteri är 43 USD/kWh och 41 USD/kWh för ett blybatteri. Studien genomförde även en känslighetsanalys på LCOS för att identifiera vilka parametrar som har störst påverkan på LCOS. Medelvärdena och resultatet från känslighetsanalysen, kombinerat med marknadsdata om framtidens kostnadsutveckling för batterilagring, användes för att estimera LCOS för år 2030. Resultatet från känslighetsanalysen visar att capex, cykler och diskonteringsräntan har störst inverkan på LCOS-formeln. Estimeringen av LCOS för 2030 indikerar att kostnader för batterilagring kommer minska avsevärt. Resultatet visar att för storskaliga applikationer kommer LCOS för ett system med ett litiumjonbatteri minska med 60 % och 68 % för ett med vanadin-flödesbatteri. För småskaliga applikationer minskar LCOS för ett system med litiumjonbatteri med 60 % och 49 % för ett med blybatteri.

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Abbreviations

BESS:	Battery energy storage system
BTM:	Behind the meter
CAES:	Compressed air energy storage
Capex:	Capital expenses
DoD:	Depth of discharge
E2P:	Energy to power
EUR:	Euro
FLH:	Full load hours
ITM:	In front of the meter
LCOS:	Levelized cost of storage
O&M:	Operating and maintenance
Opex:	Operating expenses
PHS:	Pumped hydro storage
PV:	Photovoltaic
USD:	U.S dollar
USDc:	U.S dollar cent
VFB:	Vanadium flow batteries
W:	Watt
WACC:	Weighted average cost of capital
Wh:	Watt hour

1 Introduction

In order for the costly and dangerous effects of climate change to be eliminated, greenhouse gas emissions must peak in the near future (Ralon, et al., 2017). Since the United Nations climate change conference in Paris 2015, the energy sector has continued its shift from fossil fuel to renewable energy sources. This has resulted in an increase in the demand for energy storage. The better the energy sector can store energy, the less dependent the world becomes of fossil fuels, which in turn will lead to decarbonisation. If energy storage would not be possible, energy generation had to equal energy consumption. Therefore, energy storage can be seen as moving energy through time (SANDIA, 2013). Today's modern societies would not exist if it were not for the storage of energy in its oldest form: batteries. Today it is not only batteries that store energy, in fact it is only a small fraction of the deployed storage technologies (Ralon, et al., 2017). The main storage technology is pumped hydro. Other technologies are compressed air and thermal heat storage.

Energy storage can also contribute to a more effective and reliable energy market in various ways, e.g. frequency regulation, energy arbitrage, black start and voltage support. Energy storage is also highlighted as the game-changer for solving current problems regarding volatility challenges for wind and solar applications (World Energy Council, 2016). The growth of the application of energy storage depends on several fundamental factors, such as national energy resources, regulatory framework, general grid-architecture and energy demand patterns (Eller & Gauntlett, 2017). Today, advanced energy storage technology is still expensive to implement. Therefore, the upfront investments will often have to come from government support or low-cost financing, despite of the rapid decrease in costs (Eller & Gauntlett, 2017).

1.1 Purpose of the study

As the energy sector continues to shift to renewable energy sources, the demand for battery energy storage increases. However, the various technologies and applications for battery energy storage available make cost estimations relatively complex. As opposed to energy generation, which have the single use case of generating electricity, energy storage lacks a standardized metric for estimating costs. Storing energy requires components linked to storage, charging and discharging of electricity, which entails that a system is characterized by both its energy capacity (Wh), and its power capacity (W). Thus, the cost of a system is very much defined by its application and end-use purpose.

The aim of this study is to identify and compare, from available literature, existing cost models for Battery energy storage systems (BESS). The study will focus on three different battery technologies: lithium-ion, lead-acid and vanadium flow. The study will also, from available literature, analyse and project future BESS cost development.

The objectives of this study are:

- Form a compilation that can act as a first read literature for anyone who wants to get insight in BESS and wish to understand the basics of existing cost models.
- Present mean values on LCOS for three battery technologies based on several existing cost models and market data, which can serve as benchmarks for stakeholders.
- Identify key drivers to cost development of BESS.
- Present an overall outlook of the BESS market trajectory.

1.2 Method

This study will first conduct a literature review over previous work on cost models of battery energy storage. The literature review and technical background aim to guide the analysis in terms of providing understanding of how to estimate costs of BESS.

Based on the results of the literature review, estimations of BESS costs will be performed. The study will apply a Levelized Cost of Storage (LCOS) model, which is a version of the LCOE model. Technical details of the model and assumptions grounding the analysis are presented and explained in chapter 4. The applied formula is presented in its full version in chapter 3, see equation 1.3.

The structure of the study can be summaries into the following steps:

1. Provide a literature review and theoretical background of battery energy storage and existing cost models.
2. Collect and compile information and data of different LCOS from selected sources regarding both present and future costs of BESS.
3. Calculate the LCOS for all sources and analysed technologies, using the same LCOS formula.
4. Compare respective LCOS in terms of costs, input parameters and assumptions.
5. Calculate mean values of LCOS for all three battery technologies (li-ion, lead-acid and VFB), for both BTM and ITM applications.
6. Conduct a sensitivity analysis on the LCOS formula.
7. Using information and data on future cost development, project a LCOS for 2030.

2 Technical background and cost models

This chapter includes a presentation of available technologies for energy storage, battery energy storage applications and cost models. This knowledge background serves to inform about what could be expected for future development on battery energy storage, as well as energy storage in general.

2.1 Available technologies for energy storage

Pumped hydro storage (PHS) has the greatest share of the total installed storage capacity. It is about 169 GW, which constitutes 96 % of the total installed capacity. Pumped hydro is a mechanical storage technology which pumps water to an upper reservoir with height distance from a lower reservoir. If supply is needed, gravity will drive the water down through a pipe and a turbine, which creates electricity to the grid (Ralon, et al., 2017).

Compressed air energy storage (CAES) is also a mechanical storage technology which constitutes 0.9 % of the total installed capacity, which is 1.6 GW. CAES is similar to PHS in terms of application and storage capacity (Energy Storage Association, 2018). Air is stored underground in a cavern and under pressure. When electricity is required, the stored air expands in an expansion turbine which drives the generator to produce power. As of 2017, there were only two operational large scale CAES plants in the world. One is located in Alabama, United States and the other one in Huntorf, Germany (Cárdenas, et al., 2017).

Thermal energy storage has an installed capacity of 3.3GW, which is 1.9% of the total installed capacity in the world. Energy is stored in three different forms: sensible heat, latent heat and thermochemical heat (Energy Storage Association, 2018). In short, energy is stored by changing the temperature of a storage medium. Water is usually the most common storage medium applied.

Battery energy storage has a global capacity of 1.9GW, which is 1.1% of the total installed capacity. The development of battery energy storage has a number of high-value opportunities. For instance, it is not dependent on specific geographic features and does not have the same environmental concerns for development as for instance PHS and CAES. Furthermore, it does not have as high initial investment cost or long construction period as PHS and CAES (Ralon, et al., 2017).

In short, a battery consists of three parts: an anode, a cathode and an electrolyte. The anode and the cathode are connected through a circuit and are separated by the electrolyte. The chemical reactions in the battery cause the electrons to build up at the anode resulting in an electrical difference between the anode and the cathode. The electrons want to equalize this difference, which causes the electrons to move from the anode to the cathode. The electrolyte prevents the electrons from moving within the battery and forces them to move through the circuit, which creates electricity. When charging the battery, the flow of electrons is reversed using another power source and therefore restores the original state of the anode and cathode (Bates, 2012). When charging a battery for energy storage, the power could for example come from solar panels.

There is a wide range of different battery technologies available. This report will be focused on lithium-ion, lead-acid and vanadium flow batteries. BESS will here on be the main subject in this report.

2.2 Battery energy storage applications

There are many potential applications for battery energy storage technology. The five most identifiable and widespread are peaker replacement, distribution, microgrid, commercial and residential.

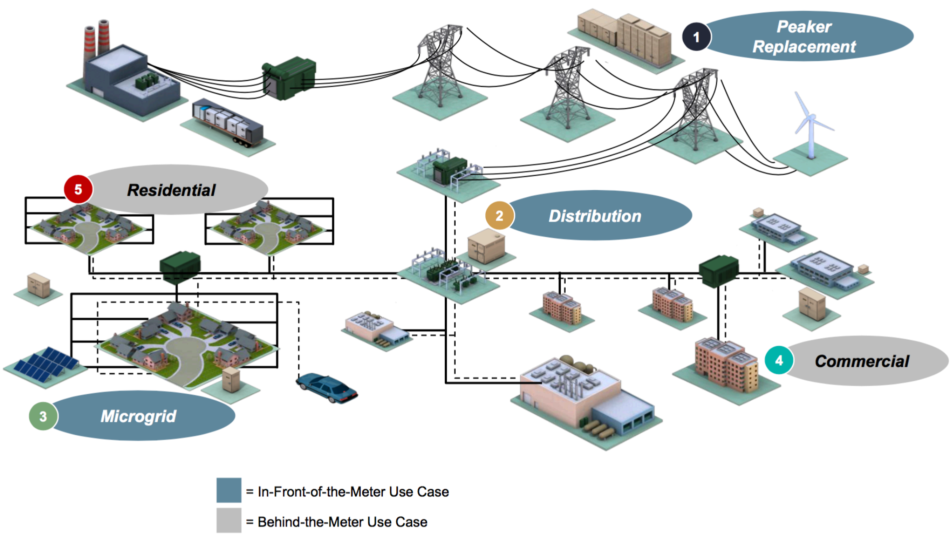

Figure 1. *Schematic view of BTM and ITM applications. Source: EPRI.*

The applications can be divided into two subgroups: In-front of the meter applications and behind the meter applications, as seen in figure 1. The difference between them is how or where the storage system is used. For in-front of the meter applications the size of the system is relatively greater; it can vary from 4 to 400 MWh in capacity. Behind the meter applications typically range from 0.01 to 0.25 MWh in capacity (Lazard, 2017).

Four of the most common use cases for these applications are:

- *Frequency regulation*; the main purpose is to maintain the stability and accuracy of the system.
- *Energy arbitrage*; energy is stored when the electricity price is low and used or sold when prices are high.
- *Black start*; when the grid gets disconnected, energy storage can be used to restore the power system without pulling electricity from the grid.
- *Voltage support*; this means maintaining the necessary voltage level in the grid and its stability.

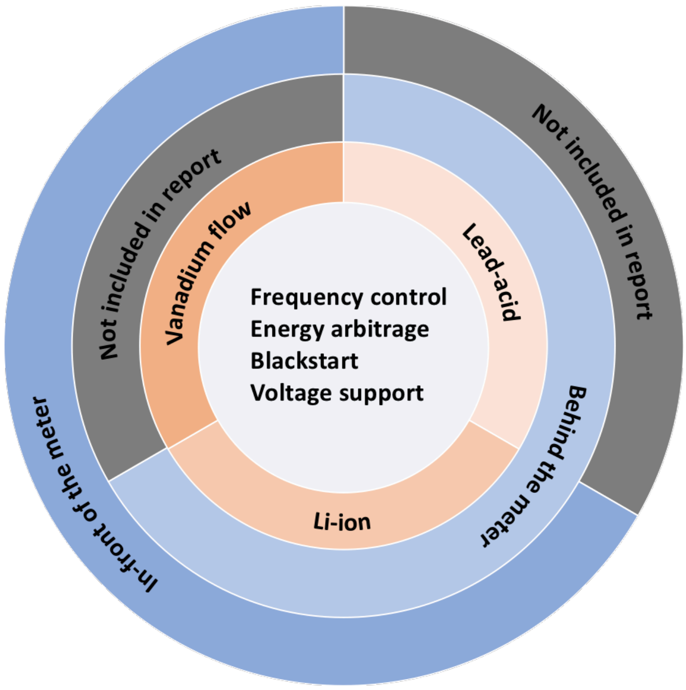

Figure 2.*Technologies analysed and usage purposes.*

As illustrated in figure 2, the battery technologies which will be analysed for behind the meter applications are li-ion and lead-acid. For in-front of the meter applications, li-ion and vanadium flow will be analysed.

2.3 Cost models

When comparing costs of battery energy storage, it is important to distinguish between the energy and the power capacity of the system (Mayr & Beushausen, 2016). The amount of energy that can be stored is the energy capacity of the system, and the rate of which the energy flows in and out of the system, is the power capacity of the system. Power can be measured in watts (W), and energy can be measured in watt hours (Wh). This means that when estimating costs in terms of USD/kW, the cost is based on the power capacity of the system. For example, a storage system that is intended for residential use is assumed to require a size of 5kW/10kWh. If the cost of the system is USD 2000, the costs based on the energy and power capacity become:

- USD2000/5kW = 400 USD/kW
- USD2000/10kWh = 200 USD/kWh

If the system then is changed to a size of 10kW/10kWh with the same total cost, the cost in terms of energy capacity will not be affected while the cost in terms of power capacity will be halved. Therefore, system size and specific use case are important to keep in mind when evaluating and comparing costs of energy storage (Mayr & Beushausen, 2016).

When comparing costs of different technologies for energy generation such as wind and solar power, the Levelized Cost of Electricity (LCOE) is the most commonly used metric (Belderbos, et al., 2017). The LCOE formula can be defined as *"the fictitious stable electricity price needed to make the present value of the sum of all costs and all revenues over the entire operational life of the unit equal to zero"* (Belderbos, et al., 2017). Energy storage lacks such a universally applied metric for calculating costs which makes it difficult for stakeholders to evaluate costs for different storage solutions (Mayr & Beushausen, 2016). In an attempt to solve this problem, a version of the LCOE has been introduced, called Levelized Cost of Storage (LCOS) (Mayr & Beushausen, 2016). The formula can be computed as follows:

$$LCOS = \frac{CAPEX + O\&M \cdot \sum_{n=1}^{N} \frac{1}{(1+r)^n} - \frac{v_{res}}{(1+r)^{N+1}}}{c \cdot DoD \cdot RC \cdot \sum_{n=1}^{N} \frac{1 - DEG \cdot n}{(1+r)^n}} + \frac{p_{elec}}{\eta} \quad (1.1)$$

Where:

$CAPEX$	= Capital expenses
$O\&M$	= Operating and maintenance costs
DoD	= Depth of discharge
c	= Number of cycles per year
RC	= Rated capacity
DEG	= Annual degradation
N	= Lifetime of system
r	= Discount rate
P_{elec}	= Charging cost
η	= Round-trip efficiency
v_{res}	= Residual value

The LCOS could then be defined as *"the fictitious average electricity price during discharging needed over the lifetime of the storage plant to break even the full costs for the investor"* (Belderbos, et al., 2017). The depth of discharge (DoD) is the amount of energy that has been discharged in relation to the total energy capacity of the battery. If a battery discharges 30 % of its total energy capacity and 70 % is unused, the battery has a 30 % DoD. This is of importance when calculating costs since the expected lifetime of the battery is shorter if the battery is being cycled at a deep discharge (Kempener & Borden, 2015). The charging cost is the cost of which the electricity is bought to be stored. The value of this parameter varies depending on the price of electricity at the specific location of the system. In some cases, it is set to zero. If the storage unit were to be coupled with an energy generation source, the LCOE of that source would be the charging cost in the LCOS formula. The discount rate is the weighted average cost of capital (WACC), which includes the desired rate of return and interest payment on debt.

3 Literature review

In a report from 2016, Apricum – The Cleantech Advisory addresses the complexity in comparing costs of energy storage in their article "*Navigating the maze of energy storage*" (Mayr & Beushausen, 2016). Because of the many different technologies and applications for energy storage, cost comparison is only relevant for a common and clearly specified use case. For example, an ITM-application could require more operating and maintenance as opposed to a BTM-application, which affects the cost. The report also includes an LCOS-analysis of both a residential storage system and a utility storage system in Germany.

A lithium-ion battery is used for both cases with a lifetime of 15 years, 250 cycles per year at 100% DoD for BTM and 350 cycles per year at 80% DoD for the ITM application. Apricum's model estimates the operating costs and residual value to be zero for the BTM application. For the ITM application, operating costs are 2% of capex and the residual value is 20% of capex.

Table 1. *Apricum's input data and resulting LCOS.*

Technology	Lifetime [y]	Capex [USD/kW]	Opex [USD/kW]	Charging cost [USD/kWh]	WACC [%]	Efficiency [%]	LCOS [USD/kWh]
Li-ion ITM	15	500	10	0.06	10	92	0.35
Li-ion BTM	15	1000	0	0.12	3	70	0.53

As seen in table 1, the discount rate is different for BTM and ITM. The capital structure of the model is assumed to be 100 % equity with a discount rate of 3 % for residential use. For utility use, the capital structure is 50 % equity with 12 % cost of equity and 12 % debt with an 8% cost of debt, which results in a discount rate of 10 % for the ITM application. The rated capacity is 6 MWh for ITM.

Verena Jülch has made a comprehensive report called "*Comparison of electricity storage options using levelized cost of storage*" (Jülch, 2016). The author has applied LCOS on four different groups of storage technologies, namely power to gas, PHS, CAES and battery. Jülch used market data, and cost data from market analysis when possible. Assumptions made for battery technology costs are based on experience within Fraunhofer ISE in different projects.

***Table 2.** Jülch's input data and resulting LCOS.*

Technology	Lifetime [y]	Capex [EUR/kWh]	Opex [USD/kWh]	Charging cost [USD/kWh]	WACC [%]	Efficiency [%]	LCOS [USD/kWh]
Li-ion	20	660-1050	13-21	0	8	95	0.23-0.37
VFB	20	930-1040	19-21	0	8	80	0.32-0.36

The rated power analysed is set to 100 MW for both li-ion and VFB, with an E2P ratio of 4. As shown in table 2, the discount rate is set to 8 % for all technologies. Operational cost is set to 2 % of capex for both li-ion and VFB. Cost is analysed with cycles at 365 per year, and a DoD of 80 % for li-Ion, and 100 % for VFB. The input of electric power cost is set to zero.

The financial advisory and asset management firm, Lazard, has made a series of reports analysing the cost and revenue of different energy storage technologies (Lazard, 2015; Lazard, 2016; Lazard, 2017). Their latest report provides a levelized cost of storage analysis of various use cases for both ITM and BTM applications (Lazard, 2017). The report had its first publish in 2015. It is conducted by 70 interviews and includes cost trends, revenue streams and project economics for each use case in the market: peaker replacement, distribution, micro grid, commercial and residential. Lazard's data is obtained from operational survey data and prices from manufactures which is validated from industry participants. The rated power/capacity analysed range between 5kW/10kWh- 125kW/250kWh for BTM and 1MW/4MWh-100MW/400MWh for ITM.

***Table 3.** Lazard's input data and resulting LCOS for BTM.*

Battery technology	Lifetime [y]	Capex [USD/kW]	Opex [USD/kW]	Charging cost [USD/kWh]	WACC [%]	Efficiency [%]	LCOS [USD/kWh]
Li-ion	10	804-1289	0	0.11-0.12	11.2	85	0.89-1.27
Lead-acid	10	556-835	0	0.11-0.12	11.2	72	1.06-1.24

***Table 4.** Lazard's input data and resulting LCOS for ITM.*

Battery technology	Lifetime [y]	Capex [USD/kW]	Opex [USD/kW]	Charging cost [USD/kWh]	WACC [%]	Efficiency [%]	LCOS [USD/kWh]
Li-ion	10-20	385-652	0.04-3.1	0.03-0.11	11.2	86	0.27-0.39
VFB	10-20	303-855	0.03-6.6	0.03-0.11	11.2	70	0.18-0.41

As seen in table 3 and table 4 the discount rate in this model is 11.2 % for both BTM and ITM. That is based on a capital structure of 80 % equity with a 12 % cost of equity, and 20 % debt with an 8 % cost of debt. The DoD is set to 100 % with 350 cycles per year. All data is obtained from the section "key assumptions".

The technical trade publication SolarPro compares LCOS for three different storage solutions (Matthias & Brearley, 2016). That is in relation to cost, cycling and efficiency using a simplified LCOS formula:

$$LCOS = \frac{CAPEX}{UC \cdot c \cdot \eta} \qquad (1.2)$$

Where *UC* is usable capacity. Solarpro's simplified equation (1.2) does not consider O&M cost or the time value of money as oppose to the more commonly used LCOS, equation (1.1).

SolarPro motivates this approach by stating that the vendor applications are said to be maintenance-free. The battery applications that are analysed are: Tesla's Powerwall in the relation to system cost, Sonnen battery eco6 in relation to cycling and Adara Power's energy storage system in relation to efficiency. Hereinafter, the focus will be on Tesla´s Powerwall in the relation to cost since that is in line with the rest of the study.

A comparison between utility and residential use has been made. Nominal capacity is 6.4MWh and the installed cost is set to 6500USD for utility scale, and 9000USD for residential. The number of cycles is 3650 and a roundtrip efficiency of 90% is used. This is based on Green mountain powers pilot program and Tesla's first Powerwall retailer Treehouse (Matthias & Brearley, 2016).

SolarPro also includes an approximation for usable capacity for the storage system over its lifespan. Since SolarPro does not have access to standardized data of usable capacity that a third party has verified, they state that the best approximation for that is the vendor's battery warranty.

Table 5. *Solarpro's input data and resulting LCOS.*

Technology	Nominal capacity [kWh]	Capex [USD/kW]	Opex [USD/kW]	Cycles	Warranted capacity[kWh]	Efficiency [%]	LCOS [USD/kWh]
Utility	6.4	1015	0	3650	18000	90	0.4
Residential	6.4	1406	0	3650	18000	90	0.56

Table 5 shows the warranted capacity in kWh. The warranty is due to stepped degradation. According to the article *"Tesla guarantees 18MWh off aggregated discharge",* this will of course make the LCOS higher since the efficiency will decline over the years (Matthias & Brearley, 2016).

A study conducted by World Energy Council (WEC) compares a number of electricity storage applications for both ITM and BTM (World Energy Council, 2016). The study focuses on LCOS and specific investment cost for the different technologies and presents two cases for storage co-located with wind power system and a solar PV system. The estimated cost models are based on a literature study where the cost data is obtained from studies undertaken in the period 2012-2015. The calculation is made by PWC and sources for the economic parameters comes from Agora Energiewende, ISEA Aachen, Fraunhofer IWES, IAEW Aachen, Stiftung Umweltenergierecht and PwC research.

The rated power analysed is set up to 10MW for both li-ion and VFB and up to 70MW for lead acid which covers all of the main applications from peak shaving down to residential use. For all technologies analysed the discount rate is set to 8 %. For short-term storage, the operational cost is set to 2 % of the specific investment cost for all three technologies.

PWC is also considering E2P which is set to 1-10. However, for the short-term analysis and the two application cases, the E2P is set to range from 1 to 4.

Table 6. *World Energy Council's input data and resulting LCOS.*

Battery technology	Lifetime [y]	Capex [USD/kW]	Opex [USD/kW]	Charging cost [USD/kWh]	WACC [%]	Efficiency [%]	LCOS [USD/kWh]
Li-ion	5-20	300-3700	7-74	0	8	85	0.15-0.7
Lead-acid	5-20	500-1700	10-34	0	8	77	0.1-0.4
VFB	5-20	1000-3500	20-70	0	8	70	0.12-0.42

During the lifetime of the storage systems, there have been no changes in price or parameters. The full-load hours of equivalent range between 365-1460 hours a year with a DoD of 70 % for short term storage with li-ion and lead-acid. For VFB, DoD is set to 100%. In regard to input of electric power, the cost is set to zero, which is shown in table 6.

In a report from 2017, the National Renewable Energy Laboratory (NREL) presents a model of comparing hardware costs between different sources (Ardani, et al., 2017). NREL states that comparing these investment costs between different sources is complicated by different system sizes and information provided by each source. To elude this problem, they separate the hardware costs of the system into costs of components regarding energy capacity and power capacity and calculate the total hardware cost for a standard system size. They also state that uncertainty exists with this method with respect to how the information is provided by the different sources.

Pacificorp introduces a model for estimating total system cost in their report from 2016 (pacificorp, 2016). Similar to NREL, the hardware costs are divided into cost regarding energy capacity and power capacity. They also include power control system cost, balance of system cost, installation cost and fixed O&M cost. The fixed O&M cost are provided as levelized over a project life of 20 years. The power control system cost and balance of system cost are presented in terms of USD/kW and the installation cost is presented in terms of USD/kWh. The total system cost can then be calculated for a given system size. The battery technologies analyzed are li-ion, VFB, sodium-sulphur and zinc batteries.

3.1 BESS market trajectory

According to a report from the International Renewable Energy Agency (IRENA), the future of cost development for BESS is promising. As deployment of renewable energy sources increase, the demand for energy storage will increase and offer new economic opportunities (Ralon, et al., 2017). According to Apricum, the market for stationary battery systems is expected to have a significant growth. They estimate a growth in capacity from 2GWh globally in 2015 to 33GWh by 2020 (Mayr & Beushausen, 2016).

One of the key drivers to this growth is the cost development of battery technologies. IRENA estimates a decrease in energy installation costs from between 150-1050 USD/kWh in 2016 to between 75-480 USD/kWh by year 2030, depending on the battery technology. IRENA estimates that the capital costs of a system with a li-ion battery will decrease with about 60 % and about 50 % for a system with a lead-acid battery. A system with VFB technology is projected to decrease in capital costs by approximately 66 %. This reduction of capital costs will increase the competitiveness of BESS in relation to more traditional storage systems (Ralon, et al., 2017).

A lot of investments have been made in lithium-ion batteries due to its wide range of possible applications. The use of lithium-ion batteries in electric cars is another industrial application and a key driver to reducing battery costs. Since the battery is the most expensive component in an electrical driven vehicle, a reduction in the price is a prerequisite for further adoption (Berckmans, et al., 2017).

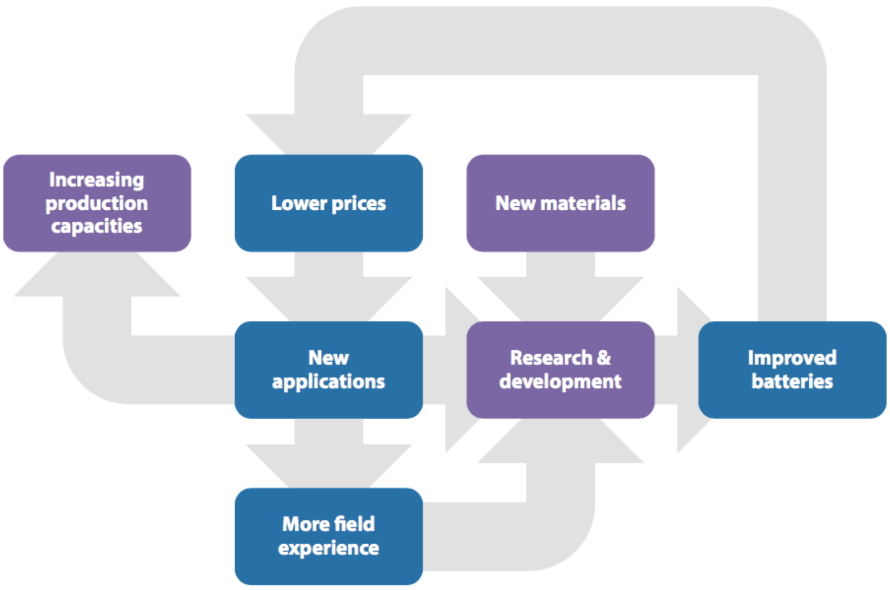

Figure 3. *Drivers to cost reduction of battery technologies. Source: International Renewable Energy Agency.*

In order to achieve cost reduction of lithium-ion batteries, as well as other technologies, there need to be an increase in production scale, better materials, more research etcetera (Ralon, et al., 2017). Figure 3 illustrates a schematic view on cost development of batteries.

For stationary purpose, IRENA estimates a significant growth in battery storage for BTM-applications to year 2030, especially for systems combined with solar photovoltaic (PV) to increase self-consumption. This is particularly true for the European market where countries often experience high commercial and residential electricity rates. They also state that the combination of battery storage and PV is likely to grow in parts of the developing world where it could help homeowners from facing blackouts and brown-outs. The total BESS capacity combined with PV could reach 45-75 GWh by year 2030, according to IRENA (Ralon, et al., 2017). Irena has also made a study for G20 where they estimate that 80 % of the world's electricity consumption could come from renewable energy sources in 2050.

Bloomberg New Energy Finance (2017) estimates that the global storage deployment will double six times between 2016 and 2030, increasing to around 300GWh.

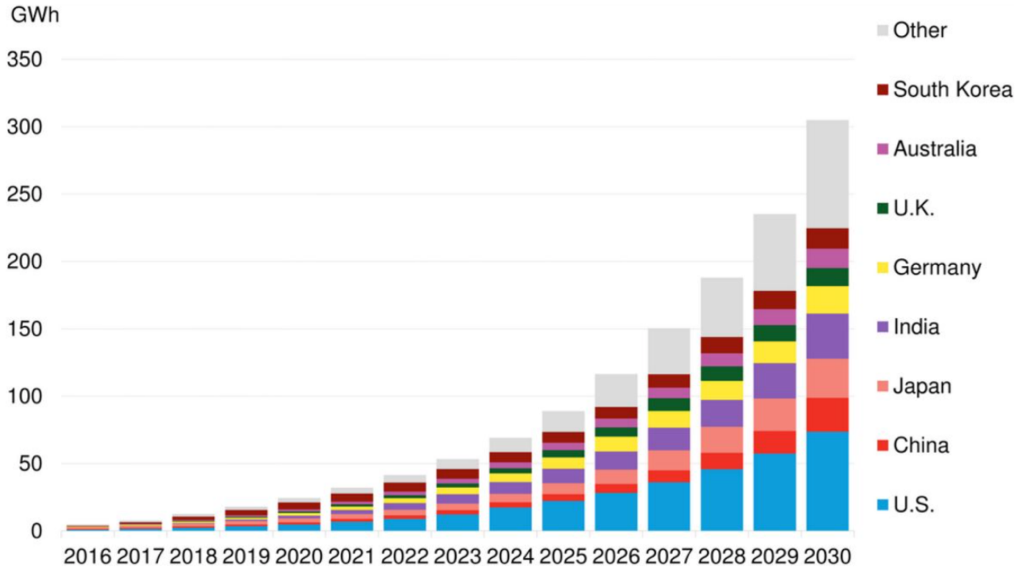

Figure 4. *Global battery energy storage deployment. Source: Bloomberg New Energy Finance.*

That is at the same rate as the market has developed from year 2000 to 2015. Bloomberg states that 70 % of the capacity installed by 2030 will be deployed in eight different countries. As seen in figure 4, these countries are U.S., China, Japan, India, Germany, U.K., Australia and South Korea (Bloomberg New Energy Finance, 2017).

4 Analysis

The literature review was made in order to achieve a full understanding of how to estimate BESS costs. The most frequently used model, LCOS, was identified and evaluated. Six different sources with differently built LCOS were analysed.

Table 7. *Table of analysed sources.*

Application	Sources			
ITM	Apricum	Lazard	World energy council	Jülch
BTM	Apricum	Lazard	World energy council	SolarPro

Table 7 displays the sources on which this study's analysis is based on. To make the analysis as accurate and relevant as possible, the cost models are divided according to which application they are intended for.

One of the objectives of this study is to present benchmark values on the LCOS for both ITM- and BTM applications. This is done by calculating mean values based on the most comprehensive LCOS estimations in open literature. Since all sources do not present which LCOS formula that has been used, the LCOS were recalculated for all sources using the same formula. This is a way of making the comparison more relevant and accurate. The formula that has been used is:

$$LCOS = \frac{CAPEX + O\&M \cdot \sum_{n=1}^{N} \frac{1}{(1+r)^n} - \frac{v_{res}}{(1+r)^{N+1}}}{c \cdot DoD \cdot RC \cdot \sum_{n=1}^{N} \frac{1 - DEG \cdot n}{(1+r)^n}} + \frac{p_{elec}}{\eta} \tag{1.3}$$

Although the different sources provide detailed information on the data that has been used, a few assumptions have been made in order to calculate the LCOS. Some sources provide their data in ranges, so the data used in this report is the mean values of these ranges. WEC provides their data in ranges which cover system sizes intended for BTM and ITM applications. The data used in this report were chosen within these ranges, which correspond to typical system sizes for BTM and ITM applications.

The residual value of the different systems was not accounted for in the LCOS comparison as it was only included in one of the cost models. The residual value of a system can significantly differ from case to case; it depends on how the system is operated and is therefore difficult to assume in general. The charging cost was not included in every cost model which was analysed and can also be different from case to case. The price of electricity is highly dependent on the geographical location of the system and is therefore difficult to assume. Consequently, the comparison is made without the charging cost, but is presented as a reference to illustrate the impact of the electricity price.

A sensitivity analysis was conducted on the LCOS formula in order to identify which factors that contribute the most to cost reduction of battery storage. Four parameters were iterated from -40 % to 40 % one at a time while the other remained constant. The parameters were capex, opex, discount rate and cycles. The number of cycles is given as the amount of times the battery is charged and discharged per year and depends on the characteristics of the system. The cycles can be calculated as:

$$cycles = \frac{FLH}{t} \tag{1.4}$$

Where *FLH* is the full load hours and *t* is the time of the discharging process. The full load hours are the total amount of hours that the battery discharges during its lifetime. Since *t* is constant, the number of cycles is proportional to the amount of full load hours. Therefore, iterating the number of cycles per year will have the same effect as iterating the lifetime of the system. The reason why the cycles are iterated instead of the full load hours is that the time of the discharging process is not given by the different sources and depends on the specific system.

A sensitivity analysis was also made for the electricity price impact on LCOS, which is based on a reference case. The reference case in this report is the mean value for BTM application li-ion and with an electricity price of 10 USDc/kWh, which is the mean retail price of electricity for residential use in the US today (U.S. Energy Information Administration, 2018).

Another objective with the report was to present an overall outlook for cost development of BESS. Aside from presenting available work regarding cost development in the literature review, a projection for LCOS to 2030 has been made. The projection is based on the mean values previously calculated for both BTM and ITM applications. The underlying assumptions for this projection are based on a reduction of capex and discount rate, and an increase in efficiency. The reduction of capex is based on IRENA's (2017) projections for cost reduction on capital costs for systems with li-ion, lead-acid and VFB technologies. They project the capital costs of a system with a li-ion battery to decrease by about 60 % and about 50 % for a system with a lead-acid battery. A system with VFB technology is projected to decrease in capital costs by approximately 66 %. Since the development of energy storage will grow significantly, WACC will decrease. This is due to higher competition; investors cannot achieve the same return on investment when new technologies are being fully deployed. The risk in such projects can be assumed to decrease due to further knowledge and understanding of BESS. Another contributing factor to the possible risk reduction could be the information gathered from the results of current BESS projects. Today, the rates in the Western world are generally at a low level and is projected to continue for some years ahead (Gamber, 2017). This could lead to a potential decrease of the WACC. The size of the reduction is naturally difficult to predict, but since the mean WACC in this report is 8.5 %, the predicted WACC has been set to 5 % for the 2030 projection. This is in line with the WACC used in the studies of the literature review, which range from 3 % to 11 %. The efficiency of battery storage technologies is assumed to be improved by 2030 (Ralon, et al., 2017) but since the projection conducted in this report excludes the charging cost, the efficiency will not have an effect on the LCOS. Including the charging cost would call for a number of uncertain assumptions and would thus require comprehensive analysis which goes beyond the purpose of this study.

Since Jülch and World energy council analyse their data in terms of Euro, a conversion to USD is made. The FX-rate used is 1.11 EUR/USD which is the mean average of the closing price between 2015-01-01 to 2016-12-31 (Investing, 2018). The date range are due to when the reports is estimated to have been conducted.

5 Results

The results from the comparison between the different sources are presented first. The mean values for LCOS are also presented for all three battery technologies for both BTM and ITM applications. The second part shows the results from the sensitivity analysis on the LCOS formula. A sensitivity analysis is also presented showing the impact of the electricity price alone. The last part presents the projection of LCOS for 2030 on all three battery technologies for both BTM and ITM applications.

5.1 Comparison between technologies

The comparison between all three technologies with resulting mean values is presented.

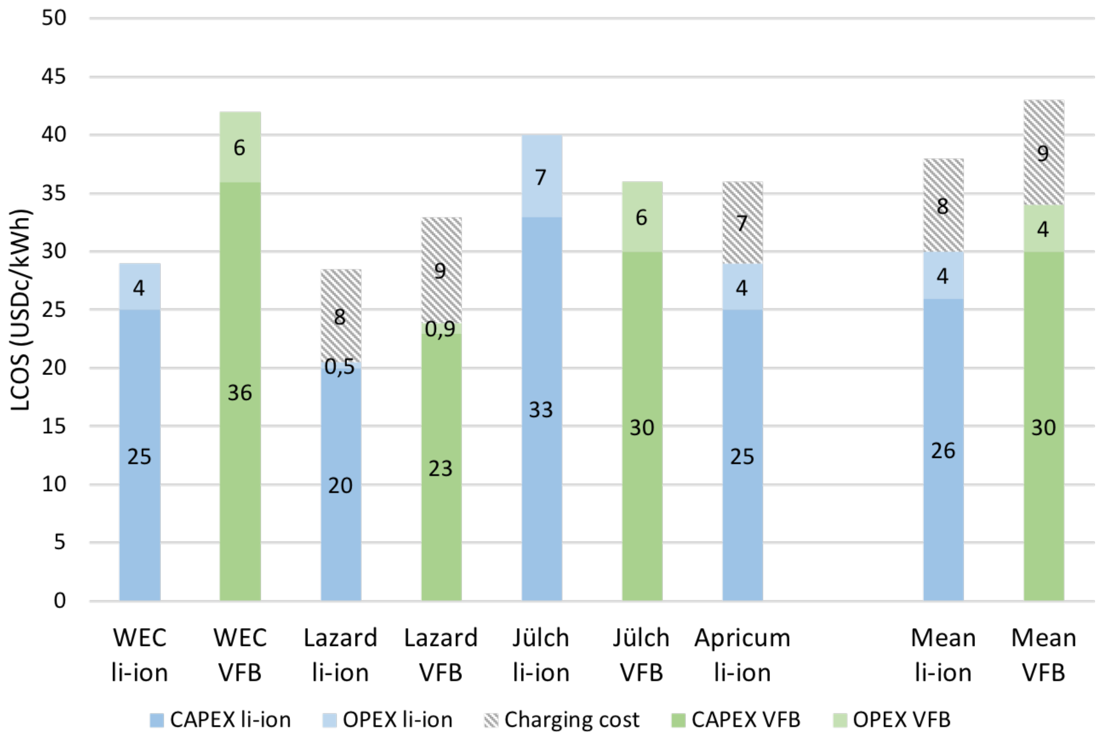

Figure 5. *LCOS for ITM applications.*

As seen in figure 5 the result for the mean LCOS without charging prices is 30 USDc/kWh for li-ion and 34 USDc/kWh for VFB. If charging prices are included, mean LCOS amounts to 38 USDc/kWh for LI-ion and 43 USDc/kWh for VFB.

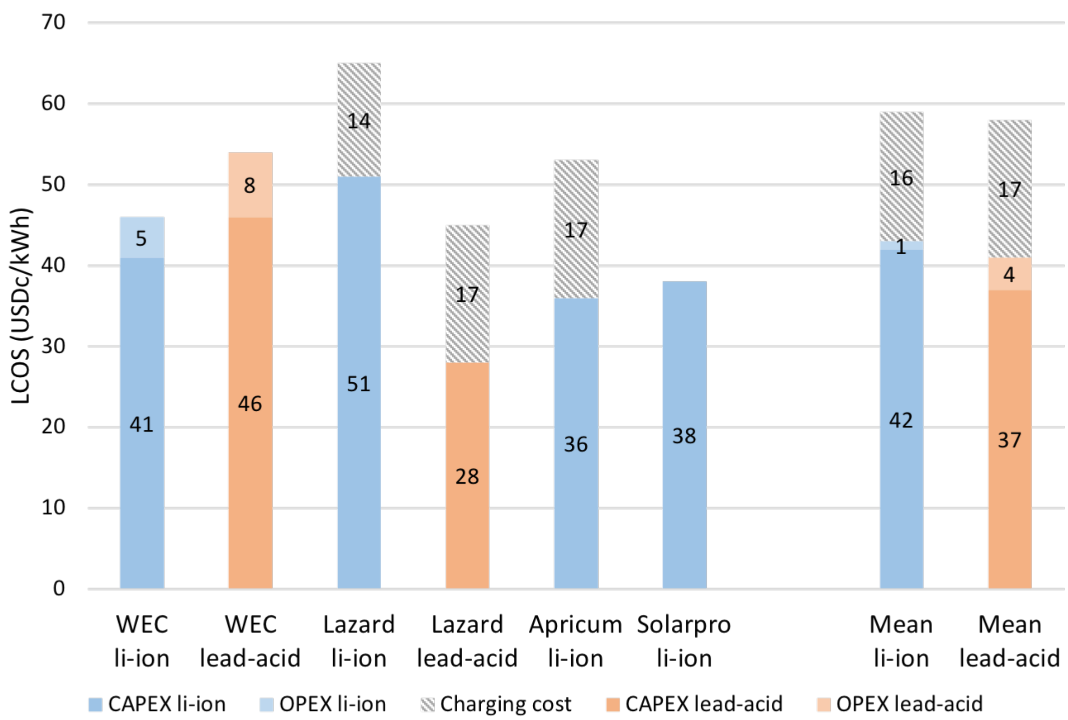

Figure 6. *LCOS for BTM applications.*

As seen in figure 6, the results of the mean LCOS without the charging price are 43 USDc/kWh for li-ion and 41 USDc/kWh for VFB. If the charging price is included, mean LCOS amounts to 59 USDc/kWh for LI-ion and 58 USDc/kWh for VFB.

5.2 Sensitivity analysis on LCOS

The sensitivity analysis shows the impact of cycles, capex, opex and discount rate on the LCOS formula for all technologies.

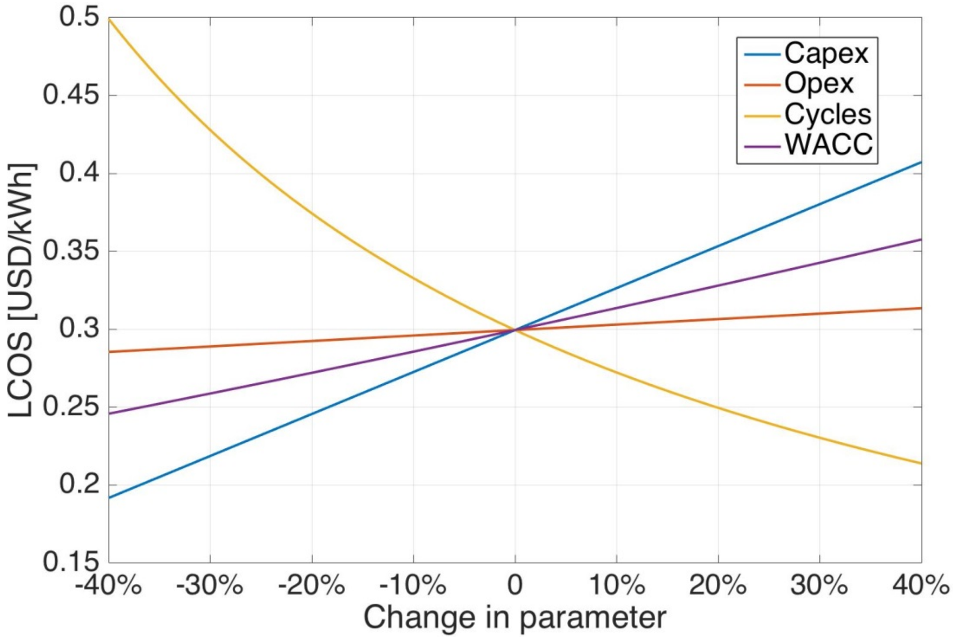

Figure 7. *Sensitivity analysis on LCOS for li-ion ITM.*

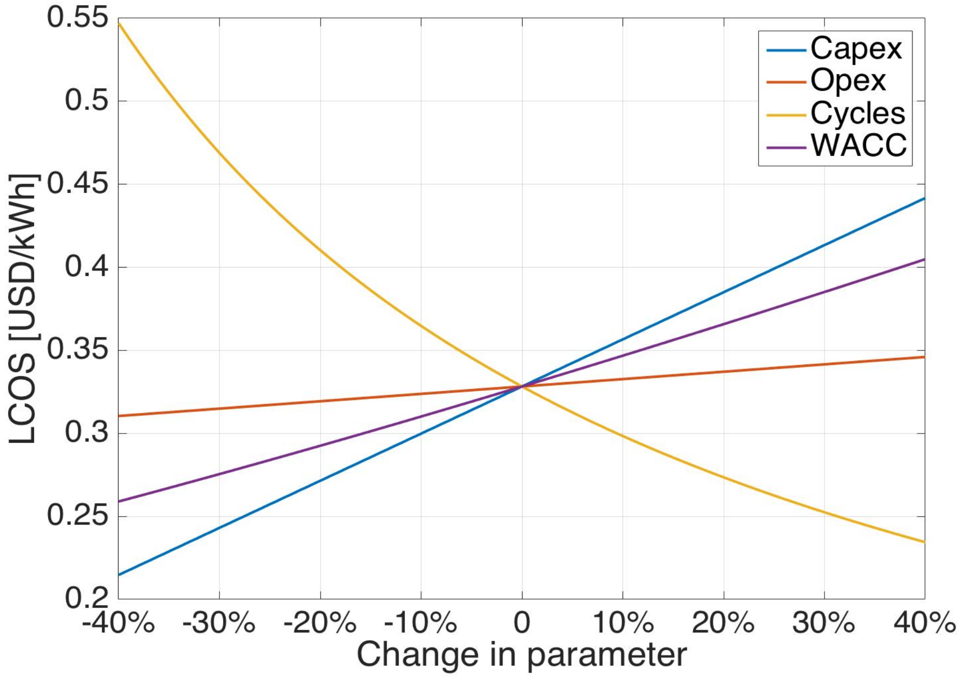

Figure 8. *Sensitivity analysis on LCOS for VFB ITM.*

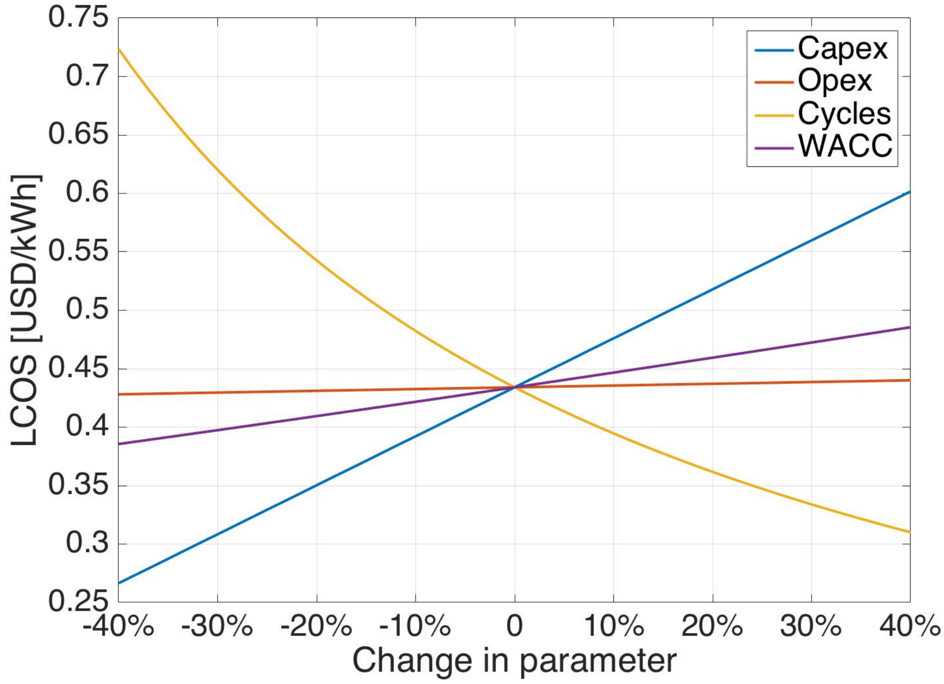

Figure 9. *Sensitivity analysis on LCOS for li-ion BTM.*

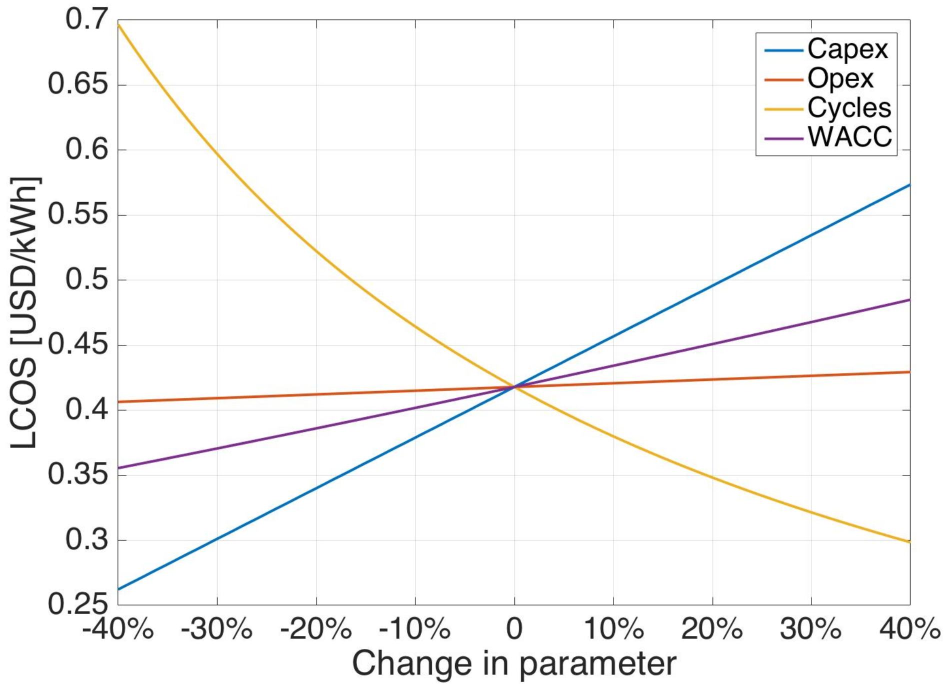

Figure 10. *Sensitivity analysis on LCOS for Lead-acid BTM.*

The sensitivity analysis shows that the biggest impact comes from cycles which correlate to the amount of full load hours. Capex and WACC also have a big impact on LCOS. For all the technologies, the figures 7-10 show that a decrease in capex with around 30 % will lead to a decrease of the LCOS by roughly 20 %. A reduction in WACC by 40 % shows that the LCOS will decrease by around 20 % for ITM applications and 13 % for BTM applications.

The sensitivity analysis of the electricity price is based on our reference case.

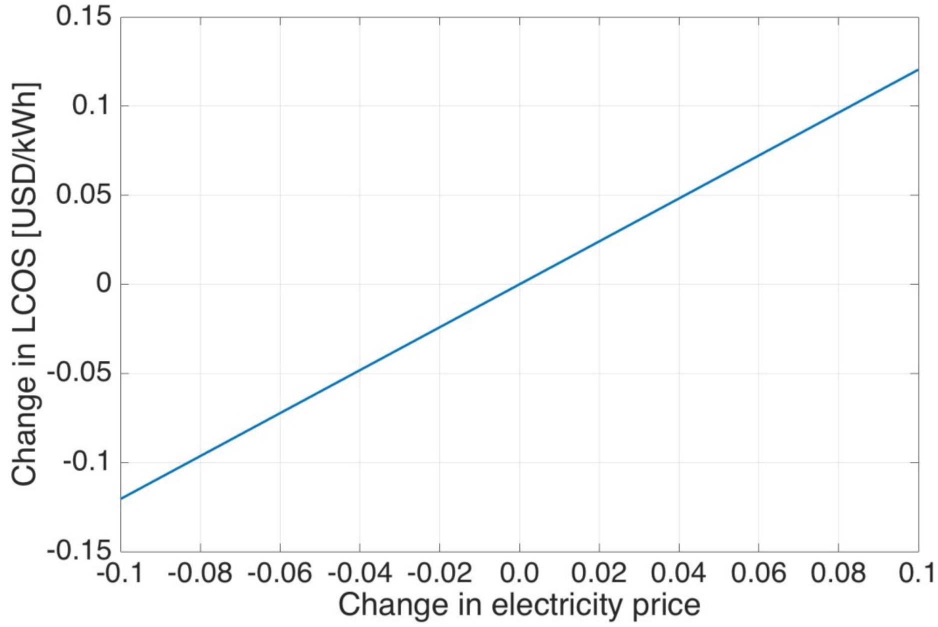

Figure 11. *Sensitivity analysis on LCOS with respect to electricity price.*

Figure 11 shows the impact of the electricity price on LCOS. The change in LCOS will be 20% more than the actual change in electricity price.

5.3 Projection for LCOS 2030

The projection of LCOS by 2030 is presented in this section.

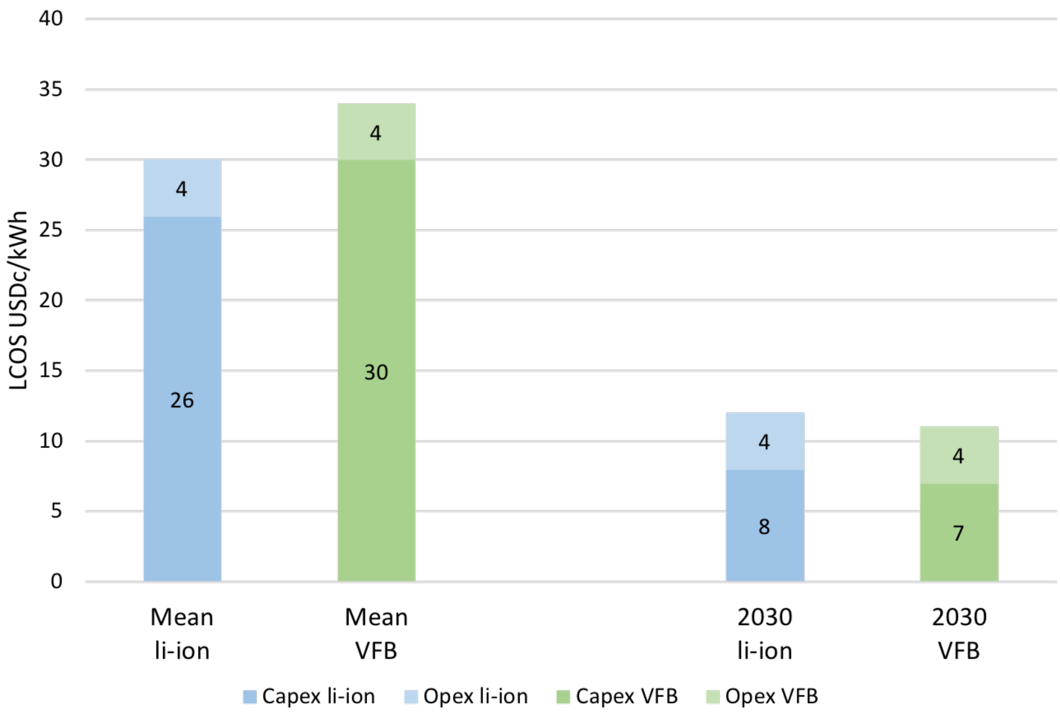

Figure 12. *Projections for LCOS 2030 for ITM applications.*

As seen in figure 12, LCOS for Li-ion is projected to decrease by 60 % from 30USDc/kWh to 12 USDc/kWh and LCOS for VFB is projected to drop 68 % from 34USDc/kWh to 11USDc/kWh.

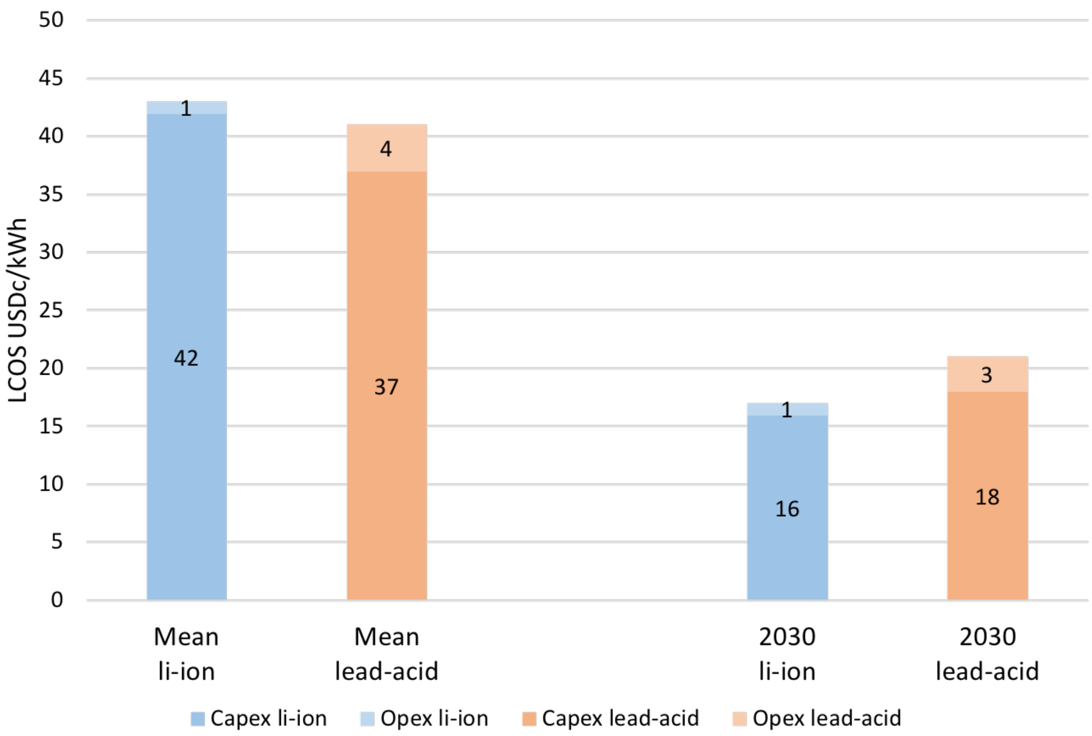

Figure 13. *Projections for LCOS 2030 for BTM applications.*

As seen in figure 13, LCOS for li-ion is projected to decrease by 60 % from 43USDc/kWh to 17 USDc/kWh and LCOS for lead-acid is projected to drop 49 % from 41USDc/kWh to 21USDc/kWh.

6 Discussion

This report aims to identify and compare existing cost models for BESS. However, the LCOS is as of today the only model for estimating costs of a battery storage system over its entire life time. As stated in the report, another way of estimating and comparing costs of a battery storage system is to focus on the specific investment costs to install a system based on system size and characteristics. These cost models do not account for costs such as O&M, residual value and charging, as well as the time value of money which makes it more difficult for stakeholders to assess the profitability of a battery storage system. Therefore, this report focuses on the most detailed and comprehensive cost model available in order to fully understand the entire cost structure of BESS. If one wishes to use information in this report to estimate or compare upfront costs, capex and system sizes are provided.

Many sources have set intervals for their cost for different parameters. In some cases, values were chosen within these intervals that seemed applicable for today. That could of course lead to faulty mean values and projections, but this is where the sensitivity analysis will be of great support. One could go further up or down in the range of a specific parameter and observe the extent of impact on the LCOS.

In regards of the projection of LCOS by 2030, the decrease in capex for all the technologies is sourced from IRENA; a study which is based on 150 data sources and expert interviews. The estimation of the future WACC could be misleading since the cost of equity varies depending on the risk and return from other investments. There could be a possible increase in risk if the current projects would have negative outcomes. However, the estimation of WACC 2030 at 5 % is still in-line with the ranges of the sources.

Opex by year 2030 are assumed to remain unchanged. The systems must be maintained, and as of today opex part is already low relative to capex. Assuming it would go down even further is unjustified. The lifetime of a system is of particular interest since its impact on LCOS is significant. According to the sensitivity analysis, an increase in life expectancy leads to a decrease in LCOS. This is due to an increase in the amount of full load hours. This report has not provided any projections of the life expectancy of BESS. Although one can assume that the lifetime of BESS positively correlates with the technological improvements of systems and standardization of products.

The sensitivity analysis which shows the impact of the electricity price on LCOS is based on the cost contribution of the charging cost, which is the electricity price divided by the round-trip efficiency. Therefore, the better the efficiency the closer to parity the changes will be.

The five sources used in this report for analysing data for LCOS are gathered from the open literature. They are made in the years between 2015 and 2018. There exist other reports which are conducted between the years 2009 and 2015, but for the relevance of today they are excluded in this report. There are several reports for example from GTM research, Lux research and Navigant that would have contributed to this report, but since they are expensive to purchase, it was not an option. For each new source that could have been included in this report, the result of our average value for LCOS would be more and more accurate to what is available on the market today. Regardless, this report gives a good guidance on where the levelized cost of storage is headed.

It is important to recognize that the results of the projection for future LCOS conducted in this report are made without the contribution of charging costs. As described in the analysis, this is due to the fluctuation of the electricity price depending on the geographic location of the system. Not considering the charging cost implicitly means that the round-trip efficiency of the storage system is not accounted for. Although the cost of electricity by 2030 is assumed to be difficult to project, the round-trip efficiency of battery storage systems may very well increase. More investments in battery technologies will lead to an increase in production scale, better materials, more research etc. (Ralon, et al., 2017) which will improve the overall performance of battery storage. Therefore, the projection for LCOS conducted in this report can only be seen as a benchmark for how capital costs and the time value of money will affect the LCOS by 2030 and should be supplemented with charging cost and round-trip efficiency for a more accurate cost estimation.

As mentioned earlier in the report, the LCOS formula calculates the levelized price per electricity unit at which the net present value is zero. The LCOS does, however, not provide an estimate of the cost of a battery storage system when it is utilized for multiple use cases. For instance, a storage system could theoretically provide frequency regulation to the grid in the morning and then be used for peak shaving purposes in the afternoon. This is a way of stacking revenues and will ultimately reduce the cost of the storage system. This is highly dependent on how the specific system is used and operated and is not accounted for in this report. In fact, a model for estimating costs for battery storage with stacked services does not exist in open literature.

7 Conclusions and future work

Assuming that the current market prediction is correct, LCOS will most likely decrease in the near future. The downturn is mainly capex driven, but parameters such as lifetime of BESS could also have an impact. According to the consensus view of the market development, the energy storage market will see a significant growth in the near future. This could facilitate the use of renewable energy sources and could be regarded a prerequisite for becoming a fossil-free society. According to the literature analysed in this study, battery energy storage will constitute a bigger part of the total available capacity in the future. A possible reason for this could be the simplicity of installing these systems in relation to traditional storage such as pumped hydro, CAES. Furthermore, the growth of the battery storage market could also be explained by the continuous growth of renewable energy sources, such as solar PV and wind power. However, battery energy storage will presumably remain a minor part of the total capacity in the near future.

The case that LCOS is the metric for future valuation of battery energy storage is not safe to say. Many reports and magazines often raise the difficulty of calculating LCOS. The measure is new, system sizes and the purpose of usage varies, electricity prices fluctuate and sometimes the systems may need subsidies in order to be profitable. Infrastructures, laws and regulations in a specific country are also parameters that must be taken into account. There exist other ways of achieving the full cost picture of a system, for example total installed cost in relation to system size and levelized cost of electricity, both mentioned in the report. In the future, new cost models might develop which may lead to more accurate estimations. For that case and given that the market will continue to grow, it is important that more research and reports are being made in the energy storage sector. That will also lead to early findings in possible shortcomings of what is done today. As mentioned in the discussion section, estimating costs for battery storage with stacked services does not exist in open literature. But Lazard is on the right track stating that this is something they will have a look at for their future calculations of LCOS (Labrador, 2016).

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9 Appendix

Data sheet

DATA SHEET FOR SOURCES PARAMETER VALUES

Source	Capex[USD/kWh]	Opex[USD/kWh]	Wacc[%]	Cycles[y]	DoD[%]	Degradation[%]	Life time[y]	Rated capacity[Mwh]	Price electricity[USD/kWH]	Roundtrip efficiency[%]	Residual value [USD]
In-front of the meter Li-ion											
Apricum	500	10	10	350	80	0	15	6	0,0600	92	100
Jülch	950	19	8	365	80	0	20	10	0,0000	95	0
Lazard	519	2	11,2	350	100	0	20	4-400	0,0300	86	0
World energy council	777	16	8	365	100	0	6	40	0,0000	85	0
Mean value	686	12	9,3	358	90	0	15		0,0225	90	25

Source	Capex[USD/kWh]	Opex[USD/kWh]	Wacc[%]	Cycles[y]	DoD[%]	Degradation[%]	Life time[y]	Rated capacity[Mwh]	Price electricity[USD/kWH]	Roundtrip efficiency[%]	Residual value [USD]
In-front of the meter Flow											
Jülch	1090	22	8	365	100	0	20	400	0,0000	80	0
Lazard	579	3	11,2	350	100	0	20	400	0,0300	70	0
World energy council	1110	22	8	365	100	0	20	40	0,0000	70	0
Mean value	926	16	9,1	360	100	0	20		0,0100	73	0

Source	Capex[USD/kWh]	Opex[USD/kWh]	Wacc[%]	Cycles[y]	DoD[%]	Degradation[%]	Life time[y]	Rated capacity[Mwh]	Price electricity[USD/kWH]	Roundtrip efficiency[%]	Residual value [USD]
Behind the meter Li-ion											
Apricum	1000	0	3	250	100	0	15	0,0050	0,0000	70	0,00
Lazard	1047	0	11,2	350	100	0	10	0,01-0,25	0,1200	85	0,00
World energy council	1000	20	8	365	100	0	10	0,1000	0,0000	85	0,00
Solar pro	1400	0	0	365	100	0	10	0,0064	0,0000	90	0,00
Mean value	1112	5	5,6	333	100	0	11		0,0300	83	0,00

Source	Capex[USD/kWh]	Opex[USD/kWh]	Wacc[%]	Cycles[y]	DoD[%]	Degradation[%]	Life time[y]	Rated capacity[Mwh]	Price electricity[USD/kWH]	Roundtrip efficiency[%]	Residual value [USD]
Behind the meter Lead-acid											
Lazard	696	0	11,2	350	100	0	10	0,01-0,25	0,1200	72	0
Word energy council	1000	20	8	365	70	0	10	0	0,0000	77	0
Mean value	848	10	9,6	358	85	0	10		0,0600	75	0