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The Potential of Lithium-ion Batteries and Vanadium Redox Flow Batteries as Distributed Stationary Energy Storage Systems for Photovoltaics

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **DANIEL LAABER**, hereby declare

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Abstract

The past decade has seen large-scale penetration of distributed renewable energy. Electrochemical energy storage systems are proving their potential to enable the transition from conventional energy generation to more sustainable forms. This thesis will focus on increasing the rate of self-consumption of on-site generated electricity by the application of electrochemical energy storage systems. In the current study, Lithium-ion Batteries and (Vanadium) Redox Flow Batteries have been identified as technologies with the greatest potential at the capacity range of 40-70kWh. In combination with photovoltaics, both systems have reached grid parity level, with an estimated payback period of 6.3 years in the region of Bavaria, Germany. The results of this study suggest that especially SMEs in agriculture may benefit from such systems and could decrease their annual electricity bill significantly. Further work needs to be done in order to assess the potential of distributed storage systems in urban areas and businesses with unfavorable load curves for wider usage of photovoltaics.

Keywords: Renewable Energy, Energy Storage Systems, Secondary Batteries, Lithium-ion Batteries, Vanadium Redox Flow Batteries, Self-consumption Rate, Sustainability

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Abbreviations

BAU	Business-as-usual
DSM	Demand-side Management
EEG	Erneuerbare Energiengesetz (Umlage)
EES	Electrical Energy Storage
FiT	Feed-in Tariff
GHG	Green House Gases
LiB	Lithium-ion Battery
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
PHS	Pumped Hydro Storage
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
RFB	Redox Flow Battery
SME	Small and medium-sized enterprises
VRB	Vanadium (Redox) Flow Battery

Acknowledgements

Though only my name appears on the cover of this thesis, it would not be possible with the support of my family. I dedicate this work to my parents and my sister who supported me in the last year by different means. Thank you, I wouldn’t be here without you.

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1. Introduction

Solar energy and wind energy have reached grid parity level in some regions around the globe. A smooth transition from conventional energy generation to a more sustainable form is gaining popularity in many regions around the globe. Yet, a smooth transition is constraining national budgets, the design of markets systems, societies and (inter)national power grids. Unresolved issues like intermittency of electricity generation remain unresolved. Electrochemical storage has been identified as a viable solution, enabling energy transition.

Energy has been an integral part of the human civilization for many centuries. Over the centuries, the predominant source of energy changed. Early civilizations used conventional biomass (e.g. timber), which then was replaced by different forms of coal. With the dawn of the 20st century, oil became the primary source of energy. Most likely, the next fuel powering our society will be based on carbon free renewable sources. Especially electricity has proven to be beneficial to us, but it remains as an unreliable source in many parts of the globe due to difficulties in storing and distributing the energy. Hence, electricity generation based on conventional fuels has been always inefficient because we generate it not when it is economic to do so but rather when needed. Fossil fuels, operating as an energy carrier, circumvent the challenge of storing, at the cost of increased harmful emissions, contributing significantly to global warming.

Increased awareness of the negative consequences of conventional electricity production, better technologies, and competitiveness of emerging technologies in the energy sector and energy security led to the increased usage of Renewable Energy Sources (RES) for electricity production. Wind, solar, hydro and to some extent also biomass power generation are getting globally more attractive and the cumulative capacity is steadily increasing. There is, however, one major drawback and that is the reliability of supply. Electricity can only be produced when there is either not too less or too much of the RES like wind, solar radiation, water flow and biomass. When the average wind speed is too low wind turbines cannot harvest the energy, if there is a storm the energy contained in wind can damage the wind turbines. Cloudy regions or areas where the sun is not shining for several months are only partly suitable for PVs. In addition, if there is too much sun the collectors absorb the irradiation heat and efficiency drops. Not all this might be a problem if the electricity produced provides only the base load but as the market penetration of RES increases peak load is increasingly provided by RES.

Electricity storage may be one solution to solve the dilemma of intermittency, yet it is described by a Policy Officer of the DG ENER, in an interview, as the weakest link in the electricity chain today (SETIS 2013). Other solutions may include smart grids, demand side management (DSM) and smart meters but their potential is limited to some extent. Despite, by definition, storing energy has always negative efficiency and excessive costs and nobody wants to store electricity for the sake of storing, if the alternative is worse. Storage also mitigates the need to provide extra capacity during peak demand, balancing costs to maintain grid stability and grid integration costs to physically connect production centers with the areas where it is consumed. Adding these services to the electricity chain is expensive and if the RES sector will become more dominant this may add up to ~$5-25/MWh (CITI-GPS 2013) or even $20-83/MWh (OECD 2012, 8).

On the contrary, storage would increase self-consumption, increase the efficiency of electricity production and would lower the need of deferral. Currently only 30% of energy produced from PV can be used efficiently. By integrating storage, this figure would increase to well over 70% (SETIS 2013). This reduces the need of additional investment in additional substations or the construction of new transmission lines. Energy conversion from fossil fuels demands less sophisticated solutions than storing electrons in a galvanic cell and technological innovation are increasing energy density of batteries steadily and (secondary) batteries are becoming more competitive over time. However, electricity storage does not focus solely on mobile aspects of our life but on the entire organization of our economic and social system. Disruptive technologies like Lithium-Ion batteries (LIB) enabled mobile communication and an increasing number of companies around the world are trying to transform the way we are using electricity at home and in the industry as well.

This gained momentum in the recent past when in the wake of the Paris Summit in 2015 more than 2000 companies and several 1000 cities committed themselves to more sustainable patterns of production. Entire industries like the emerging E-Mobility are based on the principle of storing electric energy for further use. New storage solution allows us to operate off-grid applications efficiently without the need of building transmission lines. Although it would be completely unrealistic to assume that electrical energy storage (EES) coupled with RES could eliminate the need of any transmission grid, a comparison to the communication sector where mobile handhelds replaced the need to build costly telephone cables arises. Especially regions where the grid is weak or unreliable, storage can leapfrog the necessity of the grid, if coupled with PV, and may even allow more than 1 billion people who have currently no access to electricity to be connected.

There are various (potential) electrical energy storage systems already on the market and the chosen technology depends on the specific characteristics needed and provided for. While, some applications as flywheels were already applied several thousand years ago, other forms of storing energy like pumped hydro (PHS) where not thinkable of before the industrial revolution occurred. Since then PHS provides the bulk the bulk of energy storage needed today but its potential is limited since it needs a sufficient amount of water, large areas and a certain difference in altitude between the reservoir and the turbine. Fortunate for us, technological advancement did not stop at the mechanical era but moves on to the electrochemical, chemical and pure electrical one. Secondary batteries and flow batteries are increasingly becoming more important for “powering” our society. Coupled with RES electrochemical energy storage systems will become most likely, besides PHS, the most important tool for managing our energy supply. Although the focus of media and science is currently focusing on the “high tech metal” Lithium (SETIS 2015), an increasing number of stakeholders is interested in Vanadium and Zinc-Cerium and the application in redox flow batteries. Most likely this will not result in an "either/or", but "as well as" situation where different types of technologies offer a customized solution for the specific need of the consumer.

In order to assess possible applications of the specific technology chosen it is necessary to identify the specific usage profile of the technology before it can be applied. This paper will contribute to this decision making process by comparing two promising technologies, Lithium-Ion batteries and Vanadium redox flow batteries, and defining the circumstances, where which technology is more suitable for fulfilling the task needed for. The paper is structured the following way:

The first chapter will assess the necessity of electrical energy storage systems in the wake of increasing market share of renewable energy. Based on the energy policy of the European Union and its member states, modular solutions for SMEs will be discussed. As shown further below, especially SMEs may benefit from integrating RES and medium sized EES (30-200kWh) into their business. Underlining idea of this part is to decrease energy purchases from by increasing self-consumption of electricity generated. Viable candidates for this integrating will be surveyed in Part 2. By comparing operating parameters, levelized costs and various other indicators, the two most likely competitors for the near future, Lithium-Ion based batteries and flow batteries, could be identified as viable candidates. Part 3 will implement the results of the previous studies in a case study. The final concluding chapter will conclude the previous chapters.

1.1. Methodology

This master thesis combines several methodologies. The first chapter will review policy papers and reports of International Organizations and specialized agencies in particular from the European market. For the second chapter a technical survey has been conducted. The basis for this chapter are specified articles in Journals dealing with electrochemical storage solutions and telephone interviews with notable companies providing these technologies. The third part of this master thesis implements the results of chapter one and two into a sustainable and lasting solution for SMEs. Provided with the necessary data from the Bavarian State Research Centre for Agriculture a generic pig farm (>400 pigs) in the area of Munich, Bavaria has been identified as a suitable candidate for integrating PV with EES. The software used for this was System Advisor Model (SAM), which modeled and optimized the performance of the indicated design. The software is provided by the National Renewable Energy Laboratory of the United States of America. With this software the findings of (IEC 2011), (Grigoleit 2014), (REC 2014) and (Battke, et al. 2013) will be replicated and revised. Since the software does not support Flow Batteries, voltage and current properties are tweaked in accordance to the manual provided by the NREL. The findings of this software were cross checked with HOMER. The results of this checks were not incorporated into this study

2. Part 1: Electricity generation and Electrical Storage Solutions

The aim of this chapter is to describe the current energy mix and the influence of emerging alternative technologies. With increasing market share of renewables, electrical storage solutions are becoming indispensable. This market development is further pushed by international agreements like the 2015 Paris Agreement on Climate Change, energy policies and other instruments on national and international level. In this regard, states can provide the financial means for supporting juvenile industries (e.g. subsidies and feed in tariffs) for a limited time to provide the necessary environment that supported technologies may be adapted sooner than expected. This provides the necessary push factors for markets to develop until they are resilient enough to compete with mature technologies. When they are resilient enough, competitiveness may be already sufficient to pull it even further. When this point is reached, subsidies or non-financial subsidies usually fade out until they are stopped completely. Energy policy provides the necessary legal and political grounds and legislation implements these so called push factors. Policy review can provide a forecast of future developments on the market. Since approaches differ across the globe, this thesis will focus on European energy policy and central European markets solely.

2.1. Energy policy of the European Union

The European energy policy addresses energy on various layers and dimensions. One, which can be labeled as ‘institutional approach’ aims at further integrating the European Union through legislation. The second approach ‘diversification’ aims at increasing the number of energy suppliers both, internally and externally, by transforming the energy mix, and creating physical interconnections. European states are increasingly becoming less dependent on a single source of technology and/or region for energy. The third approach is ‘behavior’driven. This approach uses technological progress and shifts consumer behavior through policies, although legislation has a guiding function. Underlying questions are ‘how much energy is consumed’ and ‘how energy is consumed’. Increase of self-consumption of electricity generated through PVs by using EES, as the overarching topic of this thesis, belongs into this category as well as energy efficiency in general.

The high share of fossil fuels in our energy mix and diminishing resources in the member states caused high dependency on external suppliers. More than 50% of the energy consumed is imported to the EU from abroad. External gas supplies contributes to 60% and oil for 80% (European Commission 2011a). With the exception of Denmark and the Netherlands all European countries share their dependency on external suppliers, especially in the CEE, with shares of up to 100% (European Commission 2014). Fragmented price negotiations, unpredictable market developments and security constraints are a heavy burden for the European consumers. In 2014, the energy bill accounted for 400€bn, of which is 300€bn for crude oil and oil products. Russia alone receives 100€bn each year from the member states for their fossil fuels (European Commission 2014). This is an unfavorable situation since most of the capital is literally burned instead of invested into lasting energy infrastructure.

Externally triggers for the European energy policy are enhancing the rate of adoption and gave many times the reason to have some sort of European energy policy in place. Climate change mitigation measures, energy security, armed conflicts and tensions in the European Neighborhood. At the same time severe accidents in nuclear power plants like Fukushima, Three Mile Islands and Chernobyl raised concern in various countries and led finally to attempts in some countries to reduce the usage of this technology or phasing out entirely. With the rise of new technologies generating energy from renewable energy sources but also extracting oil and gas from unconventional sources like oil sands and the possibilities of liquefying natural gas and shipping it, energy became central focus of our economy. Several major trends can be observed. First, natural gas is increasingly replacing 'dirtier' fuels like oil and coal are increasingly shipped from further abroad and the European customers try to diversify their supplier network by extending the pipeline grid to countries in the Caucasus, Iran and Central Asia. At the same time, Russia is trying to extend current pipelines in order to avoid transfers through Ukraine and extend market share. In total, European customers pay more than €400bn for fossil fuels each year. This money is leaving the European countries and energy prices rise in general, although in 2015 and 2016 were marked by surprisingly low prices. The second trend is that RES are increasingly becoming more competitive and may replace conventional energy sources.

Those developments and deepening of the European integration it became evident that the energy needs to be reformed in order to meet the needs of the 21th century, although energy has been crucial to the Union since the creation of the European Coal and Steel Community in 1951 and Euratom in 1957. However, until today the energy markets remained fragmented and ineffective. Only in recent years, energy became (again) central in decision making process. Energy markets are highly monopolized traditionally, independent and not interconnected.

The first oil crisis of 1973 had a serious effect on the European (energy) market. Alterations in foreign policy caused that several European countries like the Netherlands faced a complete embargo; while some countries including the United Kingdom and France were not embargoed. At the same time, the United Kingdom was facing a severe coal miner strike. These events acted as a ‘waking call’ after years of political stagnation in regard to the European Integration. Several official documents highlighted the risk of not acting and reforming the institutional setting. Especially the European Commission was keen to change the system and highlighted the negative effects on agriculture (European Commission 1974c), employment and labor market (European Commission 1974b) and energy balance (European Commission 1974d).

As a consequence, further collaboration in the energy sector with the United States was discussed with Henry Kissinger, former Secretary of State (European Commission 1974a). A more drastic approach was stated in a brochure published in 1974 calling for ‘maximum reduction possible in the degree of dependence on the rest of the world for energy’, the EC called for more ‘*solidarity between member states’* and ‘*free movement of goods*’ (European Commission 1974e). Some of these ideas were ahead of the time like ‘*rational use of energy*’ and by that decreasing the amount of energy needed by 10%, substituting coal and oil by gas and increasing the electricity share from 25% to 35% by 1985.

Yet, the European states failed to modernize the European energy market and putting in place comprehensive energy legislation. Several legislative acts laid ground for more comprehensive action to follow but several member states hindered this. While, the Single European Act (1986) called for a completion of the internal market, the Treaty of Maastricht, which created the EU, failed to implement a chapter on energy. Some states, especially those with a relative abundance and limited will to reduce their autonomy vetoed critical parts. What remained was vague language, like calling for ‘*measures in the sphere of energy*’ (Article 3). Solely article 129b (1) calls for more concrete actions like '*European networks in* *the areas of transport, telecommunications and energy infrastructures*' and the '*right of choice for their respective energy mix*' (Article 130s (2)).

Since the nineties, the creation of a full and comprehensive energy policy in EU, became increasingly popular and needed. Especially for the electricity markets, the three energy packages (1996, 2003 and 2006) were important. Consisting of directives and regulations, they aimed at reforming the national energy sectors. For the first time competitive parts of the industry (supply and production) were differentiated from non-competitive parts like the operation of energy networks. Energy markets and infrastructure were opened for third parties and consumers were allowed to switch supplier if possible. But only with the third package, which was the most comprehensive of these three, was rather successful and led to mainly three improvements (IEA 2014a). By this the cross-border trade became more harmonized and was accompanied by establishing of two agencies, one in Ljubljana, named *Cooperation of Energy Regulators* and one in Brussels called *European Networks for Transmission Systems Operators*. This measures resulted in increased competition within countries, but also across borders and reduced the link of oil prices to electricity prices (IEA 2014a). Yet this measures were not fully implemented by the member states and by 2014, 14 members were behind schedule. The completion of the internal market for gas and electricity was scheduled for the same year.

Other remaining issues are that 14 states still regulate the gas price and 16 electricity prices, larger corporation and still remaining monopolies misuse their market share and prevent third parties from entering by strategically withholding production capacity or deter likely competitors from investing. This remains an ongoing issue and the European Commission accused energy companies like E.ON of misusing its market position already back in 2008 (European Commission 2008b). In order to increase the speed of integration one measure was to speed up the rollout of smart meters, since especially the retail market for consumers was lagging behind. This process is quite demanding and will most likely not succeed until 2020 (IEA 2014a).

To distinguish between competitive and non-competitive parts of the electricity market and the opening of (electricity) markets for third parties have been important milestones for renewable electricity generation. Yet, they were not competitive enough and market structure still preferred centralized solution to human energy needs. The European institutions pushed for further legislation. This call was accompanied by a constitutional crisis and the negative referendum in France and the Netherlands. By 2009, this reflection period ended by the Treaty of Lisbon with the two parts Treaty on the European Union (TEU) and Treaty on the functioning of the European Union (TFEU). Article 194 of the TFEU provides for energy policy, now having its own chapter. Although still quite vague, it provides authorities with the legal basis to further transform the energy sector and reads as follows: '*Member States agreed shall aim in the spirit of solidarity for (a) ensuring the functioning of the energy market (b) ensure security of energy supply in the Union (c) promote energy efficiency, energy saving and the development of new and renewable form of energy and (d) the interconnection of Energy networks*'. This provision was accompanied by the 2020 Climate and Energy package, with the aim of cutting green house gas emissions by 20% (from 1990 levels), increase energy efficiency by 20% and have a market share of renewables of 20% by 2020. The long-term goal is to cut GHG emissions by 80-95% by 2050.

In 2010, the Commission then published a blueprint focusing on energy infrastructure aiming at creating an integrated energy network in Europe (European Commission 2010). The need for electrical storage systems, although predominantly large scale, was identified as a pressing need in order to fulfill this targets. In addition it called for further research and deployment of storage and charging capacities for electric vehicles and hydrogen (European Commission 2010). Although the paper calls for concrete actions it seems that concrete solutions are not identified yet and the authors took an educated guess in choosing the right technologies.

Deteriorating security situation in the ENP region brought up the energy topic to the agenda of European decision maker once again. Several disruptions of gas supply took place in 2006, 2009 and 2014 and showed the vulnerability of the European Energy market. While the first one disruption was rather short, acted as a warning signal and was over after 36 hours (European Commission 2008a), the second one in 2009 lasted for several weeks and was called “unprecedented” by the EU (European Commission 2009). As an immediate response it was urged to revise existing directives in order to be better prepared for the future. Recent developments in Ukraine increased the speed of revision and adaption of new legislation and policies.

On 25 February 2015, the European Commission adopted the so far most comprehensive energy package, aiming at unifying various aspects of previous aims and goals. This so called Energy Union Package is designed across five mutually reinforcing dimensions aiming at enhancing security, sustainability and competitiveness (European Commission 2015b).

- Energy security, solidarity and trust;
- A fully integrated European energy market;
- Energy efficiency contributing to moderation of demand;
- Decarbonizing the economy; and
- Research, Innovation and Competitiveness.

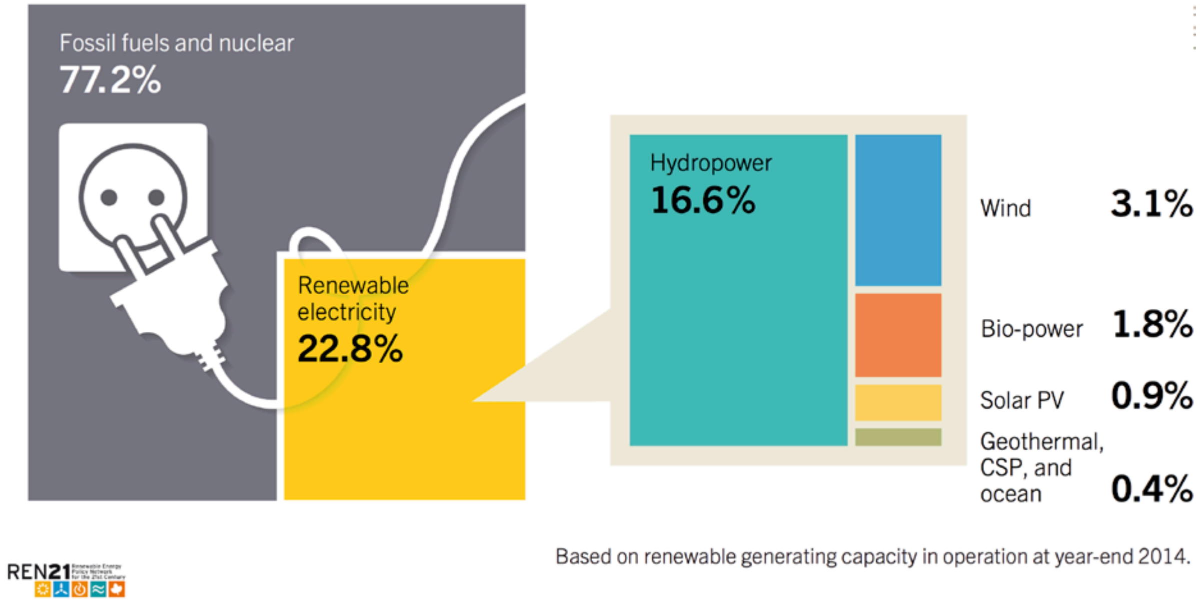
Without naming explicit technologies renewable energy sources are at the core of this document. Electrical Storage Solutions have been identified as an important contribution, especially in the field of security of supply, integrating the energy market and e-mobility.

A couple of months ahead the Commission issued a statement, reminding the Member States in the wake of the Paris Summit in November 2015, of the positive feedback mechanism of sustainable investment on the labor market and other sectors. Preliminary results of this package are that the electricity and gas markets are still not operating as they should, citizens should take more ownership (European Commission 2015c).

According to the Commission, progress has been made on various layers. First, the EU is the most carbon-efficiency major economy in the world and is successfully decoupling economic growth and GHG emissions. In between 1990 to 2014, the European economy grew by 46% while GHG emission decreased by 23% (European Commission 2015c). Furthermore, the EU is on track to achieve the renewables market share target of 20% by 2020. A new directive focusing solely on Renewable Energy and bioenergy sustainability for 2030 should be submitted by the second half of 2016. In conclusion, the European Union and its Member States are currently more or less on track to meet their targets, although much work still needs to be done to reach the long-term goals of 2030 and 2050.

2.2. (Renewable) energy generation and consumption

Electricity generation from renewable sources is becoming increasingly popular across the globe at staggering growth rates. Renewable energy, in particular wind, solar and hydro, require significant upfront investments at low operating costs and no fuel price risk. As shown in **Error! Reference source not found.**, fossil fuels are still the most dominant fuel for electricity generation. The bulk of renewable electricity generation is by hydropower of which almost one third is produced in China alone (REN21 2015).



Based on renewable generating capacity in operation at year-end 2014.

Figure 1 Estimated Renewable Energy Share of Global Final Energy Consumption, 2013(REN21 2015)

Future growth will depend on investments made today. As we can see, especially renewable energy has been at the focus of new investments. Solar, wind and hydropower are the most dominant targets of investments. Solar power was leading total investment by far during 2014. 149.6 billion USD have been invested in this particular source. This represents an annual growth of +23% in comparison to 2013. 90% of this investment went to PV technologies, while the remaining part was invested into CSP and other technologies. Wind power has been also important for many years with around 100 Mio. USD investment in 2014, 11% more than 2013. Especially China and other developing regions in the world are catching up with investment. Excluding large hydro (>50MW), 132 billion USD have been invested in renewable energy in 'developing' countries in contrast to 138 billion USD in the 'developed' countries. Still, investments in fossil fuel powered plants are still popular with 289 Mio USD total investments. On a regional level this picture is different, especially the

EU (REN21 2015).

This investment led to staggering growth rates of RES, in particular wind, solar and CSP. The following figure shows the annual growth rates of chosen sources (REN21 2015). Clearly, hydropower cannot compete with the modular characteristics of other sources. Still, major projects like the Three Gorges Dam in China with an added capacity of 22.5GW in 2008, and other projects, including the currently under construction Belo Monte Dam in Brazil with 11GW added capacity will result in higher (distorted) growth rates. Growth rates of 30% translate in doubling the capacity every 2.6 years. If, and this is rather unlikely, growth rates prevail it could result that in between 13 to 20 years the entire globe could be powered solely by solar. Clearly, growth rates of rather juvenile industries like solar will decrease over time as market share increases.

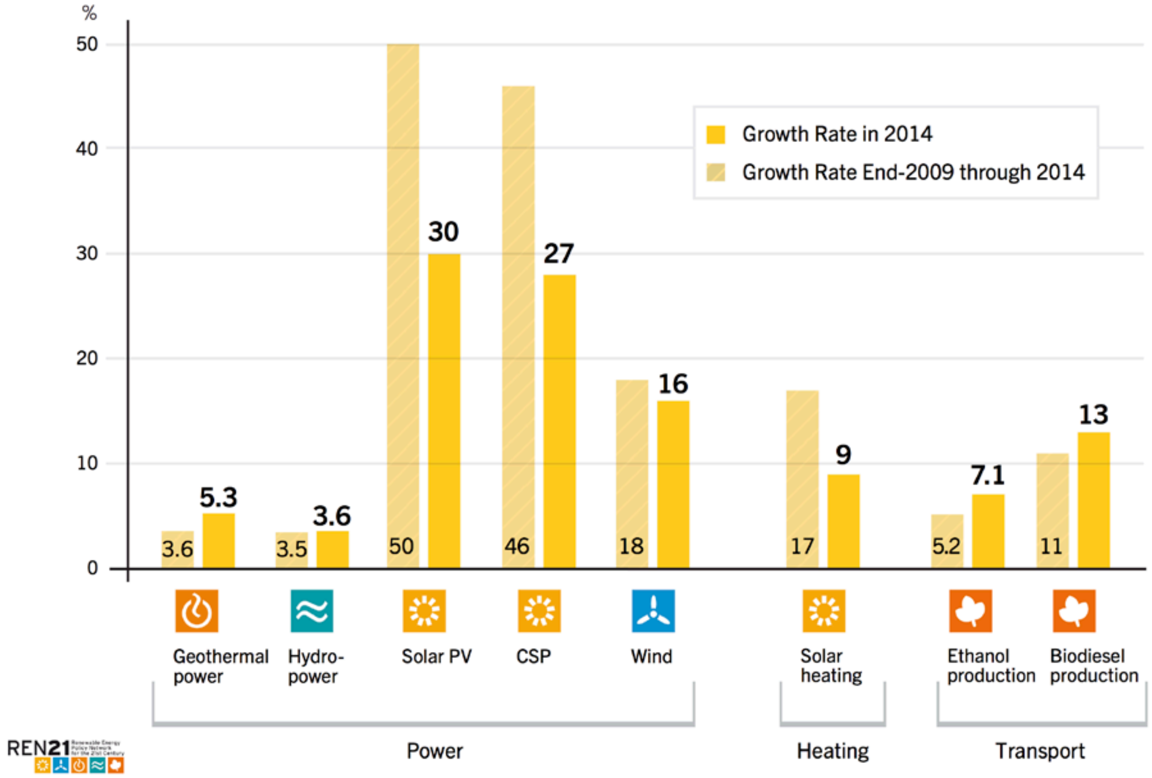


Figure 2. Average Annual Growth Rates of Renewable Energy Capacity (REN21 2015).

In 2012, the global electricity supplied amounted to 22,721TWh, which is set to increase by 100% under BAU until 2040. In accordance to this, the International Energy Agency outlined two other scenarios, which may be feasible and are more favorable to the environment. In the wake of the Paris Agreement even more ambitious targets are needed which result in greater energy efficiency. Still the world would consume 35,000TWh in 2040. If the current and predicted policies prevail the net-generation would accumulate to 40,000TWh (IEA 2014b, 208). All of them have in common that renewables will become more dominant. The following figure shows the transformation of the energy mix over the course of the next decades according to four IEA scenarios. As we see, the energy targets of the parties to the agreement are not sufficient for decarbonizing the global economy and measures that are more stringent are needed in order to meet the targets of the Paris Summit.

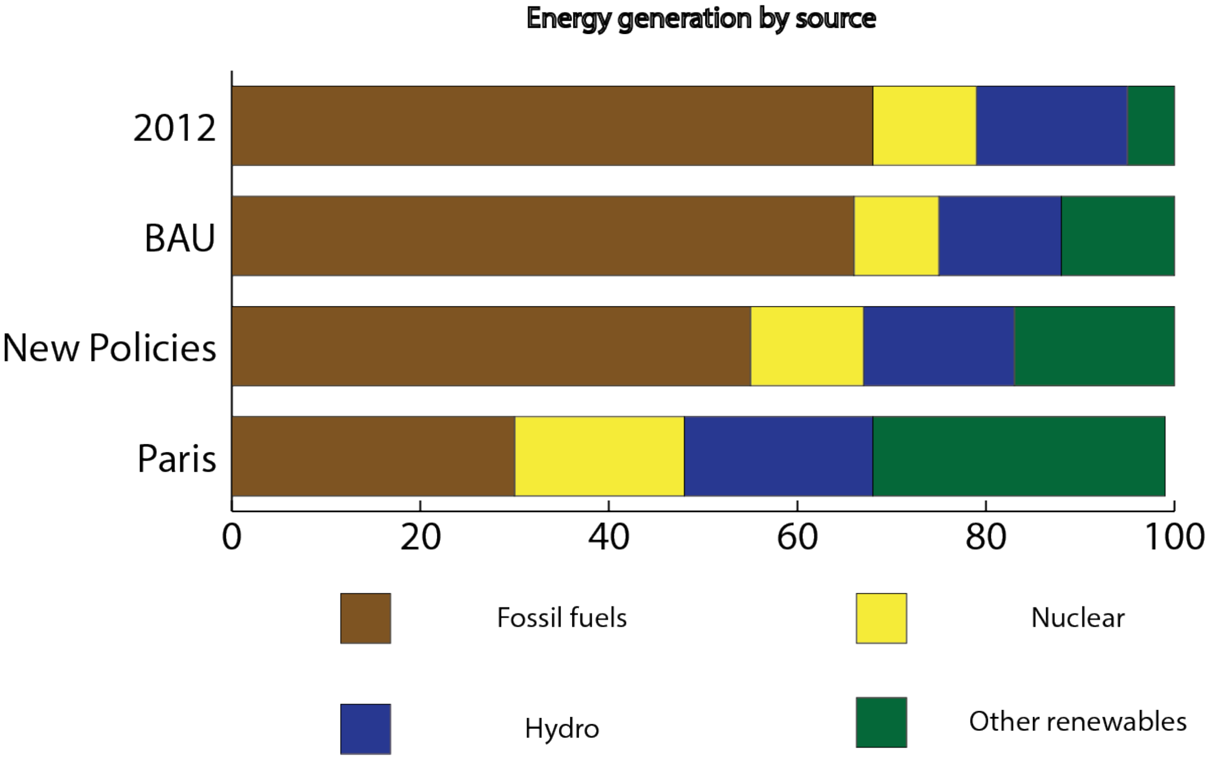


Figure 3 IEA scenarios(IEA 2014b, 208)

Driven by the policies above, technological progress and economies of scale, renewable energy has become more important during recent years. It is no longer a question of *if* but rather *when* renewable energy will become one of the dominant energy form in our energy mix. Global electricity production accounted to 22.7TWh, of which was 1.1TWh from RES and 3.7TWh hydro, in 2012 (IEA 2014b, 208). Other sources put this figures lower with 657GWh from RES in 2014 (REN21 2015).

2.3 Renewable Energy in Europe

Total net electricity generation in the European Union was 3.10 Mio. GWh in 2013. Of this, electricity was generated by 26% from coal and lignite, 17% from gas, 2% oil, 27% by nuclear power, 12.8% hydro, 7.5% wind, 2.5% solar and 0.3% others. Electricity demand is set to increase slightly by 0.8%/p.a. for the period 2012-40 (IEA 2014b, 206). The share of renewables to total energy demand is 15.3% and is set to increase to at least 20% by 2020. Although fossil fuels are still dominating in Europe, renewables generated more electricity than all coal power plants or nuclear power plants in 2013. This development is, together with increased energy efficiency, beneficial for the environment since the CO2 emission intensity decreased from 748g/kWh in 1990 to 558g/kWh in 2013. Final electricity demand by sector (industry, services and households) remained quite stable with an allocated share of roughly 1/3 each. By 2040, the largest increase of electricity demand is by buildings (Both residential and commercial) and industry. Although the final electricity demand of the transport sector is currently around 2% predictions about the future development depends on the rise of electric vehicles, which is currently unpredictable and vary on a regional level.

Nuclear energy will most likely remain a special case. With the German decision to phase out nuclear energy, RES and coal are gaining popularity. Some member states decided to rely on nuclear energy while others rejects the production or even usage of nuclear energy, Negotiations in this area will remain sensitive. It is especially sensitive for countries, which desire to not use this kind of energy but at the same, time will or has to import electricity from countries, which use nuclear power. In 2007, the European Council reconfirmed that the desired energy mix will be respected (European Council 2007). Since it is technically impossible to differentiate between nuclear energy and non-nuclear energy member states will still be able to produce the energy they want but are de facto not in the position to exclude nuclear energy entering the market.

Hydropower has been in use for many decades, based on proven technologies, high upfront costs but low operating costs. Hydropower contributes the largest share of renewables in the EU. Although electricity generation increased by almost 30% since 1990, the share declined from 94% to 42% in the same time (Eurostat 2016). This is due to rapid deployment of other renewables. The future potential is limited. Since the 80s added capacity of hydropower stalled in Europe and Northern America and is subject to increase only in parts of the world, limited to areas where there are sufficient water sources. While some countries like Norway can produce more than 90% of their electricity from Hydropower, arid region will never be able to use this technology. In 2004, more than 16% of global electricity generated was based on hydro. Estimates for the global capacity are in the range of 2,5*10^19 Joule, which is one third of projected need of electricity in 2020. According to the IEA it is rather unlikely that it will exceed 1,5*10^19 J in 2030 (Santos 2012, 140). The following figure shows the increase of total electricity added power to the grid in Europe. Especially wind and solar power has seen a rapid development in the recent past (Eurostat 2016).

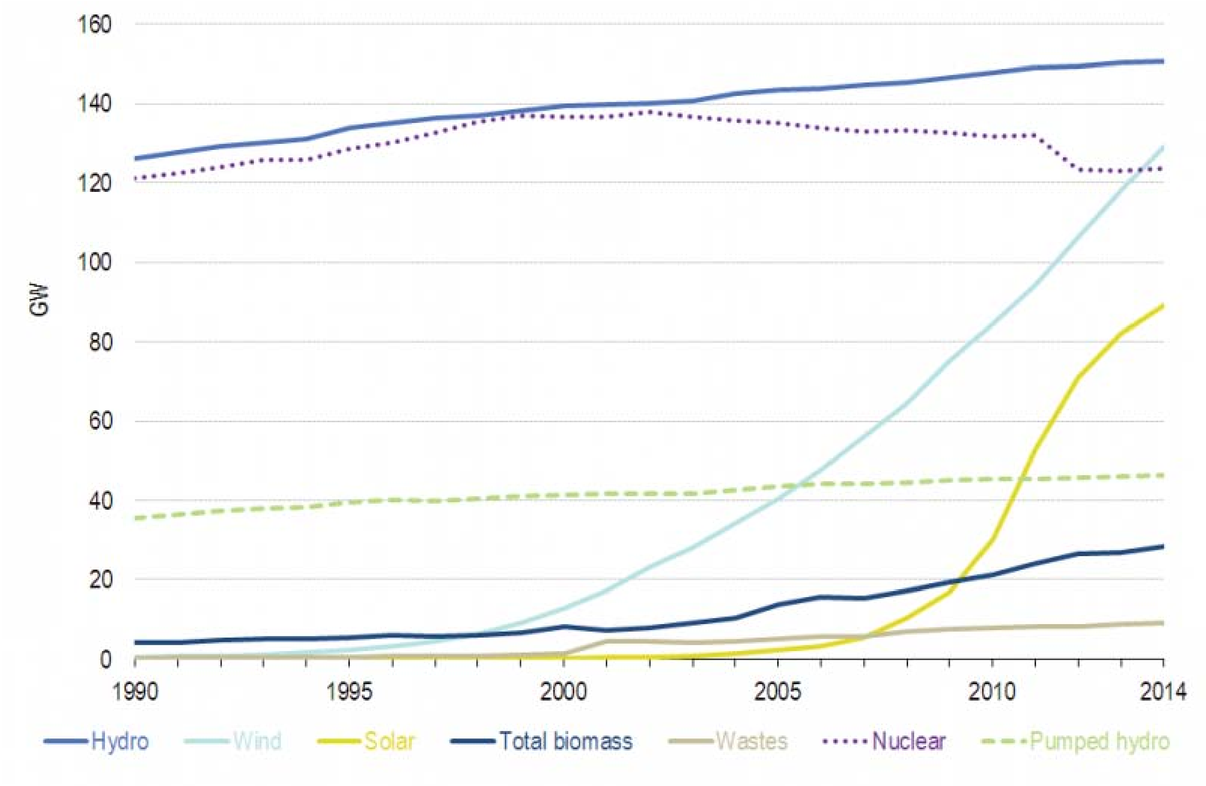


Figure 4 Cummulative added renewable energy capacity (Eurostat 2016)

Wind power generation capacity tripled in between 2005 to 2014 and is the second largest contributor to renewables since 2000 (Eurostat 2016). In 2014 over 51 GW additional capacity entered the market. This net capacity was 44% more than the previous year. Wind power accounts currently for around 370GW globally (REN21 2015). In Denmark, Nicaragua, Portugal and Spain wind generates more than 20% of the total electricity demand.

Offshore wind farms are especially popular in northern Europe, where around 91% (11GW) of the total capacity of offshore wind is currently installed. With LCOE of 15-23 c$/kWh produced, wind generated on sea is more expensive than onshore with a LCOE of 4-16 c$/kWh. At the same time offshore (120m height) wind farms can achieve full load hours of more than 3000 in the North Sea, while onshore wind farms (80m height) in central Europe typically achieve only values in between 1000-2000, depending on location (EEA 2009, 23). The potential of wind power in Europe depends on various factors, including costs competitiveness, NIMBY syndrome, conflictions with biodiversity, transmission, etc. Manufactures of wind turbines assume falling total production costs of 3-5% with each new generation (EEA 2009, 23).

Small wind turbines (Class 1 and Class 2) are increasingly popular in academia. They have typically a capacity of 1,5kW to 100kW and diameters ranging from 2,1m to 21m. Still, their adoption lags behind that of rooftop PV or conventional wind turbines. Just several hundred small wind turbines have been installed in the UK, which would be an ideal candidate for these turbines (AEA 2009). Planning restrictions, lack of information, absence of progressive financial support mechanisms are currently barriers to growth. Yet, they may be suitable substitute to PV in certain areas. Current focus of research is optimizing the harvest factor of turbines capable for slow wind speeds.

Solar power has increased rapidly in the last years and contributes currently 11% to the total capacity of renewables (Eurostat 2016). Germany as the leading market in the EU and the world has seen substantial increase over the last years, especially in the period of 2011. The growth rate slowed down, but remained among the top five dominating countries with China leading. Total capacity in Germany was close to 40GW in 2014. Operating capacity in the EU is around 87GW, but added capacity declined for three consecutive years. In 2014 only 6.3 GW were added, which is a strong decline from 22GW in 2011(REN21 2015).

2.3. Potential of renewable energy and Electrical Energy Storage Systems

The potential of storage depends highly on outcome of the push and pull factors provided for by governments and markets. Additionally, each storage solution offers use case cases, which sometimes overlap. Needed capacity and response time are the two most crucial factors for determining the right EES. Storage systems are predominantly classified by the energy form the energy is stored. Part 2 of this thesis will provide detailed information of particular technologies.

PHS, a mature technology with known costs structures, is dominating the market with share of 99.3%. Their potential is limited by the restrictions of geology, environmental impact and required dimension to achieve economy of scale. This lock-in into one technology resulted in a rather juvenile industry in regard to secondary batteries dating back to nineties. Still, recent developments pushed by the industry for electric vehicles and consumer industry resulted in a wake of more R&D for different types of batteries and/ or other storage methods including high-temperature thermal storage. Economy of scale brings the price down but at the same time allows the industry to deploy mature and emerging technologies like flow batteries to enter the market in a broader range of applications.

The net capacity of grid connected EES is indicated in Figure 5. The majority of grid connected EES is large scale.

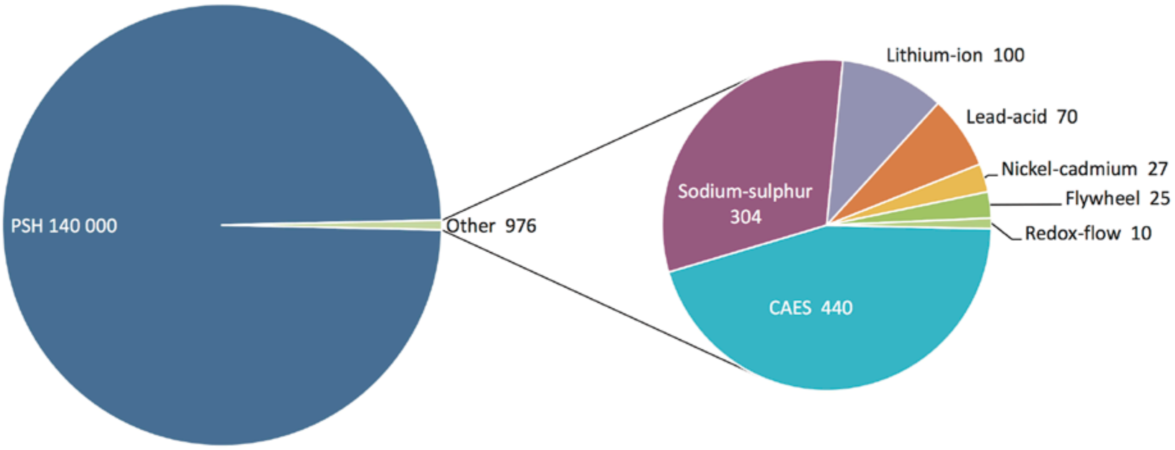


Figure 5 Global installed grid-connected electricity storage capacity (MW) in 2010 (IEA 2014b)

In the medium and long run, storage might be more cost effective and efficient solution than DSM or increased flexibility, aiming at increasing the inertia of the grid (SETIS 2013). Complete decarbonization of energy production is therefore only feasible with storing electricity for leveling peak demand and peak loads. In combination with planned electrification of the economy the need for additional storage will be zero at first, then minor and finally after a certain threshold level of penetration, depending on the energy mix, grow exponentially (SETIS 2013). For example, if the German *Energiewende* is continuing according to plan and reaches a level where renewable account to a proportion in between 85% to 95% before 2050 then by latest in 2030 EES is indispensable (SETIS 2013). Another study came to the same conclusion that without storage it is ‘virtually impossible’ to achieve 100% RES (Jungers 2015). Yet it is also not clear which technology mix will be used for storing energy, yet even its form. In that regard, it is only clear that storage technologies will be deployed on a larger scale on a global scale and PHS; based on the value it can create and restrictions in terms of size, location and environmental footprint, will most likely be just a part of the solution.

Another uncertainty is the question if in the future energy systems will remain rather centralized or pushed by PV deployment in the residential and commercial sector, more distributed. While it may be feasible find adequate large scale storage solutions for centralized power generation it is doubtful if the same applies for distributed systems since first of all energy needs to be transmitted and second questions regarding ownership in relation to energy and storage are not yet solved. Furthermore, it seems likely that no single solution could fit and be applied on a global scale. Taking into account the various sources and pattern of energy generation may they be conventional or renewable, seasonal variations, geology and proximity to the customer and state of the energy grid are just a few reasons that several technologies need to be incorporated into future energy system. Nevertheless, it is possible to assess the need of storage according to different scenarios on a macro scale and on the micro scale specific requirements are decisive for investment.

For the 8th International Renewable Energy Storage Conference and Exhibition IRES, in 2013 a study has been later published with the incentive to analyze the global storage demand if we achieve a 100% renewable electricity supply (Pleßmann, et al. 2014). Based on the highly unpredictable future prospect and uneven distribution of hydropower and other forms of renewables, only technologies with high potential like PV, onshore wind and CSP have been analyzed. By the exclusion of quite steady sources of energy, storage demand is artificially higher in this study but nevertheless indicates what kind of storage will be needed and how much. In that regard this study is also an important contribution to the question if a

100% renewable electricity supply is feasible. Included storage systems were power to gas, high-temperature thermal energy storage (TES) coupled with steam turbines and secondary batteries. The gas produced can be then used in dispatchable gas power plants, or fed into steam turbines which are used in CSP (Pleßmann, et al. 2014). One critical remark in this regard is, however, that high-temperature thermal energy storages like molten salt need some additional energy during diurnal cycles to keep the temperature at operational level. This energy is currently provided by fossil fuels.

Pleßmann came to the conclusion that the economic optimum can be achieved on a global scale when we have 21% CSP, 33% PV and 46% Wind (in total 28,600TWh). This correlates to a storage demand of in total 7.180TWh, while batteries account for 420TWh, P2G around 1960TWh and high-temperature thermal storage around 4,800TWh (Pleßmann, et al. 2014). An important consideration in this regard is that 65% of the total electricity demand is covered immediately by RES (Pleßmann, et al. 2014). The range of LCOE is between 80$/MWh to 203$/MWh depending on the efficiency and location of electricity generation.

By 2018 the global market for PV storage systems is expected to be 900MW, which is ten times larger than today. Total share of distributed storage systems is to be 10s of gigawatt by 2020 (Stark, et al. 2015). Although Europe has been considered to be a trendsetter for renewables, adoption rates of storage lag behind significantly other regions of the world, especially East Asia and Northern America.

2.4. Electrical Storage Use Cases

2.4.1. Short term storage and seasonal storage considerations

Another important factor to consider is needed rate of deferral. Applications and suitable technologies vary greatly if we want to store energy only for a couple of seconds, minutes, hours, days and even months. While batteries are in general more suitable for short term storage in the range of seconds to hours, long term storage solutions are usually large, mechanic or even convert electricity to other energy carrier like CH_4 or H_2. While electrochemical batteries achieve an efficiency of 67- 95%, PHS around 75- 83%, the pathway for electricity to gas (CH4) to electricity drops to 30-38% (Fraunhofer 2011). However, gas in the form of Hydrogen or Methane is still the preferred option to store energy over longer time ranging from days to months. Additional this conversion benefits from using existing infrastructure.

2.4.2. Flexibility

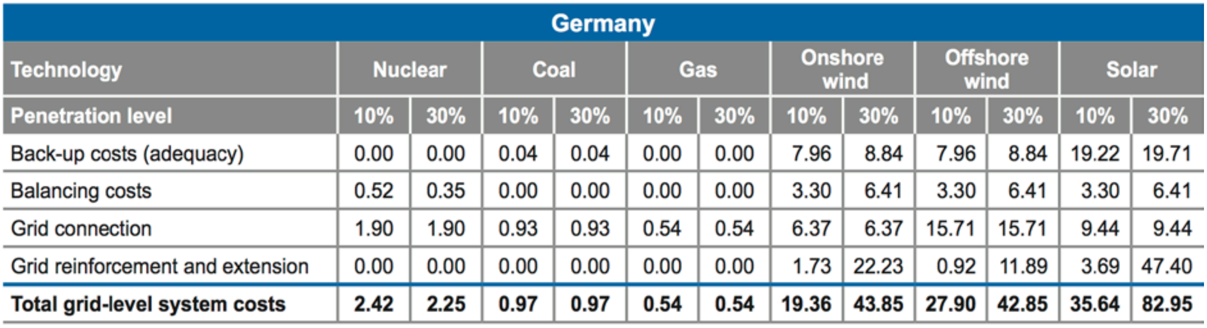
Conventional electricity production and consumption is characterized by immediate consumption of electricity produced and centralized power production in plants, which are mostly not located directly in residential areas. This means that production of electricity has to meet consumption at all times and a mismatch between these two would decrease the overall quality and supply of electricity. In Europe, electricity grids are standardized to around 50 Hertz. Lack of electricity and/or deteriorating quality of thereof, could seriously affect sensible industries, communication and hospitals as well. On-Site precautionary measures may include auxiliary power producing units such as diesel generators or storage facilities, which have a response time of milliseconds. Interruption of energy, even for one or two seconds, may damage machines and cold start may be indispensable. Especially data are vulnerable to such power outages and the financial loss of a single outage is significant.

Several analysis assessed that electric grids could destabilize if the rate of non-dispatchable RES exceeds 20 per cent of the net energy capacity if no EES are implemented (Weber, et al. 2011). Several policies, including the European Energy policy are mandating a renewable portfolio exceeding this level of RES deployment. EES are becoming therefore a necessity for every energy grid where such policies are pursued and it is likely that according to the specific needs different. Other studies, however, disagree with the 20% rate and favor, in their opinion, cost effective solution by increasing flexibility rather than storage up to a rate to 40 to 60%. Flexible CHP plants, demand side management and European power trading, offer sufficient and cost effective flexibility for balancing production and demand over the next 20 years, at least for the German market (Agora 2014).

Unlike conventional power generation most renewables (excluding to some extent hydropower, geothermal and biomass) provide only power when the renewable source is available. Furthermore, the average size of such generation units tends to be smaller and more distributed, hence closer to the site of electricity demand. This transition represents a unique challenge to the grid. In order to allow the system to operate it needs to be stabilized and allow some flexibility. The options are dispatchable plants, grid transmission lines (interconnection), energy storage and demand side management. While, larger systems are characterized by a high inertia (ability to resist changes in frequency), smaller systems and island system have typically a small inertia (IRENA 2015a, 5). Larger systems are usually controlled by automated control mechanism also known as governor control. Synchronized power plants usually operate not at full capacity but have a small extra margin which can be controlled by the governor control. This system reacts quite fast and within seconds. Renewables, on the other hand, are not synchronized but mimic synchronization by power electronics. Although they can therefore provide similar functions as synchronous generators of electricity their potential is limited. Some studies suggest that the upper limit, i.e. for Germany is around 60% market share of renewable energy, where they can provide this flexibility and increase inertia (Agora 2014).

Although renewable energy can be almost universally harvested their greatest potential is not necessary in areas where the energy is demanded. By increasing, the number of interconnections and constructing additional lines demand and supply can be connected. Severe obstacles by the civil society (i.e. in Central Europe), additional investment need and limited power output, sometimes in difficult environments like offshore wind farms make it costly and risky. For instance, in Austria the energy price composition for a typical residential flat in Vienna is the following: 40% energy price, 29% grid tariff, 16.6% VAT, 7.7% energy surcharge, 3.5% usage surcharge and 2.2% renewables surcharge (E-Control 2011). If the numbers of interconnections are therefore increasing it is more than likely that the energy costs will also increase. Another study conducted by the OECD differentiates between different RES and the additional needed investment. According to this table especially offshore wind farm and PV are costly to connect. This, however, neglects added value of on-site consumption and other external costs (OECD 2012, 8). The following table shows two scenarios, while the 10 and 30 per cent values indicate the given market share of the technology (OECD 2012).

Table 1 Grid-level system costs in selected OECD countries (USD/MWh) (OECD 2012)



Germany												
Technology	**Nuclear**		**Coal**		**Gas**		**Onshore wind**		**Offshore wind**		**Solar**	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	7.96	8.84	7.96	8.84	19.22	19.71
Balancing costs	0.52	0.35	0.00	0.00	0.00	0.00	3.30	6.41	3.30	6.41	3.30	6.41
Grid connection	1.90	1.90	0.93	0.93	0.54	0.54	6.37	6.37	15.71	15.71	9.44	9.44
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	1.73	22.23	0.92	11.89	3.69	47.40
Total grid-level system costs	**2.42**	**2.25**	**0.97**	**0.97**	**0.54**	**0.54**	**19.36**	**43.85**	**27.90**	**42.85**	**35.64**	**82.95**

This high connecting costs may result in the future in policies which favor more distributed and on site forms of electricity generation. Especially sudden spikes of solar electricity may cause tensions in the grid. Additionally, it may lead to (for the utilities) unfavorable situation of entering large sums of electricity at zero marginal costs and the paradox of negative electricity prices, as happened in Germany in May 2016.

Another solution is the integration of additional dispatchable power plants such as open cycle gas turbines (OCGT) and combined cycle gas turbines (GCGT). Since these plants are in operation only in times of need this would increase the costs significantly. Another negative side effect of this is that at least in the short term profitability of existing power plants is affected. Especially plants with high variable costs such as coal and gas but also nuclear powered plants are hit hard when renewables enter the market suddenly at zero marginal costs. Estimates of profit loss range for 10% RES market share in between -24% for nuclear energy and -54% for OCGT in the short term (OECD 2012, 9). In the medium and longterm this is however counterweighted by the incorporation of the additional costs mentioned in Figure 2 and the incorporation of new technologies and market mechanism. If the energy price will increase is still disputed. Some assess a stable increase in all scenarios (European Commission 2011) other see a steadily increasing energy price if the market shares of renewables increases (OECD 2012, 10). In the long-run complete decarbonization scenarios may be cheaper than business as usual (European Commission 2011b, 5).

2.4.3. Added value of storage for consumer

The utilization of storage can create an added value depending on the technology chosen. In order to assess the impact and understand the economic principles behind it, it is necessary to

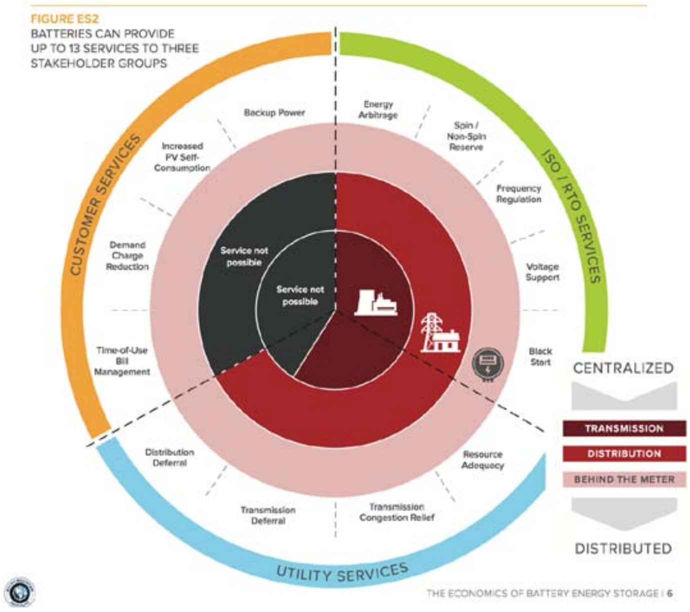


Figure 6 Provided Services of Storage by Stakeholder Group (Fitzgerald, et al. 2015)

identify the different stakeholder groups and the service a battery can provide. In short there are three major groups: customers, utilities and independent system operators/regional transmission Organizations (ISO/RTOs) (Fitzgerald, et al. 2015). In this regard the thirteen most prominent services a battery can provide are (1) Energy Arbitrage (2) Spin/Non-Spin Reserve (3) Frequency Regulation (4) Voltage support (5) Black start (6) Resource Adequacy (7) Transmission Congestion Relief (8) Transmission Deferral (9) Distribution Referral (10) Time-Use-Bill Management (11) Demand Charge Reduction (12) Increased RES Self-Consumption (13) Backup Power. The following figure shows the provided services to the different stakeholder groups (Fitzgerald, et al. 2015). While batteries can provide added value to all three of them services to the customers seemed to be most evident. The following figure shows added services according to the different stakeholders.

In addition, especially SMEs in manufacturing can benefit from optimizing the load of the facility. Especially buffering of peak loads through storage systems may be beneficial, if coupled with renewables. Frequency regulation might be sometimes necessary in case the energy quality, either of the grid or from the RES, is not sufficient. In that case technologies like flywheels may be a fitting solution. Figure 8 shows the possibilities for a load profile (IRENA 2015b).

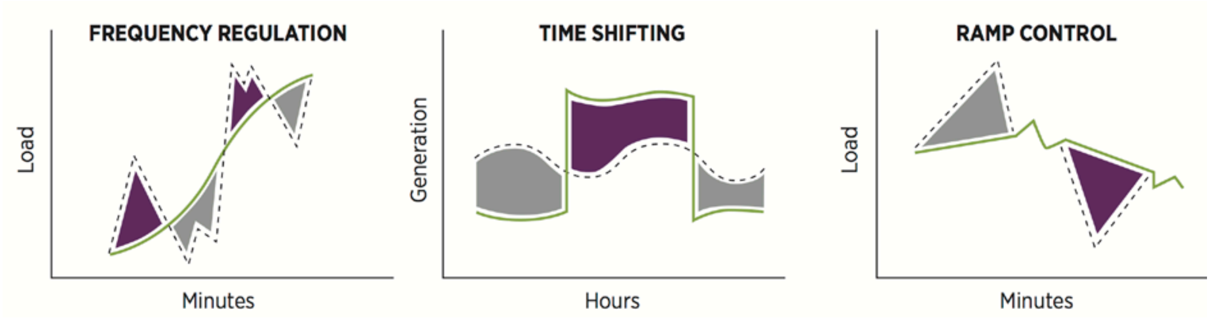


Figure 7 Services that electricity storage systems can provide to integrate power generation from variable renewables (IRENA 2015b)

Value depends on the specific need and location but according to a study from Australia currently, the greatest value can be achieved if the value is added behind-the-meter and in conjunction with PV by avoiding tariffs for electricity and load shifting. This will create the most tangible flow of income, while supply-side storage, Wholesale arbitrage and ancillary services are currently not profitable (AECOM 2015, 9). The comparison with LCOE shows the range of costs at which this additional value can be implemented. As we can see especially utilities can benefit currently from storage. The only 'competing' value is increase of self consumption (Battke, et al. 2013).

Lazard, a financial advisory company, identified LIB for frequency regulation and flow batteries for deferral as two unique use cases where the respective technologies are already cost effective for single use cases. The report states that levelized costs of storage is not adequate for measuring the true value of storage, since it neglects the possibility of stacking services. Constrain of stacking values is to measure concrete cash flows. The basic concept as laid out in Figure 8 is to assess the profitability of entire systems rather than single purposes (Lazard 2015). With reduced upfront capital costs, reduced variable costs and prolonged battery lifetime EES may become cost-efficient across all applications within the next year to decade.

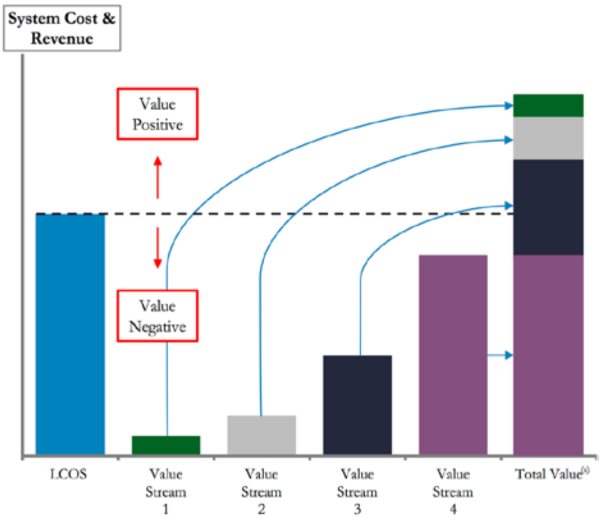


Figure 8 Stacked Value of Energy Storage (Lazard 2015)

While some added values like increased energy quality or security are hard to measure other financial benefits of EES are can. As pointed out by Lazard, single value streams may not yet be sufficient for installing storage for every use case. The most important financial benefits for consumers are as follows (Hussein and Ilinc 2013):

- Energy arbitrage: By purchasing inexpensive electricity, usually available when demand is low, and selling when prices are high may generate additional revenue. As a single stream of revenue the net benefit may be however negative, but may add up if capacities are not needed.

- Revenue increase of central generation capacity: If the supply of energy is limited and/or grid reliability is low, storage may offset renting or purchasing additional capacity.
- Reduce demand charges: Reduces the charges during peak hours and deferral to later times.
- Reduced power quality-related financial losses: In areas where the energy quality is low and inconsistent and may therefore harm the hardware, storage may provide an effective solution to increase the quality of electricity.
- Increase of self-consumption: By generating electricity from RES, storage may enable a higher self-consumption rate, thus reduce the energy bill.

As indicated in the previous chapter, especially the increase of the rate of self-consumption seems to be effective in combination with storage. The following chapter will therefore examine this potential in more detail.

2.4.3.1. Increase rate of self-consumption

Increasing the rate of self-consumption of electricity gained through PV makes sense if the costs of buying additional energy through the market are more expensive than the energy generated on-site or if the feed-in tariff is lower than the energy price on the market. Electricity generated through PV varies through the day and is usually negligible during night. Additionally, energy production peaks during midday while on average the consumption of typical households is lower during that time. SMEs, especially retail and agriculture, have a suitable load profile. Energy self-consumption turns passive consumers into active “prosumers”. If the prosumer is connected to the grid storage may decrease the need of purchasing additional from the grid. This results in lowered energy bills, thus making such system the preferred option. Figure 10 shows the benefits of such a system for residential homes. The same applies to businesses as well, although higher capacities are needed (Fitzgerald, et al. 2015).

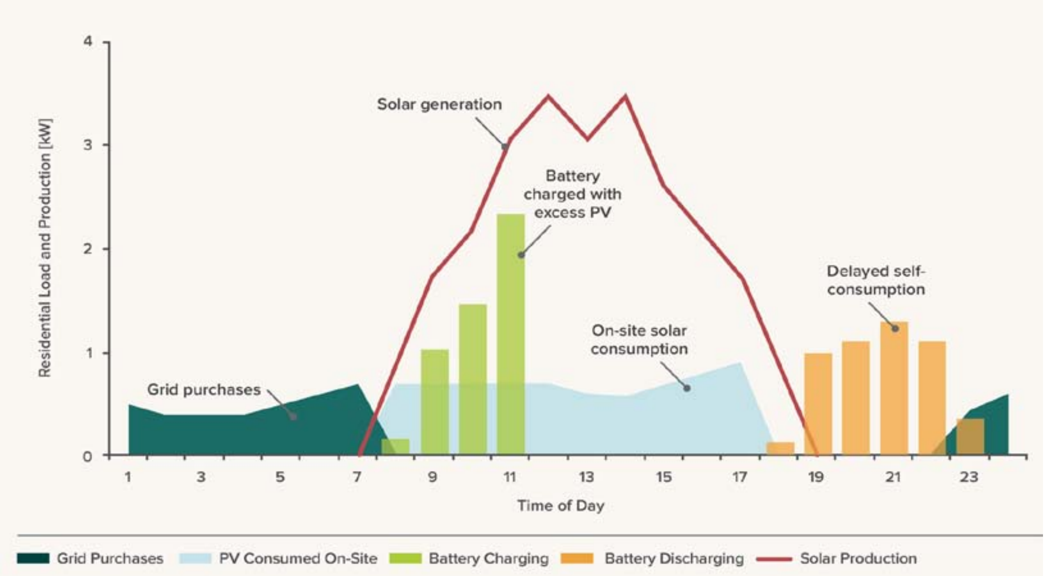


Figure 9 Load curve and storage (Fitzgerald, et al. 2015)

The formula used for determining the self-consumption rate is:

$$s = \frac{\mathit{energy\ from\ PV\ to\ load} + \mathit{energy\ to\ battery\ from\ PV}}{\mathit{energy\ generated\ by\ PV}}$$

By integrating storage into the equation, self-consumption increases at additional costs. While a system of 70kWp generates around 2640kwh in January. With the load profile of the case study in this thesis, this system would result in a self-consumption rate of 62%. By integrating storage, this figure would raise to 81%.

The increase of self-consumption depends on various parameters such as, location, orientation, peak load hours, efficiency of the panels, taxes, incentives, price, etc. Therefore, the same approach and best practice may be cost efficient in one country or even federal region and might be costly in others.

The two major PV system components are the PV-panels, charge controller and the inverter. As shown in Figure 11, especially the price of the PV modules, but also the inverter is increasingly becoming cheaper at rapid pace (IRENA 2014). Just within a decade, the costs of a system will decrease from 4.9USD to 1.92USD. This corresponds to a long-term PV learning rate of 19-23% and for Wind of 3-5% (Agora 2015).

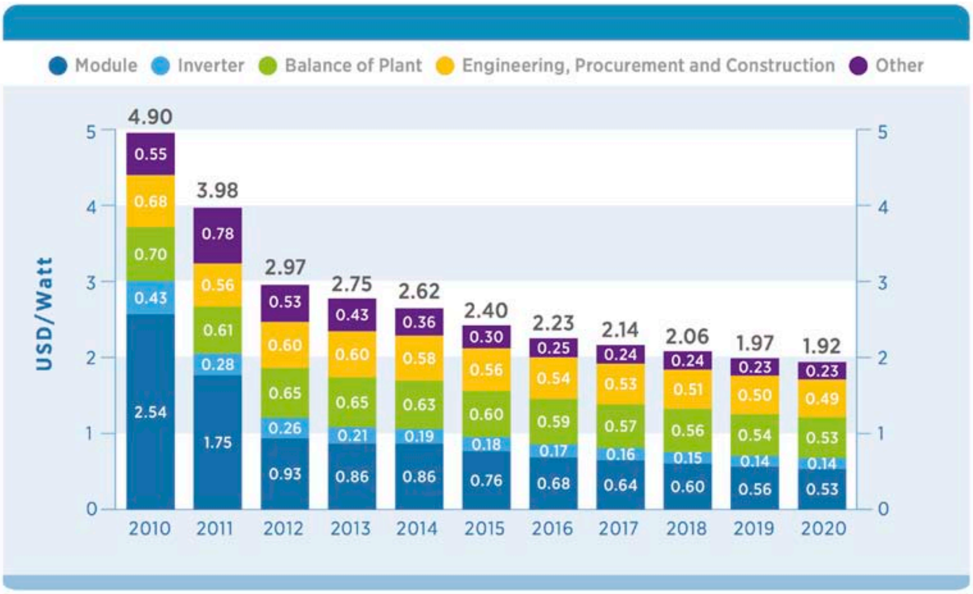


Figure 10 Projected solar PV system deployment cost (2010-2020) (IRENA 2014)

Below costs of 0.2€/Watt, pure material costs will dominate the price composition of the panels. This level is projected to be reach when accumulated reached capacity of PV systems reaches 10 to 80,000 GW (Agora 2015). Rooftop PV systems (e.g. 10kWp) reached grid parity in Germany in 2011. If the electricity price development remains stable it is assessed that by summer 2016 the grid parity for the combination PV + Storage will be reached as well (Grigoleit 2014). Figure 12 shows the grid parity development in detail (IRENA 2015b).

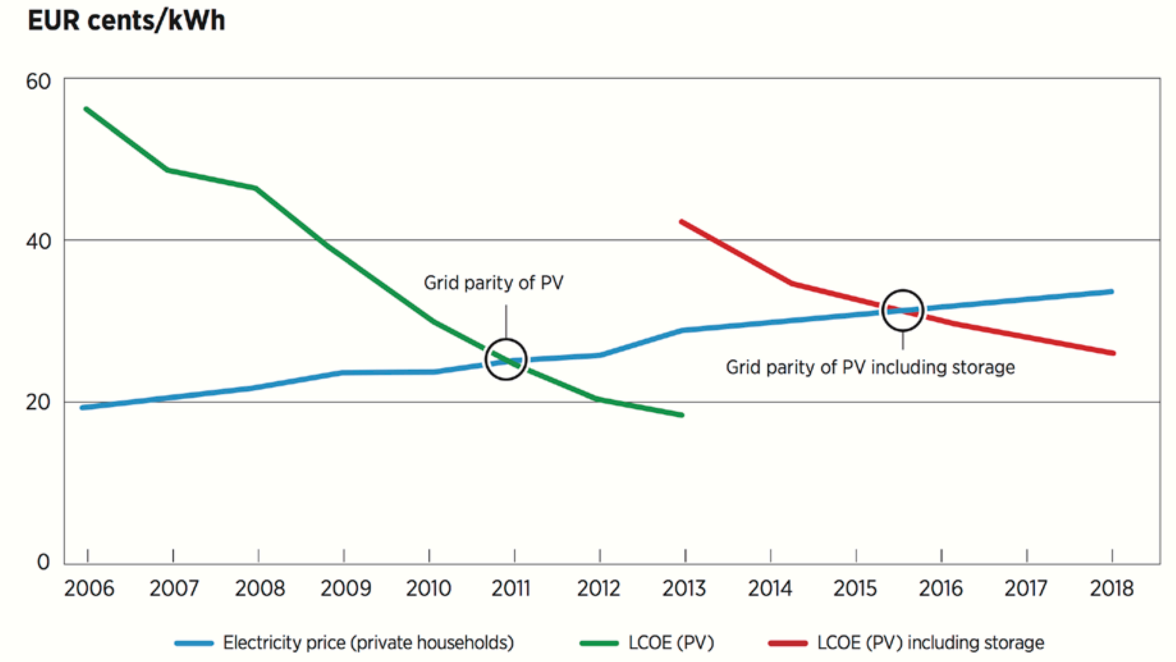
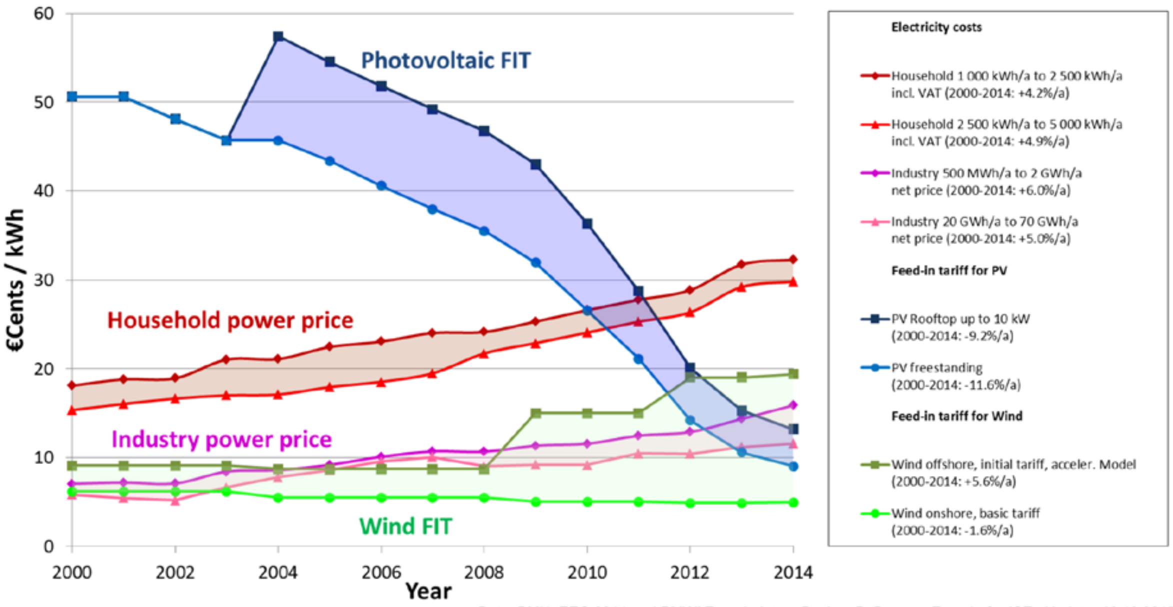


Figure 11 Grid parity of PV storage in Germany (IRENA 2015b).

Feed-In-Tariffs are decreasing on average by 9,2% p.a. (2000-2014) from around

50cents/kWh for freestanding PV (>10kW) in Germany to less than 10 cents/kWh. At the same time energy prices increase on average for the industry (500MWh/a - 2GWh/a) by 6% each year. The average energy price for industries is now around 11cent/kWh, while the FiT is less than 10c/kWh. (BMU 2015) At the same time small retail businesses pay on average 20 cents/kWh. Hence, it is more economic to consume own energy instead of selling it to the market and prosumers can save money generating their own electricity rather than obtaining it from the grid. The reduction of the FiT made it also difficult to increase the value by arbitrage. The financial benefits and added value of self-consumption is significantly lower for heavy duty industries with an average payback of 12 to 15.5 years, while retail is 7.4 to 9 years and for manufacturing 8.1 to 10.1 years (REC 2014). These Estimates are for the German market, excluding the value of storage. Figure 13 shows the projected electricity rates for the German market and the current Feed-in-Tariff scheme development (BMU 2015).



Data: BMU, EEG 2014 and BMWi Energiedaten. Design: B. Burger - Fraunhofer ISE , Update: 16.10.2015

Figure 12. Projected rates of electricity in comparison to FiT (BMU 2015)

Along the FiT, which is additional revenue for the owners of RES, the EEG (Erneuerbaren Energien Gesetz - Umweltzulage) is an additional levy with the incentive to support the energy transition. Steady increase of the market share and decreased FiT do have an effect on the EEG. Although it will increase over the next years from in 2015 with 6.24 c/kWh to 7.93c/kWh by 2021, it will steadily fall afterwards and reach an estimated level of 2.73c/kWh in 2033. By this date, however, RES should be the more cost effective solution than conventional energy sources (REC 2014). In addition to the EEG, taxes and duties apply to all sectors. In 2014, the retail sector had to pay additionally 3.7 c/kWh on electricity taxes, which is more than the other sectors and and grid charges of 3.7 c/kWh. Additional smaller taxes, duties and sales margins account for more than 7.5 per cent of the final price the consumer has to pay. In total the (retail) customer had to pay 13.08 c/kWh (REC 2014, 9). Similarly manufacturing additional charges amounted to 10.41 cents/kWh and 1.89cents/kWh for the heavy industry. The high extra charges are in stark contrast to the electricity price of 4 cents/kWh. Electricity price is set to increase slightly within the next decades, while EEG and other taxes are currently set to decline. By 2033, the average price for retail and manufacturing will remain the same, while the heavy-duty industry may not benefit from the lowered EEG in the same magnitude due to already low charges.

Having this high taxes and extra charges in mind, it might be beneficial for a company to lower this burden by installing RES or even completely defect from the grid by using EES. As already mentioned energy production from cannot be planned and may not coincide with the load. Furthermore, the load of businesses varies through the day and may be at times when the sun is not shinning or wind speed is usually too low. The orientation of the solar panels is also critical and may alter the rate of self-consumption by several percent. Usually the panels are oversized and produce during midday surplus electricity. This surplus needs to be wasted or inserted into the grid. The main idea to counterweight this issue is by adapting the energy needs of the company through DSM and if this is not possible to defer the charge by using EES to a later period and use the energy when needed.

The load curve of typical SMEs is considered to be beneficial for self-consumption since the typical load curve correlates with potential peak production from renewables, in particular PV (European Commission 2015a, 3). One best practice may be a food processing company in Rome. With an energy demand of about, 850.000kWh and variable load curve throughout the day this company decided to install 320KWp PV panels. They produce roughly 420.000kWh per year. This enabled them to consume about 89% of the on-site generated electricity which in return resulted in 35% annual saving in electricity and rooftop solar costs of around 95-100€/MWh, in comparison to more than 240€/MWh A similar example from Germany showed a 87% self-consumption rate and 15% savings (European Commission 2015a).

Sometimes energy prices for the industries need to be negotiated with the local supplier, change throughout the day, and are high when there is high demand for energy from other sectors. This gives the companies an incentive to shift the load curve according to the availability and price of electricity. Further, energy prices are the highest in the morning and the late afternoon and are lower in summer than in winter. Experience shows that even 1 cent difference in energy prices when the peak period is even as long as 18 hours significantly changes the industry (e.g. Cement industry in England) (Mitchell, et al. 1977). More recent studies confirm this and encourages companies to use DSM to shift their production to times when energy prices are expected to be significantly lower (Stigler, et al.). This lead to the conclusion that if DSM and in particular load management is properly used energy intensive processes take place when energy prices are low.

Taking into account the added value storage may provide, DSM measure might be even more efficient, if synergies are used. Almost all production chains have a limiting link, which slows down the whole process and upgrading the capacity is capital intensive (Stigler, et al.). Therefore, this limiting part of the production chain needs to operate at all time, and sometimes at all costs, even when the energy prices are higher. EES can be implemented as a viable mean to decrease the purchase of additional energy from the grid if the direct consumption of renewable energy is not possible. Especially industries like the mineral oil processing, paper and paperboard and mining industry are electricity intensive and may benefit from such solutions (Stigler, et al., 20). In the industry an energy service storage may be also a viable option. Not being confused with storing energy, energy service storage aims at storing a service or commodity. This may be for instance that electricity is used to bring it in a different form of energy like thermal or to bring a certain commodity into a different state like for instance grinding stone or turning wood into fiber. A storage facility needs then to be installed in order to use the good, usually the limiting factor, at a later time. This is however not straight forward, wood fibers may not be stored more than 24h otherwise the consistency changes and turning the fibers into white paper is then possible without added costs. Additionally storage place needs to be built and thermal energy cannot be stored indefinitely (Stigler, et al.).

If we take the Austrian paper industry as an example. Mean power consumption was around 2900kWh/1000€ value added. If we take an average electricity price of 7,3c/kwh and additional 5,2c/kwh for taxes and additional charges we get energy prices of around 360€/1000€ value added. Clearly, this means that measures in the DSM and by adding additional value through energy prices by producing energy on site could lower the energy bill drastically under certain circumstances (Stigler, et al.). Still, industry benefits in many regions from artificial low energy prices which curtails any incentives to switch to other forms of energy.

Increasing the rate of self-consumption is not only beneficial for the prosumer but also for the grid. Distributed storage can alleviate the spikes and even defer peaks in the grid load curve since self-consumption on site is increased and less electricity has to enter the grid at low price. While, the SMEs can already achieve around 90% rate of self-consumption, industries will not be able to achieve such a rate if the energy generation does not correlate to the consumption. Also the residential sector needs to be targeted since on average only 30% self-consumption is possible and by using technologies of DSM and distributed storage it can be increased to 45% to 75%. Having in mind that each of these sectors consume roughly one third of the total available energy distributed storage solution for increasing self-consumption shows great potential (European Commission 2015a). Findings of a German study show that a PV capacity of 7kWp and 5kWh usable battery capacity results in an autarky degree of 60%. Own findings[1] show that this correlation also corresponds to commercial application of PV+EES systems.

In determining the profitability of a system the net present value (NPV) is an important indicator. It gives the present value of an investment’s cash inflows (benefits) minus the present value of outflows. By increasing the self-consumption ratio, the NPV usually increases. This means that the dimensions of the facility need to match the need and it might be more economic to install less capacity, purchase the remaining need from the grid than oversizing it and decrease the self-consumption ratio. Giving a concrete example: The baseline for production with 95KWp is able to achieve a NPV of 426 EUR/kWp in Hamburg and 806 EUR/kWp in Nuremberg. By downsizing the the PV potential to 60% (57kWp) NPV increases to 508 EUR in Hamburg and 939 EUR/kWp in Nuremberg. In sunny locations the retail sector can achieve a return on equity of almost 30 percent and it is generally cheaper to generate electricity than purchasing it (REC 2014, 17). By avoiding the costs of grid

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[1] For further details, please refer to the case study at the end of the thesis.

electricity solar panel are becoming a good investment for the retail sector but even the manufacturing sector with a NPV of 600 EUR/kWp in Nuremberg may benefit from this model. With the low energy prices for the heavy duty industry most of the income will be generated from arbitrage, since the FiT is higher than the costs for purchase. With decreasing FiT this model may not be worth to pursue.

The uncertainty for increasing the number of businesses who are using this model is most likely taxes and duties. If taxes increase by 10 per cent, NPV may benefit and increases for the retail sector by 21 per cent and 29 per cent for manufacturing. In the unlikely scenario that these taxes may decrease in total over 50% within the next years, NPV would be negative (REC 2014, 23). The EEG, which is set to decrease over time and after 2021 will have a negative impact on the NPV. But contributing a significant share of the overall burden a prolongation is an effective tool to successfully implement the energy transition. Similarly, countries where the share of renewables is currently low, may benefit from such a tax.

Challenges to increase the rate of self-consumption and/or using PV for solar electricity generation are manifold. Besides the economic parameters described above, projects may fail more due to practical reasons. First, with a payback time of more than 10 years, companies are discouraged to invest into such long-term investments, especially in times when liquidity is low. At the same time bank loans require most of the time a guaranteed return over the next 15-20 years. Since avoided costs are considered to be a return, FiT remains. By phasing out of this tariff gradually, banks may reconsider to grant loans to businesses. Another challenge may arise from the assumption that by having more and more partial grid defectors on the market electricity produced at zero marginal costs enters the grid, usually at the same time, and brings an additional burden to the grid. One way of mitigating such effects is by discouraging the owners to use the grid as their ‘waste bin’.

In conclusion, energy is sometimes the limiting factor and especially energy intensive sectors need to optimize the use. There is no “single best” solution but rather a set of option where storing electricity is besides DSM and energy service storage one of them. Determined by type of process, location, temperature, operating costs and fix costs each option needs to be investigated on its own. This paper will therefore proceed with looking at EES solely and takes other options into consideration where it seems necessary. Both, in residential and commercial areas the integration of storage into the on-site RES system increases the rate of self-consumption and reduces the energy costs. Additional bonus in some regions is the possibility to recharge the battery when energy prices are lower and discharge when they are high. Emerging models of self-consumption are increasingly becoming an economic option for SMEs and industry, in particular energy intensive ones, which don't benefit from low energy prices in the range of some 10c/kWh.

2.4.3.2. Energy Islands

Not benefiting from economy of scale and increased variable costs, island solutions are generally more expensive than their counterpart which is (partially) on-grid. Energy islands are needed when a grid connection is not feasible or not wanted. Conventional diesel generators supply the appliances with the necessary load. Most often in rural regions this diesel needs to be transported quite often to the site since evaporation, even in closed tanks, is a problem. Variable costs are therefore higher and by introducing a PV or wind system plus storage may be beneficial.

Several studies assessed the potential of RES and EES and the outcome is with falling costs increasingly positive. One study compared the potential of the so-called hybrid system (Wind and PV) together with three different storage technologies (Lead-acid, RFB and LiB). In two regions, Syria and Germany, RFB outperformed the competitors with energy prices of 0,65€/kWh in Germany and 0,34€/kWh in Syria. The following table shows the results (Merei, et al. 2013).

Table 2 Optimization of an off-grid hybrid PV-Wind-Diesel system(Merei, et al. 2013)

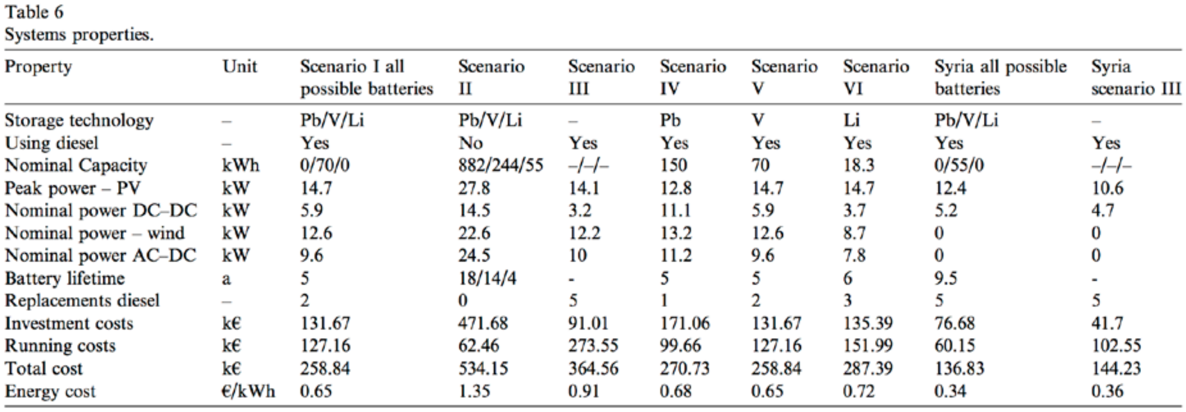

Table 6
Systems properties.

Property	Unit	Scenario I all possible batteries	Scenario II	Scenario III	Scenario IV	Scenario V	Scenario VI	Syria all possible batteries	Syria scenario III
Storage technology	–	Pb/V/Li	Pb/V/Li	–	Pb	V	Li	Pb/V/Li	–
Using diesel	–	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Nominal Capacity	kWh	0/70/0	882/244/55	–/–/–	150	70	18.3	0/55/0	–/–/–
Peak power – PV	kW	14.7	27.8	14.1	12.8	14.7	14.7	12.4	10.6
Nominal power DC–DC	kW	5.9	14.5	3.2	11.1	5.9	3.7	5.2	4.7
Nominal power – wind	kW	12.6	22.6	12.2	13.2	12.6	8.7	0	0
Nominal power AC–DC	kW	9.6	24.5	10	11.2	9.6	7.8	0	0
Battery lifetime	a	5	18/14/4	-	5	5	6	9.5	-
Replacements diesel	–	2	0	5	1	2	3	5	5
Investment costs	k€	131.67	471.68	91.01	171.06	131.67	135.39	76.68	41.7
Running costs	k€	127.16	62.46	273.55	99.66	127.16	151.99	60.15	102.55
Total cost	k€	258.84	534.15	364.56	270.73	258.84	287.39	136.83	144.23
Energy cost	€/kWh	0.65	1.35	0.91	0.68	0.65	0.72	0.34	0.36

Still, this results show that currently a full replacement of diesel and therefore oversizing is less attractive than combining the systems. This picture will change with falling levelized costs of storage and generation

2.4.4. Storage Integration with PV

At times when the adoption of solar technologies becomes cheaper and funding of these technologies by artificial Feed-in-Tariffs decreases, the integration of storage might make economic sense. The following chapter will give an overview over parameters which need to be considered if consumers want to integrate PV-storage solution or want to retrofit existing PV with additional storage in order to increase self-consumption.

While Lead-Acid batteries demand continuous maintenance and sometimes refilling of the electrolyte LIB on contrary demands only limited maintenance. Another important issue is that Lead Acid batteries generate hydrogen in form of gas. Therefore, rooms intended for the EES need to be monitored. One way to avoid such issues is replacing regular lead -acid batteries with valve-regulated lead-acid batteries, also known as maintenance free batteries. By adding either fiberglass mesh or silica dust the electrolyte changes it state into a gel form. Due to their design they can be mounted in any direction and can be used in applications where a lot of energy is required, usually off-grid. Lithium-Ion batteries need stable temperatures since their capacity and rate of self-discharge is influenced by either an increase of temperature or operating temperatures below 0°C. Studies showed that also VRB suffer from below ambient temperatures. The V^{2+} solution in one half cell of the tank begins to crystallize when cooled down to -10°C. This range can be expanded by some degrees by adding sulfate-chloride mixed electrolytes (Pan, et al. 2016).

PV panels convert solar radiation into DC. Since most electronic appliances can only use AC, an inverter needs to be installed. Battery storage systems can be installed before or after the inverter. For DC systems usually a MPPT (Maximum power point tracking) is serially connected in order to maximize the power output of PVs. In AC systems the MPPT is usually incorporated into the inverter. Depending therefore on the type of EES used, AC systems usually need the implementation of two separate inverters, one for the battery and one for the panel. The advantage is usually that the specifications of the battery and the PV panels can be separately decided. This is especially useful if the system is retrofitted and/or the location of the source of generation and storage are not close. The schematic setup is provided for in Figure 15.

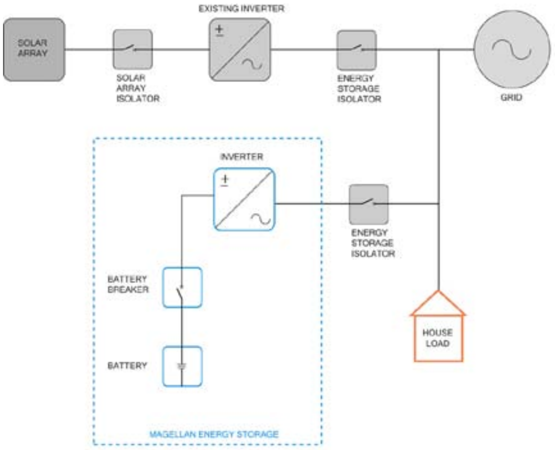

Figure 13 Photovoltaic AC-Setup(Magellan 2016)

Another important consideration to be made is if the PV-storage system is connected or not connected to the grid. If the system is AC connected an energy exchange with the grid is possible if the voltage differences are not too high. Systems, which can switch between off-grid and on-grid, are different. If the system is switched to off-grid, both - reactive and effective power, needs to be provided by the PV-storage system. As soon as this cannot be achieved the system switches back to on-grid. Frequency is regulated within milliseconds; therefore, a parallel operation is limited. Usually then the entire energy demand is provided by the grid, while the EES is getting charged simultaneously. The advantage of systems which can switch between being on-grid or off-grid is that they provide an effective mean of emergency backup in case of a blackout, while systems which cannot switch need additional measures to achieve the same value.

DC-DC converter connect usually DC storage systems with the panels. They convert the source of DC from one voltage level to another. If the voltage difference is beyond the capabilities of a DC-DC converter a DC-AC-DC inverter, including a transformer is needed.

DC storage systems are considered to be more (cost-) efficient with lowered flexibility in terms of dimensioning and the location of the system (Weniger, et al. 2015). The schematic setup is provided for in Figure 16.

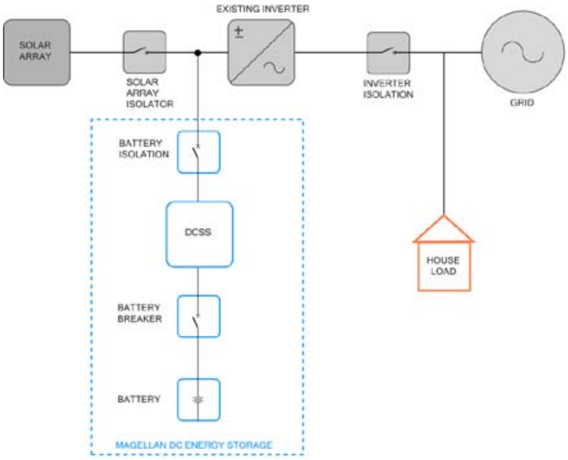

Figure 14 Photovoltaic DC-setup(Magellan 2016)

The aim of the system is to lower the energy costs by increasing the self-consumption. There are several flows possible. First, energy produced can be consumed at the same time. This is the optimal case and most efficient way. Additional energy or energy which cannot be consumed at the same time can be used for recharging the EES. Is it fully charged the remaining energy can be inserted into the grid. At times where there is not sufficient energy from the PVs the flow is reversed. A third option is also to recharge the battery by the grid. Given the fact that the efficiency is always lower it would only make economic sense if the energy price shifts significantly throughout the day. Figure 17 shows the possible options ranked by efficiency (Fraunhofer 2015).

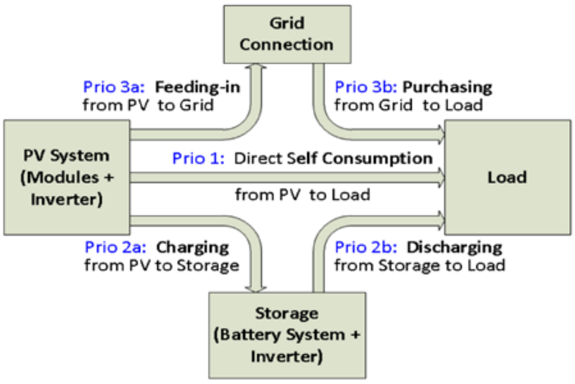

Figure 15 PV-Grid-Storage-load hierarchy

Another way of to examine the overall efficiency of a PV plus storage system is by calculating the energy return factor of PV and overall efficiency of the EES. Although this parameter may not help house owners or business to take a decision, it shows clearly the benefits for a society. A new technology will only be adapted if it is able to convert more energy from a RES than energy was used to build it. This concept is called energy return on energy invested (EROEI). Back in the seventies, PV have been criticized that it takes more than 40 years to pay back the energy which was needed for the panel. Over the years the technology became more efficient and achieved in 2005 a value in between 1,1 to 5 years. Over a lifetime of 25 years it is able to produce 5 to 23 times the energy required to produce them (Rydh and´n 2005). Other more recent studies claim a value of only 4, which would be below the proposed threshold of 7

(Weißbach, et al. 2013). Recent studies show that the EROI for PV spans approximately the same range (6-12) as oil fired electricity systems. Coal outperforms PV by the factor 2. But also in between the different PV solutions differences in efficiency and production costs, hence altered EROI can be determined. While PV based on monocrystalline Silicon achieves only a value close to 6, Cadmium telluride photovoltaics, with an efficiency close to 21% achieve 12 (Raugei, et al. 2012). The current EROEI for crude oil decreased from 100:1 to 20:1 within 100 years and it is unlikely that this value will improve over time. Unconventional sources have a value close to 10. For biofuels this value is about 2:1 (Rapier 2012, 126).

2.4.4.1. Spatial considerations

Sizing of the EES is important in order to avoid unnecessary and significant costs. It mainly depends on two parameters namely the aim of the storage and investment. While, a 100% storage system is able to operate an entire day autonomously, a 50% system can operate only half day. Therefore, especially off-grid solutions or situations where there is no Peaker present EES need to be oversized and most parts of the system are idle through most of the time. This adds up to the costs but may be still cost-effective as already mentioned in a previous chapter. Having in mind a typical consumer and no special needs in terms of energy security 30% of the total installed capacity of the solar array or wind are roughly sufficient and are a compromise between investment costs and benefits (Victron Energy). This number accounts, however, only for the residential sector since the load curve is quite similar. At this point it is not possible to give an estimate for SMEs and other sectors due to high variations in the load. It is therefore important to assess detailed energy needs of the respective companies before the integration of RES and EES is considered. Location is also an important factor. While, it is possible to dispatch batteries almost everywhere, PHS and Compressed Air Energy Storage (CAES) demands certain geological features to be economically feasible. Ambient temperature may also the array of choices.

EES seem to be a promising technology with a huge potential for electric appliances. From an economic point of view, it does not make sense to generate electricity and store the electricity for later just to generate heat or cold. It is more economic to store thermal energy rather than electricity (SETIS 2013). In this regard, if the major form of energy needed is for heating or cooling then EES are not the best choice but rather thermal storage tanks.

3. **Part 2: Comparison of Electrical Storage Systems**

Electrical Storage systems can be classified in many ways. This can be done by the form of energy stored, usage case or by comparing rated power and energy content (IEC 2011). Other than capacitors and magnetic coils, however, there is no way to store electrical energy as such. Instead, if electricity is to be stored, it must be converted to some other form of energy at the cost of conversion loss (Weber, et al. 2011). This can be either mechanical, electrochemical, chemical, electrical and thermal as shown in Figure 18 (IEC 2011).

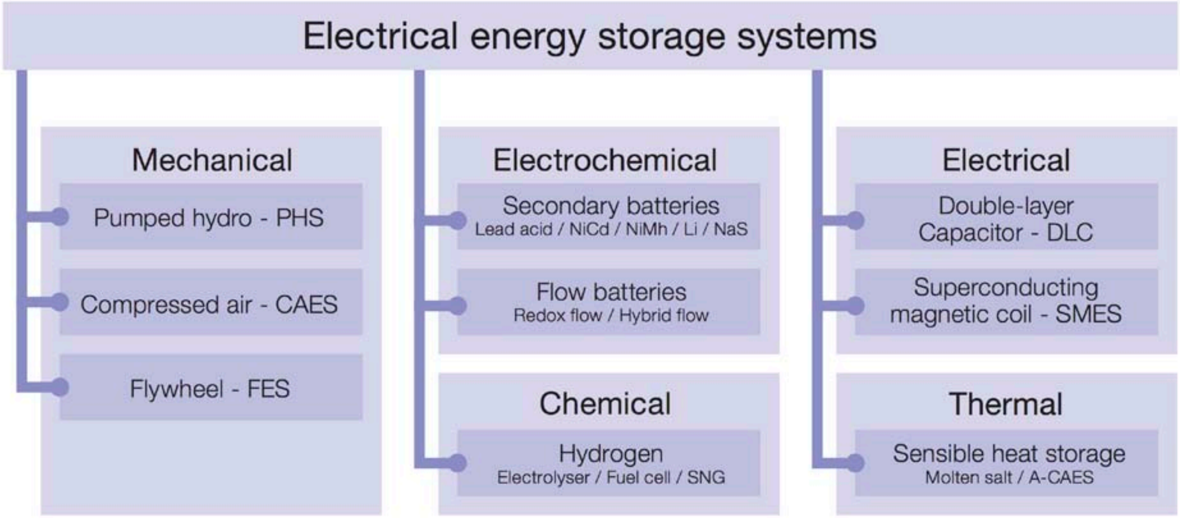

Figure 16. Electrical Energy Storage Systems (IEC 2011)

As already mentioned in the introduction, storage systems have been in use for thousands of years. Only in recent times several technological breakthroughs affected conventional storage systems and led to the rise of new ones. While, mechanical solutions are either for long term storage (PHS and CAES) or short term (Flywheels). Flywheels with magnetic bearing and operating under vacuum like conditions are an optimal tool to adjust the energy quality. They are used in the range of milliseconds to minutes.

Chemical storage has been popular in science and even policy, especially hydrogen (fuel cells) are considered to be the holy grail of energy, capable of powering our society. Yet, technological progress is rather slow and is still in the prototype phase. The same accounts for Electrical storage like DLC and SMES, with being at even earlier stage of development.

Thermal storage is already widely used together with concentrated solar systems. But, thermal storage usually suffers from low conversion rates. Electrochemical storage solutions remain as the likely enabler of a decarbonizing society in the short and medium-term. In addition, they are at different stages of development and deploying. Flow batteries are currently increasingly deployed but still not benefit from full commercialization (IEA 2014b). Technologies in the deployment and demonstration stage are usually benefiting from rapidly declining prices, while for the R&D phase prices are hard to estimate. The following figure shows the technological maturity of energy storage technologies (IEA 2014b).

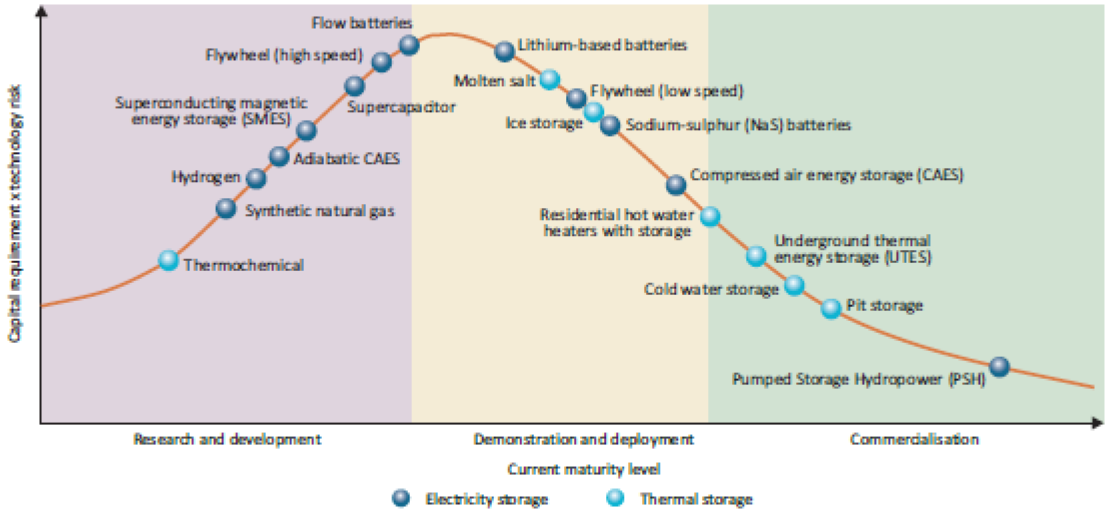

Figure 17 Maturity of energy storage technologies

Figure 18 shows various technologies and the best performing ranges (IEC 2011). As indicated, various technologies can substitute each other for a certain range. Thus, they may compete with each other. In practice the best fitting technology needs to be chosen. As already laid out in the introduction the focus of this paper will be on storage solutions which can be integrated with PV for consumer with medium demand in the range of some 10kwh to a couple hundred kWh. Three competing technologies, namely LiB, Lead-acid and RFB emerge as suitable candidates for integration. Sodium-Sulphur batteries could be a viable and affordable candidate. Due to high operating temperature (>300°C) and corrosive nature of materials involved they are currently deployed only in large scale applications of more than 1MW, although each power bank is in the reach of 30-200kW. Geographically they are also limited to wider usage only in Japan and United States. Therefore, they will be excluded from my comparison.

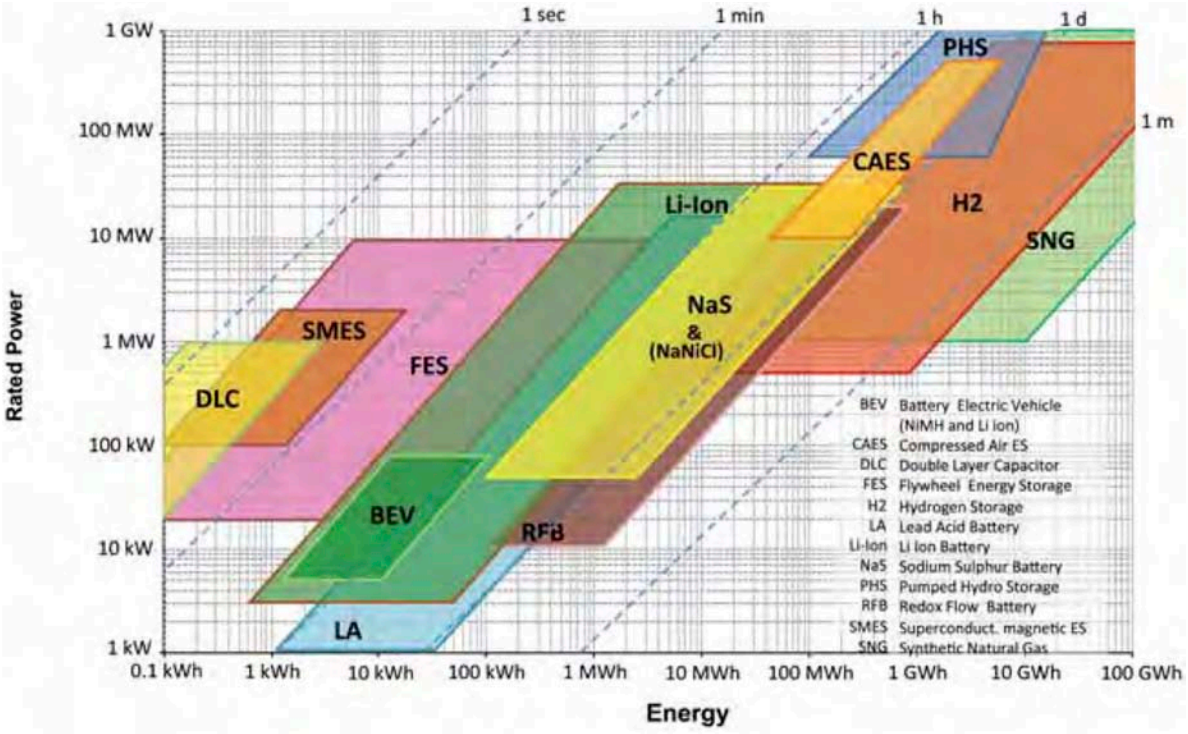

Figure 18. Comparison of rated power, energy content and discharge time of different EES technologies (IEC 2011)

Concerning battery technology, Pleßmann assumed that until 2020 lead-acid batteries will remain the cheapest option, closely followed by Sodium sulfur and others. Estimated Capex is around 250€/kWh (Pleßmann, et al. 2014). That estimate is quite conservative despite the fact that according to GM (smaller) and regarded to be quite costly EV battery cells (excluding the entire pack which adds up additional 20%) can already be produced for around 145€/kWh and less than 100€/kWh by 2021 (Cobb 2015). The three candidates perform differently under operation. The following table summarizes the characteristics of Storage systems suitable for end consumers (Ferreira, et al. 2013).

Table 3 Performance Characteristics of EES(Ferreira, et al. 2013)

	PHS	*Lead-acid*	*LiB*	*VRB*
Power rating (MW)	100-5000	0,001-50	0,1-50	0,005-1.5
Discharge duration (h)	10-100h	h	0,1-5	s-8h
Energy density (Wh/kg)	0,5-1,5	30-50	75-250	10-75
Energy density (Wh/l)	0,5-1,5	50-80	200-600	15-33
Power density (W/kg)		75-300	100-5000	
Efficiency	70-87%	70-92%	85-92%	65-85%
Durability (years)	40-100	5-15	5-20	10-20
Durability (cycles)	12.000 - 30.000+	500-1200	1000-10.000	13.000+
Capital costs ($/KW)	600-2000	300-600	1200-4000	600-1500
Capital costs ($/KWH	5-100	200-400	600-2500	150-1000
availability	95%	99,997%	97%+	96-99%

3.1. Principle of Secondary Batteries

This chapter deals with rechargeable battery systems, so called secondary batteries. Batteries are simple structured devices, which are able to convert chemical energy into electrical energy. First design of batteries date back already more than 2000 years ago to the so-called "Baghdad battery". A clay jar filled with acidic liquid was able to deliver around 1.5 Volt, stacked together they were most likely used for electroplating gold to a silver surface and/or in medicine for relieving pain. But the technology never spread until modern times. In 1799, the Italian physicist Alessandro Volta invented the voltaic cell. The cathode was made out of Copper and the Anode out of Zinc. These electrodes where mounted in an electrolyte (H2SO4), which allowed the electrons to travel from the anode to the cathode. By 1736 the voltaic cell was improved by the new design of John Frederic Daniell. This design could avoid the hydrogen bubble problem. Several improvements were still necessary but technology gradually improved over time. One major flaw was that none of these designs were rechargeable. The first true rechargeable battery which managed to become industrial standard was the Lead Acid battery invented in 1859 by Gaston Planté. By applying a reverse current, it was possible to recharge batteries. This allowed a number of new applications and accelerated the research.

There is currently a significant number of rechargeable batteries currently on the market or in research. To describe all types and subtypes of rechargeable would by far exceed the aim of this chapter, which is to give technical description of likely most dominant batteries in the coming two decades, suitable for end consumers. First, lead acid batteries will be discussed and then in comparison with Lithium Ion, the main competing technology, several reasons will be given, which accelerated the process of fading out the lead acid battery applications. In the second part flow batteries will be discussed which are from a technological perspective akin to fuel cells and secondary batteries.

But before some battery types will be discussed in detail it is necessary to analyze important parameters having an impact on the technology chosen.

The life span of batteries, sometimes also expressed on a yearly basis as the State of Health (SOH), is crucial for the success. Battery age mainly by two processes. The first is called cyclic ageing and depends on the number of times a battery has been recharged or discharged. Most batteries are negatively affected by unwanted precipitation and chemical processes inside the battery. Flow batteries, as further described below, are more resistant in this regard than Lead-acid or LiB Lib has the advantage that it usually degrades predictable over time, while Lead-acid may experience sudden failure. End of life of LiB is usually defined by a reduction of potential capacity of -20 to -30 % than initial capacity. This, however, states that LiB need to be replaced but that it purposes might shift. (E.g. Using LiB from electric vehicles as stationary source of energy), Other parameters, both external and internal like mechanical or thermal stress, may affect the life span. But even when the battery is not in use it life span may decrease over time. This factor is usually dependent on temperature, state of charge and of course time itself and is expressed in calendar years. Temperature in this regard might be substantial since test conducted by a French battery maker show that an operating temperature at 25°C corresponds to one-year calendar life time, while 50°C corresponds to 5,6 years (Saft 2014).

3.1.1. Lead-Acid Batteries

Lead-acid batteries have been invented by Gaston Planté in 1859 and are one of the oldest types of rechargeable batteries. Although their energy to weight ratio (≈35Wh/kg) and energy density (≈60-110Wh/L) is quite low they have been popular for many years because they are cheap and fairly reliable batteries, able to provide high surge currents. Especially in applications including emergency backup power supply, buffering and as car batteries. In recent years competing technologies, especially Lithium-Ion Batteries, have shown great potential and rapidly declining costs as an increasingly popular choice for equipping new applications with newer technologies than Lead-Acid. Still, Lead-acid will remain for the next years to decade an important part of the storage system market. Hence, a brief discussion is necessary before Lithium-Ion Batteries can be compared with Redox Flow Batteries.

The most important type of Lead-Acid batteries involves the compounds PbO2 (lead dioxide) for the positive plate and lead for the negative plate. The electrolyte is diluted sulfuric acid (H2SO4). The reaction equation is as follows (Industrial Power Application Engineering 2012, 5):

$$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

During discharge lead and lead dioxide is transformed to lead sulfate. The cell potential is 2.0V. Problematic with lead-acid batteries is the formation of lead sulfate dendrites when not recharged immediately after a discharge. The formation of these dendrites is more likely especially after deep discharges.

There are several types of design involving the reactive compounds. Depending on the usage either a sealed, flooded, valve-regulated-acid battery (VRLA) and absorbed glass matte (AGM). While the flooded type allows the use to directly access the cell stacks and the electrolyte is free to flow the sealed one does not allow this access. Still, the basic principle of flooded and sealed designs is the similar. The VLRA contains a little valve releasing unwanted oxygen and hydrogen during charging. The AGM introduces a glass fiber mat soaked in the sulfuric acid. A special feature is that it hinders the electrolyte from vertical motion, thus reducing the likelihood of the formation of unwanted species at the ground of the battery. Both, AGM and VRLA are maintenance free. VRLA and AGM designs have in common that the unwanted formation of oxygen and hydrogen takes place and a reformation is necessary. Since this process is exothermic a thermal runaway is possible, especially when constantly under load (Industrial Power Application Engineering 2012, 16). In practice AGM are more prone than other vented types to produce excess heat. Thus, ventilation is needed for releasing excess hydrogen and oxygen, and excess heat. An interesting feature is that vented and VRLA designs cool down if discharge takes constant place and last longer than 10 hours (Industrial Power Application Engineering 2012).

Depending on parameters like number of deep discharges, ambient temperature sealed Lead-acid batteries can provide for 200 to 300 full cycles. Since Lead-Acid batteries are not suitable for deep discharges, they are usually not discharged more than 30%DOD. This results in approximately 1200 cycles before it reaches its End of Life defined at 80% of the rated capacity. This value may be lower in stationary systems. Like Lithium-Ion Batteries this does not mean that the battery is not usable anymore but that its deterioration accelerates and sudden failure from a seismic shock. Thus, especially car batteries need to be replaced more often than stationary systems.

3.1.2. Lithium Ion Batteries

Lead is a heavy metal and could cause significant damage to human health and also power density is comparable low. Its replacement with better suited materials has been a focus of the scientific community and companies. Lithium became an obvious choice because it is the lightest metal and showed promising aspects in terms of energy density. In 1991, Sony became the first company which successfully commercialized rechargeable LIB. That innovation allowed a wide range of new appliances namely mobile phones, mobile computers and countless gadgets. Furthermore, energy density increased over time and it became a central device in the aviation industry and replaced NiCd and Lead-Acid batteries. Unresolved safety issues with LIB is still a major concern and many companies switch back to NiCd in the aviation industry. This may be temporary since many companies like *Quallion* are keen to further integrate them and even construct electric aircrafts. Still, LIB has proved to be a really disruptive technology in the modern world and has been deployed from a few Watt-hours in mobile device to megawatt-hours devices used for grid ancillary services.

The advantages of Lithium-Ion Batteries over batteries like Lead-Acid are manifold. First, since Lithium is one of the lightest materials it is weights significant less than others. For instance, energy density per mass is six times higher than lead acid.

The term Lithium-Ion refers not to one type of Lithium-Ion batteries but rather a wide array of different LIBs, characterized by different chemical composition. Contrary to Lithium batteries, which generally refer to disposable batteries like button cells, LIB use a carbon material and sometimes lithium titanate for the anode and lithiated metal oxides or phosphates for the cathode (ESA 2016). The ions are incorporated in these structures directly. Lithium-Ion cells are usually arranged in cylindrical or prismatic format which are connected together in modules, which themselves are arranged in series or parallel. These modules generate then the required voltage and are controlled by a battery management system.

The most important types of LIB are classified by the material for the cathode since as already mentioned the anode is mostly consisting of graphite. Lithium Cobalt Oxide(LiCoO2), typically used in mobile applications and prone to thermal runaway effects, Lithium Manganese Oxide (LiMn2O4) used for consumer appliances and industrial appliances. Similar to the last one is also Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2, abbreviated sometimes as NMC), which outperform most of other LIB types and are increasingly used in E-bikes, medical devices, electric vehicles and industrial applications. Lithium Iron Phosphate(LiFePO4) are in comparison high in specific power, but low in specific energy. Therefore, they are used mostly in applications where a lot of power in a short time (E.g. Car starter batteries) is needed. Similar to NMC is also Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2) but the costs are higher and some safety issues are involved with this battery (thermal runaway). They are used in industrial applications and Tesla’s electric powertrain (Model S). Lithium Titanate (Li4Ti5O12) are regarded as one of the safest LIB, can be fast charged and operate exceptionally well under low temperatures. Other applications include electric powertrains, UPS and solar-powered street lighting. Downside of this system is however low specific energy and high costs (Battery University 2016).

3.2. Principle of Flow Batteries

Redox-flow batteries (RFB) are investigated since the seventies. The concept was initially developed by NASA, but its potential to store large amounts of electrical energy has inspired more laboratories to follow suit. It sparked recent attention to the wider public, when the Breakthrough Energy Coalition, consisting of a group of widely known entrepreneurs, endorsed RFB as one of three technologies, which needed more funding and attention. The other two endorsed technologies at the eve of the United Nations Conference on Climate change were solar chemical technologies and solar paint (Chandran 2015).

Redox Flow batteries are rather bulky EES with the potential to enable deregulated and decentralized networks. They generate electricity by converting stored chemical energy by a redox reaction between different or same kind of active species dissolved in an electrolyte. They usually consist of three parts. First, the cell stacks where the energy is converted through a reversible process. The second part is independent from the stacks and physically dispatched when not in use. The third part is a pump system, enabling the reaction to take place.

The following figures shows the schematic overview of a generic RFB (Hosseiny 2011, 12).

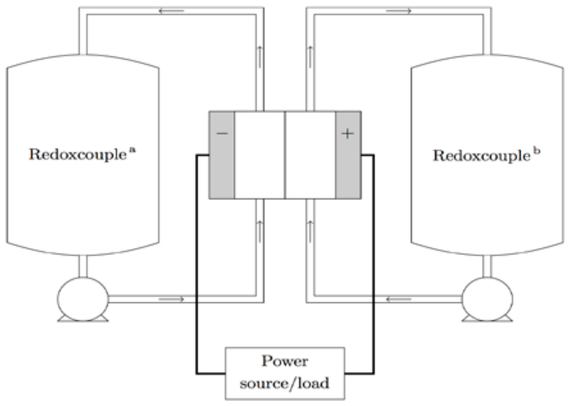

Figure 19 Schematic overview of a redox flow battery (Hosseiny 2011, 12)

The advantage of RFB is that they decouple power and capacity. While the size of the tanks determines the capacity, size of the cell stack determine power. This allows tailored solution to specific needs. Redox-flow batteries are usually classified by the contained electrolyte and if it is aqueous or not. While discharging an anolyte solution flows through a porous electrode. Then anolyte is undergoing a chemical reaction, which generates electrons. An external circuit, powering the facility, can then use these electrons. An Ion-exchange membrane then separates the charge carrying species of solution, usually (Weber, et al. 2011, 1140). By this the anolyte and separated from the catholyte solution. The chemical equation is as follows:

$$A^{n+} + xe^{-} \xrightarrow{charge} A^{(n-x)+} \, and \, A^{(n-x)+} \xrightarrow{discharge} A^{n+} + \, xe^{-} \quad , when \, n > x$$

$$B^{m+} - \, ye^{-} \xrightarrow{charge} B^{(m+y)+} \, and \, B^{(m+y)+} \xrightarrow{discharge} B^{m+} - \, ye^{-}$$

Contrary to many other conventional batteries, both the reduced and oxidized form of the reactant are soluble and stored in the electrolyte. This means that the active species can be transferred to the electrodes in the same phase; hence, the electrodes are not undergoing any physical changes during reactions. By this the design can be simplified and the cycle life of RFB is not influenced by DOD and number of cycles (Weber, et al. 2011, 1141). LIB and lead-acid batteries on the contrary, are based on the principle that species like Lithium with iron or Lithium with some phosphates need to be mixed. Thus DOD differs significantly through its usage before it reaches its End-of-Life Point. RFB on the other hand can last in theory indefinitely, but in daily operation parts like pumps, sensors and the compartments need to replaced every 25 years.

The membrane separates the two active species and prevents short-circuiting. Several arrangements exists but the most common ones are sheets, ribbons and tubes. The material used should offer the following characteristics: Good chemical stability under acidic conditions, high permeability to the charge carrying hydrogen ions, resistance to the highly oxidising environment of the positive half cell electrolyte, low permeability to the vanadium (in the case of VRB) or polyhalide ions, low electrical resistance, good mechanical properties and low cost. As indicated on page 49 this membrane is costly (Prifti 2012).

Development to date has focused in efficient ways to store electricity, in particular for portable devices and transport. One determining factor in this regard is energy density and form factor. Beside high temperate-thermal storage and PHS no technology has been yet identified to be suitable for an increased market penetration of intermittent energy sources. For applications in the commercial and residential sector size and volume are less critical, hence other ways of storing energy might be cheaper and more efficient. RFB have been identified as a suitable technology to meet the demands of these sectors (Weber, et al. 2011, 1138). A key ability of this technology is the capability to separate between power and energy. Similar to conventional batteries, energy is controlled by the size of the stacks of the cell and the amount of energy by the volume of the two tanks. By simply increasing the tank size, specific energy demand can be met.

The electrolyte flow is maintained through a pump system. Nevertheless, energy generation is also possible when the pumps are not operating due to active species close to the cell stack. This characteristic allows the system to provide some energy immediately in the millisecond range. This makes this type of technology suitable for UPS services and may replace Lead-acid batteries in this regard. Especially in regions where the grid is unreliable, it may replace the need for generators entirely.

Self-discharge is usually negligible with such systems. This is due to two reasons. First, the electrolytes are not in contact with each other and when the battery is not used, even remain in their respective tanks. Additional leakages and crossover are limited since the EES is arranged in such a way that on top we have the cell stacks and on the bottom we have the tanks. “Ordinary” water pumps then transport the liquids to the cell. By this a supplier of this technology can achieve a self-discharge rate (For VRB) of less than 1% per year (Gildemeister). The following table highlights the most promising RFB and their respective cell potential (Hosseiny 2011).

Table 4 Most common half-cell reactions in flow batteries (Hosseiny 2011)

	Cell Reactions		
Redox Flow Battery System	Charge	Discharge	Standard Cell Potential(V)
Bromide/Polysulphide	$3Br^- \rightarrow Br_3{}^- + 2e^-$ $S_4{}^{2-} + 2e^- \rightarrow 2S_2{}^{2-}$	$Br_3 + 2e^- \rightarrow 3Br^-$ $2S_2{}^{2-} \rightarrow S_4{}^{2-} + 2e^-$	1.35
All-Vanadium	$VO^{2+} + H_2O \rightarrow VO_2{}^+ + 2H^+ + e^-$ $V^{3+} + e^- \rightarrow V^{2+}$	$VO_2{}^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O$ $V^{2+} \rightarrow V^{3+} + e^-$	1.26
Vanadium/Bromine	$2VBr_3 + 2e^- \rightarrow 2VBr_2 + 2Br^-$ $2Br^- + Cl^- \rightarrow ClBr_2{}^- + 2e^-$	$2VBr_2 + 2Br^- \rightarrow 2VBr_3 + 2e^-$ $ClBr_2{}^- + 2e^- \rightarrow 2Br^- + Cl^-$	1.3
Iron/Chromium	$Fe^{2+} \rightarrow Fe^{3+} + e^-$ $Cr^{3+} + e^- \rightarrow Cr^{2+}$	$Fe^{3+} + e^- \rightarrow Fe^{2+}$ $Cr^{2+} \rightarrow Cr^{3+} + e^-$	1.18
Zinc/Bromine	$3Br^- \rightarrow Br_3{}^- + 2e^-$ $Zn^{2+} + 2e^- \rightarrow Zn$	$Br_3{}^- + 2e^- \rightarrow 3Br^-$ $Zn \rightarrow Zn^{2+} + 2e^-$	1.85
Vanadium/Air	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$ $4V^{3+} + 4e^- \rightarrow 4V^{2+}$	$4H^+ + O_2 + 4e^- \rightarrow 2H_2O$ $4V^{2+} \rightarrow 4V^{3+} + 4e^-$	1.49
Zinc/Cerium	$2Ce^{3+} \rightarrow 2Ce^{4+} + 2e^-$ $Zn^{2+} + 2e^- \rightarrow Zn$	$2Ce^{4+} + 2e^- \rightarrow 2Ce^{3+}$ $Zn \rightarrow Zn^{2+} + 2e^-$	2.4

NASA has developed the Iron/Chromium flow battery. This technology uses the aqueous solution of a ferric/ferrous redox couple at the positive electrode (FE2+/Fe3+) and Cr2+/Cr3+ for the cathode. The supporting agent is mostly HCL. Problematic was the low open-circuit potential of 0.90 to 1.20 Volts. Thus, development almost stopped in recent time because other forms showed greater promise.

Another promising solution was the bromine/polysulphide flow battery. Although it showed greater open-circuit potential (1.7 to 2.1V) and has been deployed commercially unresolved issues in relation to crossover and mixing of the electrolytes and precipitation of sulfur species and formation of unwanted compounds. This resulted in an efficiency loss over time.

3.2.1. Vanadium Redox-Flow Batteries

Due to the early stage of deploying, costs for VRB vary significantly, especially between academic and corporate sources. Costs per kWh vary currently between 250€/kWh (2015) and 1000€/kWh .They are projected to decline to 100€ by 2030 (Weber, et al. 2011, 1140). (Battke and Schmidt 2015) assessed several projects and estimated a range of 110€/kWh to 809€/kWh, with the average costs of 300€/kWh in 2011.

The composition of costs for VRB is indicated below. As the size of the device increases, the active species (V2O5) is becoming the most dominant contributor to final costs (Viswanathan, et al. 2012). For small to medium sized applications, the separator membrane is due to the multistage process in manufacturing the most expensive part. The price of Vanadium pentoxide was around 12$/kg in 2016.

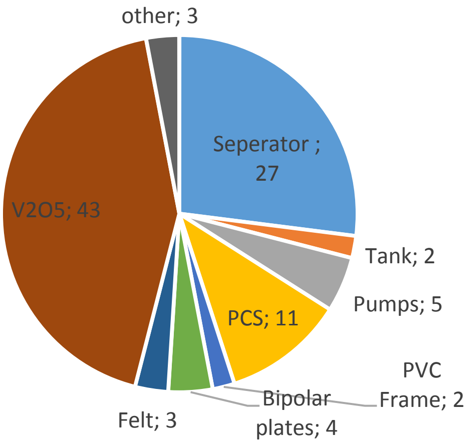

Figure 20. VRB cost structure - 4MWh (Viswanathan, et al. 2012)

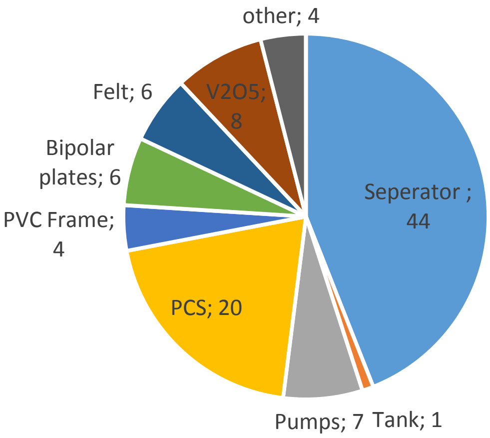

Figure 21. VRB cost structure - 250kWh (Viswanathan, et al. 2012)

Crossover of the electrolyte leads to unwanted reactions. One way to circumvent this is by using one element of two oxidation states. Crossover, which is currently almost impossible to resolve, results then in lowered efficiency but no precipitation of unwanted species, which alter the life time of the battery at ambient temperature. By this, the lifetime could dramatically improve. Scientist found that especially the chemical element vanadium promising. By using the V2+ and V3+ redox couple for the negative electrode and the V4+ and V5+ couple for the negative electrode the same element with four different oxidation states can be used for this technology.

VRB differ from secondary batteries mainly due to two reasons. First, two electrolytes in the same state are the reactive species and not like in conventional batteries an electrolyte and a (solid) electrode. Second, as already mentioned the electrolytes are stored in tanks. In the VRB, two reactions on either part of the half-cell are taking place simultaneously by the process as already explained earlier. Full-Vanadium Flow Batteries require some sort of medium for transport due to its solid phase at operating temperature. Thus, water and Hydrogen are needed for the process to take place. If water is added an additional challenge is the dilution of a half-cell and flooding the other (Prifti 2012). A second reason why a full VFB is actually consisting of vanadium oxide ions and protons is due to stoichiometry. The equation is stated as follows (Blan and Rufer 2010, 334):

$$VO_2^+ + 2H^+ + e^- \rightleftharpoons VO^{2+} + H_2O$$

$$V^{2+} \rightleftharpoons V^{3+} + e^-$$

$$V^{2+} + VO_2^+ + 2H^+ \rightleftharpoons VO^{2+} + V^{3+} + H_2O$$

In the negative half-cell charging switches V^{3+} to V^{2+} and in the positive VO_2^+ to VO^{2+}. The positive half-cell of the VRFB contains V_2O_5, which is vulnerable to high temperatures. At ambient temperatures of over 50 to 600°C, precipitation may occur and might destroy the electrolyte irreversible. Especially in sunny regions, this might be a challenge for the design and may demand additional installations in form of active cooling systems. Another unwanted side effect is coulombic efficiency decrease when ambient temperature is above 50°C for a longer period of time (Pan, et al. 2016). Yet, other electrochemical storage systems are adversely affected by ambient temperature.

3.3. Application parameters

As we have seen Lead-acid, Lithium-Ion and Redox Flow batteries are all different to each other and vary in their advantages and disadvantages. Thus it is necessary to determine which use case is the best delivered by which system. The following parameters will be considered: Surge current, usable energy, price, energy density, charge and discharge efficiency, roundtrip efficiency, ambient conditions, cycle life and general lifetime.

Costs of storage is crucial for determining the right system for obvious reasons. One way in determining the right choice is by calculating the added values of a storage system. This value is specific to a project and therefore not comparable across technologies and usage cases. An alternative is by determining the costs of storage per cycle. Drawback of such comparison is the high upfront costs of storage solutions with many cycles (e.g. VRB, CAES, PHS and to some extent LiB). In case of shorter project duration, solutions with higher costs per cycle may be more beneficial. At the same time, EES solutions are increasingly becoming cheaper. Figure 15 shows the capital costs/cycle (IRENA 2015b). Especially VRB and LiB are benefiting from current market trends and increased economy of scale.

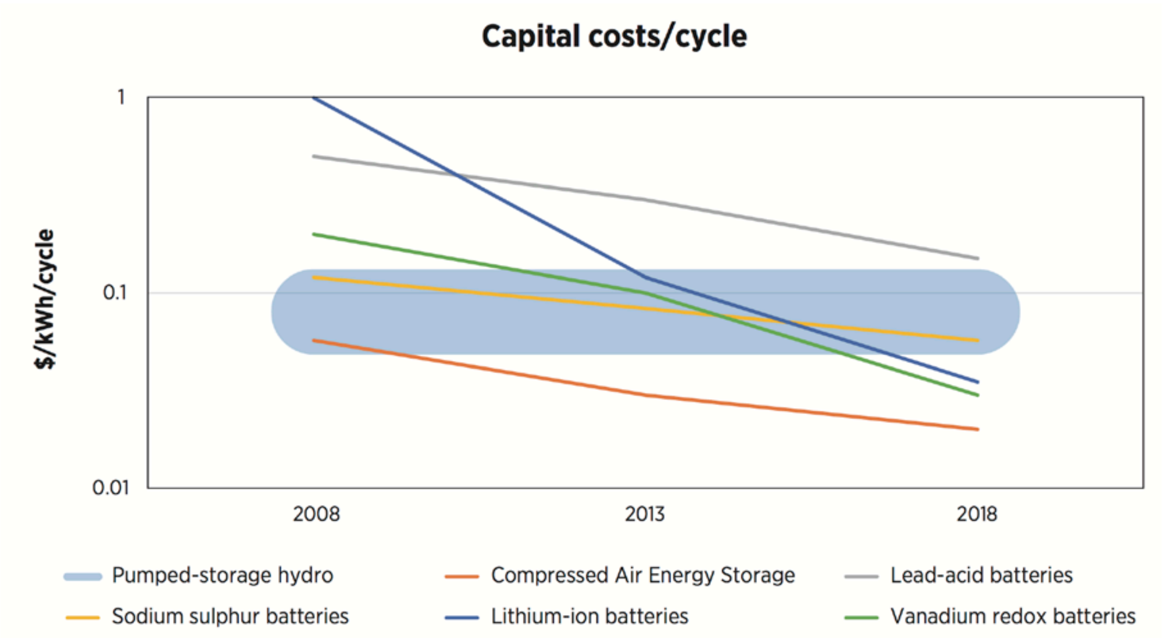

Figure 22. Cost assessments for electricity storage systems (IRENA 2015b)

Based on pure material costs a lower limit of 100US$/kWh is considered for LiB. Emerging technologies like nickel-cadmium, metal-air or RFB are challenging this threshold (IRENA 2015b). Lazard expects that capital costs for LIB will decline by 50% over the next five years and RFB by 40% on average, while it seems that Lead-acid has reached its plateau with only 5% costs decline (Lazard 2015). In combination with subsidies, they may reach grid parity sooner than without.

LIB are not really good for peak shaving since their life span decreases with each cycle, while RFB are well suited to fulfill this task. Especially PV and wind systems may benefit from this system since the actual storage capacity matches the generating capacity. Operating costs proportional to the CAPEX vary across LiB and VRFB. While for VRB it is around 2.6% p.a., LiB demands less maintenance with 1.6% p.a. The advantage of VRB over Lithium Ion is the modularity. Because the cell stacks and the active species rated for capacity are usually sold in one unit, most LiB systems are hard to upgrade after they reached a certain lifetime. VRB on the other hand are easier to refurbish since tanks and cell stacks are dispatched physically. At the same time owner of PV, arrays may consider purchasing additional panels if financial means would allow it. However, this would mean that the needed capacity of the power banks would increase. By increasing the size of the tank, VRB offer a practicable solution since the electrolyte is only a fraction of the capital costs. Depending on the inverter used, and under the assumption that desired peak power does not change significantly, upgrading existing VRB systems could be cheaper than LiB systems.

4. Part 3: Case Study

The economics of storage systems depend highly on parameters discusses in this paper. A suitable candidate for the integration of PV storage systems is animal breeding. With an average electricity demand of 400kwh/pig, especially pig farming is extensively using electricity for breeding. The major contributors are infrared lamps with a share of 20% and ventilation with 43% (Bayerische Landesanstalt für Landwirtschaft 2014). Hence, energy efficiency measures might be a viable solution for lowering the costs. At electricity prices of currently 0.26€/kWh and a Fit of 10.71€/kWh it makes sense to consume on site generated electricity. The following case study will compare the two systems (LiB and VRB). The *Bayerische Landesanstalt für Landwirtschaft* provided the load profile of a typical farm. The type of LiB used in this example will base on a generic type of Lithium Nickel Manganese Cobalt Oxide and for VRB the Gildemeister Cellcube FB 30-40. The PV modules are generic with 70KWp with a nominal efficiency of 17.78%. The location of the hypothetical farm is in the area of Munich, Germany with an average sum of global irradiation 109kwh/m^2. The cost are 0.68$/Wp for the PV module and 0.16$/Wp for the inverter. A list of assumption is provided for in Annex I. In addition, a 210kWp PV system and a 100kWh LIB has been implemented in the part about self-consumption rate and autarky.

The following table[2] gives the results of the calculation. At current estimated prices of 300$/kWh for VRB and 450$/kWh for LIB storage results in higher profits in the long run with the downside of having higher upfront costs and added complexity in the short run. Vanadium Flow Batteries outperform Lithium Ion Batteries and Lead-acid batteries in the long run due to increased cycle life.

Table 5 Case study indicators and results

Metric	*Value LIB*	*Value RFB*	*no storage*
Annual energy	76,542kWh	76,542 kWh	76,542kWh
Capacity factor	12.6%	12.6%	12.6%
Energy yield	1.103kWh/kW	1.106 kWh/kW	1.106 kWh/kW
Performance ratio	0.87	0.87	0.87
Battery efficiency	91.7%	74%	

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[2] The values have been converted to Euro.

Levelized COE (nominal)	20.55 c/kWh	19.81 c/kWh	17.65 c/kWh
Levelized COE (real)	17.29 c/kWh	16.66 c/kWh	14.85 c/kWh
Electricity bill without system (year 1)	€24,580	€24,580	€24,580
Electricity bill with system (year 1)	€2,445	€2,386	€2,437
Net savings with system (year 1)	€22,135	€22,194	€22,143
annual self consumption rate	60.30%	62.04%	51.64%
Net present value	301,087	€307,274	€325,428
Payback period[3]	6.3 years[4]	6.2 years	5.6 years
Net capital cost	€168,649	€155,350	€134,606
Equity	€50,595	€45,105	€40,382
Debt	€118,054	€105,245	€94,224

As indicated in (Fraunhofer 2015) the most efficient way of integrating storage is by consuming generated electricity directly, then charging the battery and if the battery is discharged, purchasing additional energy from the grid. As indicated below, most of the indicated energy is consumed on place.

Additional financial benefits for businesses in Bavaria are an affordable loan for the PV and storage system with an effective loan rate in between 1.15 to 1.55 over the duration of 10 years. This loan is provided by the government owned development bank KFW. Additionally, storage systems (Only lead-acid, LiB and flow batteries) of less than 2000€/kWp are subsidized by the KFW. Depending on the date of implementation, this ranges in between 25% (2Q2016) to 10% (4Q2018). For the calculation of this project a subsidy of 22% has been assumed (4Q2016) (KFW 2016b).

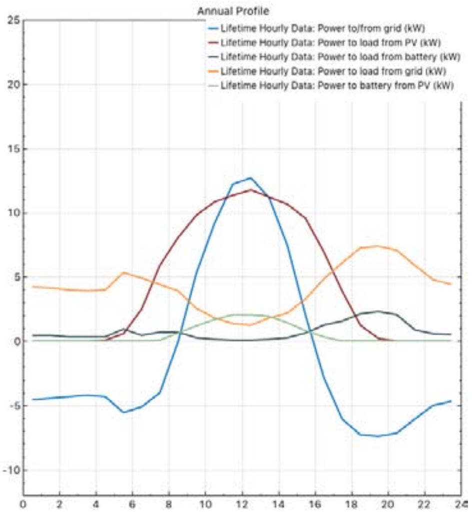

Figure 23 Annual Load profile 70kWp & 50kWh VRB

The self-consumption rate is defined as the sum of the energy load from the battery plus the PV array divided by the total energy generated. Vanadium Redox Flow Battery would

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[3] In comparison with *Homer Pro Microgrid Analsysis Tool*, payback period is slightly longer in Homer with 8.24 years.

increase the self-consumption rate from 51.6% to 62% and Lithium-ion batteries (NMC) to 60%. Yet, net savings do not correlate with this increase since values of net savings on the electricity bill are in the range of ± 50$. The findings of (REC 2014) that increase of self-consumption results in increased NPV could not be replicated. By increasing, the size of the array to 210kWp and the power bank to 210kWh self-consumption will decrease to 27%, as the share of energy not usable on site will increase drastically. According to the model used in SAM, and after the dispatch optimization, and event doubling the capacity of the battery to 500kWh, self-consumption would increase only marginally as the diurnal cycle RE is not favorable in this location.

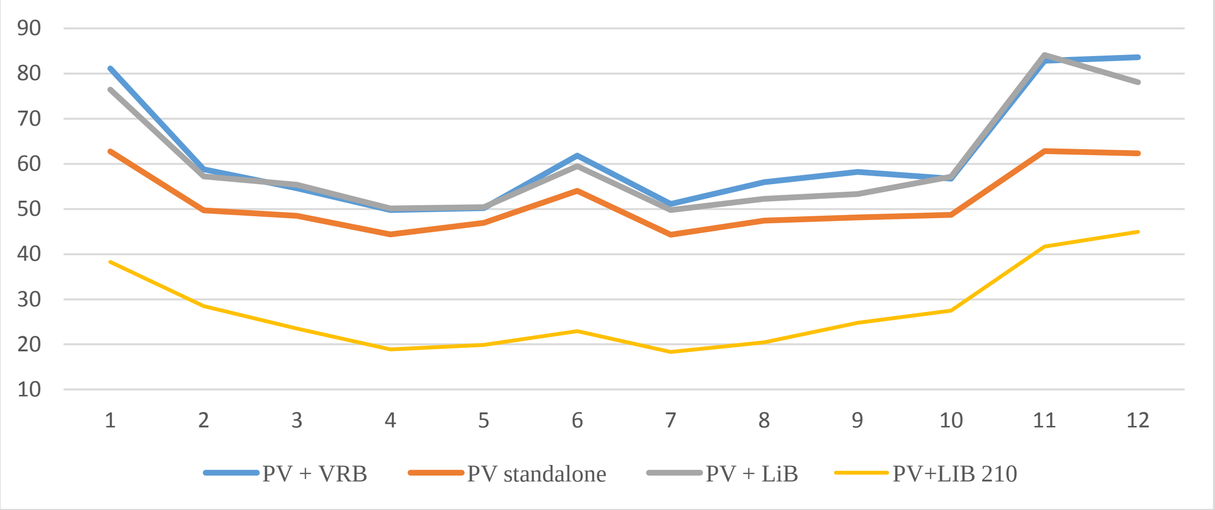


Figure 24 Self-consumption rate of PV-systems

The rate of autarky is similar to the rate of self-consumption and is defined as the sum of the energy load from the battery plus the PV array divided by the energy load. Here, the results are similar. Instead, to the self-consumption rate, where the surplus energy in summer results in lowered self-consumption, the rate of autarky is higher especially during sunny seasons. Clearly, an increase in generating and storing capacity would result in higher autarky rates. Surprisingly a 210kWp PV system coupled with 100kWh LiB storage system would result in 80% autarky rate, although this system would be sufficient for powering the facility. The economics of such a facility are with a payback period of 6.6 years favorable, although this value depends on the FiT to a great margin since this system would result in a negative energy bill of €38,000. With Net-capital costs of €467,437 this system is considerable more expensive.

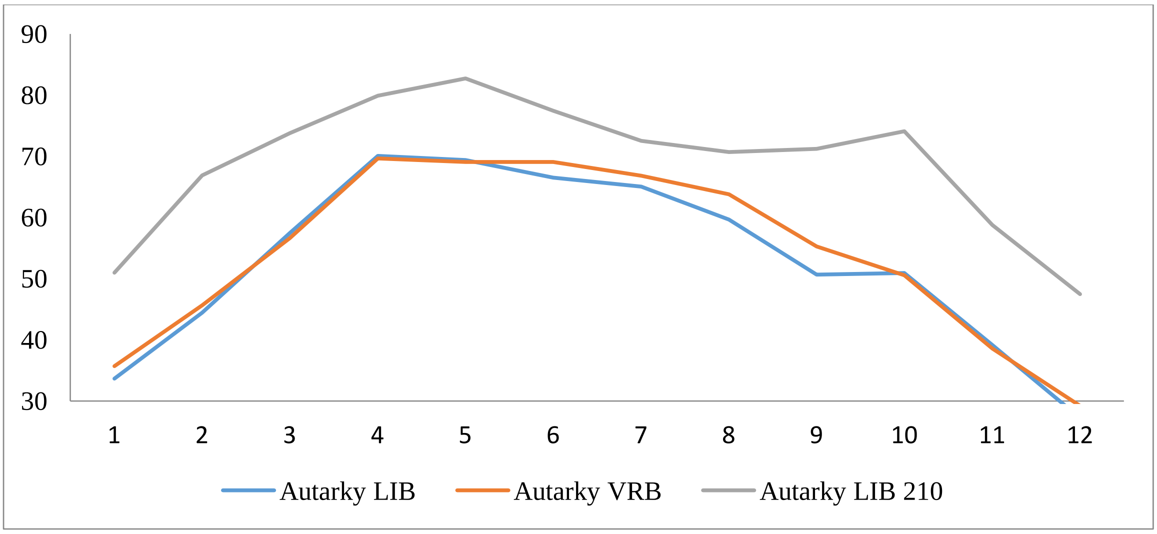
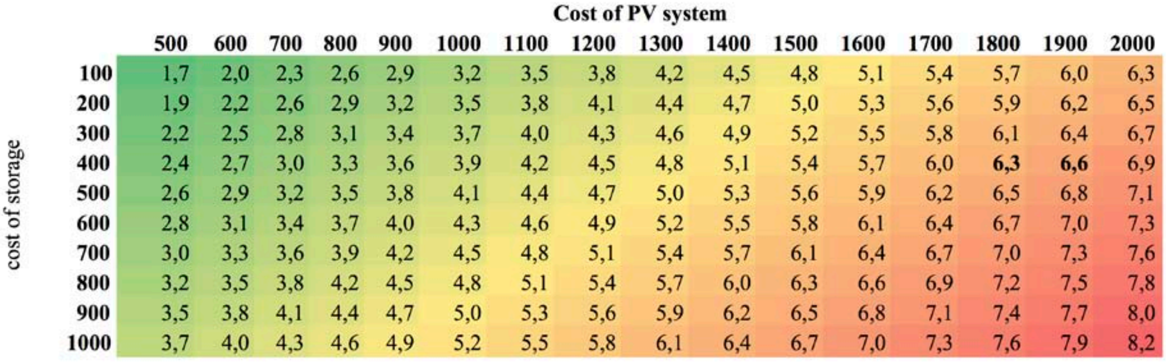


Figure 25 Rate of Autarky

Payback period is a good indicator to assess the value of an investment over the BAU scenario[5]. If the payback period is well below the indicated lifetime of a system, it can be regarded as a profitable investment. The result based on my assumptions is 6.3 years. Without considering the value of money, the following *What-If* analyses could be calculated. The results in bold are the range of PV+storage systems in my case study. As we can see with PV panel prices in the range of 1800-1900€/kWh and total storage costs of around 400€/kWh lower investment costs would result in a drastic decrease of the payback period.

Table 6 Payback Period of a 70kWp PV and 50kwh storage system at BAU scenario 26c/kWh



		Cost of PV system															
		500	**600**	**700**	**800**	**900**	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**
cost of storage	**100**	1,7	2,0	2,3	2,6	2,9	3,2	3,5	3,8	4,2	4,5	4,8	5,1	5,4	5,7	6,0	6,3
	200	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,4	4,7	5,0	5,3	5,6	5,9	6,2	6,5
	300	2,2	2,5	2,8	3,1	3,4	3,7	4,0	4,3	4,6	4,9	5,2	5,5	5,8	6,1	6,4	6,7
	400	2,4	2,7	3,0	3,3	3,6	3,9	4,2	4,5	4,8	5,1	5,4	5,7	6,0	**6,3**	**6,6**	6,9
	500	2,6	2,9	3,2	3,5	3,8	4,1	4,4	4,7	5,0	5,3	5,6	5,9	6,2	6,5	6,8	7,1
	600	2,8	3,1	3,4	3,7	4,0	4,3	4,6	4,9	5,2	5,5	5,8	6,1	6,4	6,7	7,0	7,3
	700	3,0	3,3	3,6	3,9	4,2	4,5	4,8	5,1	5,4	5,7	6,1	6,4	6,7	7,0	7,3	7,6
	800	3,2	3,5	3,8	4,2	4,5	4,8	5,1	5,4	5,7	6,0	6,3	6,6	6,9	7,2	7,5	7,8
	900	3,5	3,8	4,1	4,4	4,7	5,0	5,3	5,6	5,9	6,2	6,5	6,8	7,1	7,4	7,7	8,0
	1000	3,7	4,0	4,3	4,6	4,9	5,2	5,5	5,8	6,1	6,4	6,7	7,0	7,3	7,6	7,9	8,2

Under the assumption that energy prices are in the range of 20c/kWh, payback period is adversly affected. The following table shows the results. As we can see an decrease of electricity prices by 6c/kWh results in more than 30% longer payback periods.

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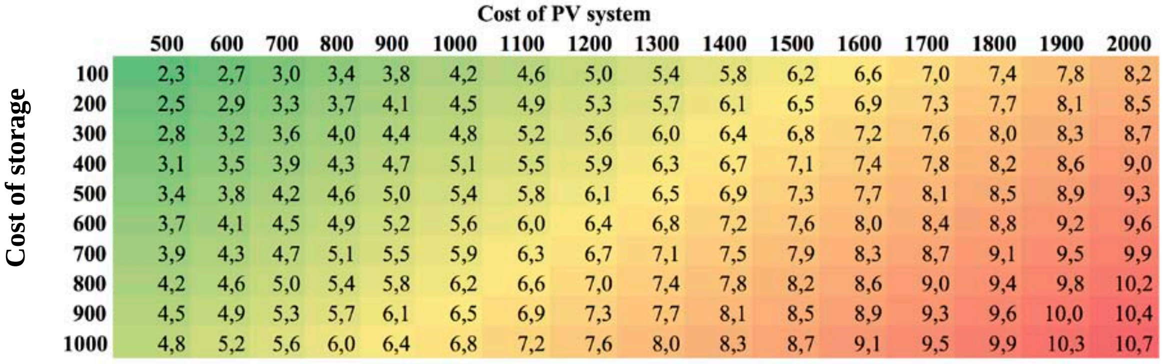
[5] The business-as-usual scenario is definewith 26c/kWh and no on-site gneration of electricity.

Table 7 Payback Period of a 70kWp PV and 50kwh storage system at BAU scenario 20c/kWh



	Cost of PV system															
Cost of storage	**500**	**600**	**700**	**800**	**900**	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**
100	2,3	2,7	3,0	3,4	3,8	4,2	4,6	5,0	5,4	5,8	6,2	6,6	7,0	7,4	7,8	8,2
200	2,5	2,9	3,3	3,7	4,1	4,5	4,9	5,3	5,7	6,1	6,5	6,9	7,3	7,7	8,1	8,5
300	2,8	3,2	3,6	4,0	4,4	4,8	5,2	5,6	6,0	6,4	6,8	7,2	7,6	8,0	8,3	8,7
400	3,1	3,5	3,9	4,3	4,7	5,1	5,5	5,9	6,3	6,7	7,1	7,4	7,8	8,2	8,6	9,0
500	3,4	3,8	4,2	4,6	5,0	5,4	5,8	6,1	6,5	6,9	7,3	7,7	8,1	8,5	8,9	9,3
600	3,7	4,1	4,5	4,9	5,2	5,6	6,0	6,4	6,8	7,2	7,6	8,0	8,4	8,8	9,2	9,6
700	3,9	4,3	4,7	5,1	5,5	5,9	6,3	6,7	7,1	7,5	7,9	8,3	8,7	9,1	9,5	9,9
800	4,2	4,6	5,0	5,4	5,8	6,2	6,6	7,0	7,4	7,8	8,2	8,6	9,0	9,4	9,8	10,2
900	4,5	4,9	5,3	5,7	6,1	6,5	6,9	7,3	7,7	8,1	8,5	8,9	9,3	9,6	10,0	10,4
1000	4,8	5,2	5,6	6,0	6,4	6,8	7,2	7,6	8,0	8,3	8,7	9,1	9,5	9,9	10,3	10,7

5. Conclusion

PV + EES solutions are promising technologies for wider usage. Yet, as indicated by (Lazard 2015), storage used for integrating PV on a wider scale is hindered by limited margins of tangible value streams. The findings of (Grigoleit 2014) that PV+EES reached grid parity in Germany could be repeated, even if subsidies for storage are excluded. In the following years, as PV panel modules will be cheaper than 0.50$/Wp and secondary batteries may reach a level of around 100€/kWh capacity, this combination will result in payback times of around 4 years and even less (Based on the data of the case study). Until then, PV standalone systems may be sufficient alone, although retrofitting an existing system may be considered under certain circumstances. In areas where electricity prices are well above 0.26€/kWh, EES are already cost-effective by a greater margin. Using storage for arbitrage is not advised, if this represents the only cash inflow. Nevertheless, diurnal fluctuating electricity prices may render EES a promising application. Storage systems can be used, if LCOE of storing is below the purchase price, for deferral. Using storage as backup has not been discussed in this thesis due to the lack of tangible cash inflow and lack of data for the European region. Calculations indicate that the system needs to be oversized and most likely to be hybrid (PV+Wind+Generator+EES) in order to meet the demand during the diurnal cycle. Based on the design choice, if using VRB or LIB, no clear most cost effective solution could be identified due to error margins of procurement. However, life expectancy, cost structure, cycle life may significantly affect the decision. Based on scalability and modularity VRBs are the better choice for systems well above 50-100kWh and LiB for smaller systems of at least 1-2kWh. Usage cases may shift these values in either direction. This corresponds well with the data provided for by (IEC 2011), although the high power rating for LIB could not be assessed in detail.

With reference to different sources of energy PV stands out as a technology with rapid declining costs. Still, the case study shows that in some locations like Bavaria, PV are suitable for lowering the electricity bill and generate small profits but not for powering the entire facility. Borrowing from the *pareto principle,* a facility with a rate of 80% autarky is possible for some time but in order to achieve the remaining 20% it is rather costly and not advised currently. A system might be more profitable if other sources like wind or smaller hydro may be incorporated into the design. Future work needs to focus on this remark but as indicated in the part about energy islands hybrid generation systems are the most cost-effective solution. Yet, a grid connected hybrid system shows some promising aspects but couldn’t be assessed in this thesis.

During research, another challenge for decision makers arose. The lack of information in particular for VRB, early stage of deploying and the limited number of supplier resulted in inconsistency in the data and cost structure. While for PV systems costs structure is more or less coherent the prices for EES vary significantly. This is due to the juvenile characteristics of this industry. Concerning this, much more R&D must be done in order to bring down costs but also improve the characteristics of EES. At this point characteristics vary significantly between technologies, which may constitute a substitute, and individual design of certain subtypes. Thus, external factors are currently the most dominant factor in deciding for a system.

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Annex

Key Assumptions of the case study.

Parameters	LIB case study	VRB case study
Location	Munich	Munich
Module		
Maximum power	73.0Wp	73.0Wp
Maximum power voltage	30Vdc	30Vdc
Module structure	Glass/cell/Polymer sheet	Glass/cell/Polymer sheet
Array size	70kWp	70kWp
Degradation rate	0.5%/a	0.5%/a
Irradiance	1000W/m^2	1000W/m^2
Inverter		
Max AC output power	4000Wac	4000Wac
Weighted efficiency	98%	98%
Nominal AC voltage	240Vac	240Vac
DC Losses	4.440%	4.440%
AC Losses	1%	1%
Storage		
Storage capacity	50kWh	50kWh
Maximum power	50KW	15.7kW
Dispatch controller	Peak shaving	Peak shaving
Roundtrip efficiency	92%	75%
System Costs		
Module[6]	0.68€/Wdc	0.68€/Wdc = €47,058.66
Inverter	0.16€/Wdc	0.16€/Wdc = € 11,764.66
Battery	397€/kWh = €19,860	300€/kWh[7] = € 15,743.70
additional costs PV		
Balance of system	0.56€/Wdc = €38,754.19	0.63€/Wdc = € 43,598.46
Engineering and other	0.75€/Wdc = €51,902.93	0.75€/Wdc = € 51,902.93

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[6] (Agora 2015)
[7] (Battke and Schmidt 2015)

Total installed costs	168,648.56	€150,350
per capacity	2.48€/Wdc	2.38€/Wdc
Electricity rate	0.26€/kWh[8]	0.26$/kWh
Increase p.a.	6%/a	6%/a
Feed in Tariff[9]	0.11€/kWh	0.11€/kWh
O & M costs		
PV[10]	16.78€/kW p.a.	19€/kW p.a
storage	1.6% of Capex p.a. [11]	2.6% of Capex p.a.
replacement costs	350€ after 10 years	1/20 p.a.
Financial parameters		
Debt percent	70%	70%
Loan term	10 years	10 years
Loan rate[12]	1.55%/a	1.55%/a
Inflation rate	2%/a	2%/a
Nominal discount rate	6.08%/a	6.08%/a
Subsidies[13]	€ 14,182.00	€ 14,182.00

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[8] (BMU 2015)

[9] (Bayerische Landesanstalt für Landwirtschaft 2016)

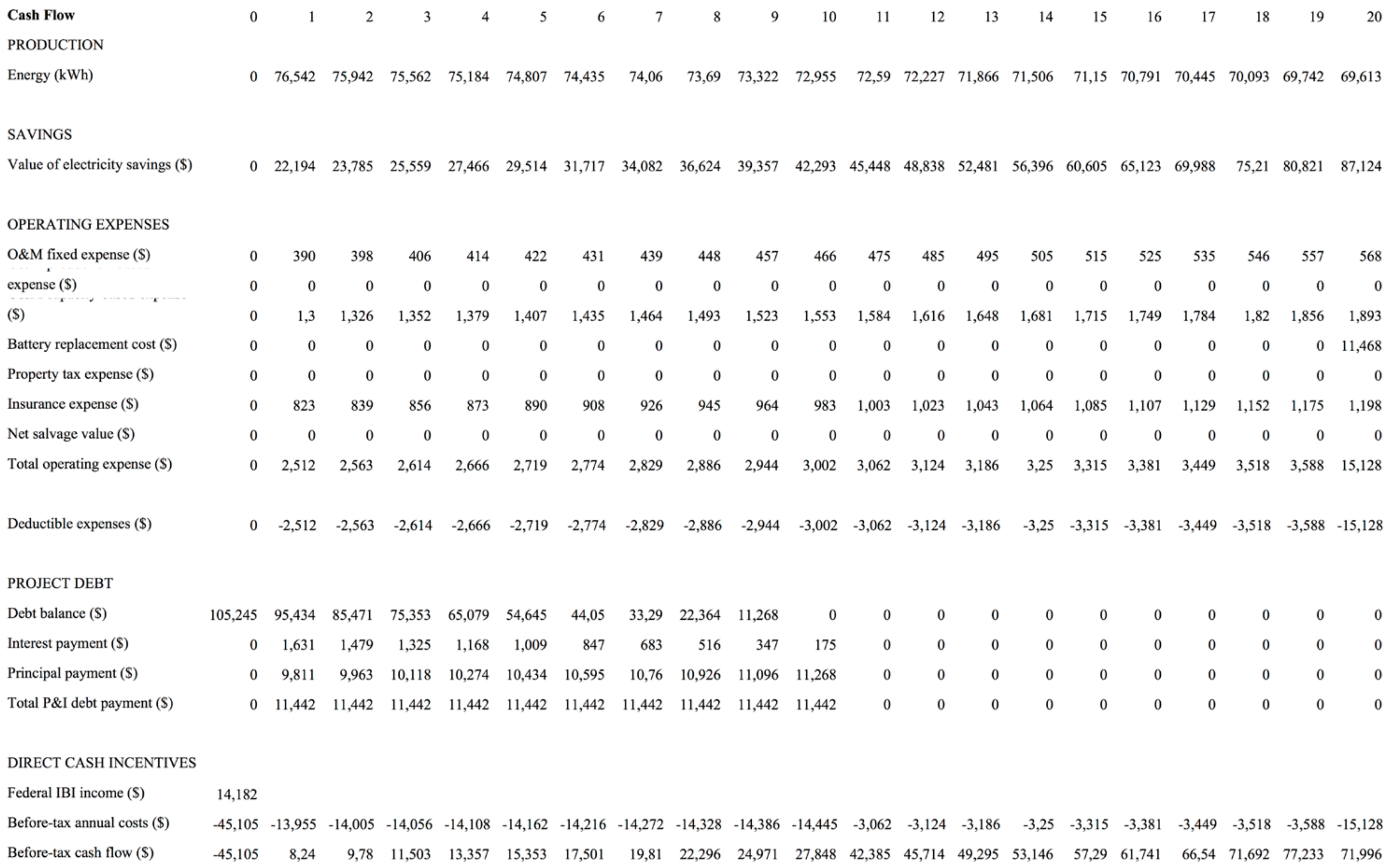
[10] (NREL 2016)

[11] (Lazard 2015)

[12] (KFW 2016a)

[13] (KFW 2016b)

Table 1 Cash Flow Case study



Cash Flow	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PRODUCTION																					
Energy (kWh)	0	76,542	75,942	75,562	75,184	74,807	74,435	74,06	73,69	73,322	72,955	72,59	72,227	71,866	71,506	71,15	70,791	70,445	70,093	69,742	69,613
SAVINGS																					
Value of electricity savings ($)	0	22,194	23,785	25,559	27,466	29,514	31,717	34,082	36,624	39,357	42,293	45,448	48,838	52,481	56,396	60,605	65,123	69,988	75,21	80,821	87,124
OPERATING EXPENSES																					
O&M fixed expense ($)	0	390	398	406	414	422	431	439	448	457	466	475	485	495	505	515	525	535	546	557	568
expense ($)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
($)	0	1,3	1,326	1,352	1,379	1,407	1,435	1,464	1,493	1,523	1,553	1,584	1,616	1,648	1,681	1,715	1,749	1,784	1,82	1,856	1,893
Battery replacement cost ($)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11,468
Property tax expense ($)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Insurance expense ($)	0	823	839	856	873	890	908	926	945	964	983	1,003	1,023	1,043	1,064	1,085	1,107	1,129	1,152	1,175	1,198
Net salvage value ($)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total operating expense ($)	0	2,512	2,563	2,614	2,666	2,719	2,774	2,829	2,886	2,944	3,002	3,062	3,124	3,186	3,25	3,315	3,381	3,449	3,518	3,588	15,128
Deductible expenses ($)	0	-2,512	-2,563	-2,614	-2,666	-2,719	-2,774	-2,829	-2,886	-2,944	-3,002	-3,062	-3,124	-3,186	-3,25	-3,315	-3,381	-3,449	-3,518	-3,588	-15,128
PROJECT DEBT																					
Debt balance ($)	105,245	95,434	85,471	75,353	65,079	54,645	44,05	33,29	22,364	11,268	0	0	0	0	0	0	0	0	0	0	0
Interest payment ($)	0	1,631	1,479	1,325	1,168	1,009	847	683	516	347	175	0	0	0	0	0	0	0	0	0	0
Principal payment ($)	0	9,811	9,963	10,118	10,274	10,434	10,595	10,76	10,926	11,096	11,268	0	0	0	0	0	0	0	0	0	0
Total P&I debt payment ($)	0	11,442	11,442	11,442	11,442	11,442	11,442	11,442	11,442	11,442	11,442	0	0	0	0	0	0	0	0	0	0
DIRECT CASH INCENTIVES																					
Federal IBI income ($)	14,182																				
Before-tax annual costs ($)	-45,105	-13,955	-14,005	-14,056	-14,108	-14,162	-14,216	-14,272	-14,328	-14,386	-14,445	-3,062	-3,124	-3,186	-3,25	-3,315	-3,381	-3,449	-3,518	-3,588	-15,128
Before-tax cash flow ($)	-45,105	8,24	9,78	11,503	13,357	15,353	17,501	19,81	22,296	24,971	27,848	42,385	45,714	49,295	53,146	57,29	61,741	66,54	71,692	77,233	71,996