UNIVERSITAT DE BARCELONA

A FUTURE OF DECENTRALISED ENERGY?

An investigation into the impact of battery storage technology

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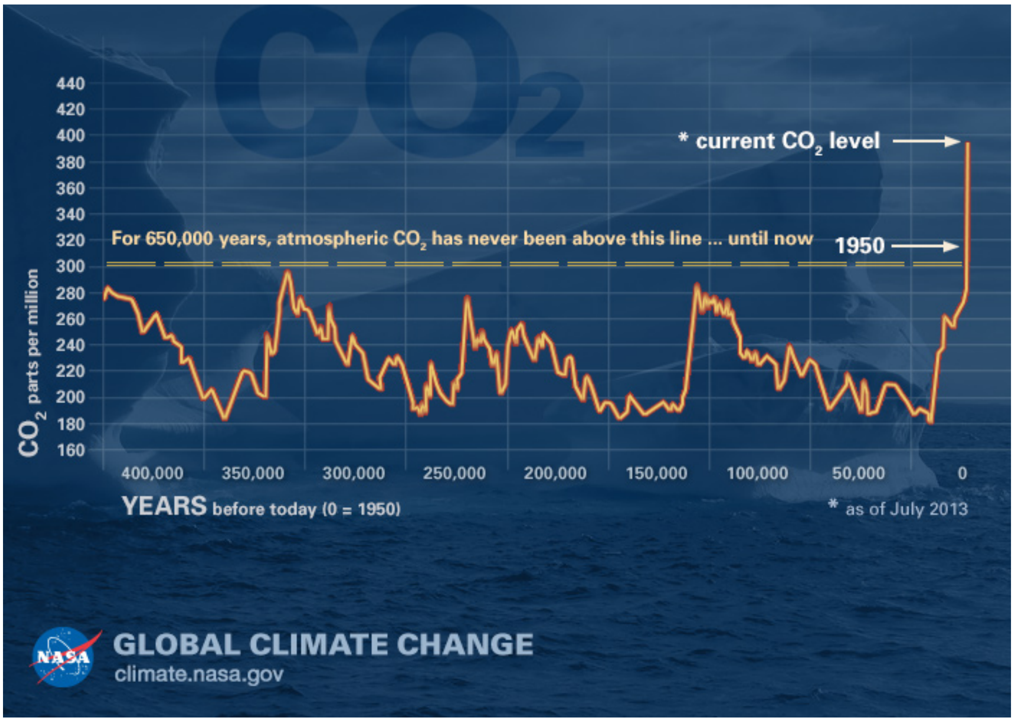
Introduction

In the second half of the 20th century scientists became increasingly aware of the effects that gases such as carbon dioxide and methane were having on the planet's environment. Initially, concerns about the warming effects of gasses were countered by suggestions that human activity could have cooling effects on the environment through the use of aerosols. However, by the 1970's scientific consensus had veered towards warming rather than cooling. In 1975, Wallace Broecker published a paper titled, *Climate Change: Are we on the Brink of a Pronounced Global Warming?* This paper is often credited with coining the term 'global warming.'

Nowadays, one is more likely to hear of 'climate change' rather than 'global warming'. Whereas 'global warming' refers simply to the earth's rising temperature, 'climate change' is a more all-encompassing concept that refers to the earth's warming *and* the side effects of that warming - melting glaciers, rising sea levels and increasing desertification for example.

The first international treaty to combat climate change was the United Nations Framework Convention on Climate Change (UNFCCC). This was negotiated at the Earth Summit in Rio de Janeiro in 1992 and came into force on the 21st of March 1994. Its objective was to stabilize the greenhouse gas concentrations in the atmosphere at a level that would, 'prevent dangerous anthropogenic interference with the climate system.'[1] This treaty was extended upon in the Kyoto Protocol by committing states to reduce greenhouse gas emissions on the premise that 1) global warming exists and 2) it has been caused by man made carbon dioxide emissions.



[1]UNITED NATIONS. (1992) United Nations Framework Convention on Climate Change [Online] Available from: https://unfccc.int/resource/docs/convkp/conveng.pdf

Figure 1: CO_2 Concentration in atmosphere[2]

Figure 1 clearly shows the effect that man has had on the level of carbon dioxide in the atmosphere. For the past 650,000 years CO_2 had never been higher than approximately 300 parts per million. At the time of writing the current level of CO_2 in the atmosphere stands at approximately 403 parts per million.[3]

The latest agreement within the framework of the UNFCCC is the Paris Agreement, which was drafted in late 2015 at the 21st Conference of Parties in Paris. The Paris Agreement is yet to enter into force, but as with previous UNFCCC agreements there are concerns regarding the lack of binding targets as well as an effective enforcement mechanism. The impact that this agreement will have on future carbon emissions remains to be seen.

Such is the concern over climate change that the Global Risks Report 2016 published by the World Economic Forum rates, 'failure of climate change mitigation and adaptation' as the greatest risk in terms of impact.[4] Climate change is linked to risks of food and water crises, profound social instability, extreme weather events, biodiversity loss and ecosystem collapse, and large-scale involuntary migration. The threats posed by the failure to mitigate the effects of climate change are severe.

Recognizing the need to provide energy, without adding to the concentrations of greenhouse gasses within the earth's atmosphere, there has been a surge in renewable energy technology during the 21st century. However, the most accessible forms of renewable energy – solar and wind have major problems regarding their reliability and stability. In other words, the failure of the sun to shine and the wind to blow 24 hours a day means that the proliferation of clean energy sources has been hindered. The intermittent nature of renewable energy is a problem that must be solved if their development is to continue. The following quote by the distinguished Czech-Canadian scientist Vaclav Smil:

'If electric utilities had an inexpensive way to store massive amounts of excess power generated by wind and solar when demand is low, which could later be tapped to meet peak demand, then the new renewables would expand much more quickly. Unfortunately, decades of development have provided only one good, large-scale solution: pumping water up to an elevated reservoir so it can flow back through a turbine to generate electricity. Not many localities have the elevation change or space to make this work, and the process

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[2] GLOBAL CLIMATE. (2015). Global Climate Change: Evidence and causes. [Online] Available from: http://globalclimate.ucr.edu/resources.html

[3] NASA. (2015). Global Climate Change: Vital signs of the planet. [Online] Available from: http://climate.nasa.gov

[4] LEVITT, T. (2016) Climate Change Fails to top List of Threats for Business Leaders at Davos. *The Guardian*. [Online] Available from: http://www.theguardian.com/sustainablebusiness/2016/jan/20/climate-change-threats-business-leaders-davos-survey

It is interesting to note that climate change was not considered to be a high concern to 1,400 CEOs from around the world. A list provided by PricewaterhouseCoopers (PwC) showed that overregulation was their greatest concern (79%), followed by geopolitical uncertainty (74%). Climate change was mentioned as a threat to business by only 50% of CEO's. Both the PwC survey and a separate survey of 13,000 business leaders carried out by the World Economic Forum (WEF) showed a relative absence of concern over climate change and environmental risk.

entails net energy loss.'[5]

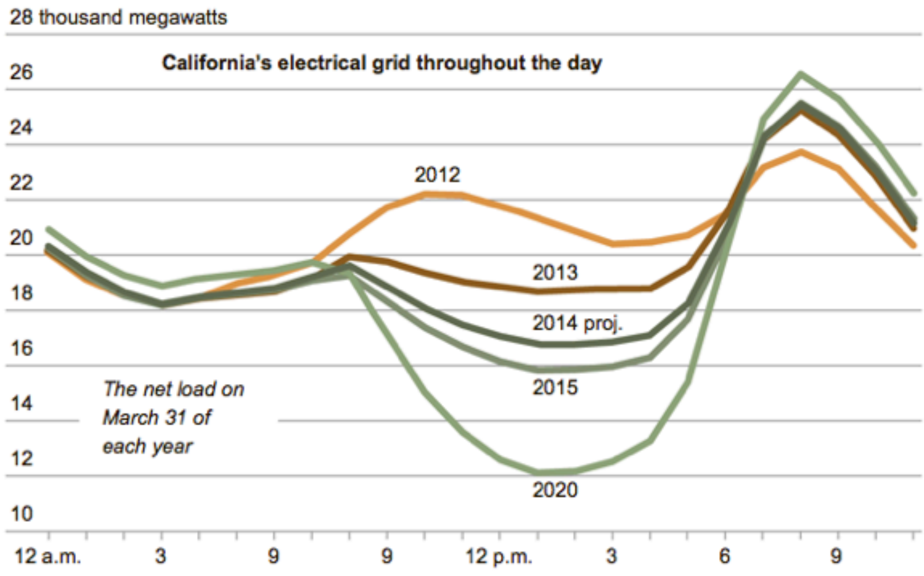
The ability to store electrical energy in a safe and economically viable manner would serve to combat the limitations that arise due to the intermittent nature of renewable energy sources. Thus, electrical storage technology could likely be a significant factor in the development of renewable energy systems and consequently a factor in climate change mitigation.

Smart grids, too, have the potential to combat the limitations of renewables. Through the use of integrated communications as well as sensing and measuring technology, system reliability can be optimized. Distributed power flow control is a noteworthy example. In this case, smart wires control the flow of power within existing transmission lines and as a result more renewable energy is supported on the grid. Arpa-E, a branch of the Department of Energy in the United States says the following on the subject:

'Smart wires could support greater use of renewable energy by providing more consistent control over how that energy is routed within the grid on a real-time basis. This would lessen the concerns surrounding the grid's inability to effectively store intermittent energy from renewables for later use.'[6]

Although of critical importance in the future of energy systems, this investigation will focus on battery storage technology rather than smart grids, with regards to their ability to utilize intermittent energy from renewables.

At present, one of the greatest challenges facing the development of solar power is the effect that it has on the daily demand for utility electric. Figure 2 below shows the net supply and demand of power on California's electric grid during a 24-hour period in 2012-13.



Source: CalISO

[5] SMIL, V. (2014) The Long Slow Rise of Solar and Wind. *Scientific American.*
[6] ARPA-E. (2011) Distributed Power Flow Control. [Online] Available from: http://arpa-e.energy.gov/?q=slick-sheet-project/distributed-power-flow-control

Figure 2: The Duck curve[7]

The above figure is commonly referred to as 'the duck curve' on account of the fact that year on year the graph represents the shape of a duck's head and body. As the amount of installed solar has increased, the demand on the grid has fallen. Before 2012 energy demand was said to resemble a camel with two humps. As one can see from the graph there were peaks in both the morning and in the early evening. This energy was mostly supplied by utility operated power plants. However, increasingly this energy has been substituted by local solar power, which by meeting local demand greatly affects the demand for energy from the grid during the day. The orange camel is transforming into a green duck.

The graph has become almost a symbolic picture of utility complaints. Utility companies regard the growth of distributed solar as a major technical problem, rather than an economic one. Of particular concern for utility companies is one part of the graph – the ramp up period in the late afternoon. This is the time period in which the energy produced from solar is decreasing while energy demand increases. According to John Farrell of Clean Technica, in traditional grid operating models, accommodating this ramp-up in energy requires, 'lots of stand by power from expensive to operate, rapid-response power plants.'[8]

As a result, there have been various suggestions attempting to 'flatten the duck'. They are listed below:

- Target energy efficiency measures for the "ramp up" period
- Orient solar panels to the west to catch more late evening sun
- Substitute some solar thermal with storage for solar PV
- Allow the grid operator more demand management via electric water heating [already done extensively by rural cooperatives in Minnesota]
- Require large new air conditioners to have two hours of thermal storage accessible to the utility
- Retire inflexible generating plants (coal and nuclear) that need to run constantly in off-peak periods
- Concentrate utility demand charges on the ramp up period
- Deploy electricity storage into targeted areas, including electric vehicle-to-grid
- Implement aggressive demand response programs (subscribing more businesses and homes into programs to shed their energy demand at key periods)
- Use inter-regional power transactions
- Selectively curtail a small portion of solar power generation

In light of this it can be suggested that the technical challenges of the 'duck problem' are manageable, in the most part with existing technology. Battery storage linked to PV systems would also be able to contribute to a solution. Excess supply stored in the day

[7] FARRELL, J. Clean Technica [Online] Available from: http://cleantechnica.com/2014/07/21/utilities-cry-fowl-over-duck-chart-and-distributed-solar-powercrying-fowl-or-crying-wolf-open-season-on-the-utilitys-solar-duck-chart/
[8] ibid.

would be able to play a part in the ramp-up period as energy demand increases in the evening as people return home from work.

It is likely that economic problems exist for utilities, and the question of to what extent their business model may be outdated is an interesting one. As more solar comes onto the grid, utility owned gas plants which meet peak load will be out bid. Furthermore, in the near future solar production will be sufficient to cut into the "baseload" power, usually provided by coal power plants, which are only economically viable operating 24 hours a day.

Thus the electricity grid is undoubtedly changing. The 20th century system of inflexible and centralised power plants with long distance transmission lines is transforming, in some cases, to distributed renewable energy. The duck graph highlights the limitations of using a 20th century grid model for a 21st century system. To utility companies the duck graph serves as evidence of the technical problems caused by the continued development or renewable energy sources. However, as we have seen it is the energy demand that is displaced by solar that represents the real problem for utilities. If an increasing number of customers seek more control over their energy consumption by moving to solar, the market share of utilities is likely to decrease. Analysis from PWC notes that the gains in renewable/distributed power systems have, 'altered the business equation sufficiently that the customer is rapidly becoming the dominant force.'[9] It is clear that the industry is undergoing a huge change as firms have traditionally led it with virtual monopolies over customers. Hence the problem facing utility companies is more economic in nature than technical. Furthermore, an abundance of renewable power changes the profitability of baseload and peaking power plants. As Farrell writes:

"Economically, an abundance of low-cost renewable energy will change the profitability of baseload and peaking power plants. Baseload power plants will suffer from a drop in wholesale electricity prices, as has happened in Germany. Fast-response power plant operators will also struggle, because while peak energy prices may remain high, more solar energy on the grid will shorten periods of peak energy demand for these power plants."[10]

Although somewhat inflexible, like coal and nuclear, renewable energy has no fuel costs and little operation costs. Therefore, in theory it should be the first power a utility company would want to use on the grid. Furthermore, though it has been suggested that 'baseload is not compatible with a renewable energy future,'[11] it is clear that quick and flexible response to electricity supply will become increasingly important in a renewable energy future. As a result, energy storage technologies may provide an important solution. It should further be noted that even if there were improvement to the grid with the use of smart grid technology, energy storage would still reduce its capacity requirements.

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[9]PWC. (2015). 2015 utilities trends. [Online] Accessed on 4/4/2015 from: http://www.strategyand.pwc.com/perspectives/2015-utilities-trends

[10] FARRELL, J. (2014) Energy Storage: The Next Charge for Distributed Energy. *The Institute for local Self-Reliance* p.6.

[11] HOPE, M. (2013). The Energiewende and energy prices: Public support and Germany's long term vision. *The Carbon Brief.* [Online] Accessed on 3/3/2015 from: http://tinyurl.commk6qnp2

Energy storage and renewables are a powerful combination that will ultimately allow for a more thorough adoption of renewable energy, something that is critical in efforts to mitigate climate change and accelerate the energy transition to sustainable sources. It is likely, although not certain, that the combination also has the added bonus of greater local control of the energy system. Thus, the 21st century dynamic offers us the possibility of a dramatically different energy future to that of the previous century: Millions of widely dispersed renewable energy plants and storage systems tied into a smart grid. The era of large and distant centralised power plants could be consigned to the past. The 21st century grid could be a democratized network of independently owned and widely dispersed renewable energy generation, with economic benefits of electricity generation dispersed as widely as the ownership.

Dr. Norbert Rottgen, the German Federal Minister for the environment, believes that the time is approaching when countries will have to make a decision on the future of their energy system:

'It is economically nonsensical to pursue two strategies at the same time, for both a centralised and decentralized energy supply system, since both strategies would involve enormous investment requirements. I am convinced that the investment in renewable energies is the more economically promising project. But we will have to make up our minds. We cant go down both paths at the same time.'[12]

The role of electrical energy storage systems, their impact, and the extent to which they are able to accelerate the transition to decentralized energy systems, is the focus of this paper.

[12] FARRELL, J. (2011). Democratizing the Electricity System. *The New Rules Project.* p. 27.

Objective

Renewable technologies have gained economic competitiveness in the recent past. This is mostly true in the case of solar energy as a result of falling PV cell costs. Despite renewable energy's increasing competitiveness it still possesses problems that hinder widespread deployment. One major obstacle is the intermittent nature of renewable energy.

This paper seeks to understand the role that battery storage technology is able to play in the dissemination of renewable energy sources and a 21st century grid system. This is principally achieved by counteracting the key disadvantage of intermittency. In order for this to be carried out, both the *technical* and *economic* aspects of electrical energy storage are to be investigated. In addition, this paper aims to show what impact the conclusions drawn from the investigation will have. The paper shows the impact of battery storage technology through several different perspectives and ultimately asks what the impact of battery storage technology will be on centralised energy systems.

This project is carried out from the perspective of Internationalisation. To internationalise is commonly defined as to put under international control or to make international in character. In economic terms Internationalisation is the process of increasing involvement of enterprises in international markets, and the spread of economic activities across national boundaries.[13]

Internationalization is evident through the increasing levels of investment in renewable energy. In order to understand the role of battery storage technology, it is necessary to understand the current trends in renewable energy finance. Renewable energy has undergone sizable changes in the recent past and before investigating the technical aspects of energy storage technologies, it is important to understand what key developments there have been in the recent past. This is done in an effort to contextualize the issue of battery storage, and to understand how it has become such a critical issue for the continued development of renewable energy sources. Consequently, a minor objective of the paper is to understand recent trends in the development of renewable energy sources.

Once the recent trends have been understood chapter one will focus on the *technical* aspects of battery storage technology. The various battery storage technologies that currently exist will be compared and the various different applications for these technologies will be investigated.

Chapter two investigates battery storage technology specifically and will have an *economic* rather than technical focus. The current status and the economic viability of the technology are understood, and its future hypothesized. This part of the paper also seeks to understand the obstacles that battery storage technology faces.

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[13] GEREFFI et al. (2001). Introduction, Globalisation, Value Chains and Development. *Institute of Development Studies.* [Online] Accessed on 3/3/2015 from: https://www.ids.ac.uk/files/dmfile/gereffietal323.pdf

Chapter three aims to assess the impact of battery storage technology. This is to be achieved by evaluating its impact from several different perspectives: Internationalization – how will the conclusions drawn from parts one and two affect states and the large energy corporations? Environmental – what is the environmental cost of energy storage solutions? Public – To what extent is the public accepting of energy storage and the consequences of its integration in the energy system?

Finally, the conclusion will sum up the findings of the paper, offer avenues for further research and suggest limitations of the paper.

Methodology

The methodology of the paper will begin with the collection of relevant information. Fundamentally, this investigation is one into the future of energy systems and the role that energy storage technology will play in their future. Thus although the paper is principally concerned with battery storage technology, it is also important to understand the problems that renewable energy faces. Firstly, an explorative investigation into problems faced by renewable energy is important. These issues have been discussed in the introduction and serve as the foundation for investigation into storage technology.

'Trends in energy finance' will show recent developments in the price of solar PV panels and the impact that it has had on the adoption of renewable technology.

Documents, peer-reviewed papers and data that relates to storage technology energy will be collected and investigated in order to have a complete understanding of the technology and its applications. This serves as Chapter one and technical in its approach.

To effectively carry out part two of the investigation, which focuses on the economics of battery storage technology several steps are necessary. Firstly, the economics are investigated at a micro level, in an effort to understand whether or not investment in residential battery systems is economically viable. Other parts of the chapter seek to understand the price development of lithium-ion technology and its impact on various associated markets.

The final part of the investigation will use a wide range of documents in order to assess the impact of battery storage from different perspectives. Documents from the European Commission, will have relevance while scientific papers will be necessary in understanding the impact that batteries have on the environment.

Trends in Energy Finance

Since 2004 China has greatly increased investment in the various parts of the solar manufacturing value chain: poly-silicon feedstock, wafers, cells and modules. In 2008 Chinese firms began reaping large benefits from economies of scale in the production of purified silicon. According to Fischer, until that point soaring global prices due to an oligopolistic market structure had hampered the expansion of the sector in China.[14] By June of 2008 the country had over 700 PV manufacturing companies,[15] and by this time China had become the largest PV manufacturer in the world with 98% of its product shipped overseas.[16]

By 2009 the Chinese government had recognized solar manufacturing as a strategic industry. Attempts were made to speed up the growth of the industry, 'principally through a combination of low-cost debt and subsidy.'[17] In the following year four of the top 10 solar PV manufacturers in the world were Chinese.[18]

During the financial crisis during 2008-09 the pace of PV installations in Europe slowed. In response, China stimulated domestic demand for their manufactured solar products. As the table below shows, Chinese annual solar installation increased over 100 times during the period from 2007 to 2012. What is noticeable from the data is how the annual installations in China are much lower than the annual output of the country. As Puttaswamy and Sahil Ali note, 'Chinese solar manufacturing policy was driven by its export potential rather than concerns about supporting domestic deployment, which were satisfied by default.'[19]

	2004	2005	2006	2007	2008	2009	2010	2011	2012
Annual output of PV cells (MWp)	50	200	370	1,087	2,589	4,676	13,018	20,000	23,000
Share of global cell production (%)	4.0	11.0	14.6	27.2	32.9	37.6	47.8	57.3	71.4
Annual PV installations in China (MW)	10	8.9	10	20	40	210	559	2200	3,567

Table 1: Evolution of Chinese PV cell production[20]

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[14] PEGELS. A. (Ed.). (2014). *Green Industrial Policy in Emerging Countries.* [Online] Accessed on 3/3/2015 from: https://books.google.co.in/books?id=C4n8AgAAQBAJ&pg=PA77&lpg=PA77&dq=evolution+of+china%25+27s+solar+PV+manufacturing+industry&source=bl&ots=l5o1-LSY2O&hl=en&sa=X&ei=NpAFVLeXNs248gWR7ILQCg#v=onepage&q=evolutio%2C%202014.&f=false
[15] PAN, J., MA, H. and ZHANG, Y. (2011). Green Economy and Green Jobs in China. *WorldWatch Institute.* [Online] Accessed on 3/3/2015 from: http://www.worldwatch.org/system/files/185%20Green%20China.pdf
[16] SEMI. China Market Growth Fuelled by Government Spending During Industry Downturn [Online] Accessed on 3/3/2015 from: http://www.semi.org/en/MarketInfo/ctr_027596
[17] PUTTASWAMY, N and SAHIL ALI, M. (2015). How Did China Become the Largest Solar PV Manufacturing Country? *Step.* p.2.
[18] PAN, J., MA, H. and ZHANG, Y. (2011) Green Economy and Green Jobs in China. *WorldWatch Institute.* [Online] Accessed on 3/3/2015 from: http://www.worldwatch.org/system/files/185%20Green%20China.pdf
[19] PUTTASWAMY, N and SAHIL ALI, M. (2015). How Did China Become the Largest Solar PV Manufacturing Country? *Step.* p.2.
[20] ibid.

As Table 1 shows, during the time of the financial crisis China was improving its position in the export markets. In 2004 the country produced 50 MWp of PV cells, a fifth of which were installed domestically. This output only represented 4% of the total global cell production at that time. Over the following 8 years the output of PV increased year-on-year. In 2012 the total output had reached 23,000 MWp and the share of the global cell production had risen to 71.4%.

Since 2004 the prices of PV cells have fallen significantly. That said, there is an element of debate as to why this has been the case. Regarding the total cost of production, the material input constitutes a high percentage. A report by the International Trade Centre found 75% of a Chinese solar PV manufacturer's total cost of production was spent on material inputs.[21] Although this study did not examine a wide range of manufacturers, their findings would suggest that if the necessary materials were to decrease in price, then it would affect the price of solar PV cells.

In 2010 the global production of solar PV cells was 20.5 GW and the prices of components had fallen from $4.5/Watt in 2000, down to $1.7/Watt.[22] Figure 3 below shows the development in recent years of the price of imported and domestic polysilicon in china. This is significant, as polysilicon is the first step in the silicon photovoltaic value chain. (Figure 4).

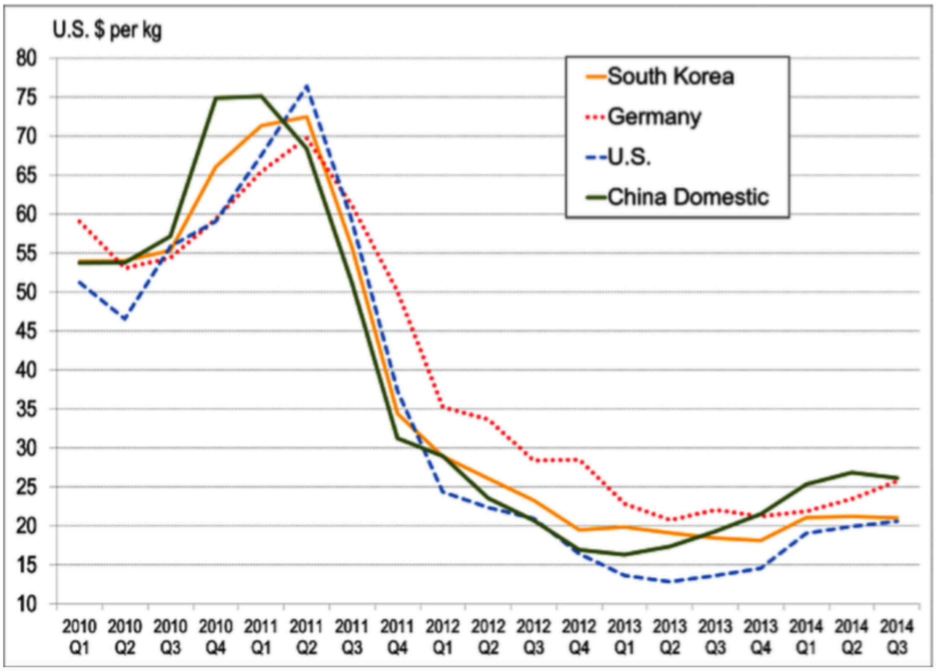

Figure 3: Evolution of polysilicon prices[23]

[21] International Trade Centre. (2015). Services in global value chains: Solar panel manufacturing in China p.vii.
[22] ibid.
[23] FU, R., JAMES, T., WOODHOUSE, M. (2015). Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness. IEEE Journal of Photovoltaics. Vol.5.No.2. p.516.

Figure 4: Silicon photovoltaic value chain

It cannot be ignored that as 75% of the company's total production costs are input costs, the strong decline in prices after 2010 is likely to have significantly affected the price of the solar PV cells produced. IRENA, the International Renewable Energy Agency, calculated that polysilicon prices accounted for 45% of the reduction of solar PV modules from Q4 2010 to Q4 2012, while other material costs accounted for 19%.[24] Therefore, in 2008, when the first Chinese firms had mastered the technologies needed for the large-scale production of purified silicon, the Chinese solar PV industry grew rapidly. Although China was already the largest PV manufacturer in the world in 2008, it was after this technological breakthrough that investment in the production of purified silicon rose sharply.[25]

The increased production contributed to a 'glut' in supply that led to further declines in prices. Puttaswamy and Sahil Ali note that the decline in prices cannot be attributed to productivity gains alone, but rather to a supply-demand mismatch.[26]

The financial crisis did not prove to be damaging to manufacturing. In fact, it is suggested by Pegels that many installers, particularly in Europe and the USA, actually became more interested in the cheaper products from china. She cites the European anticipation of further adjustments to feed-in-tariffs (FITs) as a reason.[27] Estimates vary, but at end of 2012, the worldwide annual solar PV installed capacity had reached about 31-36 GW, while global production capacity was at least 60 GW, of which China alone constituted 40-55 GW.[28][29]

IRENA notes that in 2012, all-time-low prices of solar PV modules "overshot" the expected learning curve which was the result of there being 'significant overcapacity in module manufacturing and cut-throat competition.'[30] Figure 5 shows how far below the learning curve the prices of PV modules have been since 2012, with a learning rate of 18-22%.

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[24] IRENA. (2015). Renewable Power Generation Costs in 2014. p 82.
[25] PUTTASWAMY, N and SAHIL ALI, M. (2015). How Did China Become the Largest Solar PV Manufacturing Country? *Step*.
[26] ibid.
[27] PEGELS, A. *Green Industrial Policy in Emerging Countries.* [Online] Accessed on 4/3/2015 from: https://books.google.co.in/books?id=C4n8AgAAQBAJ&pg=PA77&lpg=PA77&dq=evolution+of+china%25+27s+solar+PV+manufacturing+industry&source=bl&ots=l5o1-LSY2O&hl=en&sa=X&ei=NpAFVLeXNs248gWR7ILQCg#v=onepage&q=evolutio%2C%202014.&f=false
[28]PUTTASWAMY, N and SAHIL ALI, M. (2015). How Did China Become the Largest Solar PV Manufacturing Country? *Step*. p.2.
[29] EUROPEAN COMISSION. Memo : EU imposes provisional anti-dumping duties on Chinese solar panels [Online] Accessed on 4/4/2015 from: http://europa.eu/rapid/press-release_MEMO-13-497_en.htm
[30] IRENA. (2015). Renewable Power Generation Costs in 2014. p 82.

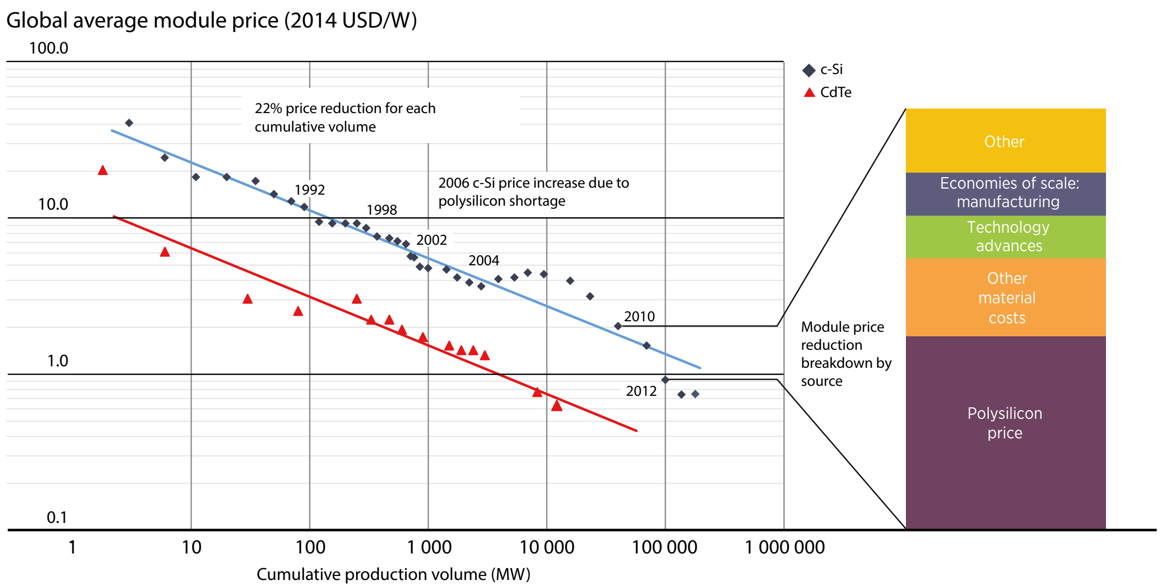

Figure 5: Global average module price[31]

It should be mentioned that both the United States and the European Union have applied anti-dumping measures against Chinese manufacturers. Consequently, profits for Chinese firms moved from 30% to less than 10%.[32] In 2012 the EU commission imposed an anti-dumping duty to be set at an average of 47%.[33] Chinese exporters also had to accept quantitative restrictions on imports. Puttaswamy and Sahil Ali believe that that the oversupply and the ensuing price war are also factors that have contributed to China's emergence as a solar manufacturing giant, as even when solar panels have continued to fall the solar manufacturers did not suffer losses. Conversely in Europe, the EU Commission calculated that between 2009 - July 2012, about 40 EU producers declared insolvency, 6 stopped production, 2 quit the solar business and 4 were taken over by Chinese investors.[34]

In addition to supply-demand asymmetries, China has become the world's dominant manufacturer of solar panels due to economies of scale. China is traditionally seen as having absolute advantage in labour costs in the manufacturing industry, when compared with industrial economies.[35] However, Chandler notes the following:

'While China does indeed have a small advantage in labour costs... that has relatively little impact on prices because solar-panel manufacturing is highly automated. The lower cost of labour in China provides an advantage of 7 cents per watt, relative to a factory in the

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[31] ibid.
[32] PEGELS, A. *Green Industrial Policy in Emerging Countries.* [Online] Accessed on 4/3/2015 from: https://books.google.co.in/books?id=C4n8AgAAQBAJ&pg=PA77&lpg=PA77&dq=evolution+of+china%25+27s+solar+PV+manufacturing+industry&source=bl&ots=l5o1-LSY2O&hl=en&sa=X&ei=NpAFVLeXNs248gWR7ILQCg#v=onepage&q=evolutio%2C%202014.&f=false
[33]EUROPEAN COMISSION. Memo : EU imposes provisional anti-dumping duties on Chinese solar panels [Online] Accessed on 4/4/2015 from: http://europa.eu/rapid/press-release_MEMO-13-497_en.htm
[34] ibid.
[35] PEGELS, A. *Green Industrial Policy in Emerging Countries.* [Online] Accessed on 4/3/2015 from: https://books.google.co.in/books?id=C4n8AgAAQBAJ&pg=PA77&lpg=PA77&dq=evolution+of+china%25+27s+solar+PV+manufacturing+industry&source=bl&ots=l5o1-LSY2O&hl=en&sa=X&ei=NpAFVLeXNs248gWR7ILQCg#v=onepage&q=evolutio%2C%202014.&f=false

United States, but that amount is countered by other country-specific factors, such as higher inflation.'[36]

Rather it is the fact that a typical Chinese PV factory is four times larger than those in the US. It is this that makes a critical difference as economies can be found in other ways, such as by negotiating better contracts with clients and more effective use of equipment.

Of further consideration is the efficiency of silicon PV modules. Not only are they the most efficient technology, but they have also enjoyed the greatest rise in efficiency from 15% in 2003, to 21% in 2012.[37] With solar PV modules, as their efficiency increases less surface area is required to make a module of a certain wattage, thus the price per kWh is reduced. Efficiency improvements reduce the Levelized Cost of Energy (LCOE) of solar PV. Analysis by Lazard found that the LCOE of rooftop solar PV was expected to decline in the coming years. This is expected to be a result of more efficient installation techniques, lower costs of capital and improved supply chains.[38]During the period 2010-2014 the global average for utility-scale solar PV is estimated to have declined by around half. Moving from $0.32/kWh to 0.16/kWh.[39]

The combination of the various factors outlined above has increased Chinese production of solar PV technology and has made the technology itself increasingly economically attractive. Swanson's Law is the observation that the price of PV modules tends to decrease 20% for every doubling of cumulative shipped volume. The method used is more commonly referred to as a learning curve. Figure 6 shows the Swanson effect over an extended period of time. Figure 7 shows the development of global PV production.

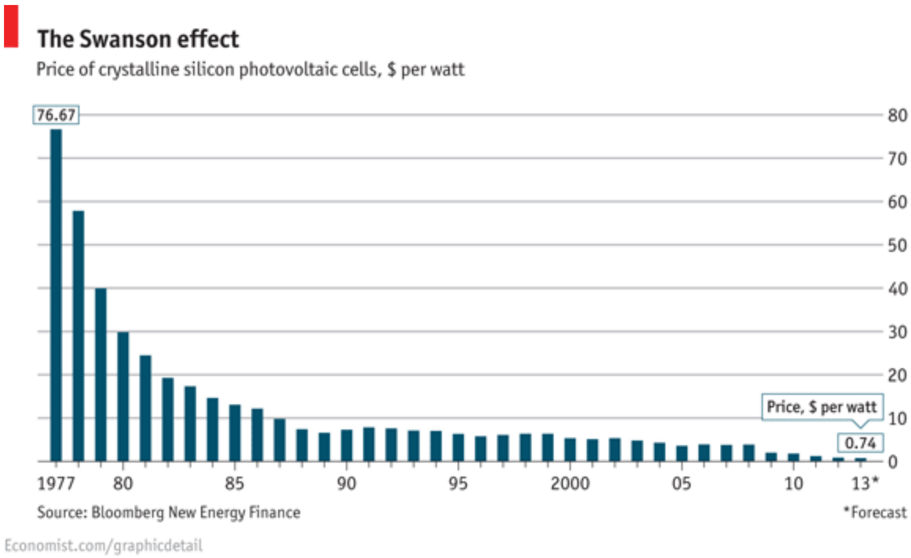

Figure 6: Evolution PV price ($/Watt)[40]

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[36]MIT NEWS. (2013). Solar-cell manufacturing costs: innovation could level the field. [Online] Accessed on 5/3/2015 from: http://news.mit.edu/2013/solar-cell-manufacturing-costs-0905
[37] IRENA. (2015). Renewable Power Generation Costs in 2014. p 83.
[38] LAZARD. (2015). Lazard Levelized Cost of Energy Analysis 9.0 – Key findings. p.1.
[39] IRENA. (2015). Renewable Power Generation Costs in 2014. p 94.
[40] ECONOMIST. (2012). Pricing Sunshine. [Online] Accessed on 5/3/2015 from: http://www.economist.com/blogs/graphicdetail/2012/12/daily-chart-19

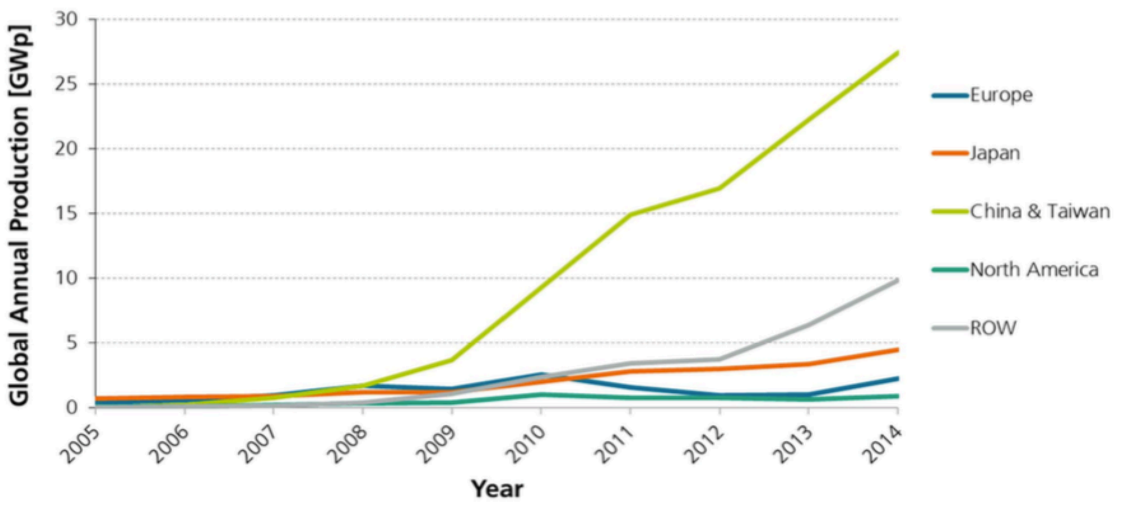
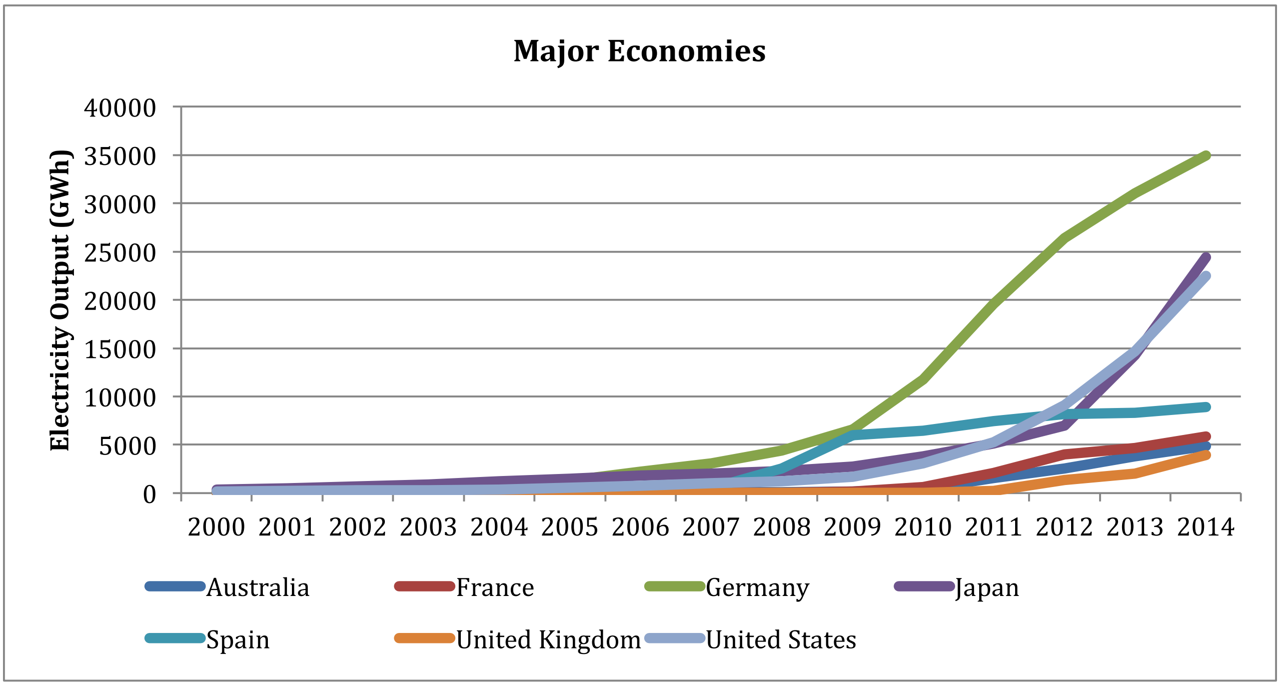


Figure 7: Global Annual PV Production[41]

As evident from figure 6 the price of silicon PV cells has fallen from $76.67 in the late 1970's to just $0.74 in 2013. According to energytrend.com at the time of writing the average current cost of a Chinese Multi-Si Cell stands at $0.32. This dramatic fall in prices is responsible for solar PV installations becoming increasingly economically viable.

Figures 8 and 9 show the increasing amount of electricity from solar PV installations.



[41] WARMUTH, W. (2016). Photovoltaics Report. Fraunhofer Institute for Solar Energy Systems ISE. [Online] Available from https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Figure 8: Electricity Output (GWh) from Solar PV Installations in Major Economies[42]

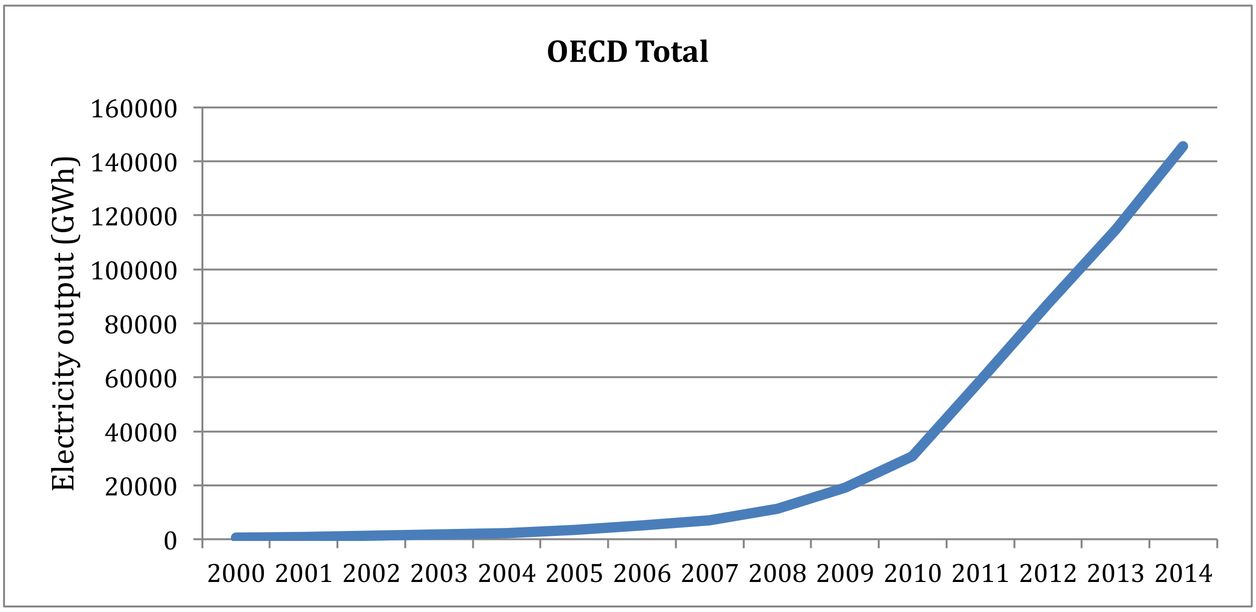


Figure 9: Electricity Output (GWh) from Solar PV installations in OECD countries[43]

Both figures 8 and 9 show that electricity output has risen dramatically in many countries over the past seven to eight years. When figure 9 is compared with figure 7, it is evident that increased global annual production has resulted in increased electricity output from solar PV installations. Although this is a fairly straightforward conclusion, it may be noted that figure 9 shows an accelerated level of electricity output since 2010. Furthermore, figure 8 shows that while Germany's increasing electricity output from solar PV has slowed slightly, the country remains significantly ahead of other major economies. The UK, Spain, France and Australia enjoy very modest growth of electricity output whereas the United States and Japan have experienced accelerated levels of growth in recent years. Due to Germany's slow down, both the United States and Japan appear on course to overtake it. The reason for Germany's position is due to its *Energiewende.* This is the German word for transition of the country to an energy mix dominated by renewable sources of energy that has been in place since the German Renewable Energy Act of 2000.

It is likely that these levels of growth will continue as in 2015 renewables continued to break records. According to Bloomberg New Energy Finance, new investment in clean energy reached $329Bn in 2015, breaking the previous record of $318Bn set in 2011. 2015 also set a new record in the amount of capacity added – 121GW.[44]

These figures can be regarded as very positive, especially when one considers how the price of oil, coal and gas have evolved since mid-2014.[45] Despite this, the figures mask the truth about European investment in clean energy. In 2015 European investment

[42] INTERNATIONAL ENERGY AGENCY. [Online] Accessed on 8/3/2015 from: http://wds.iea.org/WDS/Common/Login/login.aspx
[43] ibid.
[44] BLOOMBERG NEW ENERGY FINANCE. (2016) Clean Energy Investment: Q4 2015.
[45] Brent oil traded at $114 in June 2014 and at the time of writing stands at below $40.

only accounted for $72Bn of the total $329Bn, its lowest investment in clean energy since 2006. As investment from the Americas has remained relatively consistent in the past six years, (fluctuating in a range of $66Bn-$85Bn), Europe has been supplanted by Asia, and in particular China, as the major driving force for renewables. Chinese spending on renewable energy infrastructure reached $111Bn in 2015, a 17% increase from the previous year and almost as much as the United States and Europe combined.

Perhaps the most significant trend in renewable energy finance is the fact that the world is now adding more capacity for renewable sources than for coal, oil and gas combined. This was first realized in 2013 when the 143GW of renewable capacity was added and 141GW of capacity from fossil fuel sources. Bloomberg New Energy Finance stated in its New Energy Outlook 2015 publication the following:

'By 2040, the world's power-generating capacity mix will have transformed: from today's system composed of two-thirds fossil fuels to one with 56% from zero-emission energy sources. Renewables will command just under 60% of the 9,786GW of new generating capacity installed over the next 25 years, and two-thirds of the $12.2 trillion of investment.'[46]

In light of the evidence presented in this section, it is clear that a seismic shift towards renewable energy is already underway. Let us now turn our attention to battery storage technologies and their applications.

[46] Bloomberg New Energy Finance. (2015). New Energy Outlook 2015.

Chapter 1: Technical Aspects of Battery Storage Technologies

As stated, chapter one aims to provide a comprehensive overview of the different types of battery storage. It further aims to show various technical applications of battery storage technology in combination with renewable energy. This is in order to show the services that it is able to perform on the electricity system.

As noted in a 2015 report by the International Renewable Energy Agency (IRENA), 'Energy storage consists of a suite of technologies at various stages of development.'[47] On the opposite ends of the spectrum are pumped hydropower and battery storage. The former represents 99% of the storage in use and is economically and technically proven throughout the world.[48] The latter on the other hand, is new market development. Despite the limited current deployment of battery storage, it is critical for the purpose of this investigation that its various technical aspects are understood.

Battery Storage Technologies

The invention of the battery is accredited to Alessandro Volta, an Italian physicist and chemist who in 1799 invented the first operational battery. His voltaic pile, which consisted of coins of copper and zinc separated by cardboard soaked in saltwater, was not rechargeable. It wasn't until 60 years later that the French physicist Gaston Planté invented the world's first rechargeable battery.[49] The type of battery invented was a lead-acid battery and even though the concept is over 150 years old the battery is still known for its cost effectiveness today. In this section lead-acid, lithium-ion as well as other battery types will be investigated.

Lead-acid

According to IRENA, lead-acid batteries are already extensively deployed to support renewable development.[50] An example of this is that fact that between 1995-2009 Morocco deployed approximately 50,000 solar home systems coupled to batteries in order to provide rural electrification, while in Bangladesh there are 3.5 million solar home systems, each coupled to a battery. Typically, they are found in transport vehicles.

Pros

- Easy and cheap to produce
- Mature technology (150 years of development)
- High surge to weigh ratio (making them suitable for vehicles)
- Easy to recycle

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[47] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook
[48] ibid.
[49] EUROPEAN COMMISSION. DG ENER Working Paper: The future role and challenges of Energy Storage.
[50] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. P.41.

Cons

- large and heavy
- Short lifespan
- Environmental concerns (Lead is a highly toxic element)
- Corrosion (chemical reactions)

In addition to the cons outlined, many lead-acid batteries can suffer from low Depth of Discharge, (the amount of the battery's capacity that has been utilized and expressed as a percentage of the battery's full energy capacity). This can be lower than 20%.[51] The batteries can also have low cycle numbers (<500) and a limited lifetime of 3-4 years. Their energy density is 50Wh/kg.

Research by Garcia has shown that more recent versions of the technology can achieve 2,800 cycles at a Depth of Discharge of 50%, insuring a service life of up to 17 years for industrial systems.[52] Of final consideration is that ambient temperature may affect battery performance. This is due to the fact that high temperatures can cause internal reactions to occur, thus many batteries can lose capacity in hotter climates. Conversely, in very cold climates reactions may be slow and could even stop altogether. Lead-acid consequently, is a battery technology that 'may require integrated temperature management in the battery installation for optimal performance and safety.'[53]

Oberhofer, writing on behalf of the Global Energy Network Institute (GENI), expresses the belief that lead-acid battery technology has reached an end point in terms of its development. He writes, 'It is clear that no significant improvements can be made in capacity, density or weight. Therefore, resources on future development should concentrate on other battery technologies with higher potentials.'[54] Although their cost effectiveness has made them an important part of many technology systems, Oberhofer notes that the batteries are unlikely to make an impact on grid storage, He writes:

'These batteries are not capable of storing huge amount of energy compared to other systems like a Pumped Storage Hydroelectricity plant (PSH), while staying cost effective as the energy density is just too low. It is possible to integrate battery banks for few smaller decentralized systems (like photovoltaic [PV] systems on rooftops); but, it cant be used as a definite solution, just for the simple reason that the amount of resources are not available for the required capacity scale.'[55]

Despite this criticism it is important to note that 'Advanced lead-acid' batteries also exist. The "Ultrabattery", developed by the Commonwealth Scientific and Industrial Research Organization of Australia, uses an ultracapacitor that enables the battery to operate longer and more effectively in partial state of charge applications than

[51] ibid.
[52] GARCIA, R.A. (2013). *Off-Grid Commercial Micro-grid System Provides Energy Storage for Resort in India.* Trojan Battery Company. Intersolar Europe, Munich.
[53] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.7.
[54] OBERHOFER, A. (2012). Energy Storage Technologies & Their Role in Renewable Regeneration. Global Energy Network Institute. p.12.
[55] ibid.

traditional lead acid batteries.[56] This battery has been tested for hybrid vehicles but has also been proposed and demonstrated for power sector applications such as frequency response and smoothing.[57] Investigation into the applications of battery storage will follow shortly.

Lithium-ion

Due to the fact that Lithium is the lightest metal lithium-ion batteries have a high energy density. In addition, they also possess a high power density (the rate at which energy changes) when compared to other batteries. The combination of these two characteristics allows them to take up a minimum of physical space while providing high levels of power (kW) and energy (kWh). Furthermore, their performance, both in terms of energy and power, continues to improve. This is one reason why they are so popular in consumer electronic and power sector applications.[58]

Pros

- Highly efficient (typically 80-90%)
- High power (typically 3.7V compared to 2.0V for lead acid)
- High energy density
- Low energy loss
- Materials available in large amounts (lithium, available in seawater and obtainable through technical methods and graphite)

Cons

- Expensive
- Cells can become damaged with complete discharges
- Deteriorate if unused
- Safety concerns

The combination of high power and energy density make lithium-ion batteries an ideal technology for frequency regulation and other applications that require a relatively short discharge and high power performance. According to IRENA, one of the greatest obstacles facing the technology is safety: Lithium is highly reactive element and is combustible. This combined with the high energy density of the cells mean that they can overheat and catch fire.[59] Although safety is an obstacle to be overcome, their costs too hinder the application of the technology. Part two will show the development in prices. This will be of importance because as Oberhofer notes, 'lithium-ion batteries have an incredibly huge potential.'[60]

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[56] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.42.
[57] ibid.
[58] ibid.p.43
[59] ibid.p.43. This can lead to a situation known as thermal runaway when neighbouring cells also overheat. This leads to leaks, smoke, gas venting and/or the cell pack coming alight.
[60] OBERHOFER, A. (2012). Energy Storage Technologies & Their Role in Renewable Regeneration. Global Energy Network Institute. p.14.

Currently there are various companies that are seeking to realize this potential. They include:

- IBM – The Battery 500 Project
- Tesla – Powerwall and cars (Roadster, Model S, X and 3)
- Panesonic – Energy logic system
- Sonnen – SonnenBatterie
- Redback Technologies – Ouija Board
- Arpa-E[61]

Flow Batteries

Flow batteries are similar to other types except that the electrolytes can be exchanged. This means that as the battery is discharged the fluids are replaced with loaded ones. This makes them less affected by overcharge or discharge and means that they can be used without a significant degradation of performance. It is relatively easy to add capacity to them, as their power is a function of the number of cells that are stacked.[62] They enjoy a long life span but their major limitation is regarding their energy density, which at around 35 Wh/Kg is of a similar level to lead-acid batteries. Although worth mentioning, flow batteries will not be explored within this paper.

Sodium/Molten Salt

Sodium batteries are a further technology under development, but they are already operational in some countries. NGK of Japan has made sodium batteries for grid storage for a number of years and approximately 250MW of the batteries have been installed within the country.[63] The technology possesses several advantages: They have a high energy density (240 Wh/kg), a long life span of 10-15 years and a high efficiency rating. The batteries contain no rare elements and are fully recyclable

Their major limitation however, is that they typically need to be operated at temperatures approaching 350^{o}C in order for the sodium to be liquid. This makes them difficult and expensive to operate but most of all dangerous as liquid sodium reacts easily with water in the atmosphere.[64]

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[61] Arpa-E is technically a branch of the US Department of Energy. It was founded in 2009 under Obamas economic recovery plan to fund early stage research into the generation and storage of energy. Projects are said to rely on materials 'beyond current lithium-ion batteries.' GUARDIAN [Online] Accessed on 4/3/2015 from: http://www.theguardian.com/environment/2016/mar/03/us-agency-says-has-beaten-elon-musk-gates-to-holy-grail-battery-storage

[62] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.44.

[63] GREENTECHMEDIA. (2011). Is Sodium the Future Formula for Energy Storage? [Online] Accessed on 4/3/2015 from: http://www.greentechmedia.com/articles/read/is-sodium-the-future-formula-for-energy-storage

[64] OBERHOFER, A. (2012). Energy Storage Technologies & Their Role in Renewable Regeneration. Global Energy Network Institute. p.16.

Summary table of key factors

	Lead Acid	**Advanced Lead**	**Lithium-ion**	**Sodium - Sulphur**	**Flow**
Power Range (MW)	1 - 50	1 - 50	<100	5 - 100	1 - 100
Storage Duration	2 - 4h	1min - 8h	1min - 8h	1min - 8h	1 - 5h
Energy Density (Wh/kg)	30-40	50	110 - 160	240	35
Cycles	1,000 - 5,000	4,500 - 10,000	500-1000+	2,500 - 4,500	>10,000
Operating life (years)	3 - 15	5 - 15	5 - 15	5 - 15	15 - 20
Price per kWh ($)	50-140	140+	240 - 2,200	400	N/A
Efficiency %	70 - 90	90 - 94	85 - 98	80 - 90	65 - 85
Response time	< Seconds	< Seconds	< Seconds	< Seconds	< Seconds

Source: IRENA.

Applications of battery storage technology

It is unquestionable that battery storage in the power sector can be deployed in a variety of ways and over multiple time periods. A 2013 report by EPRI and DOE describe 14 services under 5 umbrella groups that can be provided by energy storage.[65] Below is a summary of the groups:

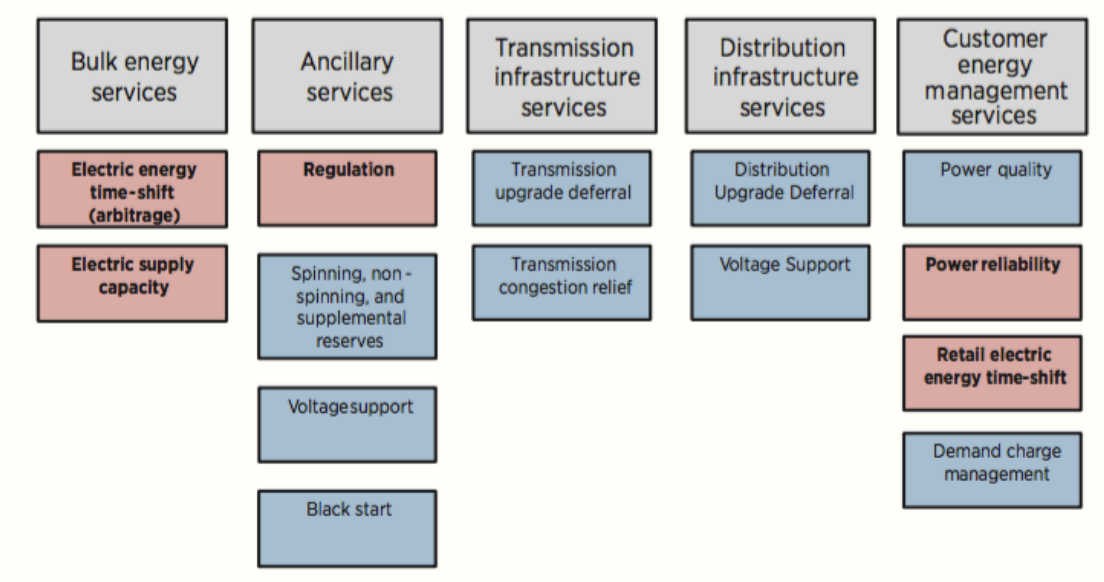


Figure 10: Services provided by energy storage[66]

Within this section, four application areas will be discussed that are most directly related to solar PV power integration. As shown in figure 7 in 'Trends in Energy Finance', the electricity output from solar PV installations has risen sharply since 2010 and is forecasted to increase in the future. Through this approach the services that are

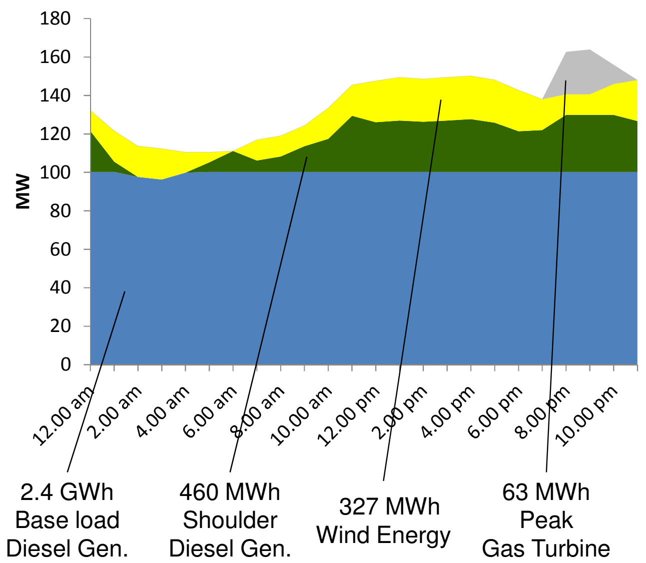
[65] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.11.
[66] ibid.

highlighted in red above will be focused upon. Specifically, and in line with the objective of this investigation, the applications compensate for the variable nature of renewable energy. It is also important to note that a single battery installation is able to serve multiple uses. As noted by IRENA, 'a combination of value streams may benefit the economics of an installation.'[67]

Battery Storage – Islands and off-grid applications

Many islands and off-grid areas use diesel generators as sources of power. The location is usually remote and the lack of infrastructure means that diesel imports are often costly. In addition to being expensive, this type of electrification has high levels of emissions and has problems regarding security of supply. Despite these issues, diesel has traditionally been used as the 'most accessible and cost effective solution.'[68]

Many islands have a lack of flexible sources and as a result would benefit from the application of battery storage, as it would help to reliably integrate significant amounts of renewable energy from solar or wind and thereby reduce the reliance on diesel or gas generation. Figures 11 and 12 below show the increased integration of renewable energy when combining utility scale wind, diesel powered electricity generation and lead-acid batteries.



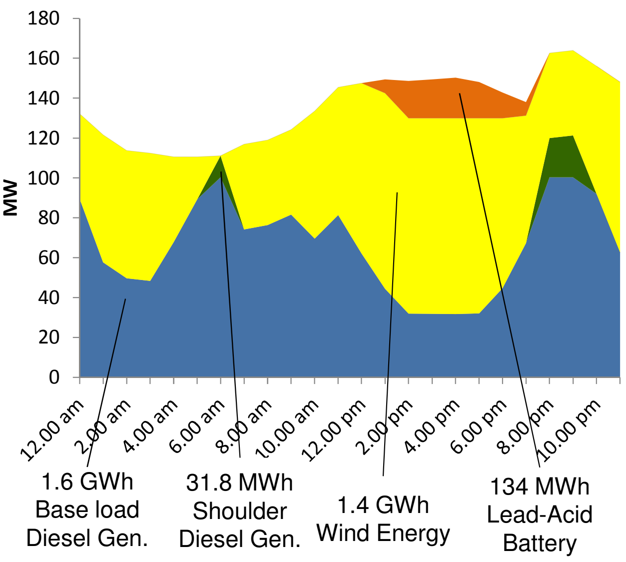


Figure 11 (left): no energy storage

Figure 12 (right): with lead-acid battery storage.[69]

The two figures demonstrate the ability of battery storage to increase the penetration of renewable energy and decrease both diesel and peak gas use. In figure 11, renewable

[67] ibid.
[68] ibid. p.12.
[69] BALZA, L. *et al.* (2014), *Potential for Energy Storage in Combination with Renewable Energy in Latin America and the Caribbean,* Inter America Development bank

energy from wind contributes to the peak demand. Its penetration however, is restricted by ‘the inability to exceed 15% of demand at any given time.’[70] Balza et al. assume this to be the maximum renewable penetration without storage and consequently believe there to be significant unrealized benefits to the scenario.

Their model determines that the electricity grid should integrate a 75.6MWh lead-acid battery system. Figure 12 shows the impact that combining renewable energy with battery storage would have on the daily load profile of the island. (The island under consideration is Barbados).

The use of battery storage was able to increase the amount of renewable energy used daily by 1GWh and reduces carbon dioxide emissions by 1,423 tones daily.[71] This would mean that emissions of over half a million tones of CO_2 would be avoided every year through the incorporation of a 75.6MWh battery system. The expensive peak generation would be displaced by lower cost renewable energy and storage, while the base load would also be replaced. It is important to note that there is a point at which it becomes too expensive for more storage to replace shoulder and base load capacity. As Belza et al. write, ‘for that reason, the model does not determine that lower cost renewable energy should replace all generation.’[72]

In summary the scenario encompasses all of the services highlighted in red in figure 10. It is an economically viable option for achieving much greater utilization of renewable energy by displacing diesel and gas generation.

Household solar PV

Battery storage at a household level represents perhaps one the most interesting avenues of investigation. This is principally because it allows for a far greater level of self-consumption of electricity produced by solar PV. Battery storage has the ability to align the electricity demand of the user with solar production. It also has the added benefit of relieving local grid capacity constraints.[73]

[70] ibid.
[71] ibid.
[72] ibid.
[73] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.14.

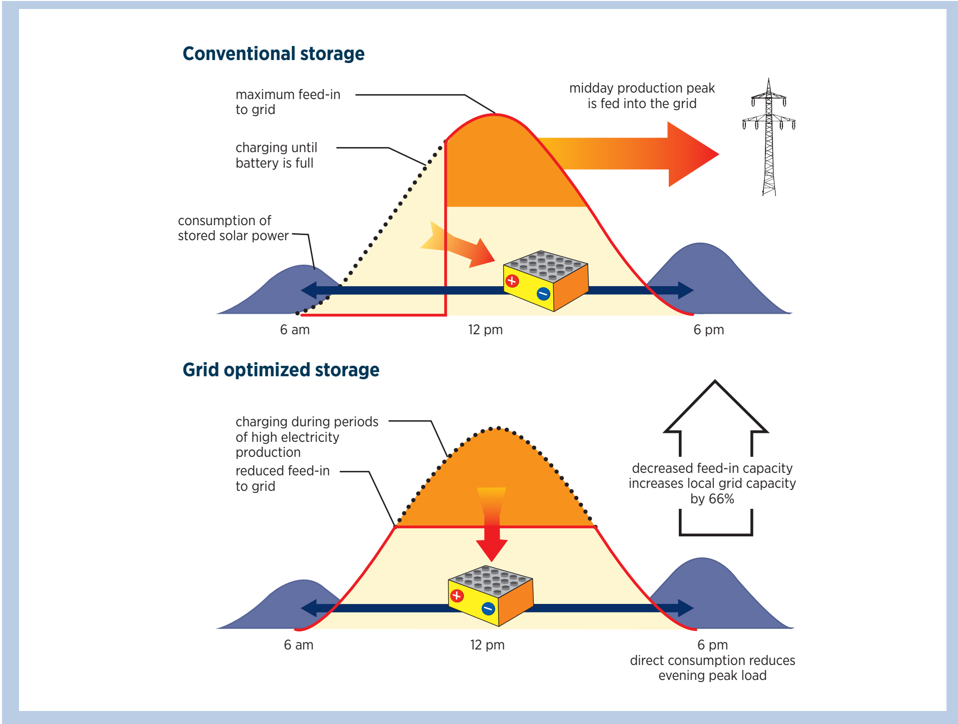


Figure 13: Solar PV and battery storage[74]

Figure 13 shows the difference between conventional storage and grid-optimized storage. The former, effectively, has uncontrolled battery charging whereas the latter has charging and PV production that takes grid demand into account. The figure shows that optimizing self-consumption of solar-PV is just one aspect of battery storage. If solar PV and storage are to prove beneficial to both the user and the local grid, then the local grid area demand must be taken into account.[75]

A simple explanation is as follows: If the output from solar PV and batteries are not controlled then the battery will begin to charge in the morning and will become fully charged as soon as possible. Such a configuration may mean that, 'peak solar production is exported to the grid during its maximum output.'[76] It is highly likely that this export will not correspond to periods of peak demand and subsequently would result in an oversupply of renewable energy in relation to demand. The consequences would be voltages that exceed supportable limits. As IRENA concedes in its technology outlook for battery storage, 'If a large number of distributed solar PV systems are running in a specific area, this practice may also limit renewable energy deployment.'[77] Therefore, integrating battery storage onto the grid can lead to the development of more renewable energy sources.

Calculations carried out by the Fraunhofer Institute in Germany have shown that 66% more solar PV can be installed in a given area where peak solar PV production is not

[74] ibid. p.15.
[75] ibid.
[76] ibid.
[77] ibid.

exported to the grid.[78] Controlling electricity feed-in to the grid from solar PV is crucial, as is matching the battery supply to household demand. Fraunhofer states that the self-consumption of solar power can double, depending on the size of the solar PV installation and battery. The example given is that the percentage of a household's consumption of PV power can rise from 30% to 60% using the combination of a five kilowatt peak (kWp) PV installation with a 4KWh battery.[79] This application of battery storage then, increases household solar power penetration, allows more solar PV in a given area and contributes to grid stability.

Of final consideration is that the attractiveness of residential battery storage depends on 'the correspondence of peak solar production with peak system demand.'[80] The closer these two times exist then the more beneficial the application is. Some households may experience peak demand during the day, but it is likely that this is more the case in gulf countries as solar corresponds with demand for air-conditioning. Rather the wider point is that 'the optimal charging algorithms will vary according to the particular electricity system and area, household and time of year.'[81]

Variable renewable energy smoothing and supply shift

Let us separate both applications:

Smoothing: Occurs as battery storage electricity is fed onto the grid while, 'smoothing' the variable production of *centralised* wind and solar generation. Figure 14 provides a clear illustration.

Energy shift supply: Excess production from renewable energy can be stored and then matched with periods of higher demand. "Shifting" the supply to take advantage of different prices. This is illustrated in figure 15.

Both applications distinguish themselves as different from regulation as they occur on the production side. The energy that is able to be stored is directly generated from the specific renewable energy resource. Battery storage regulation on the other hand, operates at the grid level.

Let us consider the following with regards to 'smoothing':

A cloud blocking the sun can cause output to fall by 90% 'almost instantly'.[82] (Unexpected decreases in output occur with wind too, but are regarded as slower.) This is liable to cause problems for system voltage levels in both the distribution network and the overall stability of the system. Naturally this would be dependent on a number of factors such as the size of the system, and its ability to deal with unforeseen

[78] Dr. BRUNO, B. (2016) Fraunhofer Institute for Solar Energy ISE – Power generation from renewable energy in Germany – Assessment of 2015.
[79] ibid. p.3.
[80] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.15.
[81] ibid. p.16.
[82] ibid.

supply/demand changes. Smoothing helps to retain system reliability and voltage concerns.[83] As figure 14 below shows, smoothing mitigates the short-term fluctuations of solar and wind.

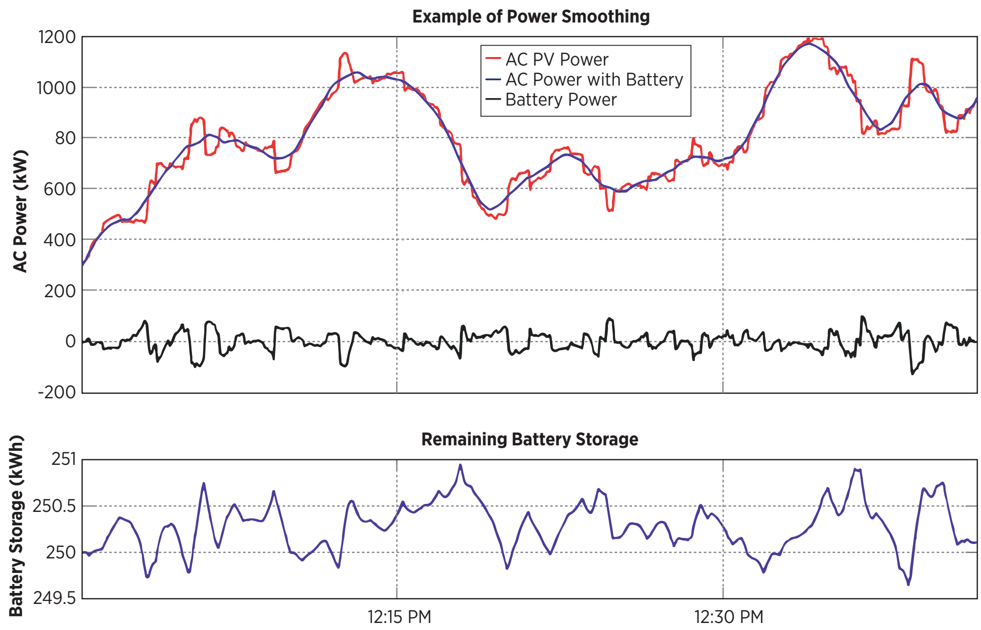


Figure 14: Smoothing from battery power storage[84]

The above figure represents the output of centralised PV production of Hawaii. The battery power is used to both charge and discharge, helping to smooth the output. The consequences of this application are that output from solar and wind can be integrated easier into the electricity network and grid stability can be optimized. This application is especially important in island and off-grid systems that might have to deal with large fluctuations in renewable energy feed-in.

With supply shifting excess renewable energy is stored for period of higher demand. System stability is one consequence of the application but moreover it allows the integration of more renewable energy. This decreases reliance on fossil fuels and avoids declining power from renewables. This application can make sound economic sense by charging the batteries when prices are low and discharging during peak demand when prices are higher. Italy currently employs a net metering scheme – *Scambio Sul Posto* – which, 'provides economic compensation for feeding in renewable energy depending on the time of day and demand.'[85]

[83] ibid.p17.
[84] ibid.p18.
[85] ibid.p.17.

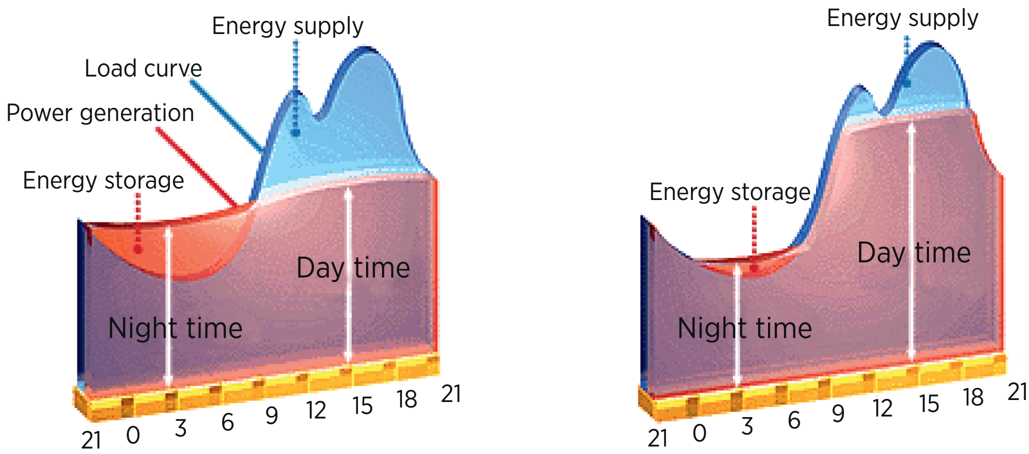


Figure 15: Energy supply shift[86]

The services provided by these applications are found under 'customer energy management services'. Both affect power reliability, and energy shifting is clearly linked to the 'retail electric energy time shift'. Many storage technologies are able to provide this service, moreover shifting renewable production is an application that is 'unique to energy storage'.[87] On the other hand, the smoothing application is particularly well suited to battery storage, as it requires very quick charging and discharging, which as has previously been shown, is a characteristic of lithium-ion batteries.

Fast regulation in grids with high variable renewable energy shares.

As shown in figure 10, this application falls under the category of ancillary services. IRENA defines these services as 'facilities than enhance the security and reliability of the electricity system as well as servicing the normal production and consumption of electricity.'[88] In order to understand these services let us consider three different time periods and control:

- Primary control – 10-60 seconds (frequency response)
- Secondary control – up to 10 minutes (regulation)
- Tertiary control – over 10 minutes to several hours (imbalances / reserves)

Battery power has the ability to provide balancing power at all of the timeframes above. As mentioned it can charge and discharge in seconds, and is 'faster and more accurate than thermal power plants.'[89] The advantages of battery storage in regulation can be summarized as follows:

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[86] ibid.p.19.
[87] ibid.p.17.
[88] ibid.p.19.
[89] ibid.p.21.

- Short term output variations from renewable energy sources can be quickly compensated
- Full negative and positive capacity for regulation. (See figure 14)
- Faster ramp-up periods than fossil fuel power plants
- Reduces the need to keep combustion turbines online. (Reduction of greenhouse gas emissions)
- Reduction of maintenance cost, as frequency regulation provided by conventional power plants may 'accelerate equipment degradation due to ramping requirements of frequency regulation.'[90]

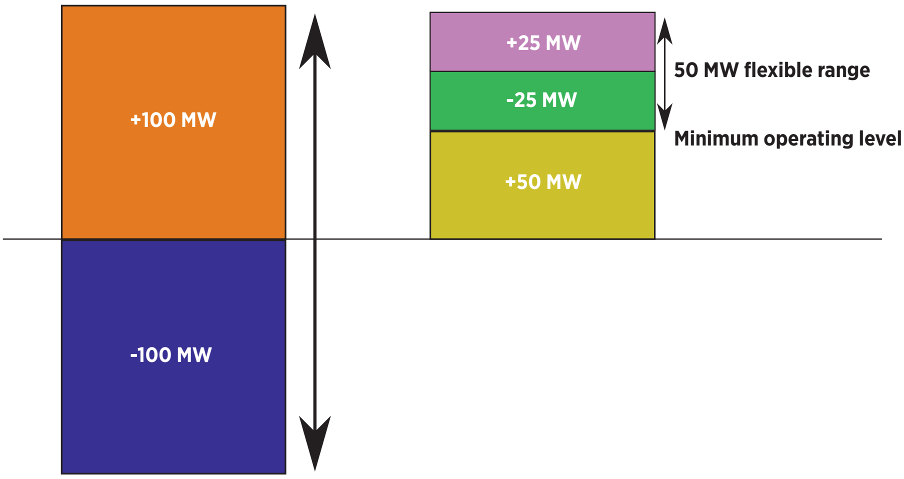

Figure 16: 100MW Battery storage (left) versus 100MW gas turbine (right)[91]

Battery storage clearly has many positives in ensuring grid stability. It is likely that its application will become even more compelling in the future as increasing amounts of renewable energy are integrated into the electricity system. It is worth mentioning that batteries used in this application will be subject to multiple charges/discharge cycles, and will be required to provide a high level of power over a short time period.

Summary

Chapter one has achieved two important steps of the investigation. Firstly, the various different types of battery storage technology are understood: Lead-acid batteries have been used to support renewable energy production. However, although still useful, the battery suffers from a number of limitations and is unlikely to undergo significant further development in the future. Not disregarding alternatives, lithium-ion enjoys advantages in terms of power, energy and efficiency and is regarded as the most promising in terms of potential.

[90] ibid.p.22.
[91] ibid.p.21.

Secondly, this section has shown the services that can be provided by battery storage. Different applications of battery storage have shown a technology able to mitigate against the intermittent nature of renewable energy in a number of different ways and in different areas. This has included both production and grid level applications as well as residential/utility scales. In achieving the five services highlighted in figure 10, one can see how one installation can serve multiple uses. The effect of these value streams on the economics of the installation will be investigated in the following section. In assessing the economic viability of battery storage, it is additionally necessary to gain understanding of how battery storage technologies will evolve, both in terms of their technical specifications and price. Prior to chapter 2 is a list of battery storage benefits:

- Consumer control – customers enjoy greater control of their bills by shifting energy use.
- Able to supply capacity and backup power (at a cheaper rate than quick response fossil fuel plants)
- Ancillary services – keeping electricity supply and demand in balance. Helps to maintain the voltage and frequency of the electricity system
    - Avoids damage to electronics/motors
    - Avoids power cuts.
- Beneficial to infrastructure - power lines and grid infrastructure wear quicker operating at peak capacity. As the energy can be shifted infrastructure investment can be reduced.
- Renewable energy support – Variable in nature, renewable energy can be difficult to accommodate for utility power plants. Battery storage responds quickly to variations in output resulting in higher penetrations of renewable energy onto the grid.
- Quality and reliability – especially true in areas of weak interconnection such as islands.
- Promotes job creation in technological and service industries.
- Reduces sizing of distributed generation systems

Chapter 2: The economic viability of battery storage technology

Although the combination of battery storage and renewables brings benefits, there is a degree of uncertainty under which conditions battery storage can be operated without policy support. This section of the paper investigates the economic viability of battery storage technology. The second part of the chapter provides a brief investigation into the price development of lithium-ion technology. The final part looks at the different markets for energy storage. It asks how markets are likely to develop and what barriers storage technologies need to overcome.

Residential Solar PV

As shown in 'Trends in Energy Finance', the price of solar PV technology has fallen greatly over the past 40 years. This has been a key factor in the increased installation of solar PV of many countries. Of the major economies, Germany has achieved the greatest electrical output from solar PV installations. A paper published by the Fraunhofer Institute explains why this has been the case:

'Thanks to technological progress, the learning curve and economies of scale the investment costs for solar PV plants, which make up the greatest outlay, have fallen an average of 14% per year – in all, almost 75% since 2006.' [92]

Figure 17 below shows the price evolution since the second quarter of 2006. The percentage in orange represent the solar module costs of the installation.

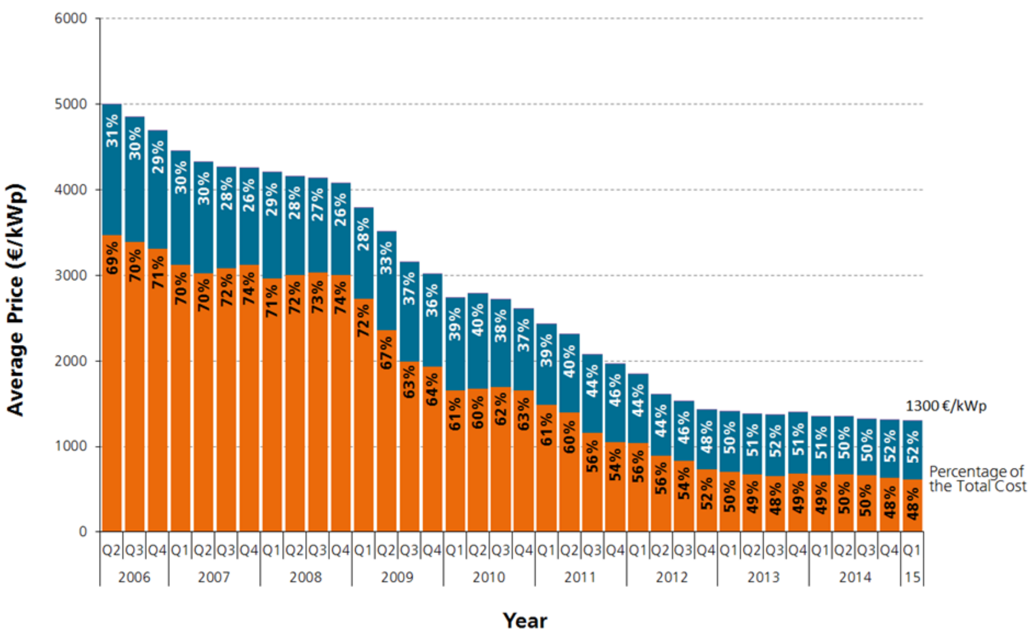

Figure 17: Average end consumer price for installed rooftop systems.[93]

[92] Dr. WIRTH, H. (2015). Recent Facts about Photovoltaics in Germany. Fraunhofer Institute for Solar Energy Systems ISE.

Although adding battery storage to residential solar PV systems can enhance the value of the electricity produced, it also increases the overall investment cost. For this reason, in Germany there exist programmes that subsidize the use of energy storage. A paper by Hoppmann *et al.* aims to investigate the profitability of storage for PV systems and determine the optimal size of the system. In doing this they seek to overcome two limitations of existing studies: Firstly, due to the uncertainties surrounding tariffs and the expectation that they will be phased-out at some point in the future, profitability is investigated without 'demand side subsidies.' [94] Secondly, especially under the assumption of no additional incentives, the sizes of the solar PV system and battery storage greatly affect the viability of the integrated battery-PV system. The reason this is the case is because the economic viability of the system is, 'strongly driven by the degree to which electricity produced by the PV system is self-consumed.'[95] The extent to which the electricity is self-consumed is dependent upon size of both the PV system and the battery storage. That is to say that currently there exists uncertainty as to when investments in battery storage will be economically viable, for a household that wishes to optimize both the solar PV and battery systems.

In order to answer the question of when and under which conditions battery storage will be economically viable with solar PV, without subsidies, they created a techno-economic model that is able to calculate profitability. The authors' investigation is carried out on 8 different electricity price scenarios and their results show the outcomes through three sections:

1. Optimal PV system size
2. Optimal storage size
3. Profitability of storage

Table 2 shows the electricity price scenarios used in the model simulations. Scenarios 1-5 all assume that the household has *unlimited* access to the wholesale market. Conversely, scenarios 6-8 all assume that the household has *no* access to the wholesale market. The outcomes of the model are illustrated for each section on the assumption or not of access to the wholesale electricity market. All of the electricity wholesale and retail price scenarios are per year.

[93] ibid.p.9.
[94] A result of this approach is that changes to the wholesale and retail prices of electricity will strongly affect storage profitability.
HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.3.
[95] ibid.

Scenario	Assumption	Electricity Wholesale Price Scenario	Electricity Retail Price Scenario
S1	Unlimited access of household to wholesale market	High: +3%	High: 2%
S2		Low: -1%	
S3		Medium: 1.5%	Medium: +1%
S4		High: +3%	Low: +0%
S5		Low: -1%	
S6	No access of household to wholesale market	Constant: 0 EUR/kWh	High: 2%
S7			Medium: +1%
S8			Low: +0%

Table 2: Electricity price scenarios used in model simulations [96]

The major points of interest from the results are outlined below.

Optimal Solar PV System Size

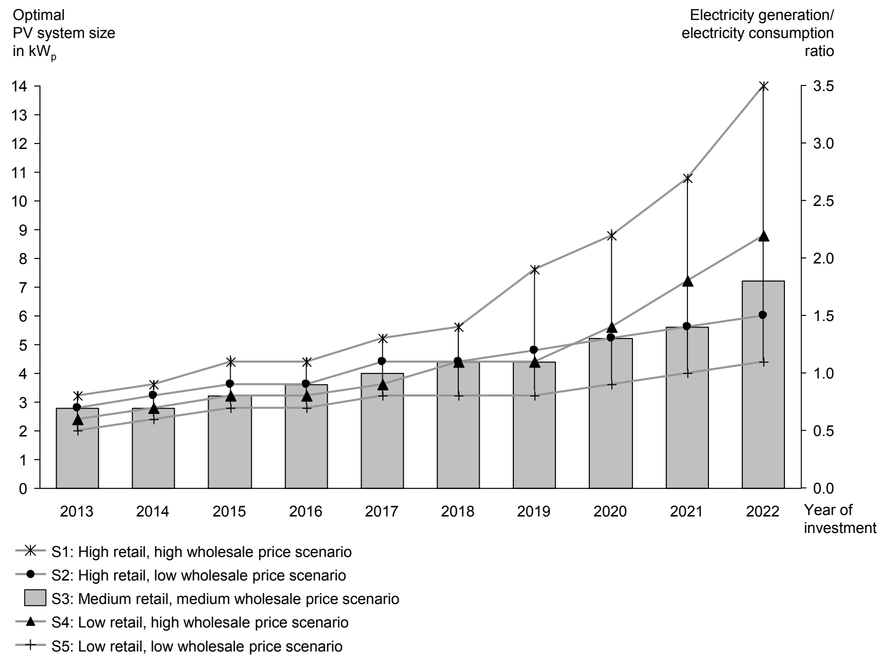

Figure 18: Optimal Solar PV plant size S1-S5[97]

[96] Taken from: HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.14.
[97] ibid.p.19.

- All investments in solar PV systems are profitable under the investigation, as no scenario has the optimum size of 0. (This is true with S6-S8 in figure 19 as well).
- When looking at S3 (medium retail price, medium wholesale price), the optimal size of the solar PV system significantly increases over time from <3kW_p to 7.
- Until 2016, the optimal size of the generation consumption ratio is <1. This means that the household generates less electricity than it consumes. The authors outline their reasoning as to why this is the case: 'This is due to fact that investment costs for both the PV and storage systems are relatively high, requiring the household to have a high rate of direct self consumption which can only be achieved when choosing a small PV system size'.[98]It should be noted that as investment costs fall the optimal generation/consumption ratio increases.
- The difference between S1 (high, high) and S5 (low, low) increases over the years and by 2022 is radically different. This would suggest that the optimal solar PV plant size is very sensitive to future retail and wholesale electricity prices. As an analysis, the authors write: 'stronger increases in retail prices favour larger PV plant sizes as they enhance the value of the electricity produced by the PV system – which substitutes electricity purchased from the grid.'[99]
- With wholesale prices, optimal system size is greater when wholesale prices are high (S1, S4). This is because it increases the value of excess electricity, which can be sold on the market at a higher price.
- Initially, it is the retail price that has greater influence over the PV system size, however this changes in the later period and the wholesale price becomes more important. On this subject, Hoppmann et al. write: 'This can be explained by the fact that with falling technology costs, the size of PV plants rises over time which leads to a situation where households, despite using storage, need to sell an increasing amount of their electricity on the wholesale market.'[100] The fact that S1 needs to sell 2.5 times its total consumption in 2022, underpins the influence that the wholesale prices can have on the optimal PV system size.

[98] ibid.p.19.
[99] ibid.p.20.
[100] ibid

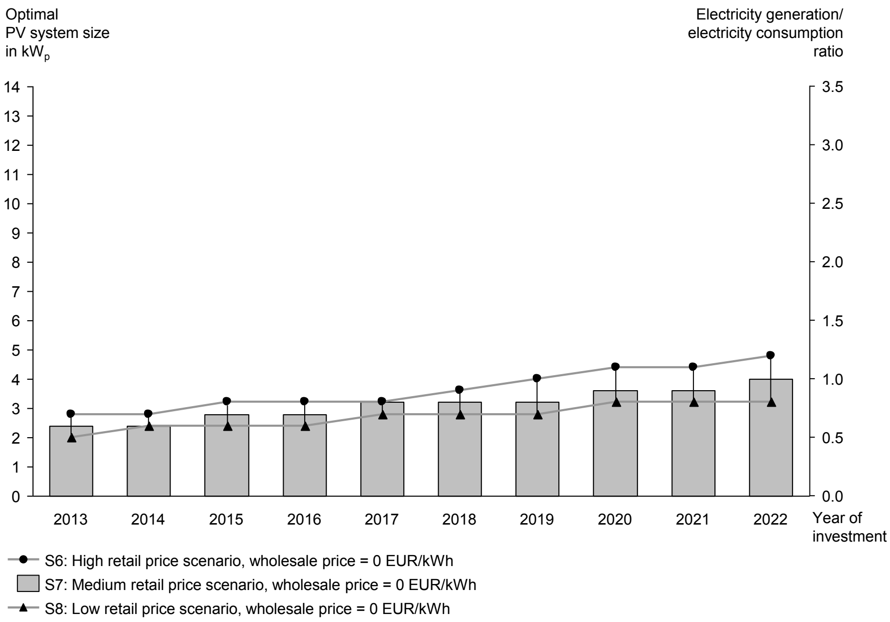

Figure 19: Optimal PV plant size S6-S8[101]

- With the assumption that the household has no access to the wholesale market the optimum PV size is significantly smaller when compared to S1-S5. This is due to the fact that any extra electricity generated cannot be sold on the wholesale market, thus the household will naturally choose the PV system size that limits the production of extra and inconsumable electricity.

Optimal Storage Size

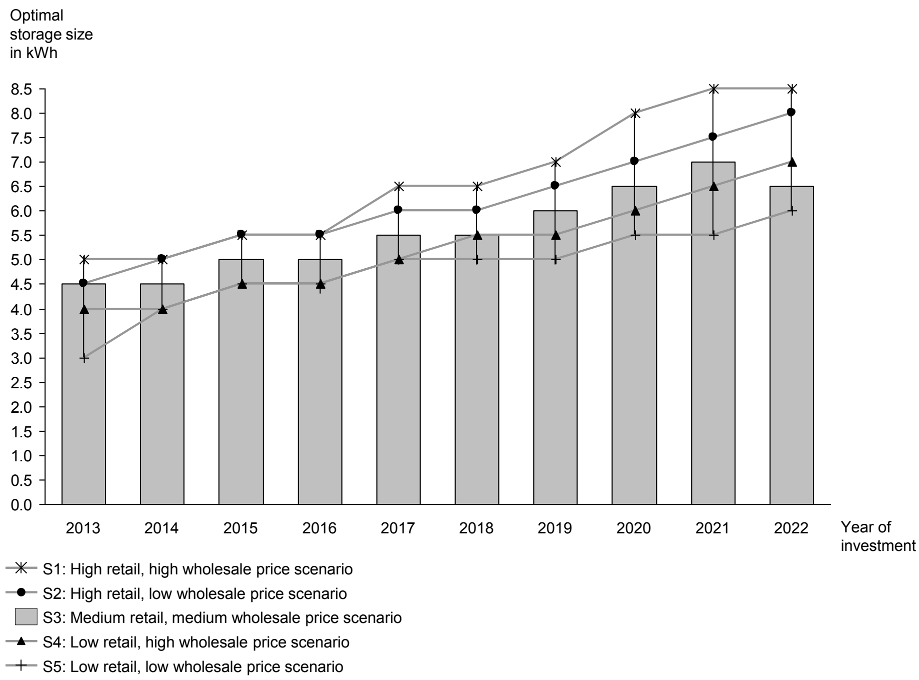

Figure 20: Optimal Storage Size S1-S5[102]

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[101] ibid.p.19.

- As with solar PV plant size, the optimal storage generally increases over the time period. In the case of S3, the optimal storage size moves from 4.5kWh in 2013 to >7 in 2021.[103]
- When considering a particular retail price, either high or low, the optimal storage size is marginally larger in scenarios that assume a greater increase in wholesale prices.[104] For example, when considering high retail prices, S1 is generally larger than S2, and with low retail prices S4 is generally larger than S5. As shown in the previous section, higher wholesale prices lead to larger PV plants. It is likely that this, in turn, raises the optimal storage capacity.

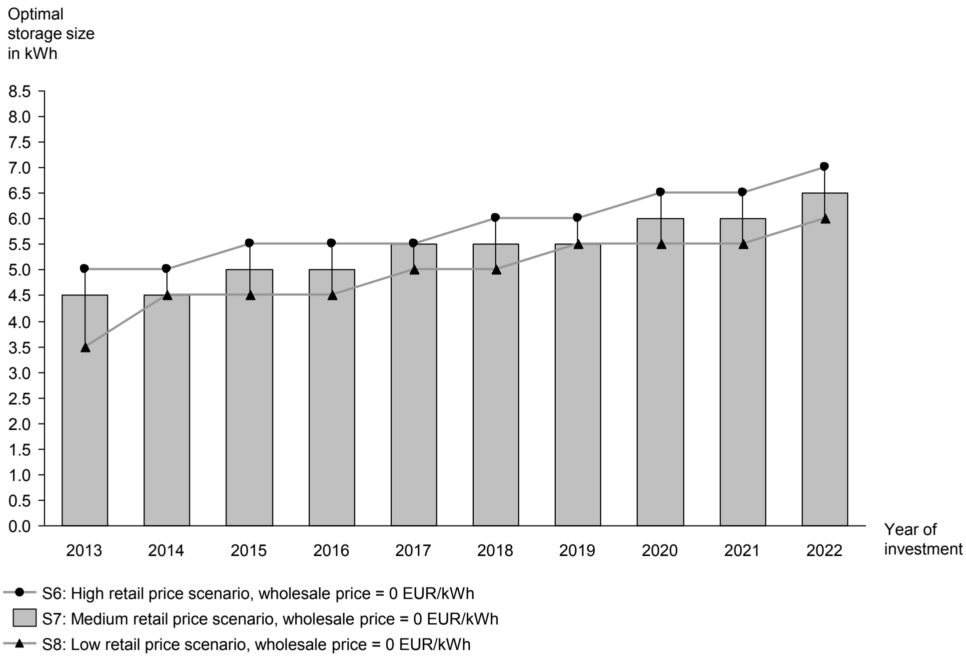

Figure 21: Optimal Storage Size S1-S5[105]

- Generally speaking, the impact of wholesale prices on optimal storage size is low. This is demonstrated by the fact that S6-S8 in figure 19 are very similar to a medium retail price scenario in figure 18.

Storage Profitability

- As shown in figures 20 and 21 investments in storage were already profitable in 2013 under all of the price scenarios.
- The profitability of storage continuously rises over time in an almost linear fashion. This means that the value of storage per Euro invested in storage moves in S3 from <0.5 to >2.5 within 10 years.

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[102] ibid.p.21.
[103] The reason S3 levels off post 2021 is due to the fact that the model includes a constraint for maximum solar PV system size. This lessens the size of storage installed under the economic considerations.
[104] ibid.p.22.
[105] ibid.p.21.

- As with optimal PV system size and optimal storage size, storage profitability depends greatly on retail prices. As is clearly visible, higher retail scenarios (S1 and S2) raise profitability.
- In later years, particularly from 2018, lower wholesale electricity prices increase the profitability of storage investments. This is when the PV systems are larger and households sell a higher share of their electricity on the market.
- The result of this is that storage investments are profitable with no access to wholesale markets (S1-S8)

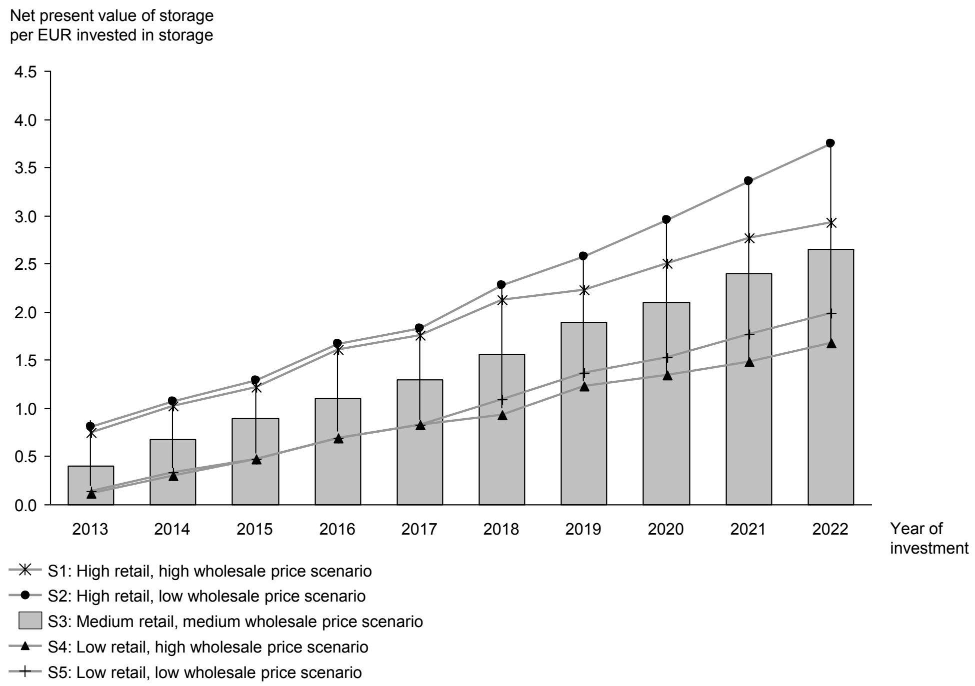
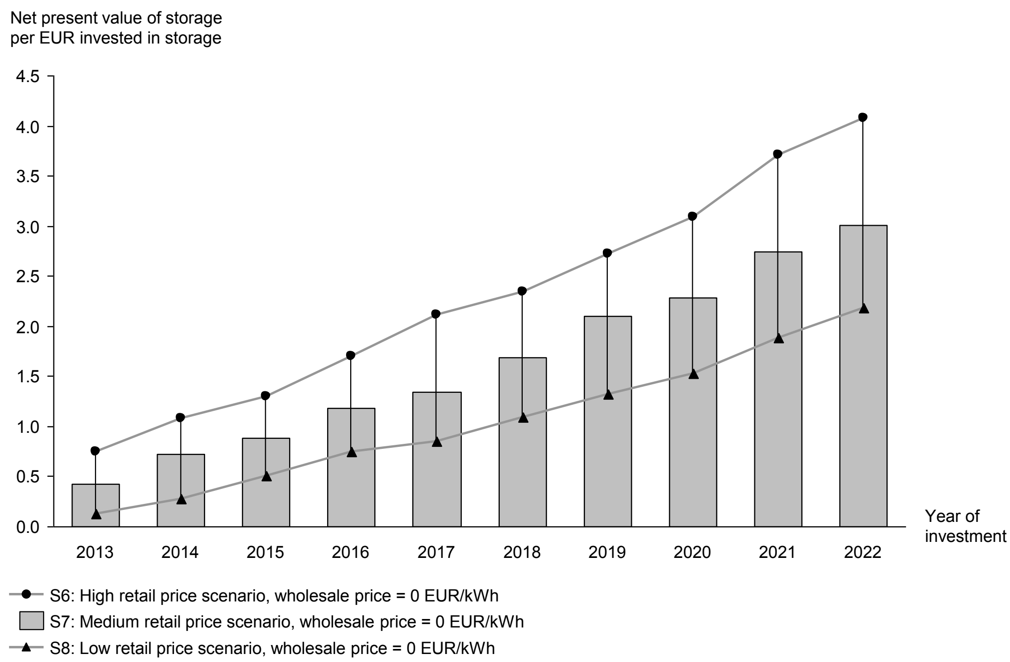


Figure 22: Storage profitability S1-S5[106]



[106] ibid.p.23.

Figure 23: Storage profitability S6-S8[107]

Summary

The results of the investigation carried out by Hoppmann et al. have been used within this paper as they serve it well. They provide a comprehensive assessment of how the sizes of the solar PV system and battery storage change over time using a number of different scenarios. Furthermore, the modelling was carried out without subsidies. The results demonstrate that battery storage is economically viable under *all* of the different price scenarios that were considered. The profitability of storage is foreseen to increase greatest with a decrease in wholesale electricity prices and a simultaneous increase in retail prices. In fact, storage profitability is not undermined even if the household has no access to the wholesale markets.

It is worth reiterating that investment in battery storage is already profitable for residential solar PV systems. As the authors conclude, the optimal size of both the system and storage rises over time and has the consequence of making, 'households become net energy producers between 2015 and 2021 if they are provided access to the electricity wholesale market.'[108] The economic viability of storage is contributed to with any development that a) increases retail prices or b) decreases wholesale prices.

Despite the usefulness of the study it does have several limitations. As the investigation was only carried out for a model household in Germany it would be beneficial to repeat the analysis in different locations. This is true as technology costs, solar irradiation, and electricity prices and consumption patterns differ in countries.[109] A wider criticism of the investigation is that the analysis focuses on retail and wholesale prices. As we have seen in chapter 1, battery storage is able to generate value through other applications such as frequency regulation and energy shifting (arbitrage). This would lead one to suggest that using a combination of different applications would further increase the economic viability of battery storage. In 'Recent Facts about Photovoltaics in Germany', the following is written:

'The predominantly decentralized way in which PV is fed into the distribution grid in close proximity to consumers reduces grid operating costs and in particular those relating to the transmission grid. A further advantage of feeding in PV is that in addition to feeding in real power, PV plants are in principle able to offer extra grid services (e.g. local voltage regulation) at cost-effective prices.'[110]

Combined solar PV-battery systems are not only economically viable for consumers, but are also able to lessen transmission costs and provide other services. As a result, the economic viability of storage is likely to be considerably greater than outlined through the Hoffmann paper.

[107] ibid.
[108] ibid.p.29.
[109] ibid.p.28.
[110] Dr. WIRTH, H. (2015). Recent Facts about Photovoltaics in Germany. Fraunhofer Institute for Solar Energy Systems ISE. P.39.

Of final consideration is the fact that lead-acid batteries were used throughout the investigation. As shown in chapter 1, this technology, although widely used and effective does not constitute the best option as it is unlikely to develop greatly in the future. The most promising battery technology is lithium-ion, which, among other advantages, has a higher power and energy density than lead-acid. The following section will explore the developments in price of Lithium-ion technology.

Price development of lithium-ion technology

It is safe to say that the price of lithium-ion technology is decreasing. That said, there are uncertainties over how much it has decreased in the past and the rate at which it will continue to decrease in the future. Obtaining an accurate assessment of these key factors constitutes an important part of this investigation and is critical in assessing the economic viability of battery storage technology. One reason for the difficulty in obtaining an accurate assessment is due to the fact that the industry is secretive with sensitive information. It is possible for example that costs are overestimated in an attempt to hide the actual costs or batteries subsidized in order to gain market share.[111]

A recent study published in Nature Climate Change analyses over 80 different estimates reported during the period 2007–2014. It describes itself as presenting a 'first-of-its-kind systematic review of the cost of battery packs,'[112] and traces the cost of lithium-ion batteries through this period. It is important to state that the batteries analysed were for electric vehicle application. However, battery packs for residential/business use are the exact same technology. The battery packs are composed of the modules and the modules composed of the cells. The application may be different but the technology is fundamentally the same. The only area where lithium-ion technology differs is with regards to the materials that companies use for the cathode and anode within the individual cells of the battery. The paper includes, 'cost estimates of all variants of Li-ion technology uses for BEV (Battery Electric Vehicles), as the aim is to track the progress of BEV technology in general and data is too scarce for individual Li-ion cell chemistry variants.'[113] Thus, the review allows us to gain insight in to the price development of lithium-ion technology.

Figure 24 below shows the development of price and there are several pertinent points that must be made. The most obvious, but also important observation is that the price of lithium-ion batteries per kWh has decreased significantly. As of 2014 there are two price estimates, (calculated as the mean), that are significant. The first, shown by the black line, represents the industry wide cost. This is $410, which represents a 14% decline annually since 2007. The second, shown with a dashed green line, represents the market leaders. Their cost is significantly lower at $300 per kWh and since 2007 they have enjoyed an 8% annual decrease. Nykvist and Nilsson point out that this is, 'of the

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[111] NYKVIST, B. & NILSSON, M. (2015) Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change. Vol. 5. April 2015. p.329.
[112] ibid.
[113] ibid.

order of two to four times lower than many recent-peer reviewed papers have suggested.'[114] Perhaps what is more significant is that by 2014 the costs were in many cases below the average projected costs for 2020, which are shown by the yellow triangles. The cost of lithium-ion technology is clearly in decline and furthermore, the costs of battery packs among market leaders are much lower than previously reported.

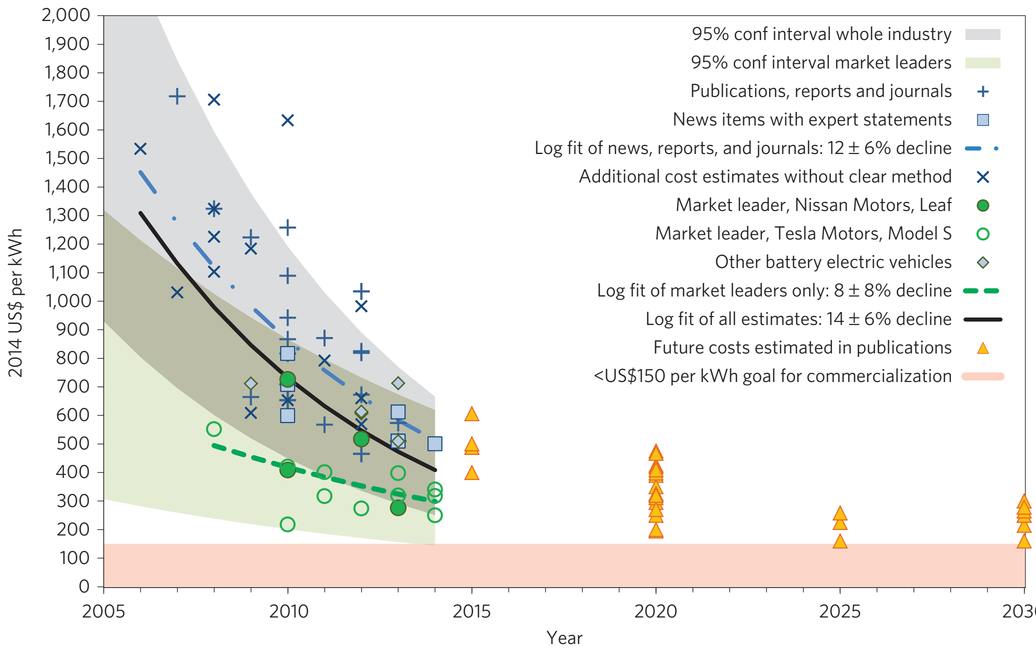

Figure 24: Cost of Lithium-ion battery packs in battery electric vehicles[115]

Regarding learning rates, the cost reduction following a cumulative doubling of production, it is true that the authors, 'recognize the huge uncertainty in aggregating different estimates.'[116] The authors state that the data has too much uncertainty to be used directly together with data on cumulative capacity to estimate learning rates. However, by using 'modelled average costs', the authors calculate a learning rate of 9% for the industry as a whole and 6% for market leading actors.[117] How this learning rate develops in the future is of great significance in understanding how economically viable battery storage technology is likely to be in the future. Catenacci et al. suggest that there are still research and development improvements to be made in anode and cathode materials, separator stability and thickness and electrolyte composition.[118] This is considered by Nykvist and Nilsson, who write that together with improvements due to economies of scale, 'a 12-14% learning rate is conceivable.'[119] In light of this it seems

[114] ibid.
[115] ibid.p.330.
[116]IEA. (2015). EV batteries: how quickly are prices falling? [Online] Accessed on 25/3/2016 from: https://www.iea.org/newsroomandevents/pressreleasesnews/3-questions/ev-batteries-how-quickly-are-costs-falling.html
[117] NYKVIST, B. & NILSSON, M. (2015) Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*. Vol. 5. April 2015. p.329.
[118] CATENACCI, M., VERDOLINI, E., BOSETTI, V. & FIORESE. (2013). G. Going electric: Expert survey on the future of battery technologies for electric vehicles. *Energy Policy* 61, 403-413
[119] NYKVIST, B. & NILSSON, M. (2015) Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change.* Vol. 5. April 2015. p.330.

reasonable to suggest that learning rates could increase in the near future. That said, Munuera and Cazzola write the following in regards to learning rates:

'The degree to which these trends can be extrapolated into the future is not clear – we have come to understand over the past few years that that learning rates for energy technologies are very rarely constant over time, and they have not been for Li-ion.'[120]

This would suggest that even if a learning rate of 12-14% were achieved, it is unlikely to be maintained over an extended period of time. Despite this the authors also state the following:

'Having said that, when excluding quoted figures or estimates, which are often not comparable, but instead at the fundamentals of the technology as well as developments in the pipeline, we still believe that there is a significant potential for cost reduction with Li-ion batteries'[121]

Whether or not this, "significant potential" translates into a higher learning rate enjoyed over a long period of time remains to be seen. Some authors have noted that many advancements at cell level have already been realized,[122] and others that a commercial breakthrough of the next generation of lithium air-based batteries is still far in the future.[123] Such perspectives give weight to the argument that the learning rate will slow in the coming years. What is clear though is that the learning rate enjoyed by technology has lead to decreasing costs for a number of years now and for the time being at least these costs will continue to fall.

Nykvist and Nilsson state their belief that the 8% annual cost decline enjoyed by market leaders is likely to represent the, 'probable future cost improvement for Li-ion battery packs, whereas the 14% decline for the industry as a whole to some degree represents a correction of earlier, over-estimated costs.'[124] This analysis would suggest that the cost level of $300 per kWh the market leaders now sets is the de-facto current cost for state of the art battery packs. What is particularly noteworthy within their study is regarding the convergence of battery costs for the whole industry. They predict that this is set to happen in 2017-2018 at around $230 per kWh.[125] Thus it appears that costs will be pushed towards $200 per kWh. This is likely to be the case without major changes to cell chemistry, but perhaps is to some extent dependent on the success of large-scale production facilities such as Tesla's Gigafactory, in order to achieve the necessary economies of scale. Speaking at the unveiling of the Tesla Model 3 electric car, Elon Musk, the CEO of tesla motors said that the Gigafactory would, 'produce more lithium-

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[120] IEA. (2015). EV batteries: how quickly are prices falling? [Online] Accessed on 25/3/2016 from: https://www.iea.org/newsroomandevents/pressreleasesnews/3-questions/ev-batteries-how-quickly-are-costs-falling.html
[121] ibid.
[122] CAIRNS, E. J. & ALBERTUS, P. (2010) Batteries for electric and hybrid-electric vehicles. *Annu. Rev. Chem. Biomol. Eng.* 1, 299-320.
[123] MAYER, T., KREYENBERG, D., WIND, J & BRAUN, F. FEASIBILITY study of 2020 target costs for PEM fuel cells and lithium-ion batteries: A two factor experience.
[124] NYKVIST, B. & NILSSON, M. (2015) Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change.* Vol. 5. April 2015. p.330.
[125] ibid.

ion batteries than all other factories in the world combined.'[126] He further stated that it would have 50GW per year of production, with the most advanced lithium-ion battery being produced.

Before moving on to the final part of the chapter it should be mentioned that Navigant, a research group, forecasts that prices will reach $200 per kWh. However, according to their forecasts the prices will reach a floor at $200 or slightly below. They state their belief that prices will be below $200 per kWh in the next 5 years but say that, 'being able to go beyond that, to $150 or $100 is potentially impossible but defiantly very very hard to do with Lithium-ion chemistries.'[127] Ultimately time will tell how low prices will fall.

Market development for battery storage technology

The final part of chapter 2 aims to develop our understanding of how the market has developed for battery storage technology. As we have seen, the costs of battery systems and integrated solar PV-battery systems have fallen in recent years. There have been increased levels of deployment and greater interest in the use of battery storage for renewable energy integration. A clear example of this is the fact that in Germany the prices for battery storage systems connected to a solar PV system fell by 25% in 2014.[128]

In 2014 the most installed battery type was sodium sulphur. This will not be the case for much longer as the market is shifting towards lithium-ion batteries and also utilizing advanced lead-acid technology. As shown in chapter 1, lithium-ion has proved itself preferable to other chemistries in regards to energy and power density, life cycles and cost. Sodium sulphur batteries remain an important battery type, but in terms of market development the shift is undoubtedly towards lithium-ion. Figure 25 below shows the estimated installed battery capacity and commissions in the power sector by battery type.

[126]YOUTUBE. (2016). Elon Musk Unveils Tesla Model 3. [Online] Accessed on 5/4/2016. Available from https://www.youtube.com/watch?v=7HOhOeKwe30
[127]NAVIGANT.(2016). Beyond Lithium-ion. [Online] Accessed on 5/4/2016. Available from https://www.navigantresearch.com/webinarvideos/webinar-replay-beyond-lithium-ion
[128] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.27.

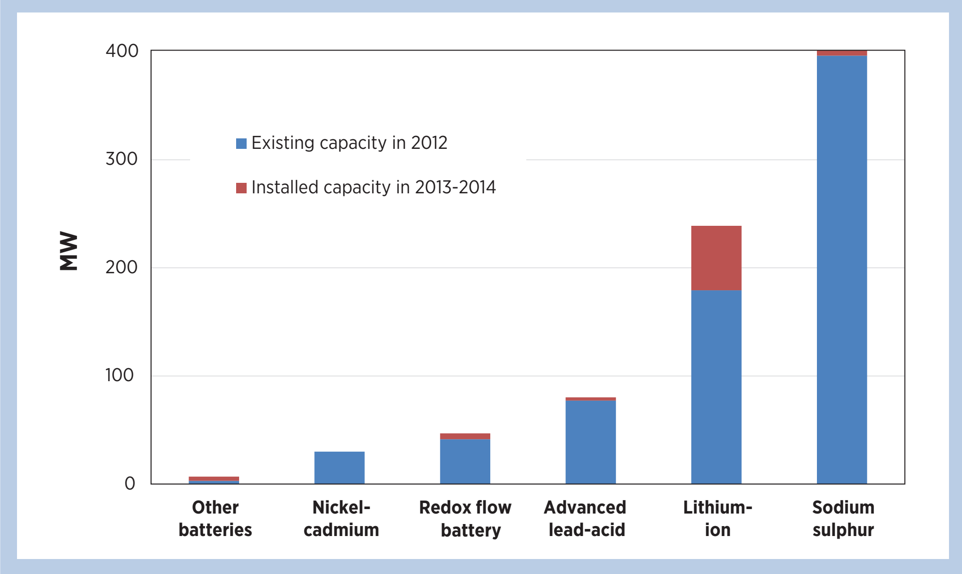

Figure 25: Estimated installed battery capacity and commissions in power sector, 2014[129]

Although the estimates are slightly old, the figure gives a clear indication of how the installed capacity in 2013-2014 for lithium-ion far outstrips other technologies. This development is unlikely to slow. As shown in the previous section, the price of lithium-ion technology has decreased greatly in the recent past and will continue to do so. IRENA notes that, 'the most dramatic cost developments have been for lithium-ion chemistries, driven by policies to deploy the technology in the electricity sector and the electric vehicle market.'[130] As lithium-ion technology permits a wide range of applications (chapter 1), there are multiple benefits for the electricity sector.

In addition to batteries becoming increasingly competitive in the market, thanks to cost reductions, it is worth mentioning that regulations are beginning to move away from an approach to grid services centred on fossil fuel.[131] Furthermore, continued research is causing more barriers to be overcome, and increased knowledge of how installations work will make residential, commercial and utility adopters more comfortable with their utilization.

Utility, residential and non-residential market segments

The utility market is expected to grow considerably in the coming years. Figure 26 below shows the worldwide forecast of battery storage capacity and annual revenue of utility scale applications.

[129] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.26.
[130] ibid.p.28.
[131] ibid.p.24.

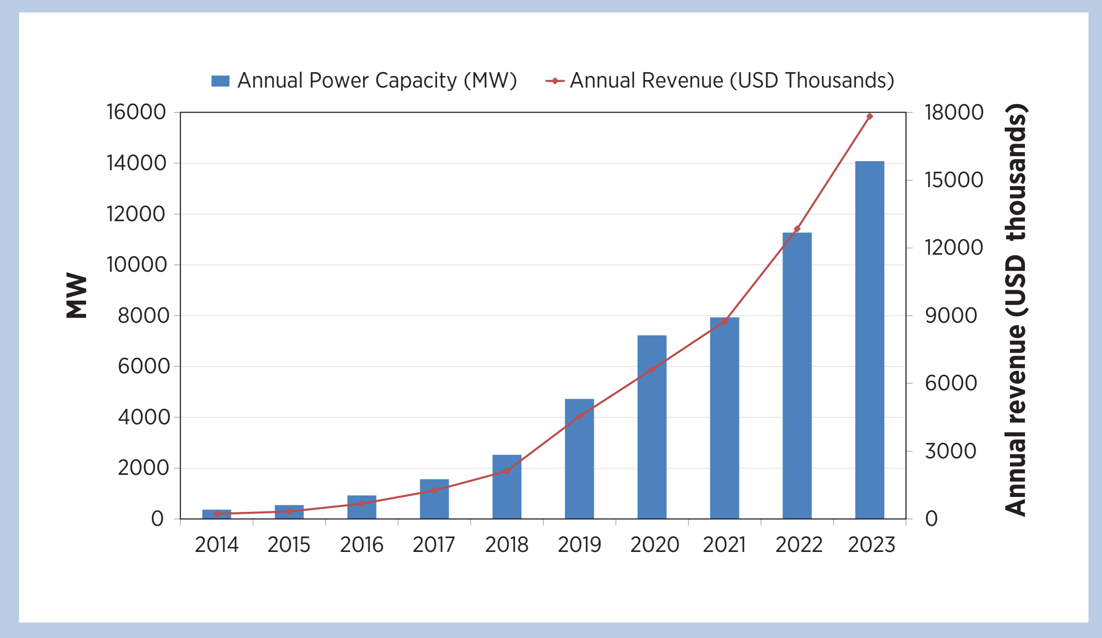

Figure 26: Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility scale applications[132]

The revenue from applications is set to increase from around $200m in 2014 to $18Bn in 2023. The storage capacity will rise from 360MW to 14GW over the same period. It should be highlighted that these estimates are for utility only and do not include batteries and solar PV systems that are "behind the meter", such as household solar PV installations. These too are undoubtedly a significant market opportunity.

Regarding battery use, Navigant expects it to be comprised of the following:

Application	2014	2023
Renewables integration	29%	40%
Reducing peak demand (shaving)	20%	37%
Energy supply shift	18%	15%
Ancillary services	17%	3%
Other	16%	5%

Table 3: Applications for battery use.[133]

The multiple applications for batteries are a key reason why there appears to be a very strong upward trend, as shown in figure 15. It must be said that predicting energy sector development is very difficult and as a result the future revenue is almost certain to differ from the estimates. The complexity is increased when one considers that there are several steps within the battery market supply chain. Many different industrial players are involved in order for the batteries to be manufactured and sold.[134] That said, the Solar Energy Industry Association of the USA, (SEIA) predicts strong growth in utility

[132] ibid.
[133] ibid.
[134] Battery market supply chain: chemical supply > battery production > integration > use > recycle/re-use

scale PV projects, and forecasts that 12GW of new utility scale PV generation will come online in 2016, almost triple that of 2015. In addition to this, SEIA also noted that 19.8GW of utility-scale are 'contracted for or under construction.'[135] Bloomberg New Energy Finance forecasts that solar will, 'boom worldwide, accounting for 35% (3,429GW) of capacity additions and nearly a third ($3.7 trillion) of global investment, split evenly between small and utility-scale installations.'[136] Their forecasting was up to 2040. In light of this it would appear that there is very strong growth in utility-scale solar PV, and that it is set for a very bright future. How much installed battery capacity there will be is very difficult to predict, but the opportunity for integrated battery-solar PV systems is certainly growing at a rapid rate. The different value streams offered through different applications of battery storage only serve to emphasize utility and economic advantages. This is especially the case with integrating a higher level of renewable energy into the energy system, the use of which is forecasted to rise in the following years.

In regards to residential and small-scale solar PV, Bloomberg New Energy Finance writes the following: 'The real solar revolution will be on rooftops, driven by high residential and high commercial power prices, and the availability of storage.'[137]The publication goes on to say that by 2040, just under 13% of global generating capacity will be small-scale PV.[138] This is highly significant. As we have already seen in chapter 2, solar PV-battery storage systems are economically viable under a range of different price scenarios. It was also found that the optimal size of both the system and storage rises over time. As lithium-ion batteries fall in cost it is likely that an increasing number of people install battery-PV systems, and reduce the amount of electricity they consume from the grid.

Before turning attention to the international market let us briefly investigate the status of the US solar market segments at the end of 2015. Figure 27 below shows the annual US solar PV installations from 2000-2015.

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[135]SOLAR ENERGY INDUSTRIES ASSOCIATION. (2016) *Demand for utility-scale solar still dominating.* [Online] Accessed on 5/4/2016. Available from: http://www.seia.org/blog/demand-utility-scale-solar-still-dominating
[136] Bloomberg New Energy Finance. (2015). New Energy Outlook 2015.
[137] Ibid.
[138] ibid.

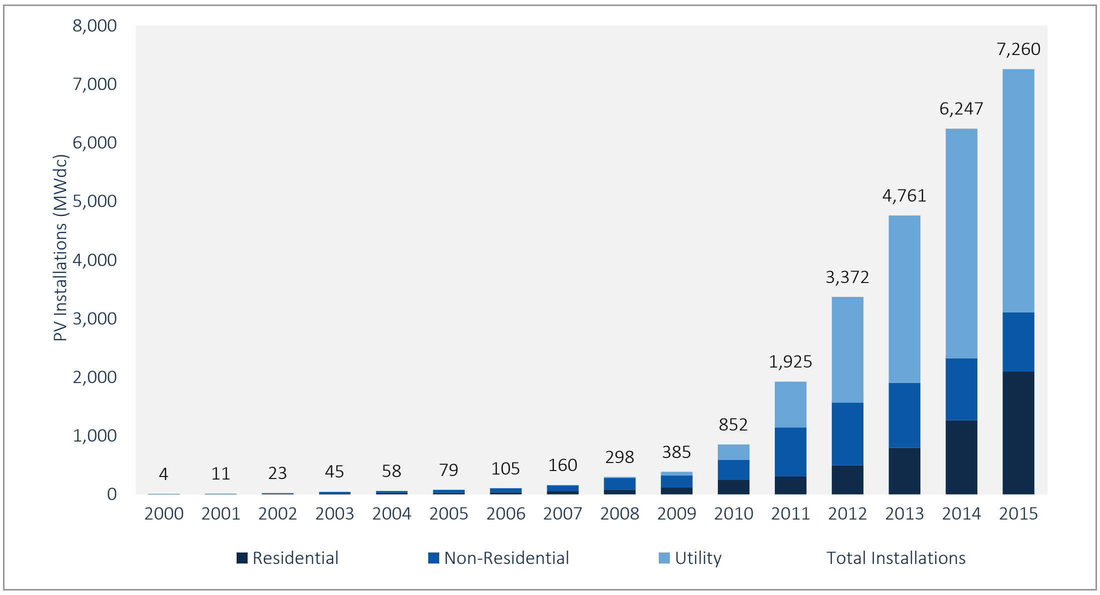


Figure 27: Annual US solar PV installations from 2000-2015[139]

- Utility solar PV installations remain the largest segment by capacity adding 4,150MW of capacity. This represents a 6% increase over 2014 and 57% of the total capacity installed in 2015. As noted, SEIA expects installations in this segment to triple to 12GW in 2016.

- The residential segment installed 2,099MW in 2015, which represented a 66% growth over 2014. The market grew at its largest annual growth rate in 2015. This is particularly impressive as it was the fourth year in which growth has exceeded 50%.

- Non-residential PV installations dropped 5% from 2014 levels with 1,011MW installed. The segment has suffered from flat-demand, but installations are expected to rise in 2015 with the installation of 'a triple-digit-megawatt pipeline of community solar projects.'[140]

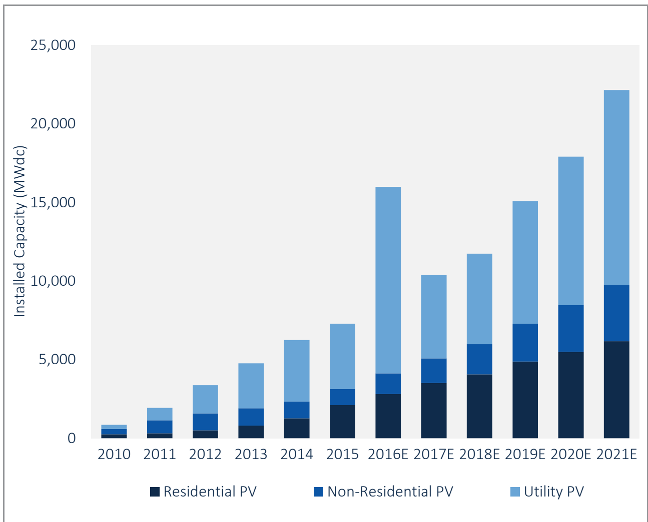
As figure 27 shows, the solar PV market in the US has experienced enormous growth. Regarding individual segments, utility scale remains the largest and is likely to remain so. Residential has been the fastest growing, but the overall growth in installations has been so great that in 2015 for the first time solar PV (29.4%) beat natural gas (29%) in capacity additions.[141]

Figure 28 below shows the US PV installation forecast until 2021 as well as the forecasts by segment. The reason 2016 has such a high level of additional capacity is due to a federal Investment Tax Credit, which was due to run out in 2016. The SEIA described congress' decision of a multi-year extension of the tax credit in December 2015 as,

[139] GMT RESEARCH & SEIA, (2016). U.S. Solar Market Insight, Executive Summary. *GMT Research & SEIA.* p.5.
[140] ibid.,p.6.
[141] ibid.

'without question…the most important development for U.S solar in almost a decade.'[142] Consequently, a considerable amount of capacity sought to take advantage of the tax credit, which explains the large amount of installed capacity forecasted for 2016.

What is the significance of this for the battery market? Well, it is likely to be very significant indeed as it greatly increases the opportunity of integrated solar PV-battery systems. In addition to the record breaking levels of solar PV capacity being added in 2015 and forecasted for 2016, there is another factor to consider: In 2015, 39% of new capacity additions in the US were made in Wind.[143] That means approximately 17GW of renewable energy was installed in the US in 2015. As has been shown in this investigation, battery storage technology is able to support intermittent renewable energy through a number of value-adding applications, and ultimately is able to achieve higher penetrations of renewable energy onto the grid. For these reasons, the market for battery storage technology appears set to increase, especially in regards to the utility and residential scale solar PV segments, not to mention large application opportunities with regards to wind power.



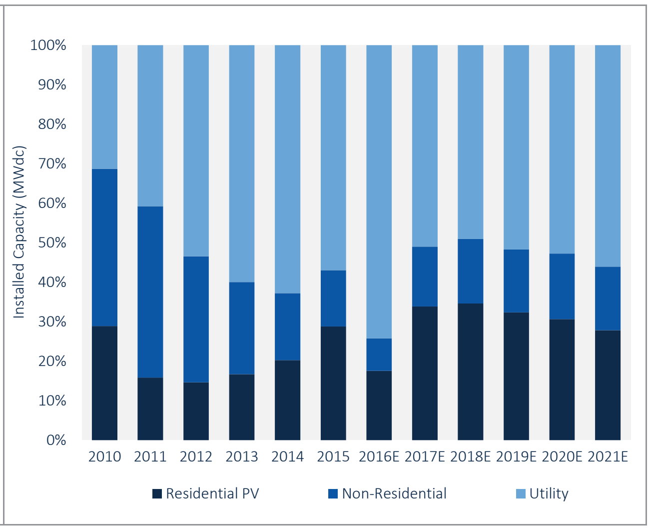


Figure 28: US PV installation forecast 2010-2021 & US installation forecast by segment[144]

Before turning to the international markets, it should be mentioned that 2015 saw a large amount of debate regarding solar regulations. The Public Utilities Commission (PUC) of California, reached a decision on net metering which has been largely viewed as favourable for solar. (Net metering is when utilities are required to buy excess electricity generated by homeowners' solar panels.) On the other hand, in Nevada the PUC has issued an order that increases customer fixed charges. This not only made it more expensive to use solar, but also made it uneconomical for those that had already signed up.[145] Although NV Energy, has proposed a 'grandfathering proposal', which allows the old rate structures for existing consumers, the debacle serves an example for the attitude of utilities towards solar. Regarding this Carl Pope writes the following:

[142] ibid. p.16.
[143] ibid. p.6.
[144] ibid. p.17.
[145] BUHAYAR, N. (2016) Who Owns The Sun? *Bloomberg BusinessWeek* [Online] Accessed on 7/4/2016. Available from: http://www.bloomberg.com/features/2016-solar-power-buffett-vs-musk/

'Utilities don't mind that solar is renewable, carbon free and enjoys free fuel – as long as they own it. But solar is also modular and decentralized, which they hate. They don't want to compete with their own customers. Rooftop threatens the sunk utility investments in centralised fossil power plants and their rigid "big to small – guaranteed return on capital" business model. Above a certain scale, rooftop solar will force utilities both to retire expensive central station power plants they want in their base rate and to transform their business model to accommodate small generator to large grid electron flow which rooftop solar enables.[146]

The themes that arise from the quote above will be focused upon in greater depth in Chapter 3. For now, let us draw the conclusion that the economic impact of the propagation of rooftop solar is unlikely to be in the best interests of utilities.

International markets

Table 4 below shows the installation targets of major markets for utility scale PV systems.

Market/Country	Installation Target	Share of Renewable Generation
China	150GW by 2020	20% by 2030
Japan	64GW by 2030	22-24% by 2030
US	-	20% by 2030
Germany	66GW by 2030	50% by 2030
UK	22GW by 2020	15% by 2020
India	100GW by 2022	40% by 2030
Taiwan	8.7GW by 2030	13.3 by 2030

Table 4: Installation targets of major markets and overall share of renewable generation.[147]

Achieving these installation targets will put utility-scale solar PV on the path to become the number one sector in terms of capacity additions over the next 25 years, which it is forecasted to become.[148]

According to an extensive study into energy storage carried out by AECOM, the key characteristics that influence investment response in international markets included the following:

- High penetrations of rooftop solar
- High penetrations of utility scale wind and solar[149]

[146]POPE, C. (2016). Rooftop Solar Wars Continue. *EcoWatch.* [Online] Accessed on 7/4/2016. Available from: http://ecowatch.com/2016/01/29/rooftop-solar-wars/
[147] ENERGY TREND. (2016). *Installed cost of utility scale PV system in the US down 17 percent.* [Online] Accessed on 5/4/2016. Available from: http://pv.energytrend.com/research/Installed_Cost_of_Utility_Scale_PV_System_in_the_US_Down_17percent_YoY_in_3Q15.html
[148] BLOOMBERG NEW ENERGY FINANCE. (2015). New Energy Outlook 2015. p.4.
[149] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.54

This suggests that the installation targets for utility-scale PV, systems shown in table 4, will have the effect of increasing the investment in battery storage technology. It is highly likely that this will also be the case with rooftop solar; that the increasing share of renewable generation as shown in figure 28 will lead to increased investment in battery storage.

U.S.A.

Currently the US is the market leader in battery storage implementation, with growth being driven by the country's 2009 federal stimulus package, the American Recovery and Reinvestment act (ARRA).[150] ARRA provided $100m for power sector battery storage projects. This amount was matched by private funds which made a total of $222m towards battery storage implementation. As shown in the introduction with 'the duck curve', the integration of variable renewable energy has created grid reliability issues. According to IRENA, this has 'drawn attention to the need to level the regulatory playing field and compensate non-traditional measures for the benefits they provide.'[151] In 2007 the Federal Energy Regulatory Commission (FERC) passed order 890. A requirement of the order was that energy storage began to be considered for ancillary and grid services. Essentially the order raised the possibility of battery storage not only providing grid services, but getting paid for them too.

In California the Renewables Portfolio Standard requires all utilities in the state to source a third of electricity sales from renewable sources by 2020.[152] The state also subsidizes battery installations by around $1.6/Watt through its self-generation incentive programme.[153] The program is one of the longest running distributed generation programs in the United States. It is expected that as the penetration of renewables increases there will be a growing demand for frequency control ancillary services. Traditionally these have been provided by slow responding fossil fuel generators such as gas turbines and coal powered generators. Battery technologies have faster response times for frequency regulation services and are able to do so with greater accuracy when compared to traditional services. In 2011 FERC order 755 was issued, which meant that the superior delivery of frequency regulation services was financially compensated. Wholesale markets were forced to pay for the actual quality and accuracy of the services provided. It is likely that this will make energy storage technologies more competitive in the frequency regulation market.

The California Public Utilities Commission has identified barriers which hinder the adoption of battery storage technology. These include the following:

- Lack of cohesive regulatory framework
- Lack of cost transparency
- Lack of commercial operating experience

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150 IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.32.
151 ibid.
152 AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.34
153 IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.32.

- Lack of definitive operational needs[154]

The lack of operating experience will improve over time as will the definitive operational needs. Regarding cost transparency, FERC order 784 was issued in order to clarify accounting and reporting rules for energy storage in ancillary markets. Thus although barriers still exist, there is clear evidence that they are being addressed and are likely to decrease in the future, making the adoption of battery storage technology increasingly viable.

On the east coast the state of New York has moved assertively to promote battery storage. On the 26th of February 2015, the New York State Public Service Commission issued an order adopting a regulatory framework and implementation plan for 'Reforming the Energy Vision' (REV). The aim is to encourage and reward participants (utilities/customers/service companies) for activities that contribute to grid efficiency. The plan has a strong emphasis in reducing both peak demand and capital investment in network infrastructure.[155] The New York Battery and Energy Storage Technology Consortium has been created and is introducing incentives which include, 'a planned $2100/kW battery storage incentive for 50% of the project cost for summer peak demand reduction.'[156]In light of this evidence, it would appear that the regulatory barriers hindering the adoption of battery storage technology are also diminishing within the United States.

Overall the policy landscape is active as since 2011 at least 10 states have introduced 14 bills related to energy storage, although it should be noted that not all have passed. Despite this the future prospects for the United States look very positive, as as we have seen installations across all market segments are forecasted to increase in the coming years. There has clearly been a focus on utility or 'front of the meter' storage recently (figure 28), but GMT research forecasts that by 2019 'behind the meter' storage, (residential/commercial/governmental), will account for 45% of the overall market, and will be led in markets such as California and New York where customers are exposed to high energy and peak demand charge tariffs.[157] As a result of these developments, the energy storage market in the US is forecasted to reach 861MW annually and be valued at $1.5Bn.[158]

Japan

Historically Japan has used energy storage to reduce the demand variability from its nuclear generators. Japan boasts the company Nippon Gaishi Kaisha (NGK), which is a world leader in sodium-sulphur batteries. However, the demand for this type is becoming overshadowed by the growth in demand for lithium-ion technology.[159] As a

[154] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.34
[155] ibid.35.
[156] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.33.
[157] BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
[158] ibid.
[159] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.42.

result of the 2011 Fukushima earthquake Japan lost 60GW of nuclear capacity and has turned to renewable energy in order to become less dependent on imported fossil fuels. The environment minister has even been quoted saying 30% of the country's energy should come from renewable sources by 2030.[160] The increased emphasis on renewable energy has been incentivized through FITs, which pay a high fixed price over 10 or 20 years. For solar PV installations of <10kW the incentive is currently $0.37/kWh, while the household retail electricity price is $0.21/kWh. This has given rise to rapid growth in solar PV, which at the end of 2014 stood at more than 10GW.[161]

Regarding battery storage, its implementation at a household level has followed the rise of renewables in spite of the high FITs. Although Japan recognizes that storage can lead to higher levels of renewable penetration, analysis by IRENA suggests that the the increasing implementation of battery storage is, 'fuelled by a desire for security of electricity supply given the recent nuclear shutdown. Other motivating factors include government subsidies and the avoidance of high retail electricity rates by increasing solar self consumption.'[162]

The subsidy program mentioned supports the installation of stationary lithium-ion batteries by individuals and businesses. It supports up to two-thirds of the cost payment system and is paid for by the Ministry of Economy, Trade and Industry (METI) with budget of $98.3m.[163] According to BNEF, the number of applications received had already exceeded the allocation of the budget before the end of 2014.[164] The subsidy program has clearly been a success in terms of homeowner and business participation.

Rather than encouraging implementation, perhaps a greater challenge for Japan regarding batteries will be producing them. The Japanese government is aiming for Japanese companies to achieve half of the world's battery storage market share by 2020. This is to be achieved in an attempt to see how mass production will aid self-sufficiency for the country by driving the cost of batteries lower.[165] The METI announced its policy on battery storage in 2012. If it is to be successful in realizing its objective, then it calculates that the Japanese manufacturers will move from a market value of less than one trillion yen in 2011 to ten trillion yen in 2020.[166] It remains to be seen whether or not this will be achieved. However, what is certain is that Japan, like the US, has a very active policy approach to energy storage. It seeks to improve upon both residential and industrial policies, create future markets and targets global blocks to the adaptation of storage technology.[167]

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[160] ibid.43.
[161] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.34.
[162] ibid.
[163] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.42. Payments are capped at approximately $10,000 for individuals and $980,000 for businesses installing battery systems with a capacity of 1kWh or more.
[164] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.34.
[165] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.42.
[166] IRENA. (2014). Policies and Regulations for Energy Storage in Japan. *Institute of Energy Economics Japan.* [Online] Accessed on 10/4/2016. Available from: http://www.irena.org/DocumentDownloads/events/2014/March/6_Tomita.pdf
[167] BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from:

Germany

Germany is a world leader in renewable energy implementation and has the ambitious targets of generating 50% of its electricity from renewable sources by 2030,[168] and 80% by 2050.[169] Energy storage is viewed as an important enabling technology in achieving these goals. In response to the 2011 nuclear meltdown in Japan, Germany plans to phase out its remaining nuclear power plants by 2023. This will have profound consequences for the energy infrastructure of the country. As increasing amounts of renewable energy are integrated onto the grid major investment will be needed in the transmission grid and storage solutions. This is emphasized by the fact that the geographical makeup of the country makes pumped hydro storage very difficult.[170] Storage technologies as well as smart grids will play crucial roles in integrating variable renewable energy and ensuring grid stability. To this end the German Federal Ministry for Economic Affairs and Energy and the Germany Federal Ministry of Education and Research are funding approximately 200 projects on energy storage with a total of €202m.[171]

Despite there being utility-scale battery storage applications, the current driver is at household level implemented with solar PV. Germany is understood to be a world leader in this area and in 2013 the country had the most solar PV installed both on a total and per capita basis.[172] Around 20% of new solar PV installations now include battery packs,[173] and current economic trends are likely to give rise to greater implementation of solar PV with battery storage. There are several reasons for this: Firstly, retail rates are above €0.30/kWh and have been rising. Secondly, integrating storage is presented with an opportunity cost, as FITs for solar generation are falling. And finally, battery costs are declining.

The trends listed above are accelerated by subsidies given to batteries. From May 2013 the German government has provided a grant of 30% the battery cost as well as a low-interest loan program for solar PV owners wishing to add under 30kW of storage to their system.[174] The overall aim is to encourage the adoption of battery storage with PV systems. It has been successful as by October 2014, around 6,500 battery-solar PV systems had been installed as a result of the subsidy.[175] In addition to this approximately 4,000 systems have been installed without government subsidy, which means that by the end of 2014 around 12% of solar PV systems were installed with a battery system.[176]

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http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
168 ibid.
169 IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.35.
170 BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
171 ibid.
172 IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.35.
173 BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
174 ibid.
175 IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.36.
176 ibid.

There is undoubtedly strong growth in integrated battery-solar PV systems for homeowners in Germany. It is logical that that this trend will only increase in future years as battery storage becomes increasingly financially attractive due to the trends outlined above. According to Deutsche Bank, the German market for electrical storage devices is expected to 'at least double between 2012 and 2025.'[177] Largely due to solar PV owners and the opportunities they are presented with, battery storage is set for a bright future in Germany.

China

China is the worlds largest producer and consumer of energy and and also boasts the most installed generational capacity. Consequently, the country plays a key role in all global energy markets. The power sector of the country has traditionally focused on coal and other fossil fuels, but in recent years this has shifted. Growing electricity demand, concerns over security of supply, energy source diversification and environmental concerns are all contributing factors. IRENA notes that China's renewable energy capacity has grown exponentially in recent years, and has some of the largest wind and solar farms in the world.[178] On the other hand, the integration of renewables has also been obstructed by a lack of transmission infrastructure. For example, in 2012 the total installed wind capacity was 75GW, but only 61GW could be utilized.[179] Other sources suggest that some wind farms lose up to 40% of their generation.[180]

Due to this, there is a new policy directive in China that requires intermittent generators to be paired with energy storage as a grid connection requirement.[181] The policy is said to apply at all levels from rooftop solar to utility wind. The implications of this policy, especially given the rise in renewable generation, is described as "staggering" in one report.[182] State Grid, the government owned transmission and distribution company, has recommended that the storage systems are sized at 14% of the installed generational capacity. In light of this, the battery market in China appears in its infancy.

Research forecasts an $8.5bn energy storage market by 2025. Many current projects focus on EV applications which are forecasted to play a large role in the increasing demand. Transport applications are expected to take an 85% share of the revenues of the quoted figure.[183] $1.3bn is likely to be made from stationary applications.[184] This will be realized through integrating higher levels of renewable energy with firms focused on

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[177] BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
[178] IRENA. (2015). Battery storage for renewables: Market Status and Technology Outlook. p.36.
[179] ibid.
[180] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.41
[181] ibid.
[182] ibid.
[183] BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
[184] ibid.

grid-scale energy storage. However, in light of the outlined policy directive and growth in renewable generation, this figure could likely be higher. Renewable integration (27%) and EV's (13%) are expected to make up the second and third largest applications, while user-side applications are expected to account for 50% of China's energy storage market.[185]

It is also noteworthy that 74% the electrical storage market in China uses lithium-ion technology.[186] This high percentage is understandable as it is the type most suited to EVs. It is also in clear contrast to Germany, where many of the batteries used for integrated solar PV-battery systems are both a different type (lead acid), and a different application (residential). That said, lead-acid batteries have proven to be a popular choice for solar integration projects on islands that would otherwise be forced to rely on imported diesel for power generation.[187]

China's energy storage industry has been growing at a rapid pace. By the end of 2014 China had 84.4MW of installed capacity on the grid (not including pumped hydro and thermal storage). This was an increase of 31MW and a growth rate of 58%, a considerable increase from 14% in 2013.[188] In addition to being the world's largest producer and consumer of energy, China is quite possibly the most ambitious: It plans to increase its wind capacity from 100GW in 2015 to 200GW by 2020. Solar is to be increased from 35GW to 50GW in the same time period.[189] The combination of these targets, backed up by a series of wide ranging reforms that started being released in 2015, suggest that the energy storage industry is set for further growth in the future. The reforms are a combination of 13 policies, the last of which will be released in 2016. The Chinese Energy Storage Alliance (CNESA) is able to provide information on the energy sector reforms and how they will address the existing barriers. These include:

- Ancillary service compensation to increase
- Peak shifting compensation to increase
- Compensation for pairing of wind farms with coal fired generation to increase
- Demand-side management to increase (with encouragement)
- Distributed generation is being encouraged[190]

With the introduction of so many reforms it will take time to understand fully the effects they have and the success they enjoy in overcoming barriers. Overall there is an increasing level of flexibility in the energy sector. New policies are favouring distributed generation and encouraging private investment, which will open the market to increased levels of competition and new sources of capital. Moreover, supply-demand reflexive pricing is to be introduced by 2020. As prices become more dynamic, (being set by market forces, rather than driven driven by policy), there will be greater flexibility and increased responsiveness from the market.

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[185] ibid.
[186] ibid.
[187] ibid.
[188] ibid.
[189] ibid.
[190] ibid.

Summary

Investigation into the markets of key countries has confirmed the findings of the AECOM study, that high penetrations of rooftop solar and high penetrations of utility scale wind and solar, influence investment response in energy storage. Of the limited number of countries included in this investigation Germany and the US appear to have the most advanced energy storage programs, with the investment focus spread across all applications. In general, the countries share a number of themes. Germany and China are seeking to improve their transmission infrastructure and all of the countries have provided incentives for those seeking to utilize battery storage. In Germany the declining FITs for renewable energy is a factor that will likely contribute to greater implementation of energy storage. As support for renewables declines, the implementation of battery storage is likely to increase. As the first part of the chapter shows, storage systems are more profitable where retail prices are high.

Regulatory changes are another common theme and are made in an effort to counter a key barrier to storage implementation – the lack of a cohesive regulatory framework. The most extensive reforms are in China, but those taking place in the US are extremely noteworthy as there is an increasing trend for services being provided by battery storage to receive compensation based on their quality and accuracy. As noted, this is likely to make certain markets related to energy storage more competitive. Creating an organised and interrelated framework, where compensation is available for the wide range of applications that energy storage can provide, while increasing competition, would logically have the effect of driving storage implementation. Not only would battery storage be able to seek compensation by providing services through an increasing number of applications, but rather a stronger regulatory framework might inspire greater confidence in further investment.

A working paper published by the European Commission identifies technological and regulatory issues as key challenges for storage. In addition to these, a strategic challenge is noted: The Commission recognises the need to develop a, 'systemic or holistic approach to storage, bridging technical, regulatory, market and political aspects.'[191] The development of such an approach will be of paramount importance to energy storage in the future. As the Commission concludes, 'the main challenge for energy development is economic.'[192] Creating the necessary environment for investment is crucial.

The chapter has shown that energy storage and its associated markets will grow for a number of reasons. Residential solar PV-battery systems have been shown to be economically viable under a number of different scenarios. For the sake of this investigation, it should be highlighted that the optimal size of these systems is set to increase which will cause an increasing number of homeowners to become net energy producers. Due to the falling cost of lithium-ion batteries, utilities and homeowners will be able to integrate higher percentages of renewable energy more efficiently. Energy storage will also give businesses and individuals more control over their energy system.

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[191] EUROPEAN COMMISSION. *Working Paper: The future role and challenges of Energy Storage.*
[192] ibid.

The use of lithium-ion technology in electric cars is a further reason why the energy storage market is set to grow. China is forecasted to earn $7.4bn in revenues from transport applications by 2025, and has a target of 10m EVs deployed by 2020.[193] In the US on the 31st of March 2016, the company Tesla unveiled its Model 3 car. This is technically the fourth EV the company has released, but represents the company's first mass market EV. Writing on their blog on the 7th of April, the Tesla team said that they had received 325,000 reservations. This corresponds to, 'about $14 billion in implied future sales, making this the single biggest one-week launch of any product ever.'[194] By means of comparison, Apple's largest launch achieved $8.5bn in sales when the iPhone 6S sold 13m units on its opening weekend.[195] (A device that also uses a lithium-ion battery). Those customers who deposited the required $1,000 are able to be refunded until the final sale of the car, with deliveries due at the end of 2017. The fact that the company did not advertise the Model 3 only serves to highlight the public desire for sustainable transportation.

Thus, although other types of battery are used, lithium-ion appears the technology of choice in most markets. As shown in chapter 1, the technology enjoys advantages regarding efficiency and lifecycle. It has also shown to be cost-competitive and enjoys 'perceived safety' according to one report.[196] The safety of the technology, as well as its environmental impacts are undoubtedly important and shall be investigated accordingly in the final chapter.

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[193] BLUME, S (ed). (2015) Global Energy Storage Market Overview & Regional Report Summary. *Energy Storage Council.* [Online] Accessed on 10/4/2016. Available from: http://neca.asn.au/sites/default/files//media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf

[194] TESLA. (2016). *The week the electric vehicles went mainstream.* [Online] Accessed on 13/4/2016. Available from: https://www.teslamotors.com/blog/the-week-electric-vehicles-went-mainstream?utm_campaign=Blog_Model3_040716&utm_source=Twitter&utm_medium=social

[195] CNN MONEY. (2016). *Tesla Model 3's first week: 325,000 orders.* [Online] Accessed on 13/4/2016. Available from: http://money.cnn.com/2016/04/07/autos/tesla-model-3-orders/

[196] AECOM. (2015). Energy Storage Study. *Australian Renewable Energy Agency.* p.54.

Chapter 3: The impact of battery storage technology in perspectives

Chapters 1 and 2 have provided insight into both technical and economic aspects of battery storage technology. The final chapter of this investigation seeks to gain greater understanding of battery storage and evaluate the impact that its increasing deployment may have. This is to be achieved by examining it through a series of different perspectives and asks what the implications of increased battery storage use will be.

Environmental perspective

This report has mostly focused on solar PV as the renewable source of energy integrated with battery storage. When compared to other sources of energy such as coal or gas powered plants, solar PV is understood to generate considerably less emissions over its life-cycle.[197] Regarding battery storage, it is a sensible assumption that the increasing profitability of storage systems will result in their increasing deployment. This raises environmental concerns over the levels of pollution that such diffusion may have. As has been shown there are various different types of battery. The different types all have different environmental impacts. As this investigation has focused on lithium-ion and lead acid batteries, it is important that the impact of their production, use and disposal is understood.

Production

The production of lithium-ion batteries is understood to have severe impacts. Normally lithium is found in the brine of salt flats. Brine is pumped to the surface and evaporates in ponds, allowing lithium carbonate to be extracted through a chemical process. There are other lithium deposits, such as sedimentary and igneous rock, but as McManus notes, 'much of the global lithium is supplied through brine deposits as it is the closest to the surface.'[198] These salt flats are located in arid territories, with the largest mines being in the Atacama desert in South America. Mines also exist in China and Tibet.[199] Regarding these locations Zacune writes the following:

'In these places, access to water is key for the local communities and their livelihoods, as well as the local flora and fauna. In Chile's Atacama salt flats, mining consumes, contaminates and diverts scarce water resources away from local communities. The extraction of lithium has caused water-related conflicts with different communities, such as the community of Toconao in the north of Chile. In Argentina's Sala de Hobre Muerto,

[197] HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.25.
[198] McMANUS. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy 93 p.289.*
[199] ibid.

local communities claim that lithium operations have contaminated streams used for humans, livestock and crop irrigation.'[200]

Thus, largely due to water depletion and pollution, the lithium extraction process is understood to have significant environmental and social impacts. This is supported by the work of McManus, who notes that lithium batteries have an impact on human toxicity and concedes that the, 'mining of lithium can cause significant human health and social impacts.'[201] However, these environmental impacts are not only confined to lithium-ion batteries. Lead acid batteries contain sulphuric acid in addition to toxic lead, which generates carbon emissions during the mining process. Although as we shall see, the environmental impact of lead-acid battery types can be reduced when correctly recycled.

In terms of which batteries are the most energy intensive to produce, here again lithium-ion fairs poorly as table 5 shows below.

	Climate change (kg CO_2 eq)	Metal depletion (kg Fe eq)	Fossil fuel depletion (kg Oil eq)	Cumulative energy demand (MJ/kg)
Lead acid	0.9	0.4	0.3	17
Lithium ion (NMP solvent)	12.5	20	1.6	90
Lithium ion (water solvent)	4.4	20	1.5	88
Nickel cadmium	2.1	1.5	0.7	37
Nickel metal hydride	5.3	3.2	1.6	90
Sodium sulphur	1.2	3.2	0.4	19

Table 5: Characterised impact per kg of battery production[202]

The table shows that the lithium-ion batteries and nickel metal hydride are the most energy intensive batteries to produce. Lead acid and sodium sulphur are the least energy demanding. In terms of metal depletion, the lithium varieties are by far the most demanding. They are also the most demanding technology, along with nickel metal hydride, for fossil fuel depletion.

In spite of this, comparing the impact of the production of batteries by weight may be unfair.[203] As has been shown in chapter 1, some batteries have superior performance per unit of weight during their life-cycle, as energy density differs between different types. Because of the differences in life-span and charge/discharge cycles that different batteries enjoy, McManus believes that to understand the true impact of production, batteries must be examined on an energy basis. Table 6 below shows a comparison of batteries on a per energy basis.

[200] ZACUNE, J, (2013). Lithium. *Friends of Earth Europe.* [Online] Accessed on 18/4/2016. Available from: https://www.foeeurope.org/sites/default/files/publications/13_factsheet-lithium-gb.pdf
[201] McMANUS. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy 93 p.289.*
[202] ibid.
[203] ibid.

Impact category	Unit	Lead acid	Lithium ion	Nickel cadmium	Nickel metal hydride	Sodium sulphur
Climate change	kg CO_2 eq	5–7	17–27	10–15	16–20	2
Ozone depletion	kg CFC-11 eq	(2.24–3.35)E–07	(3.34–5.23)E–04	(7.64–12)E–07	(5.44–6.85)E–07	1.26E–07
Human toxicity	kg 1,4-DB eq	6–8	3–5	4–6	1.7–2.1	0.6
Photochemical oxidant formation	kg NMVOC	0.03–0.04	0.03–0.05	0.38–0.59	0.12–0.25	0.007
Particulate matter formation	kg PM10 eq	0.02–0.03	0.03–0.04	0.88–1.38	0.45–0.57	0.0085
Ionising radiation	kg U235 eq	1.1–1.5	2.7–4.1	3.4–5.3	2.3–2.9	0.3
Agricultural land occupation	m^2	0.12–0.17	0.15–0.23	0.21–0.32	0.13–0.16	0.04
Urban land occupation	m^2	0.08–0.12	0.22–0.34	0.29–0.45	0.17–0.21	0.05
Natural land transformation	m^2	0.0011–0.0015	0.0021–0.0033	0.0019–0.0029	0.0013–0.0016	0.00033
Water depletion	m3	0.07–0.1	0.121–0.191	0.25–0.39	0.14–0.174	0.024
Metal depletion	kg Fe eq	2–3	28–44	7–10	9–12	4
Fossil depletion	kg oil eq	1.8–2.6	2.2–3.4	3–5	5–6	0.5

Table 6: Characterised data range for battery production per MJ capacity[204]

Under the impact categories of climate change (greenhouse gas emissions) and metal depletion, lithium-ion is the worst performer. This is true both per kg of battery production (table 5), and per energy capacity (table 6). Lead acid and sodium sulphur are the best performers. Thus, despite the advantages that lithium-ion has over other battery types in terms of energy density and power, it has clear disadvantages too. The theme of resource depletion is one that is very significant with lithium-ion technology, and as demand for lithium increases it will become increasingly so. The demand for lithium has increased dramatically in the past and this trend looks set to continue. Its use in rechargeable batteries has increased from 0% of the market share in 1991 to 80% in 2007.[205] More relevant for this investigation is the increasing use of lithium in EVs. This has lead to concerns among manufactures that consumer demand may overtake supply by 2020, and many companies have taken measures in order to secure access to lithium deposits[206] Despite their concerns, McManus estimates that there is enough lithium to meet the demand this century.[207] Research carried out by Navigant doesn't contradict this, although it does raise some interesting points: In particular their research indicated that by around 2020 the annual market will cross the 150GWh threshold. The implications of this being that pricing will begin to be affected by the demand for batteries.[208] Other necessary materials such as cobalt also face scarcity challenges. Navigant describes the sourcing of the element as 'very very constrained' as it comes from conflict zones and thus has human rights implications in its use.[209] In light of the above the environmental costs of sourcing the materials to meet this demand will be considerable. Although they may not appear significant factors today, as the industry grows and demand for materials multiplies it is likely that they will only increase in their severity.

Use

The use of lithium-ion batteries brings with it two key hazards. These can be classified as the following:

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[204] ibid.
[205] ZACUNE, J, (2013). Lithium. *Friends of Earth Europe.* [Online] Accessed on 18/4/2016. Available from: https://www.foeeurope.org/sites/default/files/publications/13_factsheet-lithium-gb.pdf
[206] ibid.
[207] McMANUS. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy 93 p.289.*
[208]NAVIGANT RESEARCH. (2014). Webinar Replay – Beyond Lithium Ion. [Online] Accessed on 19/4/2016. Available from: https://www.navigantresearch.com/webinarvideos/webinar-replay-beyond-lithium-ion
[209] ibid.

- **Chemical** – This refers to the accidental exposure of chemicals within the battery. This could be a spillage or a gas emission. In both cases the hazard is linked to the corrosive and flammable properties of the chemicals.
- **Electrical** – The current flow within a battery creates heat through the Joule effect.[210] It is important that the heat generated by charging and discharging is controlled by a thermal management system. Protection against high electrical currents and short circuits are also important. In addition to the current flow, the state of charge must also be controlled. The temperature of the battery can increase through overcharge and over-discharge as the reactions can be more exothermic than normal.[211]

The potential cumulative effects of the hazards outlined above is known as "thermal run-away." This occurs when the temperature increases, (usually in a kind of uncontrolled positive feedback), to a point that is destructive to the battery. A Recharge report on the safety of lithium-ion batteries gives an example:

'In case of a short circuit, the Joule effect will increase the cell temperature to the point where the organic solvent leaves the cell via the vent. At this time any hot spot may induce a fire. The possible consequences of this cumulative effect are…fire, toxic or harmful gas emission and the ejection of parts'[212]

It is clear that the use of lithium-ion technology is not without its risks. The battery itself is an article with no intended release of its substances.[213] If the contents are released in an accident then an emergency response will be prompted. It is noteworthy though that they are equipped with electronic protections in order to avoid their misuse, that they are shock resistant, and can be safely operated in a wide temperature range. Ultimately a truly vast amount of electronic equipment is powered by these batteries throughout the world every day. This confirms the fact that the safety of lithium-ion batteries is well managed, which has lead the technology to be regarded as one of the safest energy storage systems.[214]

Disposal

In September 2006 the European Parliament issued directive **2006/66/EC** – On Batteries and Accumulators and Waste Batteries and Accumulators. It is commonly known as "the battery directive", and regulates the manufacture and disposal of batteries within the European Union. It has the aim of 'improving environmental performance of batteries and accumulators.'[215] According to McManus, the regulations

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[210] RECHARGE – THE EUROPEAN ASSOCIATION FOR ADVANCED RECHARGEABLE BATTERIES. (2013). Safety of lithium-ion batteries. Belgium.
[211] ibid.
[212] ibid.
[213] RECHARGEBATTERIES.ORG. (2013). Battery information factsheet: Lithium-ion batteries.
[214] RECHARGE – THE EUROPEAN ASSOCIATION FOR ADVANCED RECHARGEABLE BATTERIES. (2013). Safety of lithium-ion batteries. Belgium.
[215] DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC p.5.

'form part of the producer responsibility suite of regulations and requires battery producers to take care of their waste.'[216] He notes that producers that place more than one tonne of portable batteries in the UK market are required to pay for the collection, treatment, recycling and disposal of waste batteries in proportion to their market share. This is normally done through a compliance scheme which also registers the producers with the appropriate environmental agency.[217] It should also be mentioned that producers placing less than one tonne are still required to register with an environmental agency.

The legislation is expected to increase the number of batteries recycled, meaning that the impact of resource depletion should be reduced. Gaines writes that in an ideal system, lithium-ion batteries would be sent for responsible recycling and not be exported to developing countries with less stringent environmental, health and safety regulations.[218] It is important to stress the different ways in which recycling is important for the environment. Not only is resource depletion mitigated, but as Gaines points out if they are recycled then they cannot be transported to countries which are unlikely to have the necessary recycling infrastructure to depose of the batteries correctly. In such countries the battery is likely to end up as waste with both human toxicity potential and ecotoxicity potential.[219] She also points out that the recycled product needs to be of high enough quality to find a market for its original purpose, or it must find an alternative market.[220]

Although lithium is a finite resource, it is unlikely to run out in the near future due to the use of batteries.[221] Rather, as its mining has been shown to have a high environmental cost, appropriate measures should be taken regarding its recycling process and the recovery of materials. If the batteries end up on a landfill site, then the materials within the battery are not able to be recovered. The result of this is the increased extraction of raw materials, which uses large amounts of energy and creates emissions that are harmful to the environment. In addition, if batteries end up on a landfill site then they may leach toxic chemicals into the soil. The repair and re-use of batteries is not possible. Recycling is the only way of recovering the valuable materials.

Kumar states that the battery recycling market is largely price driven.[222] It is important to remember that recycling companies are businesses and aim to maximise profit from the sale of recovered materials. In lithium-ion batteries the most valuable materials are

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216 McMANUS. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy 93 p.289.*
217 ibid.
218 GAINES, L. (2014) The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustainable Materials and Technologies. 1-2 2-7.*
219 BOYEN, ANNA. (2014) The environmental impacts of recycling portable lithium-ion batteries. *Australian National University.*
220 ibid.
221 McMANUS. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy 93 p.289.*
222 WASTE MANAGEMENT WORLD. (2011). The Lithium Battery Recycling Challenge. [Online] Accessed on 19/4/2016. Available from: https://waste-management-world.com/a/1-the-lithium-battery-recycling-challenge

cobalt, nickel and copper.[223] The aforementioned battery directive of the European Commission states that the recycling processes must achieve the minimum recycling efficiency of, '50% by average weight of other waste batteries and accumulators.'[224] Lithium-ion is within this category. Clearly there is no obligation to recycle certain materials and as a result the most valuable materials are recovered. However, based on a typical lithium-ion battery the recovery of cobalt, nickel and copper would achieve an efficiency of about 30%.[225] Therefore in order to meet the target efficiency as stated by the European Commission, more materials are required to be recovered. If aluminium, steel, lithium and manganese were recovered too, the target would be achieved as the materials constitute about 57% of the battery's composition.[226] Recycled lithium itself is up to 5 times more expensive than obtained by the cheapest process.[227] This currently makes its recovery not economically viable. As the US has no battery directive and the the process is entirely cost driven, it could be the case that only a fraction of lithium is recycled in the coming years.

Regarding Lead-acid batteries, they are said to be recycled more than any other consumer product, and in the US approximately 99% are recycled.[228] When recycling the lead the environmental impact of the batteries is significantly reduced. Furthermore, the recycling operation itself is profitable as the recycled lead is of high quality. Gaines notes that because of this there is, 'little incentive to export to places with less-stringent regulations.'[229] One major advantage of recycling lead-acid batteries is that the process is relatively simple and the materials homogeneous. Despite this, Hopperman writes that the use of lead-acid batteries is more problematic in countries which do not yet possess a, 'working recycling infrastructure.'[230] Having a functioning recycling infrastructure is of paramount importance in limiting the environmental effects of batteries.

As lithium demand is set to grow in the future and resources increasingly finite, it would suggest that recovering the materials from used batteries will become increasingly economically viable. It is not only the environmental impact of mining the required materials and their improper disposal which are reasons for recycling. Rather, the price driven recycling market may find increasing returns in recovering valuable materials. Despite this the current trend in lithium-ion technology is towards cathode materials that do not contain cobalt.[231] This threatens the profitability of recycling. It may be the

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[223] BOYEN, ANNA. (2014) The environmental impacts of recycling portable lithium-ion batteries. *Australian National University.*
[224] DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC p.27.
[225] BOYEN, ANNA. (2014) The environmental impacts of recycling portable lithium-ion batteries. *Australian National University.*
[226] ibid.
[227] ibid.
[228] ibid.
[229] ibid.
[230] HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H.. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.25.
[231] BOYEN, ANNA. (2014) The environmental impacts of recycling portable lithium-ion batteries. *Australian National University.*

case that the threat is greater outside Europe where there are no laws targeting recycling efficiencies. This would suggest that legislation similar to the battery directive may be required. A cost comparison of recycling companies showed that companies will most commonly buy batteries with cobalt, and may even charge a fee if they don't contain it.[232]

In general, the recycling processes are most commonly aimed at increasing the number of materials recovered, as well as improving environmental effects of emissions and energy consumption. Regarding lithium-ion varieties, there is a trend for these processes to become increasingly specialised in order to achieve the best results, with different batteries having a specific recycling process, each dedicated to the specific chemistry.[233] Although not the direct concern of this paper, investigation into how increased battery use would affect the US recycling industry would be interesting.

Internationalization perspective

This investigation has defined internationalization as the process of achieving international control or the process of making something international in character. In economic terms it was described as the spread of economic activity over national boundaries. Following on from environmental perspectives, let us find an immediate example of internationalisation.

According to Kumar, the concern for reliable sources of lithium has lead to inter-governmental partnerships, and also partnerships between original equipment manufacturers (OEMs) and governments. For example, EV manufacturers such as Mitsubishi have forged partnerships with lithium-exploration companies and invested large sums to develop lithium deposits in Argentina. This has been done in an effort to safeguard and secure the lithium resources to fulfil their needs. Furthermore, Japan has forged a partnership with the Bolivian government. This agreement binds Japan to offer, 'comprehensive economic aid in exchange of supplies of lithium and other rare metals.'[234]

Developments such as the ones outlined above are a clear example of internationalisation. Companies and governments are seeking increasing control over the materials required to manufacture lithium-ion batteries. This is done as requiring the materials constitutes the "upstream" part of the global value chain. Increased internationalisation, through participation in global value chains, provides the opportunity to achieve economies of scale, expand market share and increase productivity. Moreover, participation in value streams and cooperation with other partners is likely to enhance the flow of information and learning. It can also introduce new business practices and more advanced technology which could lead to greater growth and revenues. The partnerships outlined serve as an example of increasing

[232] ibid.
[233] ibid.
[234] WASTE MANAGEMENT WORLD. (2011). The Lithium Battery Recycling Challenge. [Online] Accessed on 19/4/2016. Available from: https://waste-management-world.com/a/1-the-lithium-battery-recycling-challenge

stakeholders in the lithium supply chain. As governments and enterprises seek to involve themselves in economic activity over national boundaries in order to gain control over materials, internationalisation is clearly present.

Internationalisation is also evident through increased participation in the "downstream" of global value chains. In the recent past there has been an increase in the number of solar PV suppliers entering into the US market. This is not only true of solar PV equipment but also battery systems too. To pick an example, in 2015 the Japanese company Tabuchi presented a 10kWh EneTelus Intelligent Battery System to the U.S. market for the first time.[235] It is noteworthy that the battery is designed for the residential storage market. Regarding solar power, downstream costs are forecasted to decrease. In 'Trends in Energy Finance' it was shown that upstream costs had decreased significantly over recent years. Analysis by McKinsey & Company has shown that even though module costs should continue to fall, even bigger opportunities are available in the downstream costs associated with installation and service. Their research shows that half the expense of installing residential solar systems in the US is comprised of downstream costs, and that as they become cheaper the overall costs to consumers will fall from $2.30 per watt in 2015 to $1.60 by 2020.[236] In light of this, not only is internationalisation present throughout the value chains of both solar PV and battery storage, but it may also have the effect of lowering costs. This shall be commented upon in the following section.

As an important part of this investigation is into the impact of battery storage on centralised energy systems, it is important that the potential consequences to utilities are well understood. The following and final section of the investigation will focus on battery storage technology from both the public and utility perspective, and their relationship with each other. It will investigate the dynamic between them, and show how this is set to change as a result of what been presented throughout this report. Beforehand, and in order to conclude the perspective of internationalisation, let us return briefly to 'trends in energy finance'.

'Trends in energy finance' also showed increasing levels of internationalisation as there was an increasing involvement of enterprises, mostly Chinese, across national boundaries. In addition, different parts of the solar PV value chains were present in different countries. Solar cells manufactured in China were commonly integrated into systems in Europe. It should be noted that although internationalisation has been shown to lower costs, 'trends in energy finance' showed that the low prices of Chinese PV cells impacted European PV manufacturers badly, with many going out of business. Thus, although internationalisation is present regarding Solar PV technology and battery storage technology, the low prices that brings can negatively affect businesses. Ultimately however, increasing internationalisation has been shown to play a key role in the energy transition towards a system based on renewable energy sources.

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[235] PV MAGAZING. (2015). Intersolar North America. Tabuchi's market entry points to increasing internationalisation. [Online] Accessed on 19/4/2016. Available from: http://www.pv-magazine.com/news/details/beitrag/intersolar-north-america--tabuchis-market-entry-points-to-increasing-internationalization_100020228/#axzz46Rokh8cm

[236] McKINSEY & COMPANY. (2016) The disruptive potential of solar power

Public/Utility perspective

The previous section showed how increasing levels of internationalisation contributed to falling costs. The falling cost of renewable energy is of great interest to this investigation. As it becomes increasingly competitive with traditional power generation technologies, such as coal, gas and nuclear, it has the potential to disrupt the utility sector. In 2015 the US Energy Information Administration calculated that solar energy accounted for 0.6% of total electricity generation. Although this number is very small McKinsey & Company write the following:

'The business model for utilities depends not so much on the current generation base as on installations of new capacity. Solar could seriously threaten the latter because its growth undermines the utilities ability to count on capturing all the new demand which historically has fuelled a large share of annual revenue growth.'[237]

In terms of the impact of solar on utilities, the fact that the current percentage generated through solar is so low is somewhat misleading. What is more relevant is the demand for new installations. McKinsey & Company suggest that new solar installations could account for up to half of new consumption, and that by altering the demand side of the equation, solar is able to affect the amounts of capital that utilities are able to deploy. The reason for this is that they have a predetermined return on equity.[238] That is to say that solar, in spite of its low electricity generation percentage, has the ability to have an oversized effect on the economics of utilities, and consequently the future of the industry.

As has been shown in Chapter 2, the optimal solar PV system sizes rise over time. In scenarios where excess energy could be sold on the wholesale markets, the increase in size was more significant than where this was not possible. If system sizes increase, this will raise the amount of energy households produce themselves. The use of battery storage supports this trend by allowing households to consume a larger amount of the self produced electricity. This has the consequence of reducing the amount of electricity bought from utilities. In addition, if households are able to sell their electricity on the wholesale market in the future then an increasing number of households will move from being electricity consumers to electricity producers.[239] As noted by Hopperman et al., 'this trend has the potential of fundamentally altering the existing market structure.'[240] In their opinion the fact that electric utilities are likely to be confronted with a growing number of households producing and selling their own electricity, 'fundamentally undermines their business model.'[241]

It is clear then that increased deployment of solar PV-battery systems is a threat to utilities. Not only does it reduce the amount of electricity bought from utilities, but also

[237] ibid.
[238] ibid.
[239] HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.26.
[240] ibid.
[241] ibid.

affects the amount of capital that they are able to deploy in search of the return on investment that they have previously enjoyed. It can be argued that the effects are already being felt in Europe. A Citi Group report on German utilities makes several pertinent points. It describes E.ON as the latest utility to concede that business conditions are 'irreversibly changing.'[242] The electricity utility has split its business into two, with new business called NewCo. Despite its name there is nothing "new" about the assets of the company, which include all power generation *apart* from renewables. The new business includes what are regarded by Citi Group as "riskier" assets, such as nuclear power and thermal generation.[243] Although Citi Group regards the split as 'the right thing to do', it states its belief that it was done from a position of weakness, 'given the drastic changes in E.ON's operating environment and one that avoids further destruction of value as conditions deteriorate rather than creating value from current levels.'[244] Such analysis leaves little doubt of the effect that the increasing deployment of renewable energy has on utility companies. It should be highlighted once again that as integrating battery storage with solar PV increases the independence of households, its increased deployment will bring with it further negative consequences to utilities.

From the public perspective, many members of the public will face a choice in the future. On the one hand, they can remain a traditional customer, using the electricity grid as they have always done. On the other hand, customers may find it increasingly economically viable to deflect from both utilities and the electricity grid. They may wish to cost-effectively self-generate, supplying themselves with power from integrated solar PV-battery systems. Research from the Rocky Mountain Institute (RMI) indicates that the number of people that would actually deflect from the grid is small. Rather, they regard a more likely scenario as one in which customers invest in solar PV-battery systems that are connected to the grid. In such a scenario the systems would be able to benefit from the grid and could be optimally sized, thus smaller and less expensive. This would have the knock-on effect of being economic for more customers sooner, and would lead to faster adoption.

The increased decentralisation brought about by adoption of solar PV-battery systems will reduce the need for transmission. Chapter 2 has shown that lithium-ion batteries are forecasted to decrease in the future. As customers install more and more battery capacity due to its falling prices this would logically have the effect of reducing their purchase of electricity from the grid until the grid takes a back-up role.[245] The RMI states the following:

'In Westchester County, NY, our analysis shows the grid's contribution shrinking from 100% today for commercial customers to ~25% by around 2030 to less than 5% by 2050. Inversely, solar PV's contribution rises significantly to make up the difference.'[246]

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[242] CITIGROUP. (2014). German Utilities: Let the survival game begin as the lost decade takes hold. *Citi Research*.
[243] ibid.
[244] ibid.
[245] ROCKY MOUNTAIN INSTITUTE. (2015). The economics of load defection: How grid-connected solar-plus-battery systems will compete with traditional electric service, why it matters, and possible paths forward. *Rocky Mountain Institute.* Colorado.
[246] ibid.

Such analysis supports conclusions drawn by Roland Berger (Strategy Consultants), who suggest that solar PV will change the utility industry. They note that utilities' role of centralized production will evolve from, 'delivering volumes to providing access to electricity capacity…Maintaining a balance and a functional grid capable of dealing with multi-directional power flows and power trade will change the nature of the network companies.'[247]

A key problem identified by the RMI is that between 2010 and 2030 the electricity grid of the US will require up to an estimated $2 trillion investment. These costs, which are roughly $100bn per year, are to be recovered through energy sales. Therefore, any loss in energy sales is a loss in investment as the revenue is effectively lost. The authors write that this, 'will likely have a large impact on system economics.'[248]

Below are examples of what the RMI calculates to be the maximum possible kWh sales erosion could be in the Northeast US by 2030.

- Residential
  - ~58 million MWh annually (50% of utility residential kWh sales)
  - 9.6 million customers
  - ~$15 billion in revenue

- Commercial
  - ~83 million MWh (60% of utility commercial kWh sales)
  - 1.9 million customers
  - ~$19 billion in revenue[249]

Clearly, the sales erosion suffered by utilities has the potential to be very large. Nevertheless, it is important to mention the opportunities that a large number of grid-connected-solar PV-battery storage systems presents. The fact that the customers maintain a grid connection means that their systems have the potential to provide benefits and services back to the grid. This is the case with many of the applications discussed in Chapter 1. The chapter was able to show that different applications of battery storage were able to achieve a number of different services. It included both production and grid level applications as well as at residential/utility scales, and showed how one installation could provide multiple services.

The range of value creating applications that battery storage is able to perform provides is significant. It means that although there could be a substantial load loss, the customers' grid connected systems can add value by providing services. As the RMI report notes, this will especially be the case if the value flows are monetized with new

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[247] ROLAND BERGER STRATEGY CONSULTANTS. (2015). Solar PV will change the utility landscape. *Roland Berger Strategy Consultants.* Paris
[248] ROCKY MOUNTAIN INSTITUTE. (2015). The economics of load defection: How grid-connected solar-plus-battery systems will compete with traditional electric service, why it matters, and possible paths forward. *Rocky Mountain Institute.* Colorado.
[249] Ibid.

rate structures, business models and regulatory frameworks.[250] Below is a breakdown of the potential impact on the electricity-system participants.

Implications for energy-system market participants and other stakeholders

Customers that invest in solar PV-battery systems

Analysis by RMI suggests that with intelligent investments customers could see peak pricing emerge. This would allow customers to insulate themselves from rising prices of grid-supplied electricity. The traditional grid-supplied customers, as well as those completely off-grid, were subject to higher costs. This was due to rising prices for retail customers and more expensive stand-alone solar PV-battery systems for those off-grid.

Distribution grid operators

The implications for grid operators are seen as positive. This is because customers with distributed systems should be able to provide value to the grid. According to the RMI these include, 'upgrade deferrals, congestion relief, and ancillary services.'[251] Despite this, the RMI does concede that new pricing, regulatory and business modes will have to emerge *and* mature in order to fully capitalize on the opportunities.[252]

Central generation and transmission

Solar PV-battery systems are foreseen to hasten the decline of sales from central generation utilities. Furthermore, they are also predicted to reduce peak spikes in deregulated markets and also encroach on markets for ancillary services.[253] It is likely that as an increasing number of people use solar PV-battery systems the assets will serve a diminishing load. In order for costs to be covered by this decreasing load, price increases may be required. In turn, this may accelerate further decline in sale as more customers invest in solar PV-battery systems, seeking to reduce costs. The RMI also notes that assets in the planning stages will not be able to see the future demand required to justify their capacity and generational output.[254]

Vertically-integrated utilities

Adjustments in business models will be necessary in order to capitalize on the rising adoption of solar PV and batteries. If no action is taken, then they may find themselves under strain from the systems outlined.

[250] ibid.
[251] ibid.
[252] ibid.
[253] ibid.
[254] ibid.

Future trajectories

It appears that the electricity system, that is the current *centralized* energy system, stands at something of a crossroads. The RMI summarises both paths:

'Down one path are pricing structures, business models, and regulatory environments that favour non-exporting solar and solar-plus-battery-systems. When economic and other considerations reach the right tipping point, this trajectory favours true grid defection. In the meantime, an upward price spiral based on stranded assets serving a diminishing load will make solar-plus-battery adoption increasingly attractive for customers who can, and lead to untenably high pricing for customers who remain on the grid, including low and fixed-income customers who would bear a disproportionate burden of estimated retail electricity pricing. In the future, both grid and customer-side resources are overbuilt and underutilized, leaving excess capital on both sides of the meter'[255]

The pricing structures mentioned in the quote above refer to policies such as the elimination of net metering. Net metering was mentioned briefly in chapter 2 (utility, residential and non-residential market segments) and is where utilities are required to buy excess electricity generated by homeowners' solar panels. As the electricity is not exported in this scenario it is not purchased by utilities. As the quote above shows, this trajectory favours defecting away from the grid as there are limited advantages of being connected. Moreover, as an increasing number of people defect away from the grid, prices rise and it becomes more economic for a greater number of people to defect. The phrase 'price spiral' is accurate in this sense as rising prices cause more people to defect, and thus cause higher prices as the assets (which have remained unchanged), serve a decreasing load. Increasing prices and increasing defection are locked in a vicious circle.

Regarding net metering, the findings of the RMI were that the elimination of net metering 'merely delayed significant load loss.'[256] The conclusion drawn was that, although it might be gradual, battery systems would ultimately cause a 'near total load loss even in net metering's absence.'[257] An alternate policy of fixed charges is also said to simply delay the 'ultimate load defection outcome.'[258]

In light of the above, it appears inevitable that there will be a significant loss of revenues for utilities. This is emphasised buy the fact that key policies only serve to delay the outcome. On a different topic, it should be highlighted that, "low and fixed income customers pay a disproportionate burden of estimated electricity pricing." It could be suggested that the path of grid defection is one which democratisation is least present. This is as lower earners are punished by high prices for not being able to defect to battery systems, exhibiting no voice in their energy system.

Chapter 2 also highlighted how solar PV threatens business models. It was shown to threaten the 'sunk utility investments in centralised fossil power plants and their rigid

[255] ibid.
[256] ibid.
[257] ibid.
[258] ibid.

"big to small – guaranteed return on capital business model."'[259] The key concern for utilities is that decreasing revenues will lead to "stranded assets", which is essentially when an asset becomes a liability. According to the Smith School of Enterprise and Environment at the University of Oxford, there is a number of risks that can cause assets to become stranded, as the table below shows.

Set	Subset
Environmental Change	Climate change; natural capital depletion and degradation; biodiversity loss and decreasing species richness; air, land, and water contamination; habitat loss; and freshwater availability.
Resource Landscapes	Price and availability of different resources such as oil, gas, coal and other minerals and metals (e.g. shale gas revolution, phosphate availability, and rare earth metals).
Government Regulations	Carbon pricing (via taxes and trading schemes); subsidy regimes (e.g. for fossil fuels and renewables); air pollution regulation; voluntary and compulsory disclosure requirements; changing liability regimes and stricter licence conditions for operation; the 'carbon bubble' and international climate policy.
Technology Change	Falling clean technology costs (e.g. solar PV, onshore wind); disruptive technologies; GMO; and electric vehicles.
Social Norms and Consumer Behaviour	Fossil fuel divestment campaign; product labelling and certification schemes; and changing consumer preferences.
Litigation and Statutory Interpretations	Carbon liability; litigation; damages; and changes in the way existing laws are applied or interpreted.

Table 7: Typology of environment related risks[260]

It is clear that many risks exist that can contribute to centralised fossil fuel power plants becoming stranded assets. Technology change, as the key focus of this paper, represents just one of the risks. This suggests that the combination of all the factors identified above poses a profound threat to centralised utilities, and that they will find it increasingly difficult to guarantee returns in the future. This is especially true in the case of non-exportation of solar PV, as this path ultimately leads to grid defection.

The other path is described here:

'Down another path are pricing structures, business models, and regulatory environments in which distributed energy resources such as solar PV and batteries – and their inherent benefits and costs – are appropriately valued as part of an integrated grid. Solar PV and batteries can potentially lower system-wide costs while contributing to the foundation of a reliable, resilient, affordable, low carbon grid of the future in which customers are empowered with choice. In this future, grid and customer-side resources work together as

[259] POPE, C. (2016). Rooftop Solar Wars Continue. *EcoWatch.* [Online] Accessed on 7/4/2016. Available from: http://ecowatch.com/2016/01/29/rooftop-solar-wars/
[260] SMITH SCHOOL OF ENTERPRISE AND THE ENVIRONMENT. (2016). Stranded assets and thermal coal – An analysis of environmental-related risk exposure. *University of Oxford.* [Online] Accessed on 25/4/2016. Available from: http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/satc.pdf

part of an integrated grid with for more efficient deployment of capital and physical assets.'[261]

The figure below shows the 'metaphorical fork in the road' that the electricity system finds itself at, as described by RMI.

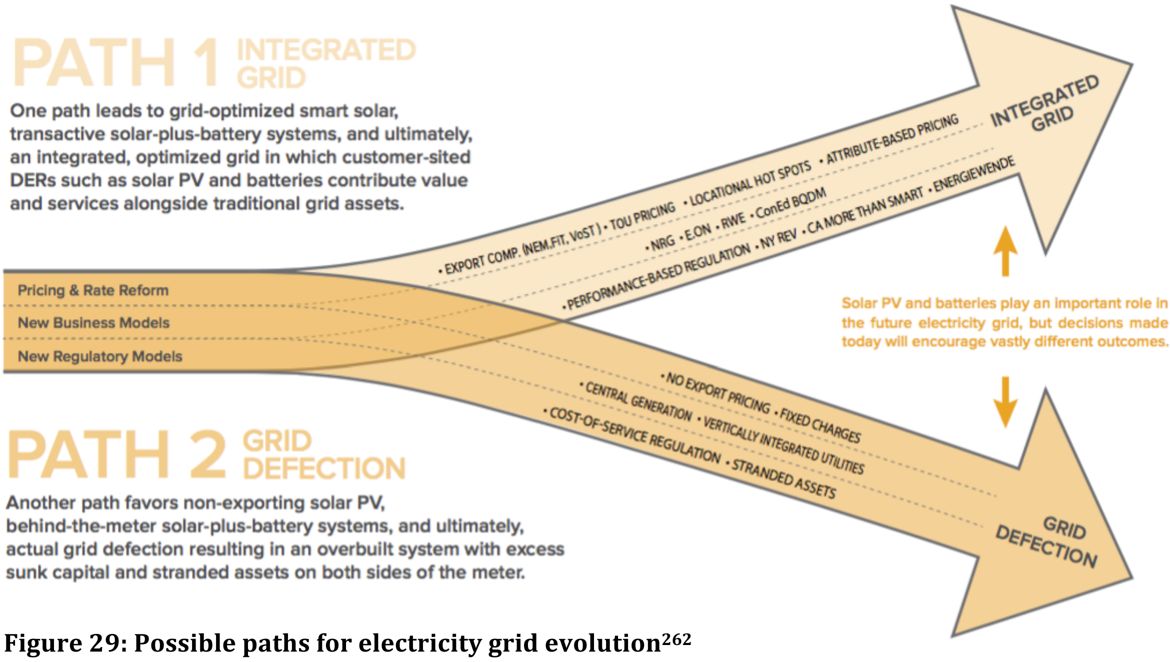

Figure 29: Possible paths for electricity grid evolution[262]

The alternate path outlined is one in which solar PV and batteries are an important part of an *integrated* grid. In contrast to the grid defection path, an integrated grid brings with it a much greater democratisation for customers as they are "empowered by choice." As shown in chapter 1, the technical applications of battery storage are wide ranging. The result of this is that if batteries are successfully integrated into the grid system, then the system-wide costs are reduced. Ultimately the path towards an integrated grid is one which both grid and customer resources are able to work symbiotically, achieving a much more efficient use of capital and assets.

Realising these benefits is understood to require reform on three fronts:[263]

- *New pricing and rate structures:* The needs of the 21st century grid are complex and pricing should evolve in different ways:
    - *Locational* – allowing congestion pricing or other incentives
    - *Temporal* – time of use and real-time pricing
    - *Attribute based* – breaking part energy, capacity, ancillary services and other service components

261 ROCKY MOUNTAIN INSTITUTE. (2015). The economics of load defection: How grid-connected solar-plus-battery systems will compete with traditional electric service, why it matters, and possible paths forward. *Rocky Mountain Institute.* Colorado.
262 ibid.
263 COVINGTON & BURLING LLP. (2015). The impact of distributed generation on electric utilities: How big, how likely and how soon? [Online] Accessed on 26/4/2016. Available from: https://www.insideenergyandenvironment.com/2015/04/the-impact-of-distributed-generation-on-electric-utilities-how-big-how-likely-and-how-soon/

- *New business models* – The need to evolve from centralised generation and the unidirectional use of the grid. Business models need to become based on grid connected customers with distributed resources and a two-way flow of electricity on the grid
- *New regulatory models* – that provide the following:
    - o Fair and equal customer access to distributed resources
    - o Recognise, quantify and monetise the benefits and costs of distributed resources
    - o Treat all customers equally

Although not explicitly mentioned in the above reforms, Hoppman et al. note that the shift towards a system of strongly distributed electricity generation will 'probably require major adaptations in the technical infrastructure of the electricity system, such as distribution grids.'[264] The concern regarding interconnection is also present in other reports on distributed generation. An MIT study notes the following:

'The integration of distributed generation presents new challenges for distribution system planning and operations, principally because the configuration of power lines and protective relaying in most existing distribution systems assume a uni-directional power flow and are designed and operated on that assumption…While the physical wires and transformers can carry power flow in the reverse direction, Distributed generation nonetheless can have adverse impacts on system reliability, power quality and safety.'[265]

The above quote appears to give support to the concerns of Hopperman et al. Just because battery storage has proven to be economically viable for households, it does not imply that battery storage and distributed generation systems are 'beneficial from the perspective of overall stability of the electric system.'[266] Despite the concerns, within this investigation the applications of battery storage have been shown to contribute to grid stability when combined with distributed generation sources such as solar PV. This is supported by Hollinger et al. who found that battery storage in residential PV systems can reduce the burden on electricity distribution grids by around 40%.[267] Even though other studies have found no positive effect of battery storage alleviating stress on the distribution grid,[268] it seems highly unlikely that by integrating solar PV-battery systems into a smart grid, improvements in grid stability would not be possible.

Improvements in grid stability emphasise the characteristics of the path towards an integrated grid as opposed to grid defection. With the reforms outlined above as well as

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[264] HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.26.
[265] MIT. The impact of distributed generation and electric vehicles. [Online] Accessed on 27/4/2016. Available from:
https://mitei.mit.edu/system/files/Electric_Grid_5_Impact_Distributed_Generation_Electric_Vehicles.pdf
[266] ibid.
[267] HOPPMAN J., VOLLAND, J., SCHMIDT, T.S., HOFFMANN, V.H. (2014). The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and Simulation Model, Renewable and Sustainable Energy Reviews 39, 1101-1118. p.26.
[268] ibid.

the necessary investment in the technical infrastructure of the grid, the advantages of a path towards grid integration are significant. These include the following:

- Low carbon
- Lower consumer costs
- Lower system-wide costs
- Improved grid stability (due to power smoothing and ancillary services in chapter 1)
- More efficient deployment of resources/assets
- Customer empowerment

It remains to be seen which path is taken. But as noted by Leia Guccione, one of the authors of the RMI report, 'there is a real cost in doing nothing…In the absence of more customer choices, customers will take matters into their own hands. And that's going to lead to sub-optimal outcomes that we see in grid defection – overinvestment and underutilised capital.'[269] The path towards an integrated grid system has without doubt been shown to be the superior option. However, what is particularly noteworthy here is the role of the customer, which in regards to energy systems has undergone a profound change.

Democratisation of energy

In the UK only 18% of people believe that energy prices should be decided by those providing the service.[270] This suggests customers' dissatisfaction with the fact that private energy companies are the ones that set the prices. In fact, over two thirds of those surveyed believe that energy companies should be run in the public sector.[271] If customers have the ability to take control over their own energy prices then they are likely to do so. The Energiewende in Germany provides the best evidence for this.

[269] COVINGTON & BURLING LLP. (2015). The impact of distributed generation on electric utilities: How big, how likely and how soon? [Online] Accessed on 26/4/2016. Available from: https://www.insideenergyandenvironment.com/2015/04/the-impact-of-distributed-generation-on-electric-utilities-how-big-how-likely-and-how-soon/

[270] DAHLGREEN, W. Nationalise energy and rail companies say public. *YouGov.* [Online] Accessed on 27/4/2016. Available from: https://yougov.co.uk/news/2013/11/04/nationalise-energy-and-rail-companies-say-public/

[271] ibid.

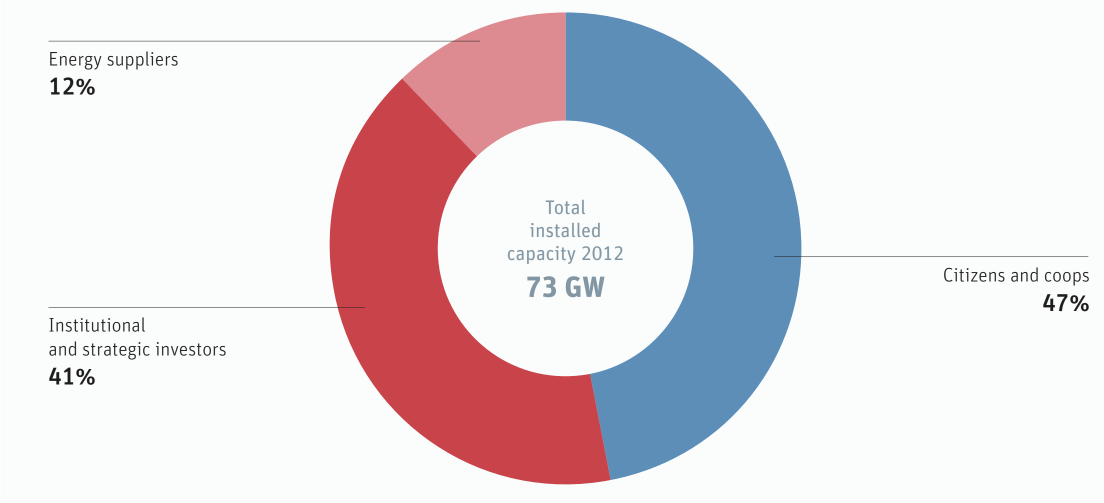

Figure 30: Ownership of German renewables in 2012[272]

The figure above shows that the energy transition is, or at least has shown to be in Germany, a democratic movement that empowers the public, allowing them not merely to be consumers but also "prosumers"- simultaneously producers and consumers. Some countries, such as the UK, promote renewables with policies such as 'quota systems.'[273] In these cases, targets are set for utilities to reach and there is a general focus on cost. In this system many proposals are rejected. In Germany it is the decision of the local government to decide where renewable sources will be built and if a FIT system is used. Utilities are under no obligation to increase their share of renewables. The official Energiewende website highlights the differences of the two systems:

'Overall, the difference between the two approaches – feed-in tariffs versus quotas – is striking. Under quotas, only the least expensive systems go up after time-consuming reviews, and they remain in the hands of corporations; under feed-in tariffs, everything worthwhile goes up quickly, and ownership of power supply rapidly transfers to citizenry. In other words, Germany is democratizing its energy sector.'[274]

It is estimated that energy cooperatives in Germany, community-owned renewable projects, leveraged more than €1.2bn in investments from 130,000 private citizens in 2013.[275] Although critics may say that only the wealthy are able to invest in such projects, this is not true. A single share costs less than €500 in over two thirds of cooperatives while some are as cheap as €100.[276] As noted by Guccione, customers are taking matters into their own hands. The increasing number of cooperatives shown in the figure below only serves to highlight this.

[272]ENERGY TRANSITION. (2012). Infographics. [Online] Accessed on 27/4/2016. Available from: http://energytransition.de/2014/12/infographs/
[273]ENERGY TRANSITION. (2012). Energy by the people for the people. [Online] Accessed on 27/4/2016. Available from: http://energytransition.de/2012/10/energy-by-the-people/
[274] ibid.
[275] ibid.
[276] ibid.

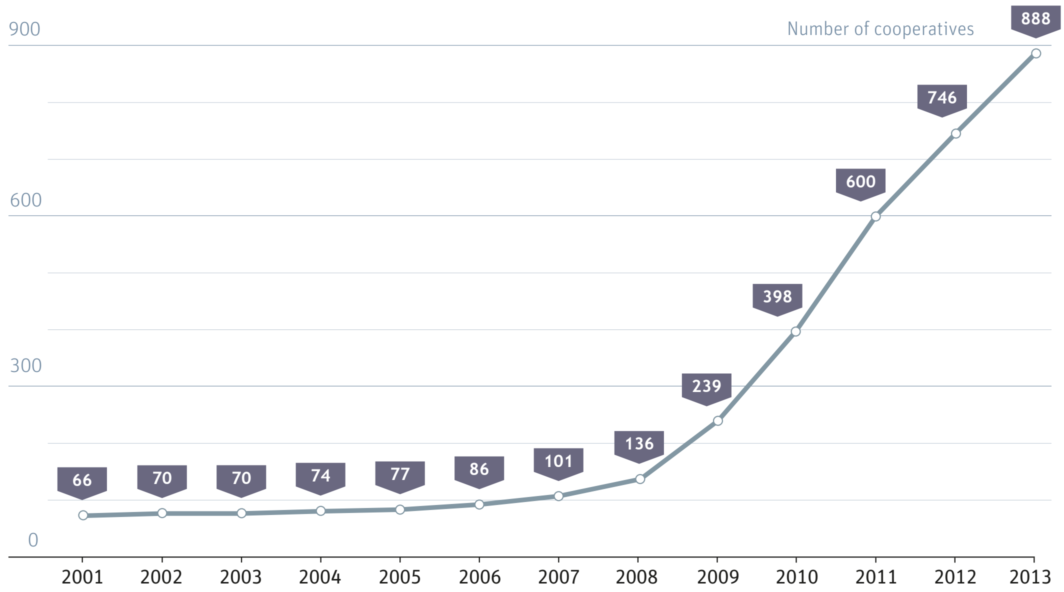

Figure 31: Number of energy cooperatives in Germany 2001-2013[277]

The increasing number of co-operatives in Germany suggests that the public is very accepting of the movement towards decentralized energy. Just as the statistics from the UK suggest a public dissatisfied with the level of control that it possesses over energy prices. The increasing levels of energy democratisation witnessed through Germany's Energiewende are quite extraordinary when compared to the 20th century model of centralised energy. Initiatives such as cooperatives play a vital role in Germany's energy transition and it should not be forgotten that the transition itself is a democratic movement, with the ability to empower the public.

As the head of Germany's Solar Industry Association (BSW-Solar) puts it, "Energy cooperatives democratize energy supply in Germany and allow everyone to benefit from the energy transition even if they do not own their own home."[278]

[277] ENERGY TRANSITION. (2012). Infographics. [Online] Accessed on 27/4/2016. Available from: http://energytransition.de/2014/12/infographs/
[278] ENERGY TRANSITION. (2012). Energy by the people for the people. [Online] Accessed on 27/4/2016. Available from: http://energytransition.de/2012/10/energy-by-the-people/

Conclusion

This paper has sought to provide a comprehensive investigation into the impact of battery storage technologies. Firstly, and in order to contextualise the issue at hand, recent trends in energy finance were investigated. It was found that the falling price of polysilicon has played a large role in the decreasing prices of PV cells. This was due to the fact that material inputs constituted such a large percentage of the manufacturers cost of production.

Large scale production, intense competition and improved efficiency led the technology to become increasingly economically viable. This was demonstrated by the Swanson effect. As a result, major economies, most notably Germany, have increased their electricity output from solar PV installations significantly over the past decade. This trend has reached the point at which the world is now adding more capacity for renewable energy than for coal, oil and gas combined.

Although there is a clear trend towards renewable energy sources, Vaclav Smil believed that the trend would be accelerated through the inexpensive application of energy storage. This was due to the intermittent nature of renewables.

This investigation has shown that battery storage has the ability to play a significant role in countering intermittency. In addition, the investigation has shown that battery storage has many more services, and brings with it much more significant dynamics.

Chapter one focused on *technical* aspects of battery storage technologies and highlighted the advantages that lithium-ion technology enjoyed over other types. The technology was shown to have advantages in terms of energy density, efficiency and power. By investigating the practical and real-world uses of battery storage, the chapter described the various services that battery storage is able to provide. As shown in the chapter, energy time-shifting, ancillary services and energy smoothing were proven to be particularly useful

As shown in the summary of chapter one, the services are numerous and bring many benefits. Power reliability, benefits to existing infrastructure, the ability to provide backup power and renewable energy support are also important. The investigation has shown that battery storage solves the intermittency problem through energy time-shifting. According to Smil, this will promote the expansion of renewables. What is more, the investigation also found other applications that further increase renewable integration, as well as bringing other benefits

Benefits are valued in economic terms. The investigation showed that in order for battery storage to become increasingly utilised, the services it provides must receive adequate compensation.

Chapter focused on the *economic* aspects of battery storage. The investigation found that integrated solar PV-battery systems were profitable under a range of different pricing scenarios. The profitability of storage was forecasted to increase over time. This fact was further emphasised in the following section which showed the decreasing price of lithium-ion batteries. The chapter also identified the lack of cost transparency, and of a cohesive regulatory framework as key barriers to battery storage. The investigation did find that many countries had an active policy environment regarding battery storage. Most noteworthy was the trend shown by the Federal Energy Regulatory Commission in 2011. Order 755 made it possible that the superior performance of frequency regulation services was adequately compensated. This trend is being driven by the need to create fair regulations and compensate non-traditional measures for the benefits they provide. These aspects are critical in facilitating and promoting investment in battery storage, and consequently play important roles in the energy transition.

The investigation found an increasing trend for batteries to be used in ancillary services and frequency regulation, where they created created value largely due to their superior performance. In addition, it was also found that there is an increasing trend for markets to pay for the quality and accuracy of the service provided. These trends compliment each other and will likely lead to the greater application of battery storage due to the services it is able to provide.

Internationalisation, which has been present in value chains throughout the investigation, has undoubtedly contributed to this increased economic viability of battery storage. Markets have been shown to be growing at strong rates, and there are increasing opportunities for internationalisation and investment. Furthermore, if there is a trend for services provided by battery storage to receive compensation based on their frequency and accuracy, energy storage markets will become more competitive, and investors more confident. Thus, the investigation has shown that battery storage market will both grow and increase in competition in the future. This is as the trend of adequate compensation provided by regulation will only serve to strengthen the battery storage market.

As well as barriers, there is the aforementioned need to develop a common approach. An approach that encompasses technical, regulatory, market and political aspects was highlighted. In order to achieve this "holistic" approach to storage, greater levels of international cooperation are required. Although internationalisation has contributed to increased competition in markets, the lack of a holistic approach towards battery storage suggests that greater internationalisation is necessary. There must be greater political and regulatory initiatives shown by the international community. This in order to achieve a common approach that has the potential to facilitate the energy transition. The lack of regulatory and political aspects in the common approach is underpinned by the fact that the technical and market aspects of battery storage have been proven to be so successful. In light of this, when noted that the EU commission believed the main challenge to be economic, it is not that battery storage is not yet economically viable, but rather facilitating the conditions for investment that is the key challenge.

Of particular significance, the investigation has shown that as support for renewables declines (FITs), the implementation of storage is likely to increase over time. This is due to the fact that integrated solar PV-battery storage systems were shown to increase in size and profitability over time. Battery storage is not only already economically viable under many scenarios, but also drives an increasing number of people to be "prosumers". This trend is leading energy to become cleaner, safer and increasingly decentralised.

The final section of the paper, regarding the relationship between the public and utilities, showed that the public is becoming increasingly active, participating in the development of renewable energy sources. As battery storage has proven to be economically viable for residential systems, and set to increase in profitability, there is likely to be an increasing trend away from the traditional consumer-utility dynamic. The investigation highlighted possible paths for the future, of which the integrated grid system was shown to be superior. This empowered consumers, as it was the more democratic option, and allowed for a more efficient use of capital.

The investigation has found that battery storage technology will have a profound impact on traditional centralised utilities. If people choose to defect from the grid completely, then battery storage allows them to become completely self-sufficient. However, the integrated grid is the superior path, and as a result it is critical that the decisions made by governments and the international community reflect this, and promote the required investment. Although the investigation has shown that utilities will be effected by an integrated grid, and lose revenues, the path of integration offers benefits for both the consumer and utility companies. The customers have the ability to export their excess energy, increasing their say in the energy system. The utilities on the other hand have less risk of stranded assets and are able to work along side integrated battery systems, with both providing value. The fact that the investigation found that seemingly utility-friendly policies, such as the abolition of net metering, only had the effect of delaying the inevitable outcome of grid defection, gives support to the argument that the creation of an integrated grid is best path for the future.

Due to the above, one can be forgiven for thinking that the electricity industry is set for major changes in the future. The truth is that change is likely to be more gradual. Regarding the effect of distributed generation on the electricity industry, Costello writes that, 'it seems inevitable that change will come but its effect on the electricity industry is still in flux and unknown.'[279] This investigation, in understanding the impact of battery storage technology, has ultimately shown what the effect on the electricity industry will be. Centralised generation is under threat from the increasing use of decentralised energy. Battery storage has been proven to accelerate this trend. This trend will only increase in the future, driven by the public desire to take control of their energy and falling battery prices. Utilities must adapt to survive, as they have already begun to do. The integrated grid offers the superior path for the future. It is technically possible and economically viable. However, it will require regulatory changes, transparent costs and political will to make sure that the future electricity system is the optimal one.

[279] COVINGTON & BURLING LLP. (2015). The impact of distributed generation on electric utilities: How big, how likely and how soon? [Online] Accessed on 26/4/2016. Available from: https://www.insideenergyandenvironment.com/2015/04/the-impact-of-distributed-generation-on-electric-utilities-how-big-how-likely-and-how-soon/

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