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Historic and potential technology transition paths of grid battery storage: Co-evolution of energy grid, electric mobility and batteries

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Historic and potential technology transition paths of grid battery storage - Co-evolution of energy grid, electric mobility and batteries [1]

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1 Introduction

Scarcity of fuels, changes in environmental policy and in society increased the interest in generating electric energy from renewable energy sources (RES) for a sustainable energy supply in the future [1]. Germany has ambitious targets to produce 35 % of the needed electricity from RES by 2020 and over 80 % by 2050 within the so called "Energiewende" [2]. The main problem of RES as solar and wind energy, which represent a main pillar of this transition, is that they cannot supply constant power output. This results inter alia in an increased demand of backup technologies as batteries to assure electricity system safety [3]. The diffusion of energy storage technologies is highly dependent on the energy system and transport transition pathways which might lead to a replacement or reconfiguration of embedded socio-technical practices and regimes (by creating new standards or dominant designs, changing regulations, infrastructure and user patterns) [4]. The success of this technology is dependent on hardly predictable future technical advances, actor preferences, development of competing technologies and designs, diverging interests of actors, future cost efficiencies, environmental performance, the evolution of market demand and design and evolution of our society.

2 Problem structure, research aim and methodology

The development of the energy system including energy storage and its dynamics are based on the co-evolution of various elements, e.g. technologies, business models, stakeholder interests, policies, "external" factors as oil prices named as socio-technical systems. Not only technologies, but the interplay between these elements needs to be taken into account when anticipating future sociotechnical trajectories of a potential innovative technology [5]. In general technology itself is part of a seamless web of highly related heterogenic elements as organizations (manufacturers, research and development, end users etc.) resources, scientific elements and legislation (law). The combination of these elements finally allows the achievement of functionalities of technology. Societal functions such as transport and energy supply are results of such clusters of heterogenic elements which can be named socio-technical systems [53].

The aim of the following research is thus to look at the socio-technical transition paths of grid battery storage and to identify major events that have influence the transition path of battery grid storage. A major problem of this task is how to present these highly non-linear transition paths in a structured

[1] Based on the report for the course on "Social Factors of Innovation A" of the PhD program on Technology Assessment (PDAT) under the responsibility of Prof. António B. Moniz

and understandable way. The multi-level perspective MLP developed by [6], [7] offers a suitable and easy applicable method to fulfil this task and is used for this research. The German energy system is used as a case study to provide a more focused research. Still the paper tries to provide a more global perspective by referring to other cases and global development regarding the topic.

In the first step a brief overview about stationary battery systems and the MLP is given to give the reader the chance of a better understanding of the topic. This is followed by a historical analysis of the co-development of battery storage, electric vehicles and the electricity grid itself. The analysis is structured in three time eras: “Electrification and emergence of electric mobility”, “The fossil age” and “Liberalization of energy markets and low carbon era”; which at the end of the chapter are interpreted through the lens of MLP to dilute the interaction of society and technology.

3 Battery storage technology

Batteries are in general a mature technology, which is utilized for more than a century for industrial products as portables, grid applications and for electric vehicles. Electricity storage in secondary batteries is based on reversible electrochemical reactions in which electrical energy is converted into chemical energy and vice versa. Batteries are normally categorized by the active materials used in the cells which in turn influence the design and the characteristics of the battery system [8]. Still they have many shortcomings in a variety of use cases and there is still high effort needed in basic research for market breakthrough regarding cyclic and calendar life time, safety and environmental concerns.

Grid battery storage has a highly vertically integrated nature due to its modularity offering various services within generation, network and demand including all voltage levels [9]. This results in a high number of potential users for battery storage systems distributed in the entire electricity system. Potential users-side actors are private and municipal utility companies, transmission and distribution system operators, end users (private households, industry), RES system integrators and manufacturers, BEV-owners or third parties. The development of electrochemical storage is closely connected to the development of the electricity network itself or electromagnetic generation of power respectively as well as to the development of electric vehicles.

4 Socio-technical systems

The properties of new technology or a system are not given beforehand, but they co-evolve with interactions which occur during development, implementation, adoption and wider use [54]. This is referred as co-evolutionary process and begins with an innovative product against existing societal-technical regimes. Thus the uptake of an innovation is also dependent on certain sociotechnical regimes which set up the rules. In case of a technological transition a replacement or reconfiguration of embedded socio-technical practices and regimes might occur (by creating new standards or dominant designs, changing regulations, infrastructure and user patterns). Emerging irreversibility’s can occur in this processes which are reinforced when actors start to invest in this paths that seem to emerge [4]. This can lead to continued re-investment in dominant designs, technology lock-in or path dependency. It is therefore crucial to understand the interplay of multiple stakeholders within existing regimes.

5 The multilevel perspective framework

The challenge is how to capture the emerging complexity of innovation. One possibility is to bundle factors in transition pathways based on the MLP framework which distinguishes three levels of heuristic, namely: Sociotechnical landscape, socio-technical regimes and niche innovations.

The socio-technical regime refers to shared routines in a certain community including scientists, policy makers, users and special-interest groups which contribute to patterning of technological development [10]. The sociotechnical landscape refers to an exogenous environment that is not directly influenced by niche and regime actors. Examples here fore can be macro-economics and –political developments, deep cultural patterns etc. Changes within on this level occur of long time, usually decades [10]. Technological niches represent the micro level within MLP. It is the place where radical novelties occur. These novelties can be seen as unstable configurations characterized by a low performance. Thus niches are considered as incubation rooms protecting novelties against dominant market selection. Small networks of specific actors are often the promoters of niche innovations [10]. The relationship of this three levels is considered as a nested hierarchy, where regimes are embedded within landscapes and niches within regimes [7]. The kernel of the concept is that innovations innovation can diffuse through the interplay within the dynamics between the three levels [7]. The phases of this diffusion is summarized in the following based on [6], [7], [10]–[12]:

1. Some new novelties emerge in niches within a certain regime and lanscape developments, there is no dominant design available. This phase is characterized by competition and expermimentation
2. Novelty diffuses into smal market niches, characterized by technical specialization. There is a small community of developer and producers deliberating power to the improvement of this technology, gradually developing new rules leading to new more stable technical trajectory.
3. In this phase a breakthrough of new technology occurs in combination with wide diffusion and competition with the established regime. Characteristics are internal drivers (improvements regarding price, performance), actors interests pushing technology diffusion which are still dependent on external factors (e.g. regime pressures due to landscape changes, internal difficulties of the regime etc.). The major point is that in this phase innovation occur as an outcome of linkages between development at all levels.
4. The last phase represents a substitution of the old regime through new technology, linked with changes on wider dimensions of the sociotechnical regime and might influence thw wider landscape developments. This proces happens gradually, as this reconfiguration takes longer time due to incumbents that stick to old technologies caused by vested interests and sunk investments.

An overview of the mulit-level perspective concept including the different levels their relation and the steps innovation diffusion among the three levels is given in figure 1:

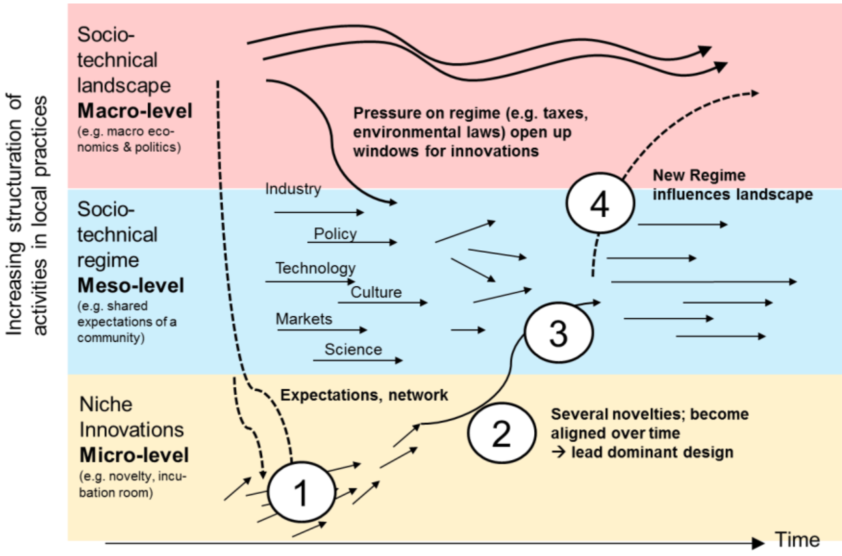

Figure 1: dynamic multi-level perspective on system innovations, including diffusion steps and levels (based on [7]; [6]).

Based on the interplay between the three levels in the MLP, different routes can be distinguished regarding the diffusion paths of novelties which are as follows (based on [6], [7], [10]–[12]):

- **Reproduction:** Radical niche-innovations may be present, but have little chance to break through as long as the regime is dynamically stable. Reinforcing landscape developments help stabilize the regime.
- **De- and realignment:** Interaction between three levels; major landscape pressure and competition between incumbent tech-nology and others until one dominates
- **Re-configuration:** Replacement of inter-locking technology by component-innovation; combination of old & new components
- **Transformation:** Change from interaction with evolving landscape, no critical interaction with landscape or niche as to underdeveloped
- **Substitution:** Novelty in stable regime diffuses through linkage to ST regime, speed of breakthrough depends on land space factors

More information regarding the relation of levels and the description of transitions paths including manifolds of case studies can be found in [6], [7], [10]–[12].

6 Socio-technical transition paths of battery energy storage

The following chapter gives an overview of energy storage from a more distant perspective and battery development in detail. The development of batteries is always analysed with the co-evolution of the electricity grid and electric vehicle development.

6.1 Electrification and emergence of electric mobility

Batteries are the one of the oldest and most common forms to store electrical energy [13]. The first rechargeable battery, the Lead Acid battery was invented by Gaston Planté in 1859. In 1860 Georges Leclanché invented the forerunner of the modern dry cell battery with electrodes made out of zinc, manganese dioxide and ammonia chloride as an electrolyte [14]. The battery was built by spiral rolled up lead plates separated by a linen sheet in a basin filled up with acid sulfur [14]. The alkaline battery also known as Edison battery was soon invented in the 1890ies [13]. These batteries were already used in the 1880s in arc lighting [15] as well as for self-propelled electric vehicles.

Around 1890 iindustrializing countries entered the craze of electric mobility and the popular press at that time celebrated every invention related to electric vehicles [16] [7]. They were easy to start and operate at low speed. They were considered as a clean, quiet, reliable mobility mode primarily suited for urban areas due to restricted storage capacity [17]. The transport sector was firstly seen as a potential vast market for batteries and represented a main driver for further research in the area of electro-chemistry [15]. This has led developers as Thomas Edison to drive research and development activities into new and more performant batteries resulting in the "Edison battery" also known as alkali battery [12] [16]. The development of this type of battery was related to the thought of Edison that the PbA battery was to heavy and uneconomical for electric vehicles. After developing the type E battery he was able to sell 14.000 cells for use in electric cars and trucks in 1903 and 1904 [16]. However electric vehicles turned a commercial failure as main problems with the internal combustion engine were solved. Electric vehicles have since then heavily loosed out against gasoline power cars within a short period as illustrated in figure 2.

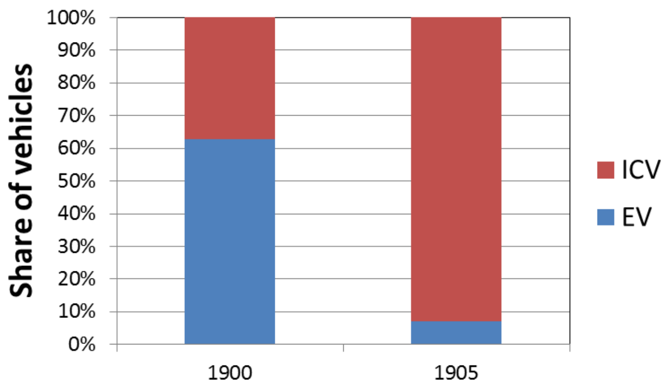

Figure 2: EV *Sales levels electric versus ICE cars* in the US [17]; [18]

Still in 1911 Edison made a list of various application fields (in total 64) which included many tasks for which the his alkaline battery was successfully applied as e.g. providing back-up power for generating stations, lighthouses, miner's lamps, and railroad signals; and lighting isolated houses and yachts [16]. Beside mobility markets Edison also investigated batteries for his Edison Light Company was also interested to store energy during peak consumption [16]. In general, stationary batteries were used in DC central stations representing a steady economic main pillar of the young storage battery industry starting from the 1890-ies.

The reason for this as that in the beginning of the 1890ies electricity systems had a highly decentralized character where small generators just became connected to local loads [12]. A main problem of these mainly DC based electricity systems was – beside poor voltage quality - that they were very peaky (mainly due to lighting), leading to oversized generators in order to satisfy load. Thus generators where often idle or under- utilized [12]. Another factor was that low voltage energy (120 V) could only be transmitted efficiently over one to two kilometres. Thus power plants had to be built nearby to user which was a costly endeavour [19]. Therefore batteries were a desirable option to perform for load levelling, enabling generator owners to run their generators more efficient. DC generators took furthermore advantage of electrochemical storage as they were able to buffer voltage fluctuations and to take up complete load in case of generator break downs [15]. About 20 %

of DC stations in the UK were supported by batteries in 1910 used for load levelling were a standard practice but also unreliable at this time [12]. Figure 3 illustrates the increase of battery use for DC-station support from 1894 to 1910 in UK.

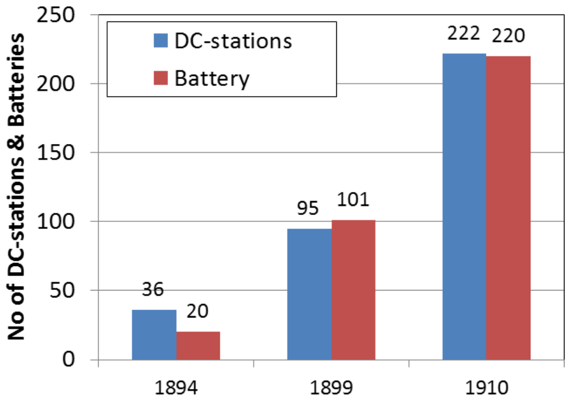

Figure 3: Example for the diffusion of batteries for DC-stations in UK [15]

However, the war of the currents between Edison (favouring DC) versus Westinghouse (favouring AC) in that time is a good example of path dependency in electrical grids [12]. The war was won by AC technology due to its favourable properties which allow it to transform AC voltage up and down through transformers. The use of high currents allowed it to efficiently transport electricity over long distances and to reduce its voltage for end use applications as lightening [19]. Through this development power plants did not have to be located in city canter's and could be built in more remote locations including a more efficient operation. However, the need of battery storage was diminished in the following years due to the further development of the electricity system: aggregated load profiles became smoother due to the growing number of large scale power plants in remote locations and the increasingly interconnected power grid. This finally resulted in the classical electricity system value chain consisting of five links: fuel, generation, transmission, distribution and customer side energy service [20]. This structure was long time characterized by a unidirectional flow of energy from high voltage levels or multi-MW power plants to distribution levels or the customers respectively. This development led to more efficient operation of generators and reduced average electricity costs making the use of batteries dispensable. Additionally first commercial available secondary battery cells were highly unreliable [12] and poorly understood. In the following decades only moderate developments regarding energy density and power were achieved [21] in secondary battery research. Yet development was achieved regarding safety, cycle stability and low maintenance. Some examples for this achievements are e.g. development of nickel cadmium battery [22].

6.2 The fossil age

In the early 50ies energy consumption was steadily growing leading to a fast growing rate of large generation capacities owned by a few utilities. These development where often reinforced through national laws as e.g. in Germany through the "Energiewirtschaftsgesetz" leading the formation (and maybe faveolization) of large, centralized and vertical integrated public owned utility companies with defined supply areas. This structures remained in many countries until the 90ies with a national regulation aiming to maintain this structures [23] [12].

However, utilities of that time had the problem that they had to bring online several baseload power plants (nuclear and coal) but did not have sufficient or only limited options for load following and peak services. This has led utilities to build up mainly large pumped hydro storage power plants including some other exceptional storage technologies (e.g. one compressed air energy storage in Huntsdorf Germany) as alternatives to mid- and peak load fossil fuelled generation options. The decision process for technology choice on that time was mainly based on techno-economic consideration where energy storage was directly compared to energy and capacity provided by equivalently sized caloric power plants. Usually the lower net-cost option was chosen by mostly ignoring additional operational benefits that energy storage can provide [24]. However this behaviour and the resulting cost pressure offered no window for battery technologies in stationary applications. This effect was reinforced through the fact that economic analysis of energy storage was difficult, as costs e.g. for balancing or ancillary services here hidden within utilities cost of service and benefits of energy storage remained hidden or highly uncertain [24]. Stationary batteries at that time were very costly and mainly used for niches as black start, stand alone or uninterruptible power supply applications [12].

In the 1970ies prices increased in oil and natural gas leading to increased concerns about security of supply. The concern about availability of oil and other fuels in 1979 was so high that energy storage was described as “a vital element in mankind´s quest for survival and progress” during an international conference including the U.S national academy of sciences [25]. This has led to shift in mobility use and electricity generation (expressed through mandates as e.g. the Power plant and Industrial Fuel Use Act in the US). Fossil resource concerns and the negative effects of pollution have also contributed to a re-emerged interest on electric vehicles in the 70ies caused by regulatory push in the US state of California and partially to environmental policies and programs in Europe [26]. This led to new advancements in battery research in anticipation of electric mobility starting in the beginning of the 70-ies [21]. There were several developments as e.g. the introduction of the first primary lithium battery in 1972 developed by Sanyo [13] or new findings as the discovery that sodium alumina had a high conductivity through scientists at Ford Motor company [13]. This represented a prelude to a revolution in solid state electro-chemicals, which resulted in the use of solid compounds that could reversibly store lithium [13].

In the early 90ies interest in electric vehicles re-emerged in US and Europe. The American state of California made a technology forcing approach to introduce zero emission vehicles mainly driven through the California Air Resource Board aiming to set strict emission standards to curb health problems in Los Angeles provoked by vehicle emissions [26]. The mandate was relaxed however later on, most notably in 1996 and when the 1998-2002 requirements were abolished market soon crushed [17]. European attempts regarding electric mobility are e.g. demonstration projects as in the case of Germany on the island of Rügen from 1992 to 1996 with 60 EV´s. A report revealed that EV´s caused higher sulfur dioxide and CO_2 emissions in relation to conventional vehicles due to the high share of coal power plants in the German electricity generation mix [27]. This has led German politics to reject the project due to environmental concerns. However, the report did not consider increasing RES capacities [28].

The installation of energy storage and electric vehicles ended after reductions in the price of oil as well as natural gas and the emergence of more efficient and cost effective combined cycle and simple cycle natural gas turbines flanked by the repeal of policy measures taken during the oil crisis (e.g. repeal of the Fuel Use Act in 1987). In the 70ies PHS and CCGT where estimated to have the same costs, whilst in the early 2000 they had twice the cost [24]. Figure x shows the relation of increasing base load power plants in relation to PHS. It can be seen in the case of Germany that PHS installations starting from the 80ies stagnated due to the changing environment. As in the case of PHS, interest diminished after 1980. Later Moli Energy developed the first secondary lithium and molybdenum-sulfur based battery in 1985 which had its drawbacks in safety issues. Sony finally introduced the first rechargeable lithium battery into markets in 1991. Whilst NaS commercialization took 40 years, Li-Ion batteries where successfully commercialized within 17 years and revolutionized portable markets. NaS battery was commercialized through the Japanese company NGK mostly used for load levelling with installations of up to 200 MW [13], it was also initially used for electric vehicles [27]. Battery research continued strongly to in improving capacities, rate capability and cycle life of battery types. Figure 4 gives an overview of the correlation of PH, coal and nuclear power plant installations and published patents of PHS, secondary batteries (aggregated from NaS, Zebra, Vanadium Redox Flow, NiCd, different Li-Ion chemistries and Lead Acid batteries) and electric vehicles.

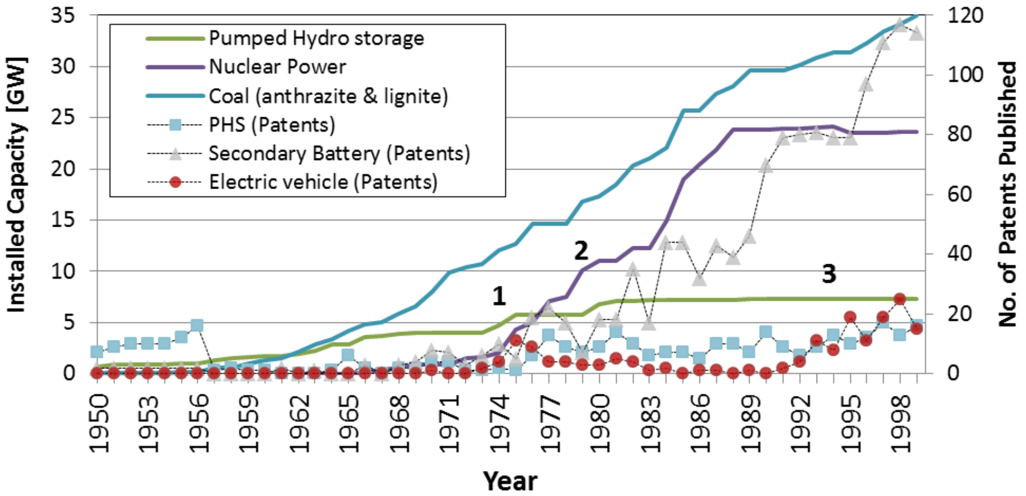

Figure 4: Installed capacity and published patents; 1 = first oilcrisis 1973, 2= second oilcrisis 1979, 3= EV hype in early 90ies (data sources [29]; [30])

In the field of mobility ICV cars maintained their dominance and electric vehicles remained as a niche with no sufficient opportunity to enter into the dominant regime. Business culture at that time was rather security focused with long planning periods and markets where centrally organized with almost no competition between utilities. Utilities were public owned and often supported e.g. through subsidies as in the case for German coal power plants [23]. There were investments in new technologies but utilities tended to rely more on traditional generation assets, so new technologies were adopted slowly [24]. This processes of adopting new technology took place within stable rule-sets and proceeded within predictable trajectories [10].

6.3 **Liberalization of energy markets and low carbon era**

Liberalization became a global phenomenon in the early 90ies. Some countries started early with experimenting liberalized markets as the United Kingdom in 1989, Chile 1982 or Argentina in 1992, representing pioneers in electricity market liberalization [31]. The reasons for liberalization varies from country to country but mainly has the objective to reduce end user energy costs in relation to monopolized markets, to reduce external especially political involvement including regulation measures as well as to open markets for new entrants. Further drivers for liberalization were politic ideology on the faith of market forces, the desire to attract foreign investment, distaste for strong unions and environmental concerns [31]. The reason for liberalization varies from country to country but most have in common the objective to reduce end user energy costs in relation to monopolized markets. Liberalization of energy markets in Europe is based on the three pillar policy of the EU namely energy security, competitive markets and the development of renewable energy sources [32] and includes further strategic and political goals (directive 2003/54/EG) [31].

At the same time a strong promotion of renewable energy systems as photovoltaics and wind turbines e.g. through EU directives 2001/77/EC took place which has set challenging indicative national targets to increase RES shares [32].[2] Several promotion strategies were adopted simultaneously to liberalization in Europe in form of investment focused (investment incentives, tendering systems, environmental taxes etc.), generation based (Feed-in tariffs, tendering system for long term contracts etc.) and voluntary focused (Investment focused Shareholder programs Voluntary agreements) [32]. This has led to a massive growth of RES in several countries as Germany, Spain and other countries. Other important steps in this were e.g. the establishment of the European Emission Trading System EU- ETS 2003/87/EG and the definition of the EU 2020 target [3].

Utilities have become more short-term and cost competition oriented due to liberalization of the sector. Unbundling has led to the situation that network operators are not allowed to own generation capacity, as it was in the case when they belonged to public utilities [11]. Utilities still temp to be conservative with a highly short term cost focus (mainly up-front investment cost) [33]. Thus utilities have invested heavily in conventional generation before the renewables rush began. This has led to a long delay of investment through electricity utilities in the field of RES. At the same time utilities had to face an increasing public pressure to “green” electricity production. This pressure was based on concerns over the impact of climate change, resource depletion and supply security (Russia and Middle East) and created uncertainty over the long term feasibility of our current system of energy supply [11]. So as RES-technology became more commercially viable, renewables such as wind turbines gained popularity among utility companies, which started to a certain degree to integrate them into the existing power grid.[4]

An event that has triggered this development or even led to shift in energy system development in at least some countries as Germany[5] was the melt down of the Fukushima reactors in 2011 through the catastrophic Tsunami. This incident has led to the radical decision of politics to force a faster phase out of German nuclear power plants until the year 2022 [34]. It has furthermore triggered Germany’s *Energiewende*, or “energy transition”, which has hammered the country’s utilities [33]. The resulting overcapacity of conventional power plants built up before RES rush has caused wholesale electricity prices to tumble. Some conventional plants cannot make enough money to cover fuel costs and are being shut down.

This represents a divergent and unforeseeable landscape change that increased regime problems that has led actors, mainly utilities, to lose faith in regulation, markets and policy [10]. A good

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[2] The directive aimed to increase the share of RES from 12% in 1997 to 21% by 2010.

[3] The targets are to cut greenhouse gas emissions by 20 %, increase the share of energy from renewable sources by 20 %, increase energy efficiency by 20 % until 2020.

[4] The development of RES was inicially seen as radical innovation where employing wind turbines and PV offered customers the possibility to escape the utility controlled grid.

[5] Before this event Germany has planned to prolong the running time of its nuclear power plants based on a set of scientific energy scenarios

example is the German utility company E.ON which want´s t quit conventional energy to focus entirely on renewables until 2016 [35].[6] The case of E.ON is seen as a game changer in the sector as it represents a radical shift in utility company behaviour.

The creation of wholesale electricity markets within a liberalized market, growing RES shares in combination public pressure market has created new opportunities and interest in energy storage [24], [36]. Electricity has a special and distinguished status in relation to other commodities due to its economic importance for the countries and its non-storable feature and environmental impact [31]. The interest energy storage in general is to a certain degree reinforced on the creation of day-ahead and forward market in combination with open intra-day and balancing, ancillary services, contingency reserves and capacity markets offering new business possibilities for energy storage [31] [24]. These markets provide transparent data as e.g. [37] or [38] for utilities or other parties to consider opportunities for energy storage in combination with renewables. The value of especially fast response services requiring limited actual energy delivery is thus nowadays evident and reveals the potential benefits of energy storage [24]. The need for these services can be seen as a main driver for the need of battery energy storage resulting from increasing shares of intermittent generation. These sources have a highly fluctuating generation behavior which only correlates partially with load and spot market prices. Furthermore decentralized generation (DG) is increasing through the use of roof top photovoltaics as in the case of Germany. Thus residual storage is seen as a potential vast market in countries where DR penetration is high. Germany is such a country where grid parity of PV-Systems is reached since 2012 due to high electricity retail prices making self-consumption of solar generated energy in combination with battery storage more viable [39]. Thus Li-Ion technology on a residential level is becoming more and more interesting for grid applications. Nowadays uninterruptible power supply represents one of the main markets for battery energy storage (market size about 2 billion € in the EU), which is especially triggered by the telecommunications sector. Further relevant energy storage markets are stand-alone electricity systems in rural areas or mobile services [40]. From an economic view point battery storage is not viable as whole sale markets are “only energy” based where capacity is rewarded. Furthermore RES production – especially from PV, causes price decreases during peak times lowering the potential revenue for storage technologies and conventional generation capacities. This effect is reinforced by growing photovoltaic capacities which cause a high cost pressure on other energy conversion technologies.

At the same time as liberalization took place, Li-ion with various cathode chemistries and NiMH technology have captured and enabled the portable electronic market, invaded the power tool equipment market and is penetrating and enabling the EV market on condition that improvements can be achieved in terms of cost and safety [41], [13]. This has maybe led to a new momentum of EVs that could lead to new developments in electrochemical energy storage that might be also used for grid applications. Currently about 13 EV and 12 PHEV models are offered by 2014 with a number of 60.000 vehicle sales each. Still EV market is very small with only as share of 0.39 %. Together with PHEVs EVs have reached about 3.5 % in 2014 with a maximum of 3.84 in 2013 [17]. Figure 5 shows the amount of patents in the field of EV´s[7] and various battery types[8]. Especially EV and the segment

[6] Critics worry that the company is now trying to offload its bad assets and that the new offshoot won't be able to generate enough revenue in the green energy environment to finance the phase-out and demolition of its nuclear plants.
[7] EVs are considered in general, including PHEVs
[8] The field of Li-Ion includes NCA, LFP, NMO, LCO

of Li-Ion show a high correlation. An extreme increase of patents can be observed starting from the year 2007 to 2008. This comes especially true for Lithium Ion batteries and might be mainly related to the market introduction of several portable devices as smart phones and tablets.

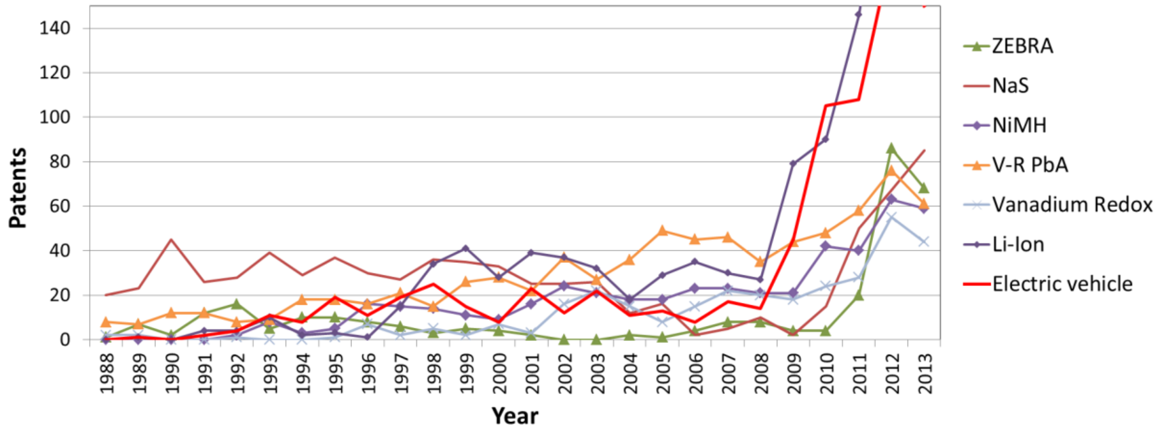

Figure 5: Development of patents in the field of various battery types and electric vehicles (own graph, datasource: [29])

There are signs of a co-evolution of electric mobility and stationary battery storage that can be observed nowadays. Tesla announced its "*Powerwall*" home battery storage system that can be used to charge electricity generated from solar panels, or to store electricity when utility prices are low [42]. Mercedes Benz also introduced its "*Mercedes-Benz Energiespeicher*" which is a stationary Li-Ion battery for residential storage. Both, Tesla and Mercedes initially developed batteries for EVs [43]. Both areas mobility and stationary energy storage are highly independent from each other as high market diffusion of electric vehicles might enable potential economies of scale. Integration of this systems can be realized via stationary systems (e.g. with new batteries or second life cycle of traction batteries) or indirectly in a quasi-stationary way by so called vehicle to grid (V2G) systems (battery electric vehicles allowing bidirectional power flow) introducing even a new sub-regime of "electric transport" into the energy system that might become relevant in the future [44]. However, battery storage is seen as a precondition to enable a RES based energy generation which is need for sustainable transport systems [40]. An overview of RES growth in relation to EV sales until nowadays is given in figure 6.

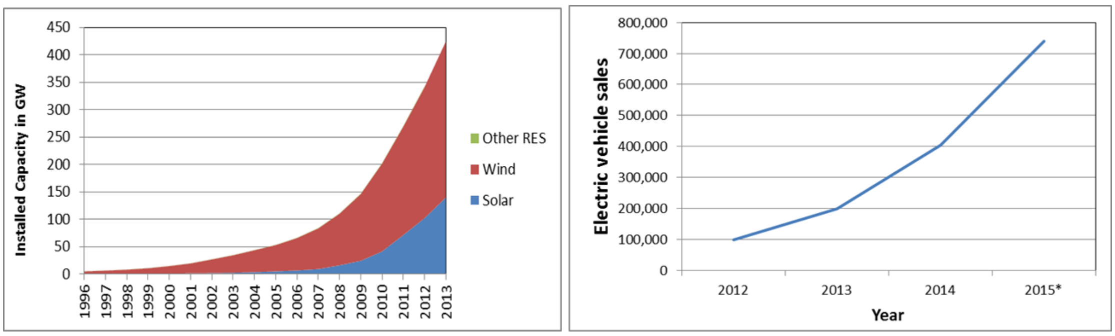

Figure 6: Comparison of global EV market diffusion and RES installations (source [45])

Starting from nowadays the energy system is undergoing again a significantly change in which bidirectional power flows occur from low voltage levels from residual energy generation to high voltage grid levels. This increasing market roll out of fluctuating decentralized energy resources (e.g. photovoltaics) represents a difficult issue for grid stability. This is reinforced through the decreasing number of existing residual energy generation capacity as coal and nuclear power plants. The future grid will have to face greater challenges by providing clean power from a high share of renewables in combination with more dynamic loads with less controllable generation capacities [3]. This development is based on national policies as in Germany with its ambitious target to produce 35 % of the needed electricity from renewable energy systems by 2020 and over 80 % by 2050 within the so called “Energiewende” - Energy transition [2] which is flanked by the German government. Within this transition solar and wind energy are the most promising technologies among other renewable energy systems providing about 75 % of the required energy in 2050 [46]. Anticipated technology concepts as smart grids and virtual power plants might enable completely new application areas for battery energy storage. At the same time there are several promising materials under development as Lithium Sulfur (Li/Sx) or other cathode types as composite materials or Li/Air [47] which are currently under research and might represent a disruptive and enabling innovation in this field.

6.4 **Interpretation of socio-technological transition paths**

In general it can be said that Energy storage itself (no matter if batteries, PHS or CAES) is dependent on other system developments and does not represent a separately identifiable system (Grünewald 2012).

The landscape pressure of during the electrification era was led by industrialization and high trust in euphoria in technological innovation. There was no common electricity sector policy, developments were strongly innovation led. Early electricity markets were characterized by private owned businesses with a strong focus on revenue where techno-economic knowledge was held by innovators as Edison, Tesla or Westinghouse. Energy storage technologies at that time were PbA and the Alkaline battery which were used for load levelling, lightening, telegraphy and electric mobility [12]. Batteries where initially mainly developed in anticipation of electric mobility and became instrumental for shaping the development of DC grids. This entire process can be understood as a socio-technical reconfiguration process [12]: the battery as a niche product was adopted by the temporal regime that days and became an important add-on for DC stations. The emergence of AC grids represented a conservative invention contributing to the forward “momentum” of an existing technological system [48] which led to a transformation of the entire regime, making stationary battery and their services obsolete. Batteries were insufficiently developed to take advantage of this change, which was enacted by regime actors as Westinghouse who reoriented the existing development trajectory.

During the fossil age one can suggest a reproduction of the regime where the predominant energy conversion technologies were nuclear and coal power plants. There was some pressure on the regime e.g. during the oil crisis but the regime had sufficient problem solving potential to solve them. This might be expressed through the initial use of large PHS power plants and later on single and combined cycle gas turbine power plants which diminished the need for storage [24]. New innovations in batter storage were present but they had little chance to bread through as the regime maintained dynamically stable. Some exceptions were some projects utilizing NaS or NiCd battery technology for load levelling, black start or UPS applications [13]. However, battery developments as Li-Ion and NiMH were the prelude to the massive revolution of portables starting at the end of the 90ies. There was a high lack of new construction but interest in stationary energy storage did not disappear during this period of low-cost peaking fuels. There was plenty research and development continued together with an increasing number of projects [24].

Liberalization has led to a severe transformation of the former state owned highly vertical integrated energy companies in Europe. Utilities were obliged to conduct an ownership and legal unbundling of their divisions of electricity generation, transmission and distribution (grid) as well as consumption [23]. Still electricity markets in Europe where long time characterized by an oligopoly as in the case of Germany (Vattenfall, E.On, RWE and EnBW). The sectoral policies are based on a liberalised energy whole sale market and regulated electricity transportation networks [12]. Stationary batteries are still used in niche markets as UPS, black start or increasingly in residential storage [40]. The entire liberalisation process represented a re-configuration process of the entire regime until 2011 where initial radical innovations (e.g. wind turbines and PV) where developed in niches a showed to have symbiotic relations with the regime (as they represented a modification of utilities generation portfolios). They were after a delay easily adopted through utilities as an add-on in existing structures. This comes also true for battery storage which represents an add-on for e.g. residential PV-systems or ancillary services. Since 2011 a new development triggered through the Fukushima incident can be observed that can be interpreted as a re- and de-alignment in the regime due to a divergent landscape change and increasing regime problems lead actors to lose faith. This has led to severe tensions on the regime regarding socio-economic, -technical and political factors that might open windows for niches.

An overview and summary of the entire energy system, electric vehicle and battery development including all relevant regimes is given in figure 7.

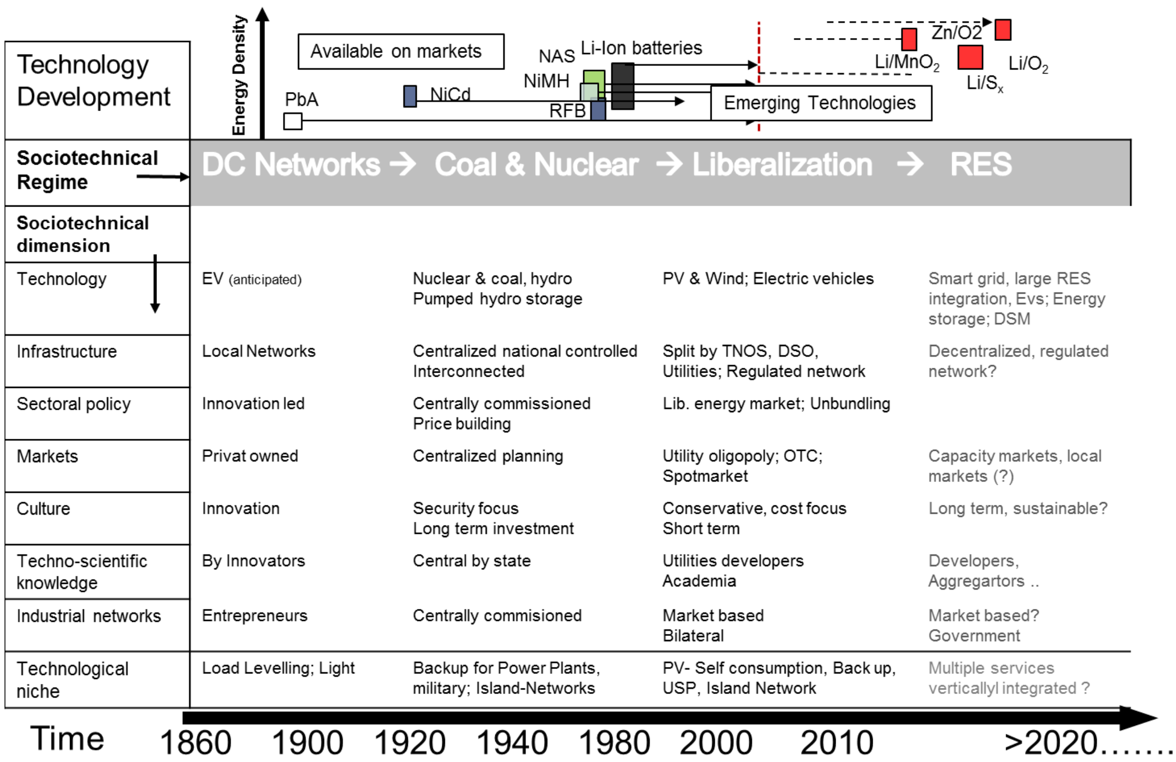

Figure 7: Overview of co-evolution of energy system, battery storage and electric mobility (inspired by [12])

7 Conclusion

The electricity system forms a complex, infrastructural, existing socio-technical system with different predominant regimes including individuals, companies, embedded rules, institutions and policy making. Such big systems are characterized by stability and lock-in and swifts towards a more sustainable energy system are hindered by sunk costs in technologies (power plants, cables etc.), skills and belief systems [11]. There is high uncertainty about the pathways of the electricity system towards a “greener grid” but it is clear that internal changes of existing regimes (the liberalized energy market) will happen in line of the German energy transition and that battery storage will certainly be a part of it. Yet of socio-technology pathways inhibit a high degree of non-linearity which becomes visible when analysing the historical socio-technical transition paths of grid battery storage.

All phases of socio-technical transitions are shaped by anticipation of a game changing emerging technology (as several times in the case of batteries developed in anticipation for electric mobility and then used for load leveling in DC grids or later during the oil crisis). Some technologies are more resilient to changes in socio-technical landscape (Grünewald 2012), as pumped hydro storage maintained its role after DC grids in the “fossil phase” as they fitted into the regime and still represent the dominant design. Batteries represent a special case due to their properties and do not so easily fit into the current socio-technical regime. There are several tensions on the regime based on concerns based on environmental concerns, unforeseeable incidents and changing market conditions. Undoubtable these tensions might lead to windows for stationary battery storage. Yet a regime based problem occurs. Unlike conventional technologies as generators, PHS or transmission lines, around which existing sub-regimes evolved, grid connected batteries (stationary or V2G etc.) don´t represent a natural subset of any of them [12]. Battery energy storage offers value streams and functionalities within the entire value chain influencing all surrounding sub-regimes of the electricity grid. This environment makes it difficult to directly allocate values streams to one of the sub-regimes (e.g. who benefits from investment deferral and distribution system operation?)[4]. Thus it is unclear how battery energy storage will be integrated into the grid, how it will be operated and who will be a main adopter or investor of it. This results from the fact that stakeholder roles within are not really established yet and seem rather to be continuously shaped and regrouped [4] [12]. Involved actors thus have to act under insufficient information and are highly dependent on shared expectations of the present [49]. This new situation may offer new potentials for battery storage through a high number of new technologies and application fields and the reemergence of electric mobility. Still it seems, the final word on the degree of penetration of battery storage in the grid and transportation sector will be political, but technology can win out if all else is equal as it was the case during electrification [13]. In general it can be said that transition pathways might help to better understand changing drivers for energy storage and might allow a more reflective assessment of potential futures of a technology

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