Technological Forecasting & Social Change xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment

T. Versteeg [a,b,*], M.J. Baumann [b,e], M. Weil [b,c], A.B. Moniz [b,d,e]

[a] VU University Amsterdam, The Netherlands
[b] Karlsruhe Institute of Technology, ITAS, Germany
[c] Helmholtz Institute Ulm (HIU), Germany
[d] Universidade Nova de Lisboa, FCT, Portugal
[e] CICS.NOVA research center, Portugal

ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 6 September 2016
Accepted 23 September 2016
Available online xxxx

Keywords:
Constructive Technology Assessment
Visions and expectations
Grid energy storage
Emerging technology
Energy system
Socio-technical system

ABSTRACT

The last decades have shown an increasing amount of research into expectations of science and technology. Especially for emerging technologies, expectations held by different stakeholder are guiding the direction of research and development. In this article the results of an investigation into the expectations of specific actors regarding the development of emerging battery technology for applications in the power grid are presented. It is set up as an explorative study within the framework of Constructive Technology Assessment (CTA). A number of studies since the 1990s have indicated a growing need for energy storage options in the power grid, where batteries appear to be capable of providing a range of valuable services to the grid. Cost-effectiveness on a large scale will however require considerable technical improvements. The configuration of energy storage may differ in the specific location and exploitation of the storage assets, as well as in the investments in new storage capacity. In this study the visions and expectations of several relevant actors are analysed using interviews and surveys in terms of expectations of technological development, expectations concerning stakeholder roles, and channels of interaction between the relevant actors. The results indicate a divide in expectations between the user side of the technology (the electric power industry) and the development side (academic researchers). Opinions differ with respect to the obstacles to technological development, the actors relevant in early technological development, and the most suitable channels for interaction between these actors. It follows from the theoretical background that conflicts in expectations provide the opportunity for the acceleration of technological development and adoption through stakeholder participation. Small interactive workshops, where conflicts identified in this paper are discussed, were identified as a suitable channel in order to reach consensus in visions and expectations for battery technology.

1. Introduction

New developments in energy production and the behaviour of consumers require changes in the configuration of the power system, in order to assure an efficient and reliable power supply. Energy storage may be one of those changes, as a means to smoothen out the intermittent energy production by renewable energy sources (RES). Battery systems are often mentioned as a suitable technology for this purpose. However, the general consensus seems to be that before one can make a viable business case for batteries, the technology first has to develop further. Different chemistries, such as Lithium-Polymer, Lithium-Sulphur and Metal-Air batteries, are promising new battery types that could make distributed energy storage economically viable. But in order to develop new systems and maximize the value proposition of decentralized storage, different parties will need to cooperate and experiment with new systems in real practice.

For the storage of electric power to become widely adopted in the electric power system, it will require both technical innovation to produce better storage technologies as well as system innovation within the energy industry to integrate electricity storage in the supply chain. Innovation of large socio-technical systems are usually complicated processes that may take a long time and include a lot of contingencies. This is partly due to the inherent dependence on many different actors, making the system difficult to steer. Also, big socio-technical systems are characterized by stability and lock-in effects where swift changes are hindered by sunk costs in technologies (power plants, lines and cables, etc.), skills and belief systems (Verbong and Geels, 2010).

* Corresponding author at: Karlsruhe Institute of Technology, ITAS, Karlstraße 11, 76131 Karlsruhe, Germany.
E-mail address: Manuel.baumann@kit.edu (M.J. Baumann).

http://dx.doi.org/10.1016/j.techfore.2016.09.024
0040-1625/© 2016 Elsevier Inc. All rights reserved.

It is crucial for technology forecasting and public planning to better understand long term patterns of innovation of certain energy technologies, such as energy storage. Particularly in the context of climate change and the ongoing energy transition (Huenteler et al., 2015). Constructive Technology Assessment (CTA) has been suggested as a suitable framework for the analysis of the social aspects of technological development of battery development. CTA has been developed as a soft intervention practice aimed at aligning expectations of different stakeholders in order to facilitate this kind of innovation. The involvement of different stakeholders in the design process of emerging technologies should result in the adoption of new technologies that are better suited for the needs and expectations of society (Baumann et al., 2014; Schot and Rip, 1997; te Kulve, 2012).

This paper presents the results of a study of the expectations of different stakeholders regarding the development of emerging battery technology for applications in the power grid. The research is set up as an explorative study within the framework of CTA. This consists of a review of scientific literature on storage technology and related power grid developments, and empirical research with surveys and interviews about the expectations held by experts and stakeholders on the issue. In this paper we first present an introduction of sociotechnical systems and the relevant concepts for CTA. This is followed by the research methodology before the results of the literature review and the empirical research are presented. Furthermore, the results are discussed in light of the theory, as well as recommendations for further research.

2. Constructive Technology Assessment: an approach to analyze emerging technologies and market uncertainties

According to Robinson (2010), CTA focuses on the wider interaction of the broad range of actors (including society) that have a "stake" in the development, deployment and use of new technology fields. This approach is based on theory of sociotechnical systems. In this theory technology is viewed as part of a seamless web of highly related heterogenic elements, such as organizations, institutions, resources, scientific elements and legislation. Societal functions such as transport and energy supply are results of such clusters of heterogenic elements which can be named socio-technical system (Geels, 2005). In order to understand how technological development takes place in an existing or changing socio-technical system, multi-actor dynamics have to be taken into account (van Merkerk and van Lente, 2005; Parandian, 2012).

Technological development, in its core, is a process driven by the decisions of the actors involved. In the early phases of technological development it is hard, if not impossible, to accurately anticipate the technical and economic impacts that a technology may have. Decisions are made in a context of uncertainty. Therefore, decisions are based on a system of beliefs: visions and expectations held to be true by the actors, but with little basis in reliable facts (van Lente, 2012). Emerging technologies and changes in science do not pre-exist themselves. Rather, their potential is shaped by expectations and visions. These two factors are told to play a significant role in mobilizing resources on a macro level (e.g. national policy through regulation and research patronage), the *meso* level of industry sectors, and at a micro level within engineering and research groups and in the work of single engineers or researchers (Borup et al., 2006).

Despite this context of uncertainty, it is important to make decisions in the early development phases. This is because technology is still malleable in early development, but loses this quality during development due to a process called entrenchment. This is related to the power-control dilemma, first posited by Collingridge (1980) and described by Berkhout (2002, p.3) as follows:

> "During the development irreversibilities can arise that set the technology on a certain trajectory that determines the outcomes of technological change. …. This dilemma describes a double bind on technological development because, on one side, one only has the opportunity to steer technological change in the early development of technology, before entrenchment has set in, but on the other hand, one only has the knowledge to know how to influence technological change in the late development of technology, when it is already too late."

Constructive Technology Assessment (CTA) offers an opportunity to account for this dilemma by broadening the design of new technologies through feedback from technology assessment activities into the development process. CTA involves the identification of stakeholder expectations, and ultimately aims at aligning these expectations to influence, rather than assess, technological development (Schot and Rip, 1997; van Merkerk, 2008).

In the following paragraphs the concepts behind the approach taken in this work are explained. Important concepts include emerging irreversibilities and the operationalisation of expectations of technological development into general expectations, positionings and spaces. Some general patterns in actor dynamics are also discussed.

2.1. Emerging irreversibilities

Entrenchment of technologies is the result of several irreversibilities that emerge during the development of a technology. From conception of a technological possibility, to its diffusion into the market, a technology becomes gradually more entrenched. This entrenchment is steered by the actions of the actors involved, for instance by the investors and developers that drive the development into a certain direction. Van Merkerk and van Lente (2005) introduce the term emerging irreversibilities to refer to patterns that enable certain actions and interactions, while constraining others. This process is driven by the fact that almost all resources are limited, including human and of course financial resources. This means that for any resources put into a certain project, another will have to do without. The first decision in distributing resources creates a disparity between different options. As these decisions are based on the beliefs of stakeholders, studying these beliefs provides insight into the irreversibilities that are emerging. Based on this, stakeholder beliefs are taken to be the best indicator for the futures of emerging technologies, and the object of analysis in this paper.

2.2. Expectations of emerging technologies

Expectations can play a big role because of the inherent uncertainty of technological development. Decisions have to be made within the context of uncertainty, and treating expectations as facts decreases the subjective degree of uncertainty. As such, expectations have three effects that make up their impact: legitimization, heuristic guidance and coordination (van Lente, 2012): expectations that are circulating among stakeholders raise attention to a technology and legitimize investments that carry high risks with them (as investments in emerging technologies generally do). Expectations offer direction when there is no objective way of deciding between many possible different paths that may be taken in scientific research and technology development, much like a heuristic deals with complexity and uncertainty. Finally, expectations move across boundaries, thereby providing coordination between distinct groups and communities, and across levels (Borup et al., 2006). Coordinated action across different research groups leads to mutually reinforcing research efforts in one specific direction, and coordination across levels (the research groups, sectors and innovation networks, and governments and society) leads to a wider economic and social basis for technological development. Through these effects, expectations constitute themselves as driving forces of the emerging irreversibilities discussed above.

The power of expectations depends on the degree to which they are shared (Borup et al., 2006). The 'sharedness' ensures that actors act accordingly to these expectations. Expectations thus inspire new technological developments that subsequently have to be protected by other

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

collective expectations. Clear instances of shared expectations can be found in sector or industry roadmaps or other foresight results (van Lente, 2012). These formalized expectations may be the easiest to identify, but they do not represent the whole landscape of influential expectations. Many decisions are made on more tacit expectations, only expressed in a more informal capacity. These informal expectations are the beliefs and ideas that actors may hold without them being written down or expressed in a more formal capacity. It has been observed that roadmaps sometimes underrepresent wider socio-technical contexts for innovation and may articulate inconsistent levels of optimism or ambitions across different technology stakeholder groups (Winskel et al., 2014).

2.3. Positionings

Aside from general expectations held by actors of the potential performance of a technological artefact, expectations held about other actors are particularly important. In industry, and even in research, actors continuously try to adapt their plans to the intentions of others. In the context of emerging technology, these roles of different actors in relation to the technology, otherwise known as stakeholder roles, are undefined and fluid. van Merkerk and van Lente, 2008 use the term *positionings* and emphasize the influence of positioning on the development of emerging technologies. Positioning refers to the allocation of roles, in line with the *positioning theory* in social psychology (Rom and Van Langenhove, 1999). The foundation of this concept lies in the idea that for emerging technologies, the concept of stakeholder roles does not really apply. This is the case because stable roles of actors in respect to the technology have not been established yet: they are continuously being shaped and altered, based on expectations of the roles one attributes to themselves and other actors, as well as the expected roles other actors attribute to them. Nonetheless these roles, or rather the expectations of roles i.e. positionings, are an important concept to consider and factor in emerging irreversibilities from an actor point of view.

In interactions, actors use positioning to express their role and the roles of others (actors or artefacts). For emerging technologies roles are still undefined and actors are still finding their place. Actors have the option to base their positioning on how they have historically been involved with similar technology, or on the role other actors expect them to take. These positionings are expressed in statements by actors about the future (visions and expectations). As an extension of the concept of positioning, a position is defined as an accepted or established role, which means there exists consensus among actors about the role of an actor or artefact.

2.4. Spaces for interaction

Besides expectations (and positionings carried within them), the circulation of expectations through interactions are an important factor. Van Merkerk (2008) identifies the channels of communication between stakeholders as an important factor in trajectory formation. He uses the concept of spaces, to indicate the way that interactions are organized. Spaces can be anything that provides opportunities for interaction. Van Merkerk (2008, p.34) defines their function as follows:

> "Spaces allow a variety of actors to assemble for deliberation, negotiation and aggregation (…). They are a locus for particular kinds of events, an opportunity for particular action and a gradient for and thus a constraint on the range of actions."

As such, a distinction needs to be made between the space itself, and the occasion for creation of a space. The occasion for creation of a space also offers the opportunity for interaction between actors, but only when this opportunity becomes a structural channel for interaction, is it considered a space. In the field of emerging technologies, actors are often confronted with the absence of spaces, and the need for the creation of them (van Merkerk, 2008). In this context interaction is bound to happen through existing, unspecialized spaces, or the occasion for creation of new spaces.

2.5. Enactors and selectors

Rip and Kulve (2005) identify two categories of actors which are involved in technological development: enactors and comparative selectors. Enactors are actors who try to realize a new technology. They identify with a technology. They construct scenarios of progress and identify obstacles to be overcome. In other words, they think in *enactment cycles*. This represents a concentric kind of thinking, in which the context in which technology is developed is taken into account, but is still second to the actual hardware that is central (Rip and Kemp, 1997). Enactors are technology actors, the developers and manufacturers of a technology, or some government agencies such as national laboratories or technology programs who have rallied behind a certain technology. Societal actors on the other hand see alternative technology options and take a position of comparing and selecting; they think in *comparative selection cycles*. Selectors are the eventual users, societal groups and other governmental agencies who take a more distant perspective than the ones mentioned above. This difference in thinking between the two types of actors can result in conflict. Enactment cycle thinking is characterized by an emphasis on the positive aspects of a technology, which is accompanied by a tendency to disqualify opposition as irrational and misguided, or following a personal agenda. Enactors might get frustrated when they have to convince the public and they find explaining the promise of their technology is not convincing enough. Loci where enactment cycles and comparative selection cycles interfere offer opportunities for bridging events, and this is where CTA comes in. By orchestrating bridging events, creating and orchestrating forums where interaction can occur, the different actors can probe each other's reality. A good example of such a forum would be an interactive workshop, where different actors share and compare their scenarios of the future of a technology.

3. Research design and applied methods to explore barriers, expectations and opportunities

It was argued above that it is essential to create a holistic understanding of the future development of emerging technologies, in this case new battery technology. In order to understand potential innovation problems in uncertain socio-economical environments such holistic understanding must be built on a coherent research design and the applied methods should be chosen accordingly. Thus, this study is comprised of two parts: first a literature study was conducted in order to identify the relevant issues surrounding battery technology development and the applications in the electric power grid. Second, different stakeholders were consulted in order to identify informal expectations that exist among stakeholders. In this section the methodology is briefly explained.

The literature study served as an inductive, preliminary step from which the technical landscape was identified. From the literature a stakeholder analysis could be performed along the supply chain of present battery technology for stationary and mobile applications, as well as the value chain for storage services in the electric power system. Also, the formal (published) expectations regarding battery storage were uncovered. Results from this study were summarized in Chapter 4.

In the empirical part of our study, the expectations of two different stakeholder groups were investigated; actors from the development side of technology, and from the user or application side. In the case of new battery technology, this would, in the first place, be researchers from technical research institutes. The users are less well defined, as there is no clearly defined or established market for stationary applications yet. However, it is clear that the potential users should be sought in the electric power industry, which consists of a few major actors, as well as other users of battery systems (think of vehicle-to-grid or battery repurposing configurations). In line with the theoretical framework presented above, developers are expected to behave like enactors, whereas the potential users are more likely to behave as selectors, with the corresponding views on storage systems as technological artefacts. Although this hypothesis has to be confirmed, the label of enactors and selectors will be applied to the group of development side actors and the group of user side actors, respectively, in the rest of this paper.

Eight interviews have been conducted, of which four were with stakeholders that fall into the category of enactors, and four interviews were with selectors. The participants were selected from the professional networks of the authors that include corresponding research groups and people met at congresses on storage technology. Interviewees all worked for different organizations from each other. The researchers interviewed all worked directly on the development of new technology for electrochemical energy storage. The respective positions of the actors within the research organizations differed as well: One candidate was a promotion (PhD) candidate (P2), whereas two were post-doctoral researchers (P3, P4) and the last one was the head of a research group (P1). From the industry participants, two participants worked in supervising positions in the R&D departments of large European electric utilities (P7, P8), one participant worked as a consultant and external project manager in the electric power sector (P6), and the last participant worked on the development of car sharing services with electric vehicles for a large automotive company (P5).

The main instrument for the empirical study is a survey build through an iterative process of testing and confirmation with the in-depth interviews. The first four interviews (two enactors, two selectors) were used to create and improve the survey, and four more were conducted in order to confirm the researcher's interpretation of survey results. Aside from input for the surveys, the interviews provide valuable in-depth insights into the rationale behind stakeholder expectations as well, and as such are first analysed separately from the surveys, before the results are integrated.

Two surveys were made; one for enactors and one for selectors. The surveys were kept as similar as possible, only accounting for the differences in knowledge about and involvement with the technology. For the development side survey 220 researchers from the largest battery research centres within Germany were approached, as well as 8 additional researchers from other countries. This has rendered 38 responses (37 from Germany, 1 from UK). This exercise does not aim to achieve any representative sample but only to work over a meaningful number of answers that reveal expertise and that can point out a group of new questions and possible problems in the field for further research. In the survey, participants were asked closed questions regarding development expectations, positionings and spaces. These topics were treated with a list of potential obstacles to innovation, stakeholders, and channels of communications respectively, as well as with a small selection of statements derived from the preliminary interviews or literature. All answers were based on a Likert scale of 6 options. For statements, these options are *Completely disagree*, *Disagree*, *Neutral*, *Agree*, *Strongly agree*, and *Do not know*. It should be noted that, whereas in the interviews a complete narrative of the vision of certain groups is sought, in surveys only a few aspects can be investigated. These aspects were chosen in order to be able to support or adjust the narrative constructed in the interviews.

The results represent ordinal data with a large margin of error (~16% at a confidence level of 95%). This means that the statistical analysis one can do with this data is limited (Allen and Seaman, 2007). The answers to the statements are presented in exact percentages. Answers to the lists are coded from −2 (not at all threatening/relevant/suitable) to 2 (very threatening/relevant/suitable), centering on 0 (neutral/do not know). From these the mean is calculated in order to create a ranking. It should be stressed, however, that for ordinal data, as is the case with Likert items, the coding represents a ranking order, but not a relative degree of difference. As such, the numerical value attributed to the ranking of an item, cannot be interpreted quantitatively, and should be regarded as purely instrumental for the illustration of the ranking. For completeness, the frequencies of responses are provided in the supplementary material available online.

A selector survey was distributed among actors from the electrical power industry via online communities for professionals in the electric power industry, but this rendered only 14 responses, from participants from 7 different countries and 7 different types of businesses. Due to the limited number of responses and the heterogeneity of this group from a very large population, the margin of error is very large, resulting in a low validity. Due to this low validity, the focus of this paper is on the enactors, and only the results to the lists in the selector survey are discussed to enable comparison to the enactor survey results.

4. Literature review

4.1. Storage services

There are a multitude of services that electrical energy storage (EES) could provide in the power grid. That energy storage can be used to smoothen out the intermittent generation of renewable energy by wind turbines or photovoltaics is mentioned most often in literature (e.g. Grünewald, 2012). The value of storage can also come from the deferral of investments in further generation or grid capacity, reduction of operation costs of generation facilities, reduced emissions and fossil fuel use of current generation facilities and increased reliability of the power supply. In this section the most important services that energy storage could provide to the power grid are briefly discussed, as well as the different storage technologies with a focus on developments in battery technology.

4.2. Storage services

The current electric power industry uses a just-in-time inventory system (Dunn et al., 2011a, 2011b). This means that power needs to be used directly when it is produced. Demand varies greatly over the course of a year, a day, or even a minute, causing the need for generation to be ramped up in order to respond to these changes. However, this ramping up takes several minutes, so energy balancing capacities are required at all time for quick responses. The bulk of production is based on predictions of the hourly and seasonal consumption, and several types of reserves are employed by electric utilities in the case that these predictions fall short, or in case of failure (Weedy et al., 2012). Reserve capacity today is mostly in the form of fossil fuel burning generating modules. This type of reserve makes up 95% of the reserve capacity in Europe (the other 5% is mostly in pumped hydro energy storage) and these assets generally run at lower efficiency and at higher emissions than the bulk generators that run at a constant rate to provide the base load (Dunn et al., 2011a, 2011b). Due to the variability of energy demand, much of the generation capacity that is required during peak consumption hours sits idle for most of the year. Aside from this idle capacity, the up- and down cycling of production decreases the overall efficiency of power plants, reduces the life time of the generation assets and increases the maintenance costs (Dunn et al., 2011a, 2011b). By storing electricity when demand is low, and releasing it when demand is high, the load could be spread out over the day, thereby increasing the baseload and relieving the need for extra peak capacity (see Fig. 1). Pumped hydro storage (PHS) is seen as the only commercial viable and available large scale storage technology nowadays for these services.

The issue of the variability of demand for centrally produced energy is exacerbated by an increasing number of decentral energy generation units (e.g. roof top photovoltaic). The intermittent character of most of this generation also poses a serious threat to the reliability of the grid, if the share of the total load is high: sudden changes in solar irradiation or wind power can cause significant imbalances between generation

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

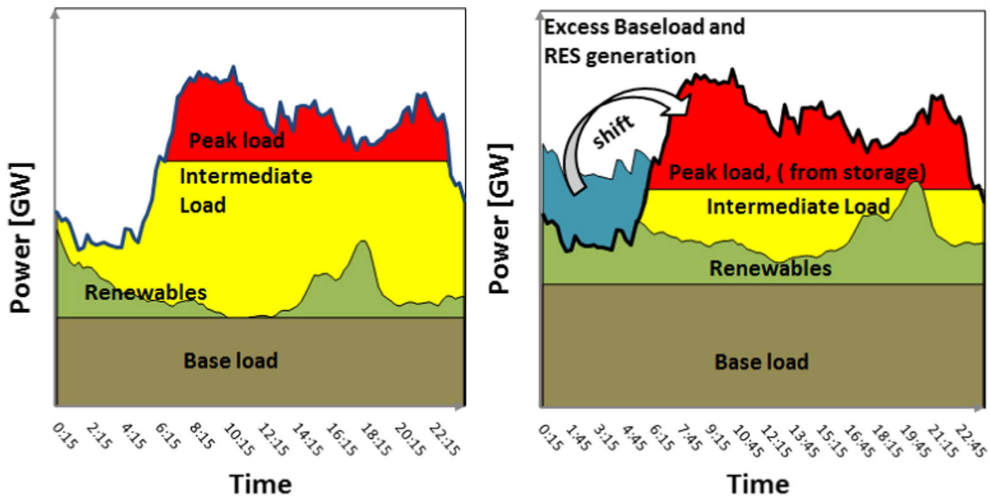

Fig. 1. Illustration of a typical grid load profile (left) and the same grid load profile with load shifting through storage (right) inspired by (Dunn et al., 2011a, 2011b).

and load, resulting in changes in voltage and frequency in certain parts of the grid. Such changes, if large enough, can cause emergency shutdowns that lead to blackouts within the grid. Without significant energy reserves to regulate load, voltage and frequency, there appears to be a limit to RES penetration above which the grid becomes critically unreliable (Yang et al., 2010). In the absence of energy storage (and other flexibility options e.g. demand side management), renewable energy would have to be backed up by fossil-fuel burning reserves that generally run at lower efficiencies than the larger generators that run at a constant rate. The need for such back-up capacity diminishes the 'green' benefit of RES.

Related to this issue is the fact that new, distributed generation facilities such as those using RESs can introduce congestion in the power grid, which would traditionally require the reinforcement of cables and transformers (Weedy et al., 2012). EES is one option that can limit the impact of new generation facilities to the grid, by shaving the peak load on the transmission or distribution grid, thereby limiting and deferring new construction activities.

Other services that EES could provide include energy trading and back-up power for reliability and uninterruptible power supply (UPS) (EPRI, 2010): Large scale storage could be used for energy trading, by storing power when the price is low, and selling when the price is high. Storage on longer timescales for back-up power can improve the reliability of the grid as well as provide reserve power for sensitive locations, such as hospitals and data/communications centres. Energy storage systems with an advanced management system may also be able to provide several services simultaneously, depending on system characteristics such as the discharge and reaction time.

4.3. Energy storage technology

Given the variety of energy storage services discussed above, the requirements for energy storage vary greatly in terms of capacity and running times depending on the specific application. There is a number of energy storage technologies with diverse characteristics eligible for providing these services. These technologies store electricity either as mechanical, chemical or electrochemical energy, or directly as electricity (Ibrahim et al., 2008). Examples of mechanical systems are pumped hydro energy storage (PHES) and compressed air (CAES). Chemical are systems such as fuel cells (FC), whereas batteries (BES) or supercapacitors (SC) are electrochemical. Capacitor or super magnetic energy storage (SMES) stores electricity in an electric or magnetic field, respectively. Fig. 2 gives an overview of the different technologies and their characteristics.

These different technologies all have their advantages and disadvantages. The mechanical systems are generally mature technologies, but have certain geographical requirements that render most sites unsuitable (Dunn et al., 2011a, 2011b): CAES, for instance, requires rock

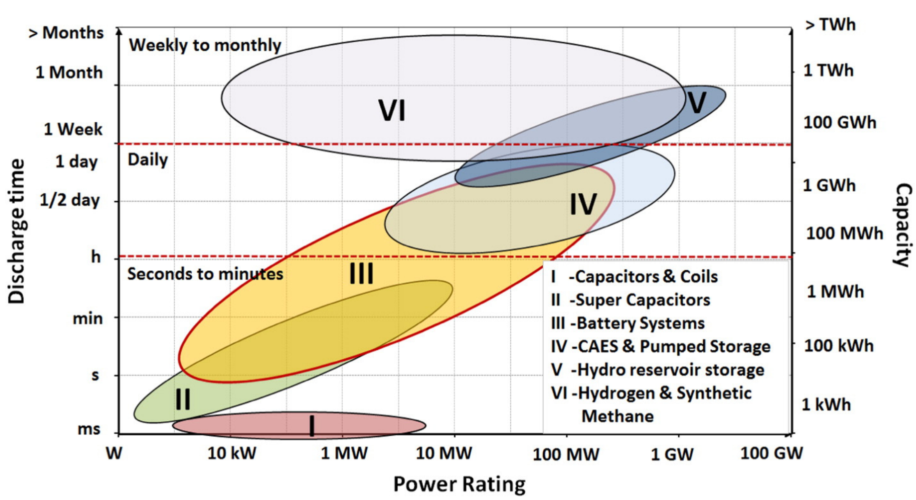

Fig. 2. Comparison of Different storage technologies based on characteristic capacity and discharge time (EPRI, 2010) (Sauer, 2011) (Leonhard et al., 2008).

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

caverns for air injection and PHS requires two superficial water reservoirs situated in different altitudes connected by a penstock. This requires firstly proper locations for the basins and secondly a suitable height different between these. Furthermore, energy has to be transported from the location of generation to the storage location and from storage to the demand areas. As some energy is lost in transport and remote locations may require the additional construction of transmission lines, not all technically suitable locations are financially viable. The other systems are still in early development, particularly for large scale applications. With respect to energy conversion efficiency and lifetime, they are still immature. In this paper the focus is on BES, as the technology is suitable for a broad range of applications and is rapidly being developed around the world (European Commission, 2013; US DoE, 2013). This development is driven not only by the need for stationary storage, but mainly for mobile applications such as in electric vehicles and portable devices (Tarascon, 2011), (Dunn et al., 2011a, 2011b).

4.4. Battery technology

Battery technology is generally seen as an interesting technology for grid-connected storage, given the modular configuration and high round trip efficiency of some battery types. Currently, the technology dominating the battery market (mainly in mobile devices and cars) is the lithium-ion battery (LIB) (Bruce et al., 2011). However, these batteries have limitations, both theoretically and in practice, that put restrictions on e.g. driving ranges achievable with full electric vehicles as well as on achievable cost reductions (among other things). The wish to overcome these limitations is an important driver for the development of new battery types that may be very suitable for stationary applications as well. There are a number battery types based on different chemistries in the pipeline. Among these, Lithium-Polymer, Lithium-Sulphur (Li-S) and Metal-Air are considered the most promising technologies to produce significant improvements on the performances of systems currently available in the next 10 to 20 years (Meisenzahl et al., 2014; Simon et al., 2014; Thielmann et al., 2010). An overview of different battery technologies is given in Fig. 3. The battery types in the red field can be seen as completely new development whilst the types in the green field are already available on markets or at least on a demonstration level.

There are also endeavours to develop batteries with lower energy densities, but with high efficiencies and low costs, specifically for stationary applications (e.g. redox-flow batteries) (Doughty et al., 2010).

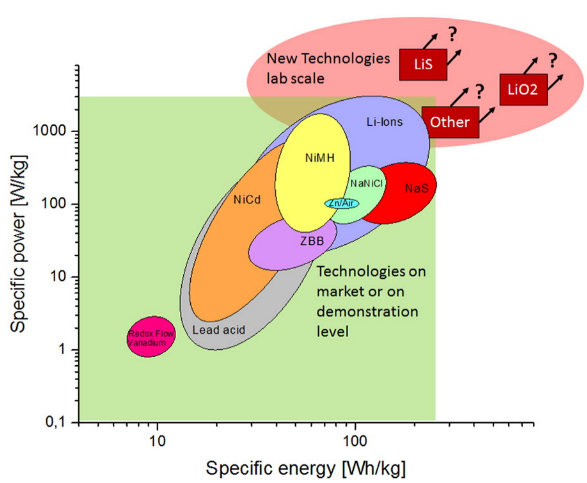

Fig. 3. Ragone plot of existing and emerging technologies based on data from (Baumann et al., 2013), (Stenzel et al., 2014).

4.5. Relevant Stakeholders

It has been shown that the impact of storage can affect many parts of the electric power system, and with that it affects a large group of agents: power producers, both central (utility) and decentral, transmission system operators and distribution network operators (TSOs and DNOs). Beside these stakeholders, energy storage also has implication for end user organisations, such as those particularly sensitive to interruptions in their power supply, like hospitals or data centres. It has to be mentioned that these potential users perceive the risk of incompatibility with the conventional energy, high initial installation cost and difficult operation (Yun and Lee, 2015).

In general, energy systems consist of a multitude of different technologies from several industry sectors (e.g. conversion, extraction and end-use of energy). Most of these technologies are not developed by energy companies as utilities but enter the electricity sector as specialized equipment from other sectors (e.g. semiconductors (solar panels) or electro-mechanical machinery (gas turbines) (Huenteler et al., 2015). This principle can be applied to the case of electrochemical energy storage as well. As mentioned above, the development of batteries is driven not only by the need for stationary storage in the energy system: The need for a larger driving range for electric vehicles and better batteries for portable devices are important drivers as well. Technologies as Li-ion with various cathode chemistries and others as NiMH and NaNiCl technology have captured and enabled the portable electronic market, invaded the power tool equipment market and are penetrating and enabling the EV market on condition that improvements can be achieved in terms of cost and safety (Tarascon, 2010; Whittingham, 2012). This means that manufacturers of these products may therefore be regarded as indirect stakeholders in the development of battery technology that may be used for grid-connected services. Although they are very different products (large storage systems for power generation, vehicle battery, or small batteries for portable devices) developed by different companies, all may have coinciding interests in the development of certain technologies. Integrating batteries into the electricity system may however require different efforts because, as Kemp (1994) and Yun and Lee (2015) state, innovative companies do not only have to develop better technologies, but they also have to put immense efforts into shaping the market through persuasion of consumers in order to increase their perceived benefits and to decrease perceived risk. Tesla for example 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 (Tesla, 2015). Mercedes Benz also introduced its "*Mercedes-Benz Energiespeicher*" shortly after this announcement. Both, Tesla and Mercedes initially developed batteries for EVs (Mercedes, 2015). The areas of mobility and stationary energy storage are highly independent from each other as high market diffusion of electric vehicles might enable potential economies of scale.

Implicit so far has been the importance of government bodies: much of the support for the development of battery technology comes from public funding agencies, and utility companies in many countries are (partially) publicly owned. Some government bodies also publish regular roadmaps that document the formal expectations regarding developments in the energy sector that often include or even focus on energy storage (European Commission, 2013; US DOE, 2013). Furthermore, the energy sector is heavily regulated, and regulation can act as a driver, as well as an anchor on technological development (Foxon et al., 2005). For instance, in most of Europe, DSOs are prohibited from trading energy, which effectively means that under current regulation they are generally not allowed to feed energy into the grid or to take large amounts of energy out of the grid (Oosterkamp et al., 2014). Transport losses and temporary solutions for grid-failure or maintenance are not included. As this rule currently also applies to storage and other flexibility options, it excludes DSO's from contributing to the development of this technology. A good example where regulation acts as a driver for technological development is the promotion of renewable

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

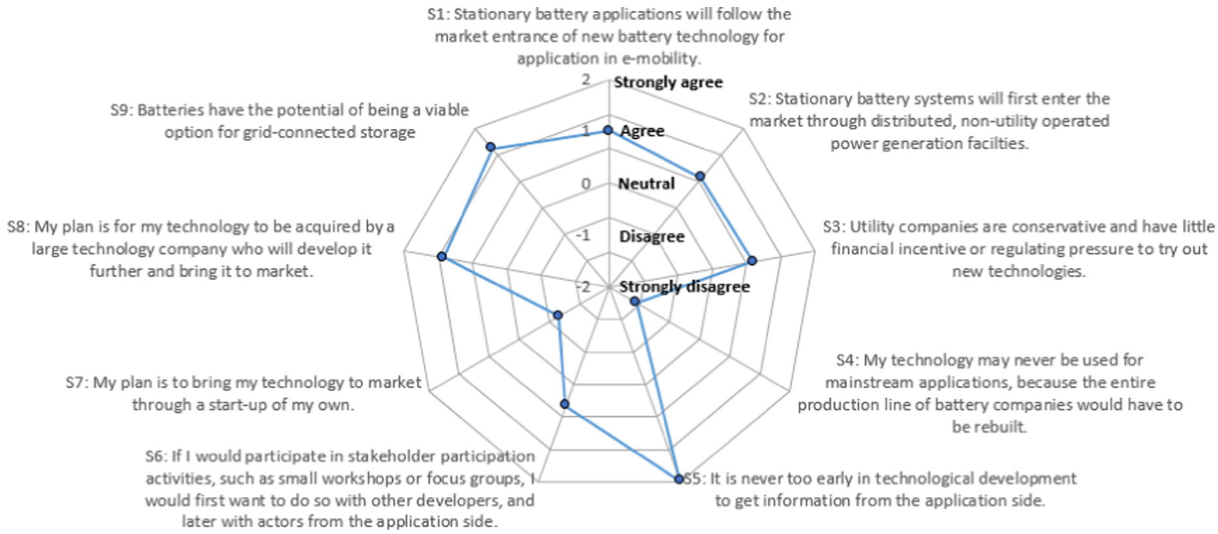

Fig. 4. Survey statements from the enactor survey. The graph shows the mean of the value labels attributed to the responses.

energy systems as photovoltaics and wind turbines e.g. through EU directives 2001/77/EC that took place in the early 2000s which has set challenging indicative national targets to increase RES shares.

5. Survey & interview results

In this section the results of the interviews and surveys are discussed. As the interviews served to provide input for the surveys on the one hand, and a tool for interpretation of survey responses on the other, interview data is discussed anecdotally in juxtaposition to the survey. Themes that were treated are expectations of technological development (and specifically obstacles to development), relevant stakeholders, and channels for communication between the relevant stakeholders that may benefit development.

5.1. Expectations on emerging battery technologies

Responses from experts in interviews as well as the survey responses (see Fig. 4, S9) confirm the formal expectation from much of the literature that battery technology is generally seen as a potentially viable technology option for grid connected storage. However, the participants generally agree that this application for batteries will follow the application of new battery technologies in electric vehicles (Fig. 4, S1).

A combination of these opinions is expressed in the following quote of interview participant P1, in relation to the battery type the participant focuses on in his work:

> "The main advantage [of lithium-sulphur batteries] comes from its high energy density, so people sooner think about mobile. But it is also quite cheap, so it could be advantageous for stationary applications as well."[1]

This statement is an example of how many actors, as indicated in the survey, view stationary battery applications as secondary to electric mobility.

Generally dismissed was the statement that the technology in question may never be used in mainstream applications due to the incompatibility with existing production lines, with only 8% in agreement versus 71% in disagreement (Fig. 4, S4). This statement was inspired by a statement from interview participant P2:

> *"You would have to change all the technology, as* [my technology] *is totally alternative to the current technology to make electrodes by coating metal foil".*[2]

In this interview, the specific technology concerned electrodes that were nanostructured in a way that was incompatible with the standard role to role foil coating method of electrode production. An explanation for the fact that most researchers feel that this statement does not apply to their technology may be that their technology is designed to be compatible with the standards of battery production.

The fact that researchers do not view the disruptiveness of their technology, otherwise defined in this work as incompatibility of a technology with existing technologies and/or production lines, as a likely threat is also reflected in the ranking of potential obstacles.

Fig. 5 shows a list of potential obstacles in the development of new battery systems, ranked on the basis of the ratings or relevance by the development side actors. This ranking shows a general priority given to obstacles concerning more or less intrinsic properties of the technology; stability and performance issues are seen as most important, followed by the costs, safety and achieving economy of scale. Obstacles related to users, competing technologies, regulation and the before stated disruptiveness are generally rated as unimportant.

These obstacles can be seen as originating from factors external to the technology. Quite surprising is that environmental impact is ranked as least threatening of the obstacles. This may be because of an implicit assumption that the use of stored electrical power is intrinsically more environmentally friendly than direct use of chemical energy from fossil fuels.

The observation that researchers tend to give priority to the characteristics of the hardware of the technology was also made in the interviews. Participant P2 said the following:

> "my focus is only what is the chemical composition, what is the electrochemical performance, so really like how many cycles can I make and how do I do it…"[3]

This statement seems illustrative for the attitude of an enactor, described in chapter 3 as the concentric systems view of technology. This is discussed in more detail in the discussion.

[1] Transcript P1; l. 76-78.

[2] Transcript P2; l. 75-76

[3] Transcript P2; l. 104-105.

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

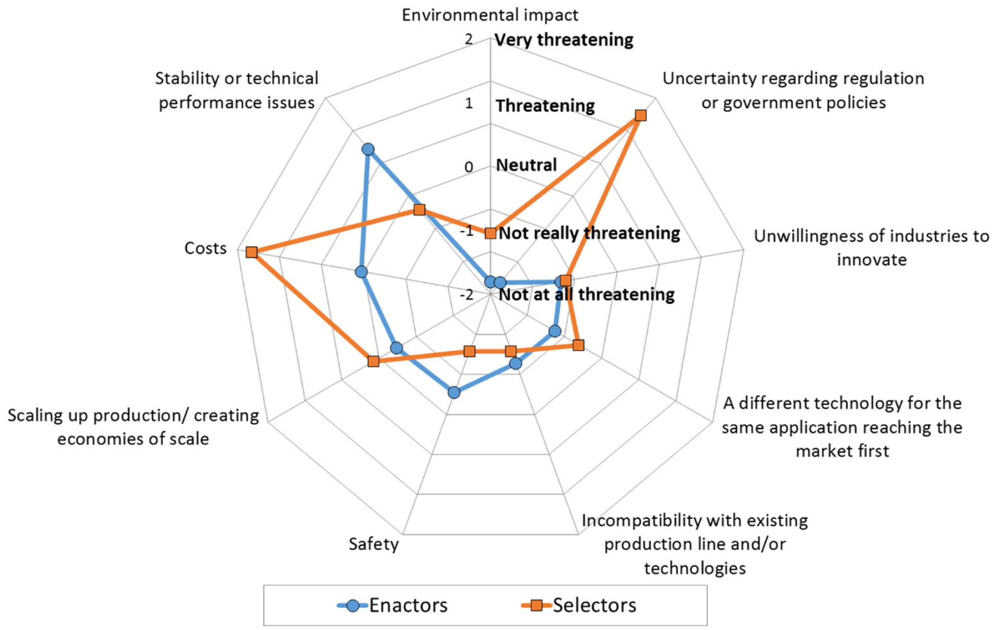

Fig. 5. Relevance of obstacles to technological development. Relevance attributed by enactors in blue, and by selectors in orange. The graph shows the mean of the value labels attributed to responses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An aspect that could not be treated in detail in this project is the specific dynamics of the expectations of the stakeholders. In order to understand not only what the expectations are today, but also how they will develop in the future, it is important to study how expectations spread between actors. This point is closely related to studying the important spaces around today, and tracing the sources of expectations. The fact that the power of expectations depends on the degree to which they are shared adds to this point. Future research into the dynamics of expectations in the electric power industry would be essential to improve understanding of the direction of developments in this industry, and of how to influence these developments.

5.2. Positionings of relevant Stakeholders

The ranking of stakeholder relevance (Fig. 6) indicates quite clearly that researchers generally assign a higher relevance to technology actors (battery component manufacturers, chemical companies, car manufacturers and battery system producers), than to the potential users in the electrical power industry. Actors from the electric power industry are collectively at the bottom of the ranking, with a generally negative appreciation of relevance. This preference was also observed among the participants from the development side in the interviews.

Regardless of this estimate of relevance, a large majority of participants has responded in agreement to the statement that it is never too early in the development of a technology to get information from the application side of that technology (Fig. 4, S5). This indicator of interest in the potential users of technology is further confirmed by the responses to statement 6: only a small majority of the researchers that participated indicated an initial preference for interactive workshops with other developers over workshops with actors from the application side. A similar position was observed in the interviews, as shown in the following quote from participant P1:

> "It is also useful to get information from application side so that you get the technology to market faster"[4]

In comparison to the responses of the selectors, the difference in importance attributed to regulation is particularly striking: For actors from industry, uncertainty regarding regulation is considered the second most threatening obstacle, whereas by development side actors, it is generally seen as unthreatening. In the list of stakeholders, regulation actors were ranked third most important by selectors, whereas enactors have generally ranked regulation actors as slightly irrelevant or uncertain. The importance attributed to regulation actors by the participants in the interview was similar to that found in the survey. As participant P5 said:

> *"From a macro-economic view, I expect, it* [grid-connected storage] *will be cost efficient, but therefore first the laws regarding the regulation of grid operators have to be changed."*[5]

Where actors from the electric power industry were collectively rated as the least relevant actors in the development of new storage technology in the development side survey, this was not the case for the selector survey. This may, of course, be expected as this does involve self-reflection: the actors from the electric power industry are ranking themselves. This makes interpretation difficult: had these actors not considered themselves as relevant actors for the development of energy storage systems for grid-connected storage, they would probably not have participated in the survey. Nonetheless, it indicates that many actors from the electric power industry do envision a role for themselves, and each other, in the development of new storage technology.

5.3. Relevant spaces and channels of communication

With regard to channels of communications (Fig. 7), scientific publications and conferences are rated as the most suitable by the enactors. This indicates that the traditional means of communication in the science community are preferred over others that are perhaps more common in industry. Interactive workshops, a practice gaining in popularity in the scientific community, are ranked, on average, as suitable as scientific publications, followed by expert panels or focus groups (Horst, 2013; Khan et al., 2016). This indicates that formal, interactive means of communication (conferences, workshops, expert panels), are

[4] Transcript P1; l. 67-68.

[5] Transcript P6; l. 39-40.

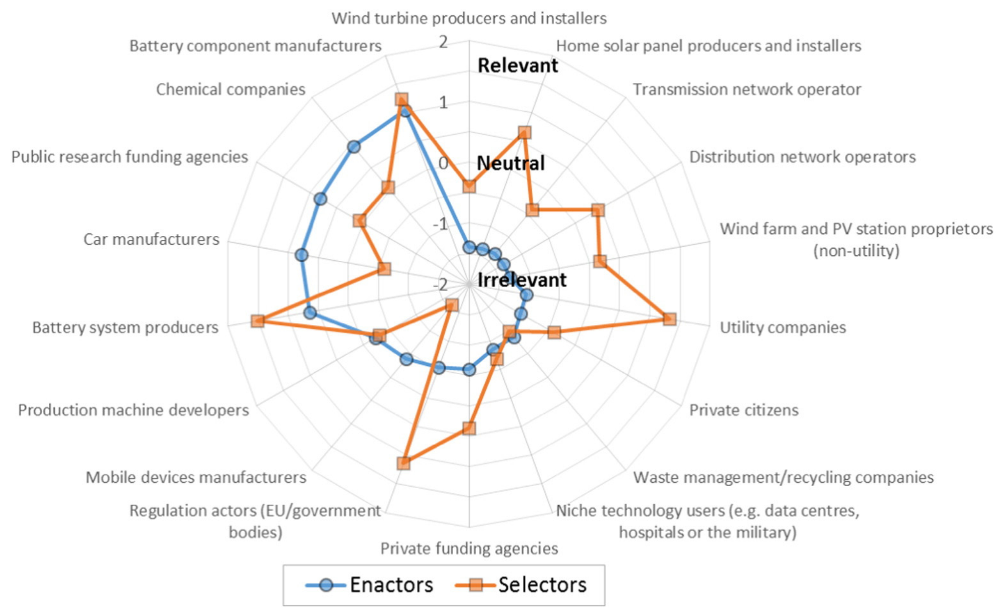

Fig. 6. Relevance of stakeholders in technological development. Relevance attributed by enactors in blue, and by selectors in orange. The graph shows the mean of the value labels attributed to responses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

generally considered very suitable. On average, all channels of communications are deemed suitable by the participants, indicating that all interaction is considered beneficial. With regard to workshops with potential users, one interview (P3) produced the following statement:

> *"These [stakeholder workshops] are only when the technology is already out of the lab. Otherwise they* [other stakeholders] *don't have interest. At the current development phase you only have scientific papers and conferences."*[6]

That enactors do find these interactive workshops between actors from development as well as application relevant was already remarked above (Fig. 4: S6). This quote illustrates however, that the expectation that selectors may not be interested yet appears as a barrier. This becomes more striking as the participants from the selector side have expressed the same interest in this kind of workshop.

Regarding channels of knowledge transfer, selectors indicate a stronger preference for interactive formats than the enactors did. Ranked most important are small interactive stakeholder workshops, followed by expert panels and conferences. Scientific publications, the least interactive channel, are ranked the least suitable. One of the interview participants (P7) gave a motivation for the importance of interactive channels in the following. When asked how fast development could best be facilitated, he answered:

> "*It's not really clear to me how we improve the situation except for getting everybody to talk together as much as possible. And, you make sure that policy makers are included in that discussion. Because we are used to having conferences and such things, but actually persuading policy makers to come and speak at and them actually staying to listen to other speakers is quite difficult I think.*"[7]

This statement expresses the importance attributed to regulation actors, as well as the preference for interactive fora as felt by an actor from industry.

One of the observations in this project was that the willingness among developers and potential users of battery technology to take part in stakeholder participation activities is very limited. This is indicated by the low response rate for interviews and surveys: both for the interview and the enactor survey the response rate was 15% after multiple requests. In part this can be attributed to a lack of interest. Secrecy and mistrust regarding intellectual property and competitive advantage have also been observed to contribute. These barriers to participation pose a challenge to further research steps, as industry and regulation actors can generally be expected to be even more closed-off than academic researchers, and are definitely more difficult to approach. Suggestions to improve on these problems would be to offer a clear benefit for participants, aside from just sharing the findings. Especially for more intensive participation (say a workshop) this would be helpful.

5.4. Discussion of survey results

Chapter 3 introduced theory and concepts that were used to analyse and frame the results from the research. Here, three concepts were central: expectations, positionings and spaces. It was found that the data could be coded with these concepts. In this section we discuss the correlation of the results with these concepts from theory.

In the survey, expectations of technological development were covered by a number of statements (Fig. 4: S9, S1, S2 & S4), as well as with a ranking of potential obstacles. Positionings were reflected in several statements (Fig. 4: S3, S5, S6, S7 and S8), together with a ranking of different stakeholders. Spaces were treated with a ranking of channels for communication. Although this does cover the three concepts, the investigation stays relatively close to the surface. Positionings include expectations of the activities of an actor in relation to a technology. In this paper we were only able to cover expectations of the influence of different actors, without discussing how the role of that influence. Also, the focus was on traditional stakeholders, offering little opportunity for the discussion of new stakeholder roles. A similar situation is the case for spaces, which strictly refers to structural, regular interaction between stakeholders. This aspect was not discussed in full in the interviews, nor treated in the survey. The consequence of this is that, when participants discuss a workshop as a one-time event, it actually concerns what in the literature is called an occasion for the creation of spaces, instead of the actual space. Similarly, the expectations of technological development could have been treated in much more detail.

[6] Transcript P3; l. 63-65.
[7] Transcript P7; l. 273-277.

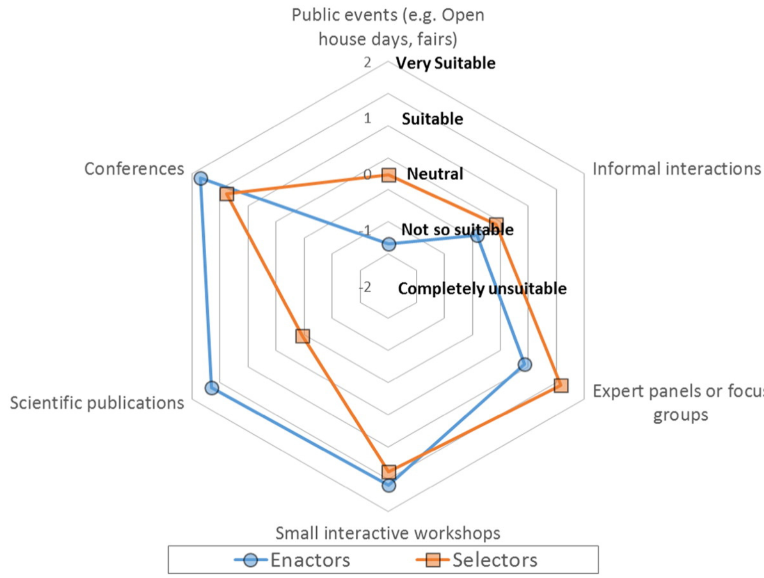

Fig. 7. Relevance of channels of knowledge transfers between the relevant stakeholders. Relevance attributed by enactors in blue, and by selectors in orange. The graph shows the mean of the value labels attributed to responses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Although the concepts are considered to be convenient for the coding of the data, there does appear to be some overlap between categories: for instance, the argument that unwillingness of industries to innovate might be an obstacle to innovation, generally classified here under the concept expectations, is repeated in the statement that industry is often conservative, in the category involvement, of the concept positionings. The involvement of regulation actors, generally a positioning, is also related to the obstacles that one may perceive in obstructive or uncertain policy and regulation. This overlap does not appear to be a strange finding: the observation that obstacles to innovation might follow from the positionings of actors is an essential characteristic of the theoretical framework. However, a difficulty to distinguish between concepts is a serious flaw in a theoretical system. Nonetheless, stressing the nuances in the differences between the positionings and the general expectations can still make this framework functional.

The visions of developers participating in this project have been found to, on average, exhibit the characteristics of the concentric systems view of technology typical for enactors as described in chapter 2: researchers have indicated to give priority to issues related to the intrinsic properties of their technology, such as the stability and safety of the product, as well as stakeholders related to the hardware (technology companies). Application side actors on the other hand have indicated more priority for the external factors than the developers. Factors such as the regulatory framework and competitive technologies. With this, the results corroborate to some extent the general division of stakeholders into enactors and comparative selectors. Whether the actors involved in this project also exhibit further characteristics and patterns of enactment cycle thinking and comparative selection cycle thinking is hard to determine based on the data presented in this paper. Further research, where more elaborate qualitative scenarios are constructed with the participants would be necessary to establish this (Rip and Kulve, 2005).

Literature on CTA discussed in chapter 3 proposed the format of small interactive workshop as the preferred space for bridging the differences between enactor visions and comparative selector visions. The results in this research indicated that the stakeholders involved generally see this format as a suitable channel of knowledge transfer between different stakeholders, and indicate that such a bridging event may contribute to the development of the technology. As indicated, the findings of this paper should contribute new questions and new challenges that stakeholder networks related with energy production and distribution can face in the recent future, based on informing stakeholders, developing scenarios and interactively comparing these scenarios with several different stakeholders. This paper provides an overview of recent developments and indicators of the promise of next generation batteries that may be instrumental in such a project. It also provides an overview of different expectations as well as an indication of which stakeholders are considered relevant by directly involved actors. This may serve as a good starting point for such a project and to build a frame for a workshop and to broaden the perspective of both selectors and enactors.

The results from the survey and in depth interviews indicate that there are many different issues for which stakeholder alignment can be very important. These range from concrete issues identified as relevant, relating to the value of characteristics of storage systems (size, weight, lifetime, efficiency, safety, environmental impact), to framework conditions of the market for electricity storage (regulation, value streams and aggregation schemes). The fact that these can be divided into two categories indicates that stakeholder involvement activities can be applied in different forms, from two different perspectives: from the perspective of the technological artefact in order to answer the question 'What market does this technology address and how can this technology be designed in order to best fit this market', and from the other side to answer the question 'how can the market conditions be optimized for this technology'. This division in perspectives may the case particularly for highly stratified and regulated industries like the electric power industry. Health care would also fall into this industry. The need for both perspectives also depends on the disruptiveness of the technology: does this technology require innovation of the techno-economic system?

Not all actor groups identified as relevant have been involved in this study. Given the scope of the project it had been decided only to focus on the two main actor groups, which were researchers as enactors of emerging battery technology, and electrical power industry actors as the selectors. The response rate to the surveys was insufficient to reliably differentiate between sub-groups. For enactors, for instance, the results from this research suggest that awareness of factors extrinsic to the technological artefact is much greater for people higher up in the hierarchy of the research institute. The population of selectors included in this project was much more diverse, but rendered fewer responses. This also warrants more investigation, to distinguish between expectations of different groups within this population.

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

6. Conclusion

In this paper we have discussed the results of a preliminary CTA study by analysing the visions and expectations of actors relevant for the development of emerging battery technologies for grid-connected energy storage. It has been argued that, as emerging technologies are still in an early phase of development, researchers in academic institutes are at the moment the main actors involved with technological development. However, industry roadmaps and policy documents indicate a similar interest from electric power utilities as well as governments. The visions of actors regarding the development of the technology were investigated using the concepts *Expectations*, *Positionings*, and *Spaces.* These actors were scientific researchers as enactors, and professionals from the electric power industry as selectors.

For the actors researched in this project, enactors and selectors, their responses have indicated that a large majority sees batteries as a viable option for grid-connected storage. More specifically, however, it has been observed that researchers working on new battery technology are focused more on high energy density batteries for electric vehicles, and view stationary application as a secondary market for next-generation batteries. This observation is indicative of a direction in battery development, being focused at lightweight, small size batteries. These characteristics are essential for mobile applications, but not so relevant for stationary storage. Characteristics like costs, longevity and environmental impact may be of more importance for stationary systems than energy density is. Note, however, that there are battery systems for which stationary applications are the main focus (e.g. redox flow batteries).

On the application side, the market for stationary storage systems is generally attributed more priority: interview participants all indicated to have very little doubt that this market will take off in the next decade, regardless of the success of EVs. Related to this point is the observation that application side actors view the connection with the market of batteries for EVs as indirect, related through increased research effort into and growing production of batteries and, perhaps, through the public image of energy storage. Further differences in expectations that have been identified are in terms of the obstacles that might threaten the successful innovation for stationary battery systems. Developers have indicated to see the issues related to the intrinsic properties of battery systems as relevant (stability and performances of the batteries, the costs of the system and safety). The application side on the other hand seems to give priority to obstacles based on the framework conditions for stationary storage, such as competing technologies and uncertainty regarding regulation and government policy.

In the interviews and survey, the development-side actors have generally indicated that they find technology companies the most relevant; manufacturers of battery components, producers of battery systems and chemical companies. Furthermore, public research funding agencies were indicated as relevant. The application-side actors that were involved in this project have indicated that other actors from the electric power industry are very relevant. The argument being that for viable business cases, some alignment between generation utilities and network operators (distribution and network) would be necessary. Also, the importance of including regulation actors was stressed, due to the possibly constraining effect of regulation. This opinion was not shared by the enactors, who have ranked regulation actors as being generally irrelevant.

In general, both sides of the technology (development and application) have indicated interest in involvement with the other side of the technology, even in early phases of development. Constructive interaction was deemed an important step towards improvement of the conditions for the development of new technology for stationary storage. Furthermore, regarding spaces for this interaction, small interactive workshops were mentioned and rated as suitable channels by both sides of the technology. This appears to offer opportunities for the broadening of design of emerging battery technologies, such as the promising Li-S battery, for the specifics of grid-connected applications. It should be noted, however, that given the findings of this project, such a workshop would only address a small part of the issues facing storage technology. Other than cell chemistry, the regulatory framework and aggregation of storage services are important issues to be addressed for the formation of viable business cases with battery systems.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2016.09.024.

References

Allen, I.E., Seaman, C.A., 2007. Likert Scales and data analyses. Qual. Prog. 40 (7), 64–65.

Baumann, M., Zimmermann, B., Dura, H., 2013. A Comparative Probabilistic Economic Analysis of Selected Stationary Battery Systems for Grid Applications In unknown IEEE, Alghero, Sardinia – Italy.

Baumann, M., Zimmermann, B., Weil, M., 2014. Emergente Energiespeicher Für Stationäre Anwendungsgebiete Im Fokus Der Prospektiven Systemanalyse. Technikfolgenabschätzung – Theorie Und Praxis.

Berkhout, F., 2002. Technological regimes, path dependency and the environment. Glob. Environ. Chang. http://dx.doi.org/10.1016/S0959-3780(01)00025-5.

Borup, M., Brown, N., Konrad, K., van Lente, H., 2006. The sociology of expectations in science and technology. Tech. Anal. Strateg. Manag. 18, 285–298 (July–September).

Bruce, P.G., Freunberger, S.A., Hardwick, L.J., Tarascon, J.M., 2011. Li–O_2 and Li–S batteries with high energy storage. Nat. Mater. http://dx.doi.org/10.1038/nmat3237.

Collingridge, D., 1980. The Social Control of Technology. St. Martin's Press, New York.

Doughty, D., Butler, P., Akhil, A., Clark, N., Boyes, J., 2010. Batteries for large-scale stationary electrical energy storage. Electrochem. Soc. Interface 49–53.

Dunn, B., Kamath, H., Tarascon, J.-M., 2011a. Electrical energy storage for the grid: a battery of choices. Science 334 (6058), 928–935. http://dx.doi.org/10.1126/science.1212741.

Dunn, B., Kamath, H., Tarascon, J.M., 2011b. Electrical energy storage for the grid: a battery of choices. Mater. Grid Energy (October 18).

EPRI, 2010. Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. Palo Alto, CA.

European Comission, 2013. DG ENER Working Paper: The Future Role and Challenges of Energy Storage.

Foxon, T.J., Gross, R., Chase, A., Howes, J., Arnall, A., Anderson, D., 2005. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy Policy 33 (16), 2123–2137.

Geels, F., 2005. Processes and patterns in transitions and system innovations: refining the Co-evolutionary multi-level perspective. Technol. Forecast. Soc. Chang. 72 (6), 681–696. http://dx.doi.org/10.1016/j.techfore.2004.08.014.

Grünewald, P., 2012. The Role of Electricity Storage in Low Carbon Energy Systems: Techno-Economic Drivers and Transitional Barriers. Imperial College London.

Horst, M., 2013. A field of expertise, the organization, or science itself? Scientists' perception of representing research in public communication. Sci. Commun. 35 (6), 758–779. http://dx.doi.org/10.1177/1075547013487513.

Huenteler, J., Tobias, S.S., Ossenbrink, J., Hoffmann, V.H., 2015. Technology life-cycles in the energy sector – technological characteristics and the role of deployment for innovation (February 17, 2015). http://dx.doi.org/10.2139/ssrn.2566463 Available at SSRN: http://ssrn.com/abstract=2566463.

Ibrahim, H., Ilinca, A., Perron, J., 2008. Energy storage systems—characteristics and comparisons. Renew. Sustain. Energy Rev. 12 (5), 1221–1250 (Jun.).

Kemp, R., 1994. Technology and the transition to environmental sustainability. Futures 26 (10), 1023–1046. http://dx.doi.org/10.1016/0016-3287(94)90071-X.

Khan, G.F., Lee, S., Park, J.Y., et al., 2016. Theories in communication science: a structural analysis using webometrics and social network approach. Scientometrics 108, 531. http://dx.doi.org/10.1007/s11192-015-1822-0.

Leonhard, W., Buenger, U., Crotogino, F., et al., 2008. VDE-Study: Energy Storage in Power Supply Systems with a High Share of Renewable Energy Sources. VDE, Frankfurt am Main.

Meisenzahl, S., Sittig, P., Höck, M., 2014. Zukunftstechnologie Lithium-Batterien - Technologie-Roadmap Für Lithium-Gerätebatterien. Chem. Ing. Tech. 86 (8), 1180–1186. http://dx.doi.org/10.1002/cite.201300035.

Mercedes, 2015. “Mercedes-Benz Energiespeicher.” ACCUMOTIVE. August https://schlauerspeichern.de/.

Oosterkamp, P., Koutstaal, P., van der Welle, A., Joode, J., Lenstra, J., Hussen, K., Haffner, R., April 2014. The role of DSOs in a Smart Grid environment. Ecorys, Energy research Centre of the Netherlands (ECN). Report for European Commission and DG ENER, Amsterdam / Rotterdam.

Parandian, A., 2012. Constructive TA of Newly Emerging Technologies. Stimulating Learning by Anticipation Through Bridging Events PhD thesis Technical University Delft.

Rip, A., Kemp, R., 1997. Technological Change. pp. 327–400.

Rip, A., Kulve, H., 2005. Constructive Technology Assessment and Socio-Technical Scenarios 1 pp. 49–70 (February 2007).

Robinson, D., 2010. Constructive Technology Assessment of Emerging Nanotechnologies. Experiments in Interactions PhD thesis Universiteit Twente, Enschede.

Rom, H., Van Langenhove, L., 1999. Varieties of positioning. J. Theory Soc. Behav. 21, 393–407. http://dx.doi.org/10.1111/j.1468-5914.1991.tb00203.x.

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024

Sauer, D.U., 2011. Überblick Über Die Speichertechnologien. presented at the Fachgespräch der Bundestagesfraktion BÜNDNIS 90/DIE GRÜNEN Die Speicherfrage – Stolperstein für die Energiewende?, Berlin, September 11.

Schot, J., Rip, A., 1997. The past and future of constructive technology assessment. Technol. Forecast. Soc. Chang. 268 (1996), 251–268.

Simon, B., Ziemann, S., Weil, M., 2014. Criticality of metals for electrochemical energy storage systems – development towards a technology specific indicator. Metall. Res. Technol. http://dx.doi.org/10.1051/metal/2014010 (March).

Stenzel, P., Baumann, M., Fleer, J., 2014. Database Development and Evaluation for Techno-Economic Assessments of Electrochemical Energy Storage Systems. IEEE, Dubrovnik Croatio.

Tarascon, J.-M., 2010. Key challenges in future Li-battery research. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 368 (1923), 3227–3241. http://dx.doi.org/10.1098/rsta.2010.0112.

Tarascon, J.M., 2011. "Key Challenges and New Trends in Battery Research." presented at the US DOE EFRC Summit and Forum, Washington DC Renaissance Penn Quarter Hotel.

te Kulve, H., 2012. Emerging technologies and waiting games. Sci. Technol. Innov. Stud. 6 (1), 7–31.

Tesla, 2015. "Powerwall: Tesla home battery." Teslamotors.com. August http://www.teslamotors.com/powerwall.

Thielmann, A., Isenmann, R., Wietschel, M., 2010. Technologie-Roadmap Lithium-Ionen-Batterien 2030. Fraunhofer-Institut für Fystem- und Innovationsforschung ISI, Karlsruhe.

US DOE, 2013. Grid Energy Storage.

van Lente, H., 2012. Navigating foresight in a sea of expectations: lessons from the sociology of expectations. Tech. Anal. Strat. Manag. http://dx.doi.org/10.1080/09537325.2012.715478.

van Merkerk, R.O., van Lente, H., 2005. Tracing emerging irreversibilities in emerging technologies: the case of nanotubes. Technol. Forecast. Soc. Change 72 (9), 1094–1111 (Nov.).

van Merkerk, R.O., 2008. Intervening in Emerging Nanotechnologies: A CTA of Lab-on-a-Chip Technology. University of Twente.

van Merkerk, R.O., van Lente, H., 2008. Asymmetric positioning and emerging paths. Futures 40 (7), 643–652. http://dx.doi.org/10.1016/j.futures.2007.12.007.

Verbong, G.P.J., Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technol. Forecast. Soc. Chang. 77 (8), 1214–1221. http://dx.doi.org/10.1016/j.techfore.2010.04.008.

Weedy, B.M., Corey, B.J., Jenkins, N., Ekanayake, N., Strbac, G., 2012. Electric Power Systems. 5th ed. John Wiley & Sons Ltd., West Sussex, UK.

Whittingham, M.S., 2012. History, evolution, and future status of energy storage. Proc. IEEE 100, 1518–1534. http://dx.doi.org/10.1109/JPROC.2012.2190170 (Special Centennial Issue).

Winskel, M., Markusson, N., Jeffrey, H., Candelise, C., Dutton, G., Howarth, P., Jablonski, S., Kalyvas, C., Ward, D., 2014. Learning pathways for energy supply technologies: bridging between innovation studies and learning rates. Technol. Forecast. Soc. Chang. 81, 96–114. http://dx.doi.org/10.1016/j.techfore.2012.10.015 (January).

Yang, Z., Liu, J., Baskaran, S., Imhoff, C.H., Holladay, J.D., 2010. Enabling renewable energy—and the future grid—with advanced electricity storage. JOM.

Yun, S., Lee, J., 2015. Advancing societal readiness toward renewable energy system adoption with a socio-technical perspective. Technol. Forecast. Soc. Chang. 95, 170–181. http://dx.doi.org/10.1016/j.techfore.2015.01.016 (June).

Thom Versteeg has a background in physics and interdisciplinary research. The article presented is a product of his MSc thesis project from the VU University of Amsterdam, in collaboration with ITAS. Currently he is working as a consultant on flexibility options in power distribution for the largest network operator in the Netherlands.

Prof. Dr. António Moniz is coordinator of the PhD program on Technology Assessment at Universidade Nova de Lisboa (Portugal) since 2009. At the Institute for Technology Assessment and System Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT) he is the coordinator of the working group on Robotics Technology Assessment and member of the research area on Innovation processes and impacts of technology. Other research focuses are on future trends on mobility and transport inter-modalities and on scenarios building methods.

Dr.–Ing. Marcel Weil is a scientific group leader since 2007 in the field "Systems Analysis for Emerging Energy Technologies" at the Institute for Technology Assessment and System Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT) and since 2011 a scientific group leader at the Helmholtz Institute Ulm for Electrochemical Energy Storage (HIU), responsible for "Resources, Environment and Sustainability". He is a principal investigator for the program "Technology, Innovation and Society" of the Helmholtz Society. His research focuses on prospective system analysis for emerging technologies and life-cycle oriented economic, ecological, and social assessments of future energy storage systems.

Manuel Baumann has been working in the field of system analysis and technology assessment with a strong focus on life cycle based approaches at ITAS since 2012. The main focus of his current work is electrochemical storage systems for stationary energy storage and electric mobility. Currently he is developing an integrative CTA-based multi-criteria decision model for a sustainability analysis of energy storage systems as a part of his PhD in Technology Assessment.

Please cite this article as: Versteeg, T., et al., Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.09.024