Universiteit Utrecht

# *Enabling the Low-Carbon Energy Transition of the EU: Barriers of Electricity Storage*

## Master's Thesis Sustainable Business and Innovation

Author: Wouter le Rütte - wouterlerutte@gmail.com
Student no. 3844994
University supervisor: Dr. Joeri Wesseling - j.h.wesseling@uu.nl
Second reader: Prof. dr. Marko Hekkert - m.p.hekkert@uu.nl

**Abstract**

Large-scale, stationary electricity storage is widely regarded as one of the solutions to the flexibility challenges posed by the integration of an increasing share of variable renewables. While the energy transition is gaining traction among policymakers and industry players, enabling technologies like electricity storage are not receiving the same amount of attention as renewables and face significant hurdles in their widespread uptake. However, the success of electricity storage inherently depends on other developments in the energy transition. Contextual interactions are essential.

Research into sustainability transitions is often centred around either the TIS or transition management approach. This study builds on previous integration attempts by complementing the TIS with another key innovation process that stresses the role of agency in the window of opportunity presented by the energy transition context. In addition, this study is unique in expanding the TIS approach to the European level, which is valuable as the EU is adopting an increasingly centralised approach to transitions. Seventeen experts, sampled from most relevant stakeholders in the European electricity sector, were interviewed. Policy recommendations are given to address those barriers that are the most pressing to the system.

This study found that the barriers of electricity storage are heavily interrelated. The most pressing barriers can be identified in the form of regulatory uncertainty, a lacking strategic vision for the energy transition at large, as well as lacking remuneration possibilities in a market design that ideologically favours storage ownership by market players instead of by grid operators. These barriers are responsible for a majority of the other barriers that the system is facing and deserve priority on the policy agenda.

This study was the first attempt with an extended TIS methodology with a contextual system function, combined with an unconventional European scope. Future research should experiment more with the newly introduced system function in different case studies and transitions. In addition, the European scope requires more maturing in future research designs.

**Keywords:** *electricity storage - barriers - European Union - technology neutrality - transitions - TIS - MLP*

**Abbreviation list**

CAPEX - Capital expenditure
CIGRE - International Council on Large Electric Systems
CORDIS - Community Research and Development Information Service
DSO - Distribution system operator
EASE - The European Association for Storage of Energy
EBA2050 - European Battery Alliance 2050
EERA - European Energy Research Alliance
EC - European Commission
ECA - European Court of Auditors
ENTSO-E - European Network of Transmission System Operators for Electricity
ES - Electricity storage
ETIP SNET - European Technology and Innovation Platform Smart Networks for Energy Transition
EU - European Union
EUROBAT - Association of European Automotive and Industrial Battery Manufacturers
EV - Electric vehicle
IEA - International Energy Agency
IRENA - International renewable energy agency
MLP - Multi-level perspective on socio-technical change
P2X - Power-to-X
REDII - Revised Renewable Energy Directive
R&D - Research & development
SET-Plan - Strategic energy technology plan
SF - System function
TIS - Technological innovation system
TM - Transition management
TRL - Technology readiness level
TSO - Transmission system operator
V2G - Vehicle-to-Grid

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## 1. Introduction

According to the EU, its “transition to a low-carbon, secure and competitive economy” (hereinafter: the energy transition) is well underway (European Commission (EC), 2016). Considering the scale and the ambition of the energy transition, a major transformation of the current energy system is required to reach the goals of 45% decreased greenhouse gas emissions in 2030 and 80-95% in 2050 respectively (EC, 2012, 2014; World Energy Council, 2014). As the energy sector is responsible for a large share of the world’s greenhouse gas emissions (US Environmental Protection Agency, 2018), it should come as no surprise that the uptake of renewable energy technologies (hereinafter: renewables) in the electricity grid is receiving a great deal of attention. However, rapid uptake of renewables puts increased pressure on the grid, mostly related to the intermittency challenges of, particularly, solar and wind energy.[1] The variability of these new renewable forms of generation could jeopardise the stability of the grid that is currently provided by fossil fuels, which are dispatchable[2] and therefore more reliable. This constraining barrier to decarbonisation is often overlooked and does not receive the same industry, political and media attention as the uptake of renewables (New York Times, 2010). If left un(der)addressed, these challenges will inevitably slow down, and possibly even halt full decarbonisation (EASE and EERA, 2017; Helm, 2017).

Electricity storage (ES) is widely considered to be one of the long-term solutions to this barrier (Deloitte, 2018; Denholm et al., 2010; EC, 2018; Taylor et al., 2013), as it can provide flexibility to the grid (EASE and EERA, 2017). Nevertheless, ES is still facing significant hurdles. As the uptake of renewables is set to increase in the following years in accordance with the EU’s climate goals, the need for more flexibility, and thus storage, will have to grow correspondingly.

The adoption of the Clean Energy for all Europeans Package, the cardinal energy transition legislation project of the EU, underlines the commitment to govern and regulate the energy transition on a European level. While increased harmonisation of energy policy in the EU is challenging as it is a sensitive national jurisdiction (Nilsson, 2012), a full-scale energy transition requires at least coordination on a European level (Laes et al., 2014). Many facets of the energy transition are of a transboundary nature and can only be addressed by European rules (Nilsson, 2012).[3] In addition, harmonisation of support schemes can decrease investor uncertainty (Newberry et al., 2015). A strong European governance framework can accelerate the energy transition, also on the member state level (Nilsson, 2012). This is why it makes sense to research the topic beyond national systems.

[1] Within the energy world, the term variable renewable energy is prefered and the word “intermittent” is usually avoided. Intermittency would imply that the weather on which these technologies relies is entirely unpredictable. Weather is predictable to a certain extent, but the electricity that can be generated each day or each hour can vary.

[2] Dispatchable refers to the fact that electricity can be generated and used at the desired moment, and to distribute, or dispatch, it when the regulated entities desire to play into efficient supply and demand. Fossil fuels are burnt and provide steady flows of electricity, and their generators can be turned on and off relatively easily.

[3] Grid interconnections are a good example. The European electricity system has grown more interconnected over the last years, which strengthens grid stability.

Infrastructure-based technologies - of which many ES technologies can be counted - are subject to a "network effect" that benefits technologies that fit within the system architecture (Taylor et al., 2013). In a dispatchable, carbon-based electricity system, ES does not fit into the architecture. Accordingly, ES deployment is particularly dependent on how the electricity system as a whole develops (Grünewald et al., 2012). ES synergises well with the variable and sometimes decentralised nature of renewables. Simultaneously, it has been argued that ES technologies do have the potential to disrupt current regimes (Winfield et al., 2018). Yet, it considered more frequently that ES will not be a motive force behind the energy transition, but instead can decide the fate of alternative energy transition pathways (Taylor et al., 2013).

In addition to technological change, transitions also require institutional change that radically alters the set of rules, customs and beliefs (Fuenfschilling and Truffer, 2014). To address sustainability transitions, both innovation and transition studies offer valuable insights. The multi-level perspective (MLP) on socio-technical transitions (Geels, 2002), and the derived transition management (TM) approach (Loorbach, 2007; Rotmans et al., 2001), focus on creating the right environment for socio-technical regime change by considering the context. The technological innovation systems (TIS) approach has a stronger focus on the system configurations for the development of specific technological innovations (Hekkert et al., 2007). Consequently, several attempts have been made to devise an integrated framework by combining the MLP and the TIS (Markard and Truffer, 2008; Meelen and Farla, 2013). The technological aspect of the TIS can benefit from the contextual perspective that the MLP offers, whereas the TIS can compensate or the lack of concrete analysis in TM approaches. Therefore, an integrated approach is beneficial to this research.

The literature acknowledges that governing sustainability transitions are highly political projects (Kivimaa and Kern, 2016; Meadowcroft, 2009; Scrase and Smith; 2009; Shove and Walker, 2007). It is questioned whether successful cases of transition governance can be applied to different political contexts (Heiskanen et al., 2009). Research on sustainability transitions in the EU almost exclusively comprises studies that consider a sample of nations that represent the EU geographically, rather than investigating the supranational elements. Especially now that the EU is increasingly attempting to harmonise its energy and climate policies (Wettestad et al., 2011), the EU level deserves more academic scrutiny. In addition to integrating the TIS and MLP approaches, analysing transitions at EU level, with less clearly defined analytical boundaries, requires some adjustments to the existing approach. Consequently, this research considers a novel focus by expanding on integrated transition literature and exploring transition research on an EU scope.

This research aims to identify the drivers and barriers of large-scale, stationary ES on a European level. Large-scale excludes residential storage and focuses on grid- and industrial-scale installations in the power system. Storage devices from the transport sector are also excluded. By performing a structural-functional analysis that incorporates the transition approaches, the systemic weaknesses of ES are sought. Ultimately, tailor-made policy suggestions will be given to address the identified barriers. This leads to the following research question:

***What are the barriers to the deployment of large-scale, stationary electricity storage in the power system of the EU?***

This research aims to identify the barriers of ES in a technology-neutral manner. The results will largely be indiscriminate between storage technologies and apply to ES as a provider of services. Therefore, the operating level is not just a TIS but rather a cluster of TISs that represent a socio-technical system of ES services, similar to the method of Grünewald et al. (2012). When no comprehensive data on all technologies are available, trends in lithium-ion batteries will be displayed. This is due to the fact that these batteries are often considered synonymous to ES and, correspondingly, there is more available data.

This thesis is divided into several sections. Firstly, the theoretical background on sustainability transitions will be discussed. A methods section provides the analytical frame and assumptions. Afterwards, the results of the structural-functional analysis will be extensively discussed. Lastly, a discussion and conclusion will finalise the thesis.

# 2. Theoretical background

## 2.1 Conceptual theories for sustainability transitions

Addressing large societal challenges requires long-term transformative change (Rotmans et al., 2001). The TIS and MLP approaches have different origins and characteristics, but their conceptual base and the goal of seeking to explain sustainability transitions is largely the same; the TIS is positioned on the meso-level, which corresponds to the regime layer of the MLP (Markard and Truffer, 2008). Unsurprisingly, attempts to integrate these theories have been made. Together, they capture the predicament of ES; technological development (like in a TIS) that is inherently connected to the very same macro-level developments that triggered the energy transition (like in the MLP). The TIS is rather inward-looking and focuses on the technology, while the MLP revolves around the underlying problem of the transition (Weber and Rohracher, 2012), and thus captures the *context* of a transition. Therefore, a joint approach would provide a holistic perspective that neither frameworks can provide individually.

### *2.1.1 The TIS*

The TIS approach is focused on the development and diffusion of a technology within the innovation system and identifies the strengths and weaknesses of the system to facilitate therein (Hekkert et al., 2007). The approach builds on the idea that technological innovation occurs in an interactive system of actors, institutions and technologies (Carlsson et al., 2002). The “functions of the TIS” notion clearly distinguishes the key innovation processes in the system, and the system functions (SFs) are depicted in Table 1 (Hekkert et al., 2007; Suurs and Hekkert, 2012).

*Table 1: Simplified overview of the SFs of the TIS. Based on insights from Hekkert et al. (2007),, Hekkert and Negro (2009), Meelen and Farla (2013), Negro and Hekkert (2008), and Suurs and Hekkert (2012).*

| **Function** | **Description** |
|---|---|
| *Entrepreneurial activity (SF1)* | Experimentation to bring theoretical concepts to the market. This involves a significant amount of risk-taking and new business models. |
| *Knowledge development (SF2)* | The amount of generated knowledge and learning activities. |
| *Knowledge diffusion (SF3)* | The distribution and exchange of knowledge between actors in the system |
| *Guidance of the search (SF4)* | The activities that shape the needs and expectation of actors regarding their support for the technology in question. |
| *Market formation (SF5)* | The markets that are available for the technology, including artificially created ones, that can compete with the incumbent ones. Financial feasibility of the new technology is a key term. |
| *Resource mobilisation (SF6)* | The amount of human, financial and material capital that is available for the execution of the other functions |
| Support from powerful groups/legitimation (SF7) | The activities that counteract resistance to change, of which lobbying activities in favour of the technology is a good example. |

The TIS is not limited to a geographical area (Grin et al., 2010), and could, in theory, be extended to a European level. In addition, the TIS has developed to such an extent that its dynamics are measurable for analysis (Suurs and Hekkert, 2012).

### *2.1.2 The MLP*

According to the MLP literature, socio-technical transitions take place within a balanced interplay between the “niche”, “regime”, and “landscape” levels (Geels, 2002; Kemp and Loorbach, 2003). Geels has visualised this phenomenon in a conceptual framework that is depicted in Figure 1 (Geels, 2002; Geels and Schot, 2007; Rip and Kemp, 1998). Geels (2005) has demonstrated that transitions are only successful if changes in all three levels are linked and strengthened by each other.

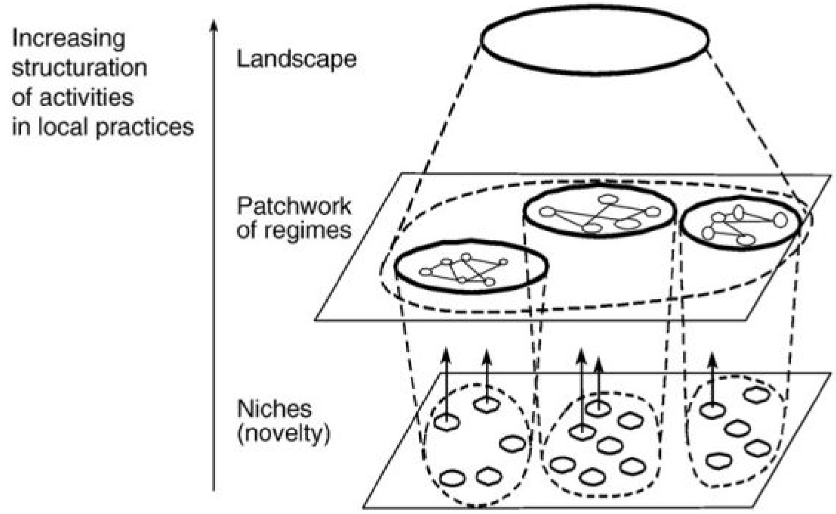


*Figure 1: The nested hierarchy of the Multi-Level Perspective on socio-technical transitions. Adopted from Geels (2002)*

The "niche" represents the micro-level, consisting of individual actors and technologies, and local practices (Rotmans et al., 2001). In strategic niche management literature, it is argued that niches can develop internally having three processes: (1) voicing and shaping of expectations (2); ... A process of building a conductive network (3) A learning process (Kemp et al., 1998; Schot et al., 1996). Niches need to be protected, potentially by policy, to shield the radical innovations that emerge from these experimental environments from the "(...) harsh selection pressures from the incumbent regimes" (Raven, 2012, p. 126). Experimentation in the niche is also one of the pillars of TM (Loorbach, 2007). The "regime" represents the meso-level, consisting of dominant practices, rules and assumptions that guide private sector action and public policy (Rotmans et al., 2001). Changes that occur solely on the regime-level generally focus more on dynamic stability (Rotmans et al., 2001). The "landscape" corresponds to the macro-level: slow-changing processes that provide the context of the operation of actors (Geels, 2002; Rip and Kemp, 1998). An example that is often used is fluctuating oil prices (Geels, 2002; Grünewald, 2012), but climate change is perhaps most relevant for decarbonisation. In addition, while landscape developments are often outside the sphere of influence of one actor, it is accepted that regimes could also affect the landscape, e.g. through international law (Van der Vleuten and Högselius, 2012). This has to be acknowledged particularly when looking at changes on a European level.

Landscape pressures on the regime can cause reconfigurations, which allows new technologies from the niche to be adopted (Grünewald, 2012). In other words, when both landscape and niche developments occur simultaneously, this offers windows of opportunity for the niches to break through the incumbent regime (Loorbach, 2010; Smith et al., 2010; Verbong and Geels, 2010). However, the MLP is often criticised for having an unclear analytical approach, and particularly when studying the regime (Loorbach and Verbong, 2012). Therefore, in this research, the MLP serves to provide external context to the TIS, in particular in relation to the overarching energy transition that the TIS otherwise would hardly have captured. This external context includes the electricity regime and renewable technologies that are also influenced by the energy transition.

## 2.2 The integrated approach

*2.2.1 Integration on the functional level*

Even though Weber and Rohracher (2012) have greatly contributed to identifying transition failures within the TIS interpretation through the introduction of systemic failures that are specifically relevant to transitions, it still does not address the interactions with external systems and developments. Yet, this external view is fundamental for ES (Grünewald, 2012; Taylor et al., 2013). While many of the takeaways from MLP and TM are very valuable to transitions, they describe mainly policy or governance instruments (Voß et al., 2009) rather than having a system *processes* perspective that a structural-functional analysis offers. For ES, this external view must, therefore, be *explicitly* incorporated in a viable framework that reconciles these theoretical complications.

Bergek et al. (2015) have also affirmed how investigating these TIS-*context* structures could benefit transition research; it could help policymakers and analysts in understanding the particularities of each transition (Bergek et al., 2015) as transitions of the extent of the energy transition are rather specific. It can also, amongst others, capture the political context of the TIS (Bergek et al., 2015), or policy rationale/regime. In Hekkert et al. (2007), these external developments of the system are addressed through functional patterns in the form of motors of sustainable innovation (Suurs, 2009).

Meelen and Farla (2013), in their integrated model for policy, have addressed this external view by categorising points of intervention: "TIS-landscape interactions", "TIS-regime interactions" and "TIS-TIS interactions". While their integrated model is designed for policy, it does capture the external orientation beyond the TIS well. The TIS-landscape interactions partially overlap with SF4 of the TIS (Rogge and Reichardt, 2016). Bergek et al. (2008b) already the functional importance of these TIS-TIS interactions by arguing for "*positive externalities-economies"* as a SF of the TIS. Bergek et al. (2015) also coined the term "structural coupling" as incorporating the context of other TIS with overlapping structural elements into the focal TIS.

Still, the unique context of ES in which it is so heavily dependent on other developments in the energy transition that these interactions are not simply contextual factors to take into account, but the manner in which system actors respond to these interactions can be decisive for the "window of opportunity" of specific technologies in the transition and the overall effectiveness of the latter. Therefore, this research proposes SF8, which, rather than being an innovation process, could be considered a transition process. It relates to the agency that is shown in acting on external developments beyond the TIS. They would not receive enough analytical attention if it is just integrated into the contextual interpretation of the established SFs. SF8 will be called *"External transition orientation"* and represents MLP/TM elements.

For the TIS-landscape interactions, this means aligning policy and industry behaviour in consistence with landscape developments. The TIS-regime interactions focus on the destabilisation of the incumbent regime. More specifically, it relates to the extent that system actors are undertaking action to weaken the electricity regime in terms of the carbon lock-in by policy or other forms of behavioural change.

Lastly, the TIS-TIS interactions relate to the beneficial externalities with other TIS. The TIS-sector interactions will focus on actions that move beyond a silo approach and towards more sectoral and technological integration.

ES, the development of renewables, but also sustainable transport solutions are all influenced by the same energy transition. Complementarities between these industries could be beneficial to all, if not for the mere financial argument that economies of scale reduce costs and total R&D expenditure could go down. Accordingly, this concept has been named “sector coupling” and has gained traction, both in overall strategy in sectors and transition as well as in policy.

*2.2.2 Policy measures*

Public policy can have a strong role in addressing many of the systemic weaknesses of the TIS (Kivimaa and Kern, 2016; Negro et al., 2008). The TIS literature is extensive and is also clear on what specific policy measures could be taken to address the systemic failures that underlie poorly performing functions of the TIS (Wieczorek and Hekkert, 2012).

As innovation is usually oriented on economic growth rather than societal transformations, it often inadvertently reinforces the regime rather than disrupt it. Therefore, transition policy alongside innovation policy is needed to effect sustainability transitions (Alkemade et al., 2011). The TIS approach has partially incorporated transitional elements compared to the traditional innovation system approach (Weber and Rohracher, 2012). While the innovation system approach has a strong focus on structural change, the TIS has been more successful in bringing about transformations, as its functional approach gives more attention to system change rather than mere structural optimisation. However, as mentioned earlier, it is still focused on a single emerging technology and hardly takes the transition’s context outside of the TIS into account (Weber and Rohrachter, 2012).

Transitions not only require disruptive innovation but also wider change in the socio-technical systems (Kivimaa and Virkamäki, 2014). Consequently, the system, and corresponding policy instruments to that end, need to focus on both creative (niche-developing) and destructive (regime destabilising) elements (Kivimaa and Kern, 2016). It is argued that, when looking at the balance between *creative* and *destructive* elements, the latter is of greater importance when the new, alternative technological innovations have already developed to the extent that they are no longer at a very early stage (Kivimaa and Kern, 2016). Many ES technologies have indeed surpassed this stage and are mature and market-ready (EASE and EERA, 2017). This inclusion of destruction of socio-technical regimes addresses critique on the TIS approach that it does not pay enough attention to the regime level (Kern, 2015; Smith and Raven, 2012).

While TIS policy requires systemic instruments to increase the functional performance, it is argued that non-systemic instruments are well suited for effecting regime destruction (Meelen and Farla, 2013). Especially policy that changes economic incentives can accelerate regime change (Turnheim and Geels, 2012), e.g. tax measures and consumption quotas (Meelen and Farla, 2013). Kivimaa and Kern (2016) have proposed a taxonomy of policy instruments that incorporated elements of TM and were specifically designed for regime destabilisation. These insights can supplement the systemic policy instruments from TIS literature. In addition, by analysing the policy rationale in the EU (within the TIS-regime interactions), the policy recommendations can also be refined towards realistic implementation.

The innovation system approach does not target market failures directly by policy but instead focuses on the failures that keep the system from working properly (Kieft et al., 2017). However, it is also possible that system failures are interacting and their roots are caused by a different failure (Kieft et al., 2017). Understanding the interactions between system failures cannot just help to overcome said failures, but increase the quality of SFs (Wesseling and Van der Vooren, 2016). Conclusively, identifying the failures in the system increases the rationale for policy interventions (Weber and Rohracher, 2012).

### *2.2.3 The integrated framework*

The integrated framework will largely follow the TIS analysis makeup but adds a new SF that incorporates the external context. The integrated framework is depicted in Table 2.

*Table 2: The integrated framework.*

| **Function level** | **Description** |
|---|---|
| ***Traditional system functions (TIS)*** | |
| Entrepreneurial experimentation (SF1) | Experimentation to bring theoretical concepts to the market. This involves a significant amount of risk-taking and new business models. |
| Knowledge creation (SF2) | The amount of generated knowledge and learning activities. |
| Knowledge diffusion (SF3) | The distribution and exchange of knowledge between actors in the system |
| Direction of the search (SF4) | The activities that shape the needs and expectation of actors regarding their support for the technology in question. |
| Market formation (SF5) | The markets that are available for the technology, including artificially created ones, that can compete with the incumbent ones. Financial feasibility of the new technology is a key term. |
| Resource mobilisation (SF6) | The amount of human, financial and material capital that is available for the execution of the other functions |
| Support from powerful groups / legitimation (SF7) | The activities that counteract resistance to change, of which lobbying activities in favour of the technology is a good example. |
| ***Contextual response (MLP)*** | |
| *External transition orientation (SF8)*<br>● *TIS-landscape interactions*<br>● *TIS-regime interactions*<br>● *TIS-sector interactions* | *The response of system actors to the conditions within the context of the larger (energy) transition. It entails the response to landscape pressures, the extent to which regime destabilising behaviour is being undertaken. It also covers the proactive interactions of system actors with other sectors and synergising technologies that are beneficial to the energy transition in a holistic sense.* |

# 3. Methodology

## 3.1 Research objective

This study aims to identify the drivers and barriers of ES, specifically on a European level. It also seeks to find corresponding policy instruments that can address the systemic causes of these barriers. The EU level does not entail selecting a representative collection of member states but instead seeks to capture the supranational system that lies beyond the national systems of EU member states. Particularly as the EU gradually secures more control over energy and climate policies through the Energy Union (EC, 2017), and Brussels is now the lobbying capital of the world (The Guardian, 2014), it is worth investigating the EU level.

While the specific services that these technologies can offer generally differs slightly, the role of all ES technologies is largely consistent. There are plenty of structural couplings or structural elements that are overlapping (Bergek et al., 2008); the same legislation, policies and, mostly, actors. However, this research is technology-neutral. In practice, this research does not discuss the TIS of one storage technology in particular, but rather the socio-technical system of ES. A similar approach has been used in Grünewald et al. (2012). When no comprehensive data on all technologies are available, trends in lithium-ion batteries will be displayed. Lithium-ion batteries are one of the major technologies and generally more data can be found on this technology.

## 3.2 Research design

As the theory section outlines extensively, a conceptual framework is used that combines different insights on approaches that study sustainability transitions. This research largely follows the structure of a structural-functional analysis as performed by Wieczorek & Hekkert (2012). However, a new SF is added to capture the broader context of the energy transition. In addition, the scope is expanded. Specific attention will be given to the interconnection between barriers. In addition, the assumptions and adjustments of the structural-functional analysis to the European level are given in section 3.2.2.

### *3.2.1 Research steps*

In deviation from many structural-functional analyses, the methodology puts emphasis on the interconnections between the different SFs. Finding the interconnections has therefore been added as an individual research step to help concentrate on the system failures that are most important.

A brief structural analysis provides more information on the relevant actors, institutions, infrastructure, and networks for ES. Subsequently, a functional analysis determines how the SFs are performing. The drivers and barriers are identified in accordance with the traditional SFs as well as the newly identified SF of this conceptual framework. The underlying reasons behind poor functional performance are categorised into the formulated system failures, as incorporated into the conceptual framework, and considered the barriers in the system. Interrelations between the causes of the failures are also considered when determining barriers and defining policy. The policy rationale of the EU is also briefly analysed to find the most effective way of providing recommendations. This leads to a set of tailor-made policy recommendations. A selection of policy instruments is extracted from the literature, as well as interviewee suggestions and the researcher's insights. The research steps are depicted in Figure 2.

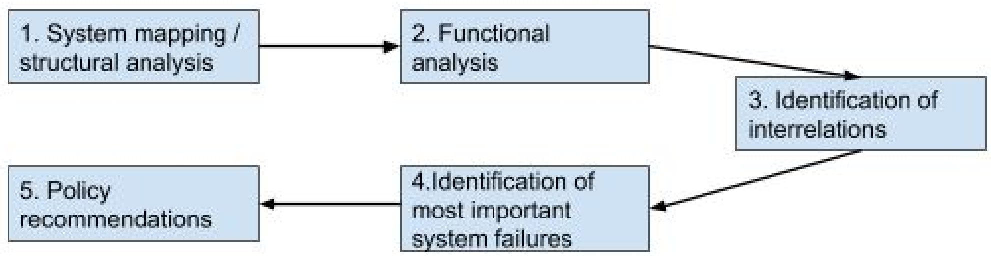


*Figure 2: Research steps*

*3.2.2 The European level*

The EU, despite representing a geographical area, is still mainly a governance concept. To avoid conceptual confusion, it must be explained what is meant by the EU level. First and foremost, the difference is that the governmental actors are EU institutions rather than national governments. No adjustment will be made for companies. This raises some implications for individual SFs. SF4 will be guided by, amongst others, EU law and policy, as well as common positions of European advocacy groups. The market activity, as meant in SF1, SF5 and SF6, are taken as an accumulation of activities in the member states, without specifically referring to the different conditions in these countries. The development of knowledge, SF2, has become relatively borderless in the information era, as well as through the dispersed nature of projects subsidised by the EU. SF3 will be interpreted as the knowledge exchange that takes place in EU workshops, stakeholder fora in Brussels, international conferences throughout Europe, and similar events. Legitimation will look at lobbying and similar activities that take place in Brussels. Still, this does not mean that notable differences between member states cannot form barriers or deserve mention. SF8 will focus solely on the European energy regimes and sectoral interactions and policy in the EU.

## 3.3 Data collection

Data collection consists of both desk research and interviews with relevant actors in the ES supply chain.

*3.3.1 Interviews*

In addition to traditional diagnostic questions about the SFs and the causes of the barriers, the interviewees were also asked what policy measures they would propose to overcome the barriers on an individual basis. This should deserve extra scrutiny as the European scope may yield some unique policy recommendations that may not have been covered in the literature. Moreover, asking the interviewees about policy recommendations contributes to establishing interrelations.

If the proposed policy instruments by the interviewees corresponded to those found in the literature, it would reaffirm that the (extended) TIS approach can also be applied on a larger geographical scale (Grin et al., 2010). Semi-structured interviews were transcribed and coded in vitro[4] in a semi-closed manner (Gaztambide-Fernandez, 2009), using the eight SFs as question categories while leaving leeway for unforeseen insights. The used interview guide is added in Appendix I.

*3.3.2 Desk research*

The desk research is largely composed of the analysis of policy documents, reports, roadmaps, legislation, and similar documents of the EU or organisations operating on the European level. Some lobby data of corporations is available online through the EU's transparency register. As many as one hundred and seventy-six literature articles, sixteen policy documents, eight pieces of legislation, fifty-four non-academic reports or articles, and twenty-four news articles were collected, read, consulted or cited for this research. The database of Scopus is consulted to identify knowledge development, by looking for "electricity storage" in the abstract. The first fifty articles are checked to ensure it is about grid ES. A deviation of five articles is allowed. Subsequently, it is assumed that all articles are about ES and represent the trends in academic knowledge development.

It is very challenging to find aggregate data, particularly centralised information on EU funded projects. CORDIS is a database that collects many of the projects. BRIDGE, an initiative that seeks to collect all the *energy storage* projects, has a small projects database, of which some are of relevance to ES. Beyond that, data that suits the scope is very hard to come by. Figures and numbers are in most cases aggregate data on either all scales of storage. Consequently, interpretations of the data are sometimes left to the creative discretion of the researcher.

## 3.4 Sample

Generalising the private sector/business as a stakeholder group would not be sufficient for ES. Instead, battery suppliers, transmission system operators (TSOs), distribution system operators (DSOs), utilities, research centres, and other industry players all have different (and sometimes competing) stakes, views and roles in the development of ES. In addition, national *energy storage* associations from EU member states were interviewed as they will have a good overview of the developments both on a national and a European level. A civil servant from the European Commission was interviewed in order to capture the governmental sector. Lastly, the Secretariat of the European Association for Storage of Energy (EASE) was interviewed, as they represent the industry on a European level and are very knowledgeable about European policy. The researcher has insiders access to the membership of EASE, and its member base was used for gathering a representative sample of the aforementioned stakeholder groups.

It was aimed to have at least two different interviewees from every stakeholder group, in order to ensure that responses are not arbitrary. Most interviewees gave their personal views that are heavily shaped by, but not given at the direction of their respective organisations. Consequently, the

[4] In vitro coding entails the selection of categories by the researcher.

organisations and names of the interviewees are anonymised. The list of interviews is depicted in Table 3.

*Table 3: The conducted interviews.*

| Actor | Organisation | Position of interviewee | Interview code |
|---|---|---|---|
| Utilities | Major Italian utility | Head of European Regulation and Innovation | UTI1 |
| | Major Spanish utility | Innovation Manager | UTI2 |
| Transmission System Operator | Major Spanish TSO | Regulatory Affairs | TSO1 |
| | Major French TSO | Advisor Energy Storage | TSO2 |
| Distribution System Operator | Major Dutch DSO | Advisor Smart Grids & Europe | DSO1 |
| | Major Spanish DSO | Innovation Leader | DSO2 |
| Battery producers | Major German electronics firm | Head of Research Group | BAT1 |
| | Major Asian battery firm operating in Europe | Director, Energy Storage Systems (EMEA) | BAT2 |
| Research institutions | Dutch applied research centre | Senior Geoscientist Integrator | RES1 |
| | French energy research centre | VP European Affairs / Deputy Director | RES2 |
| Other storage experts | Storage expert working for a large Asian electronics and battery firm operating in Europe | Director Power Business Batteries | OTH1 |
| | Storage expert working for a British storage startup | Lead Analyst | OTH2 |
| Government | European Commission | Policy Officer Directorate-General Energy (main contact energy storage) | GOV1 |
| National Energy Storage Associations | Irish Energy Storage Association | Technical Advisor | NAT1 |
| | Energy Storage NL | Project Manager | NAT2 |
| European Association | EASE | Senior Policy Officer<br>Technical Advisor / former SAFT (battery manufacturer) employee | EUR1<br>EUR2 |

The governmental stakeholder only comprises of one interviewee. Conversely, an extra stakeholder group *other storage experts* was created to make up for the lack in the total number of interviewees. In addition, most interviewees have high ranking positions within their respective organisations. Therefore, despite the conservative number of interviews, each of them carries more weight instead and hence is more representative.

For the sake of scientific integrity, it must be emphasised firmly that neither EASE nor any of the organisations that have delivered the interviewees have directed this research.

## 3.5 Operationalisation

As the TIS analysis approach is established, the traditional indicators of previous TIS analyses can be largely copied. However, as the TIS concept is supplemented in this research, new indicators have to be included that capture the added *transformative* elements. This indicator allocation is depicted in Table 4.

*Table 4: Operationalisation of the SFs for ES. Adapted from Hekkert et al. (2009) and Hekkert et al. (2011).*

| System functions | | Indicators |
|---|---|---|
| SF1: Entrepreneurial activities | + | ES projects started |
| | + | Actors engaging in ES |
| | + | Positive business case for ES |
| | - | Projects stopped |
| | - | Lack of actors |
| | - | No business case |
| SF2: Knowledge development | + | R&D activity in ES |
| | + | ES research or non-research publications |
| | + | ES research projects |
| | - | Lack thereof |
| SF3: Knowledge diffusion | + | Conferences, workshops, research stakeholder platforms on ES |
| | + | Information exchange through project collaborations |
| | - | Lack thereof |
| SF4: Guidance of the search | + | Shared visions between stakeholders on ES |
| | + | Positive expectations of ES |
| | + | Positive regulations on ES |
| | - | No shared vision between stakeholders |
| | - | Negative expectations of electricity storage |
| | - | Negative regulations on electricity storage |
| SF5: Market formation | + | Positive electricity market policy for ES |
| | + | Growth in ES capacity and market size |
| | + | Cost-competitiveness of ES |
| | - | No positive electricity market policy for ES |
| | - | Little growth in ES capacity and market size |
| | - | Uncompetitiveness of ES technologies |
| SF6: Resource mobilisation | + | Subsidies, investments, expertise, available workforce, available materials and infrastructure that support ES |
| | - | Lack thereof |
| SF7: Legitimacy | + | Lobbying activities to improve technical, institutional and financial |

| | | |
|---|---|---|
| | | conditions for ES |
| | + | Acceptance of ES within the electricity sector |
| | - | Lack of lobbying activities for ES |
| | - | Lobby for other technology that competes with ES technologies |
| | - | Active lobby against ES |
| | - | No acceptance of ES within sector |
| SF8: External strategic orientation | + | Availability of landscape pressures that are consistent with the added value of ES |
| | + | Changes in the values and assumptions in the European electricity system towards decarbonisation and ES adoption |
| | + | Destabilising policies that favour ES technologies over the status quo |
| | + | Cross-sectoral, cross-technology and cross-industry collaborations, relations and connections concerning ES services |
| | + | Sector coupling policy or strategy relevant to ES |
| | - | Lack thereof |

The SFs are assigned values between 1 (very weak) and 5 (very strong) based on the researcher's interpretation of the interview results as well as the results from desk research. Very weak means that almost all data assigns a negatively fulfilled value to the SF. Very strong that almost all data suggests a positive value. The underlying reasons for poorly performing SFs are categorised in line with the identified system failures, as this will facilitate the selection of policy instruments. The interviewees are also explicitly asked to grade the SFs. This helps reduce arbitrary misinterpretations of interviewee responses. The grades assigned by the interviewees and the grades found by the researcher as a result of interpreting all data, including the interpretation of interview data, are averaged. The researcher's interpretation weights for two thirds and the interviewees' assessment for one third.

Afterwards, the conclusions are analysed in light of the theoretical framework to define the system failures. Interconnections between SFs are also directly derived from the interviewees' answers. The referrals to systemic problems that are caused by other SFs, or influence each other in a different manner, are counted and are displayed in a diagram with arrows.

Addressing identified interconnections are guiding in determining policy recommendations as it is more efficient to tackle the system failures at their core. This results in more efficient policy solutions.

### 3.6 Data analysis

Every interviewee is labelled with an "interview code": an abbreviation of three letters combined with a number, as displayed in Table 3. Results stemming from interviewees are referenced by these interview codes. Results that are shared by a majority of the interviewees, i.e. more than eight, are referenced simply by "MAJ". In the rare situation that there is unanimity, the reference is "ALL".

In principle, all interviewees' comments are included in the data. The comments that elaborate on, nuance, or explain the main findings are included even if supported by just one single interviewee. Alternatively, points that are no direct contradiction of the main findings but rather offer a different view will also be included even if just supported by one interviewee. However, when interviewees contradict each other, i.e. arguments that go against the majority, points are only included if at least raised by two separate interviewees. Dissenting arguments raised by only one interviewee are dismissed unless they find support in desk research. This system aims to reconcile goals of internal validity with including as many insights as possible.

The results of the coded interviews were compared with findings from the desk research for consistency and discrepancies.

### 3.7 Validity, reliability and suitability

The validity of research can be improved by decreasing the likeliness of coincidental or arbitrary results by data triangulation (Yin, 2003). To that end, the high number of nine different stakeholder groups ensures that the answers are not biased; having parties that have stakes in the technologies as well as having more conservative parties balances out swings in either direction. In addition, the interviewees are experienced in the sector. They have not answered from their official capacity at the organisation, but rather from their own informed expert opinions. Moreover, the validity is strengthened by extensive desk research.

Reliability can be ensured by a clear description of the research steps and the manner in which the data analysis has been performed. As described in section 3.6, very few points raised by the interviewees have been excluded to ensure that, in this relatively novel subject, the research is not steered towards a certain direction as a result of the research methods. Moreover, the interviewees were asked largely the same questions. When comparing the answers and scores provided by the interviewees, these did not deviate much from the researcher's interpretation. This strengthens the reliability.

In terms of external validity, as this research uses data that is specifically relevant for the EU as a whole, the results are not transferable to individual member states or to the international community outside of the EU.

## 4. Results

This section will discuss the results of the structural-functional analysis. The structural analysis maps the system of ES in Europe, after which the functional analysis delves into the performance of the SFs. The underlying causes of poor SF performance are then collected and analysed, and subsequently discussed in the subsection on interconnections to reveal which barriers are most pressing on the system.

## 4.1 Structural analysis

On the role of storage, actors are mostly in agreement; ES will be important in the integration of renewables (BAT2; DSO1; EUR2; NAT2; OTH1; OTH2; TSO1) as they can provide the necessary flexibility in the system that variability of renewables require (BAT2; EUR2; GOV1; OTH1; UTI1). In addition, ES allows for more energy efficiency as plants do not have to shut down (BAT2), which results in reduced costs throughout the whole value chain (OTH2). ES will allow for more energy security (BAT2; OTH2), and particularly for islands (BAT2; EUR2). It can also replace current grid infrastructure like electricity cables (OTH2).

As is well established, the structural elements of a TIS consist of actors, networks, institutions and technologies/infrastructure. These structural elements are discussed individually.

### *4.1.1 Technologies*

Firstly, it must be emphasised that ES in this research refers to installations that can feasibly support *flexibility*[5] in a *decarbonised* electricity grid. Lithium-ion batteries, which is often treated synonymously with ES, currently only represent a small percentage of battery storage, let alone ES in general (EASE and EERA, 2017). Many of the *energy storage*[6] technologies, which is broader than ES, as displayed in Figure 3, could fulfil that role.

[5] This should be distinguished from technologies that cannot provide such flexibility. For example, hydro storage is an established ES technology but is not suited for the decarbonisation process because it cannot provide on-demand flexibility to compensate for the intermittency of renewables. *Pumped* hydro, on the other hand, uses renewable energy during the day to pump the water back up the dam only to release it again when demand is highest. Therefore, it can provide on-demand flexibility and consequently falls within the scope of ES in this research.

[6] Energy storage is written in italics in the text throughout this document to highlight the difference with electricity storage. This is not the case in figures, tables and names.

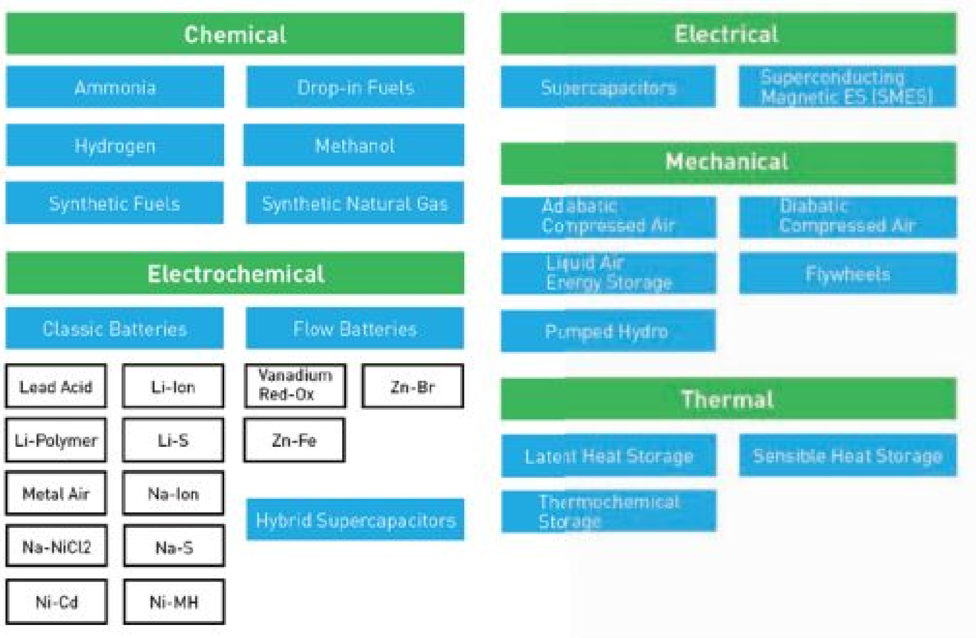


*Figure 3: The energy storage technologies currently available. Source: EASE and EERA (2017)*

While most ES provide the same services, there are different technological families. This is also displayed in Figure 3 in the green headers. It broadly refers to the technological manner in which the electricity is stored, but it says little about what services it can perform. Every technological family, e.g. mechanical storage, which relies on forces, has varying and overlapping applications. An overview of all storage applications is added in Appendix II. The selection of a specific technology will always depend on the financial, geographical and technical circumstances of the situation. In addition, not all ES technologies have the same discharge time and storable capacity, which inherently affects its applications. The differences in discharge time and storage capacity are depicted in Figure 4.

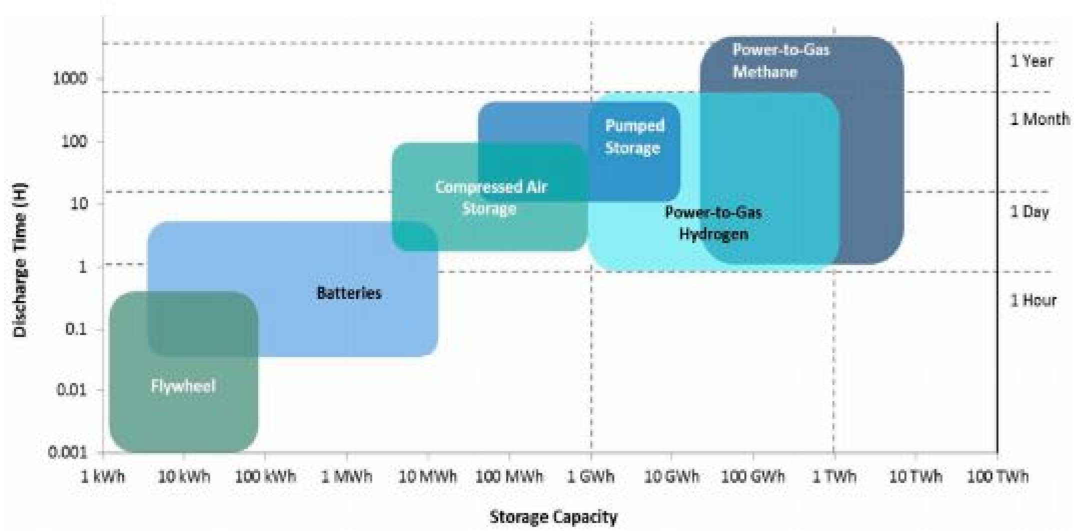

*Figure 4: A few ES technologies and their discharge time and storage capacities. Source: Moore and Shabani (2016).*

As can be derived from Figure 4, flywheels and pumped hydro storage have vastly different capacities and discharge times, and thus different applications. Nonetheless, both are from the mechanical storage family as they both rely on the use of forces.

Recent research has revealed that lithium-ion batteries are projected to make the most gains in terms of their levelised cost of storage.[7] As a result, it is likely to be a preferred choice for many applications (Schmidt et al., 2019). Despite its projected price advantage, there will still be situations in which other technologies are more suited. Lithium-ion batteries might play a large role in the future, but it is unlikely that ES capacity will only be offered by one or two technologies. As Figure 5 displays, lithium-ion is well suited for short- and medium-term applications in direct ES storage. It is not also evidently not suited for longer durations, like seasonal storage. For the latter, Figure 4 illustrates that hydrogen and pumped storage are better suited.

| Storage Segment | Storage Type | Storage Duration[1] | Lead-acid | Ni-Cd | Li-ion | NaS | $NaNiCl_2$ | Flow |
|---|---|---|---|---|---|---|---|---|
| Fast-acting storage | Power quality | <1 min | 🟢 | ☹ | 🟢 | 🟠 | 🟠 | 🟢 |
| | Power system stability | 1 – 15 min | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 |
| Power storage | | 15 – 60 min | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 |
| Energy storage | Daily | 6 h | 🟢 | 🟠 | 🟢 | 🟢 | 🟢 | 🟢 |
| | Weekly | 30 – 40 h | 🟠 | ☹ | ☹ | 🟢 | 🟢 | 🟢 |
| | Monthly | 168-720 h | ☹ | ☹ | ☹ | 🟠 | 🟠 | 🟠 |

*Figure 5: Applications for batteries. Source: EASE and EERA (2017).*

Usually expressed in technological readiness level (TRL), several ES technologies have reached the highest form of development: proven and commercialisable. Batteries are considered to be the most developed (DSO2), as is also reflected in Figure 6. Pumped hydro storage is a very established technology which is arguably one of the only that is competitive now (GOV1).

[7] The levelised cost of storage is an economic term that reflects the net present value for storage investments per unit of capacity delivered.

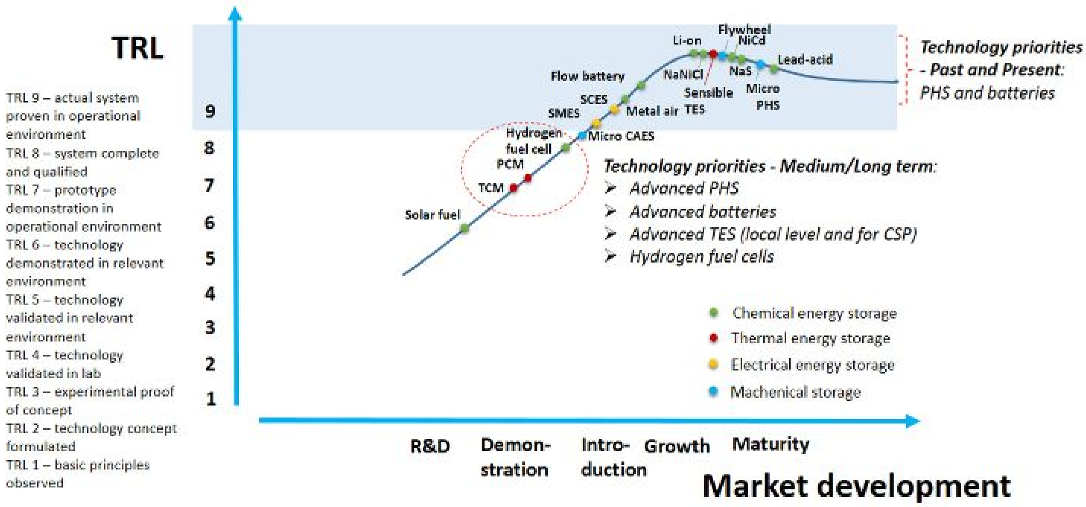


*Figure 6: TRLs vs. market development. Adopted from Nguyen et al (2017).*

As many research programmes happening for over two years since this source was published, one can expect that more technologies have reached these levels.

### *4.1.2 Actors*

Relevant actors for this research are DSOs, TSOs, utilities, storage technology producers and integrators, advocacy groups, research institutions and governments and energy regulators. DSOs and TSOs jointly maintain the network; utilities generate and sell electricity services; storage technology producers sell the (components of) storage devices, whereas integrators, which sometimes are the same actors, install the technology into an operational system; advocacy groups inform and advise governments on ES-supportive policies; research institutions help advance the technological and commercial development of ES; and the governments and regulators create and enforce legislation. Financiers are not included as an individual actor group as the investment case is not very strong; many of the investments come from the other actor groups. Educational centres are excluded as their presence is negligible; there are virtually no university programmes or other educational courses offered for ES (yet).

In this research, governments are not national governments and regulators are not national regulatory authorities, but the European institutions: the European Commission that proposes legislation, and the European Parliament and the Council of the European Union that jointly amend and subsequently pass laws. Some interviewees raised the point of an emerging role for an aggregator for decentralised storage (DSO2), but that would not apply in the case of grid-scale storage. National regulatory authorities are responsible for enforcement of domestic and European energy law.

A summarising overview of the actor structure of the system of ES is displayed in Figure 7.

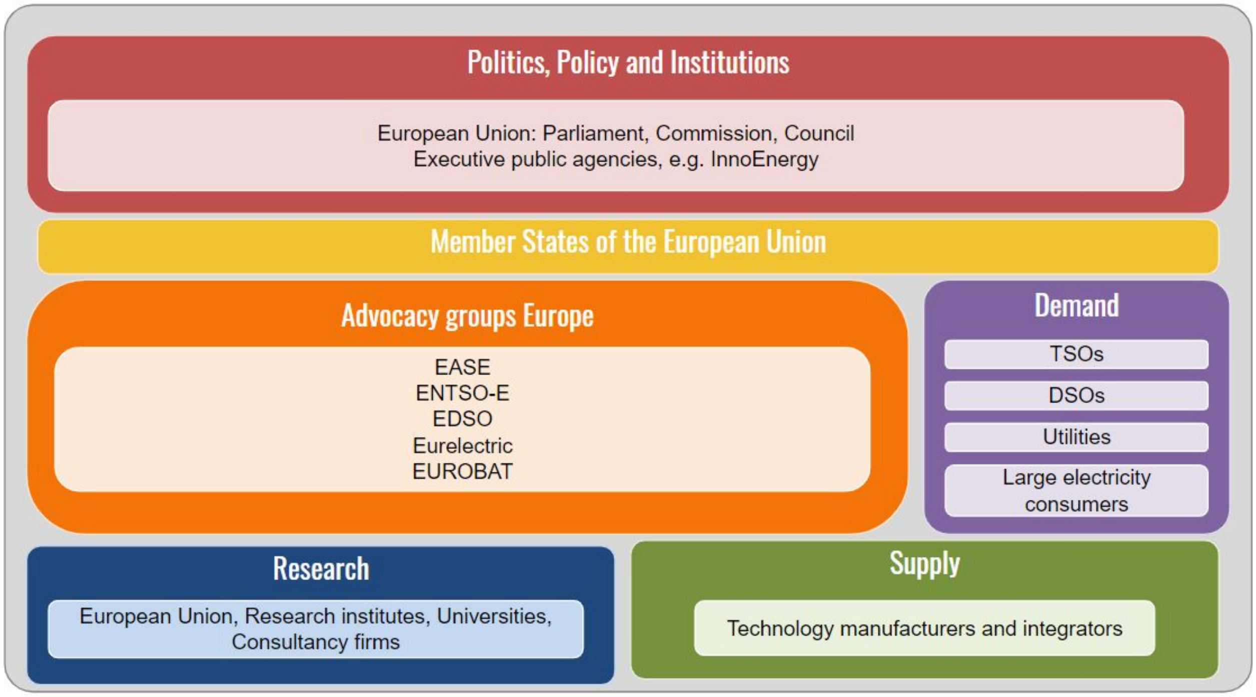


*Figure 7: Overview of the actor structure of the ES system.*

*Advocacy*

Advocacy groups play an instrumental role in the European energy sector and energy policies. Advocacy groups are numerous and varying in size and scope. TSOs are, by law, united on a European level through the European Network of Transmission System Operators for Electricity (ENTSO-E). A similar organisation exists for DSOs: the European Distribution System Operators (EDSO). These groups represent the positions of the regulated entities[8] in European policy-making and stakeholder events. Importantly, EASE represents the interests of all actors interested in ES. However, many ES technologies also have their own advocacy group; EUROBAT for batteries and Hydrogen Europe for hydrogen technologies are among the most prominent. Even national energy regulators are represented through the Council of European Energy Regulators (CEER). Through these advocacy groups, the stakeholders can be more or less centralised to the European level. Research institutions do not have an advocacy group as such. Nevertheless, the European Energy Research Alliance (EERA), the research arm of the Strategic Energy Technology Plan (SET-Plan), coordinates research into low carbon energy technologies and also performs top-down advocacy for additional research groups.

EASE's membership of forty-three almost exclusively consists of larger, established players. One notable exception being Highview Power, which is considered one of the more promising European startups (Startus Insights, 2019), providing liquid air storage. On a geographical note, EASE membership is largely western European. Notably, exceptions are one state-owned Polish energy firm, and two Greek companies (of which one is state-owned). All other organisations are western.

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[8] TSOs and DSOs jointly are also called regulated entities or network operators. For the sake of clarity and consistency, the term regulated entity is used throughout this research.

*Research*
Research is performed by universities, consultancies, private research institutions, but also for a large share by industry. The EU is not conducting research as such but, instead, have set up European funds that research actors can appeal to.

*Industry*
The European battery industry is very weak compared to Asia (BAT2; EUR1). However, there are some smaller European players. SAFT is an established battery producer from France. In 2016, Northvolt was founded: a Swedish sustainable battery manufacturer. Northvolt is mainly funded by car manufacturers and the European Investment Bank (Reuters, 2019). Northvolt is set to compete with the dominance of Asian battery manufacturers. LG Chem and Samsung are among the large Asian multinationals that dominate the battery market in Europe.

For other technologies, Europe has a relatively larger domestic industry. Maxwell Technologies, even though recently acquired by Tesla, is one of the leading suppliers of supercapacitors, an electrical ES technology. Moreover, many European energy firms of the likes of Shell and Uniper are heavily involved in hydrogen Power-to-Gas technologies. Startups are often bought by larger firms. Shell recently bought Sonnen, a German startup in *energy storage* systems. While the technology market is fully competitive, smaller companies are often acquired and the market is thus often led by the bigger firms.

Demand for ES technologies theoretically could come from DSOs and TSOs, who are responsible for grid maintenance and thus benefit from storage as an enhancer of smart grids and a replacement for grid reinforcement. Regulated entities normally do not face competition. However, regulated entities are legally not allowed to own and operate storage, so have to leave many services to commercial players and are not entitled to invest in ES. The rules of the European electricity market design merely allow regulated entities to own and operate storage devices in case of a market failure, and only if it forms an integrated network component. Instead, utilities are the main beneficiaries, as the intermittency of variable generation could be compensated by ES. They are also not legally limited to own and operate storage and could provide many of the services to the regulated entities as well. However, utilities are often bound to regulatory limits as well as electricity prices are sometimes capped. Most utilities are large firms. Lastly, large industrial corporations that use large quantities of electricity are increasingly interested in storage to guarantee supply and to be able to make smart use of electricity price differences throughout the day. Smaller players are rarer, as storage devices are CAPEX-intensive and remuneration is limited.

The different services, as depicted in Appendix II, are a good representation of the ES demand sources and markets.

*4.1.3 Institutions*

On the European scale, the Clean Energy for all Europeans package is the main policy framework for the energy transition. More specifically, the Electricity Directive, the Electricity Regulation, and the Revised Renewable Energy Directive (REDII) are the legislative elements that are relevant to ES. The latter sets targets for renewable energy, which affects ES. The Electricity Directive and Electricity Regulation set the market conditions for electricity, in which ES, for the first time in European regulation, is mentioned (Delta-ee and EASE, 2019). In addition, the EU released a long-term strategy that sets out how the energy transition targets are envisioned to be achieved. Lastly, the Network Codes are a set of technical requirements for installations in the electricity grid. These pieces of regulation form the policy context that is relevant, as there are no policies that specifically target ES.

As the Electricity Regulation and Electricity Directive, complemented by the Network Codes, lay down rules to harmonise European electricity systems as much as possible, the institutional makeup of national electricity systems is largely similar. However, there are regional differences in rules that do not fall under the European rules that are relevant to storage. Some countries, like the UK and the Netherlands, in practice tax storage devices twice: once for taking electricity out of the grid, and once again for putting it back in. However, these challenges are tried to be addressed on both a European and national level (Current News, 2019; EASE and EERA, 2017). The introduction of a definition of *energy storage* under the Clean Energy Package is a good first step (EUR1; EUR2).

### *4.1.4 Networks*

For the purpose of informed policymaking, the European institutions often organise stakeholder events or consultations. In Brussels in general, there are a plethora of events in which several stakeholders from different sectors come together to exchange ideas. Advocacy groups initiate interaction between many national entities in the same sector/niche area. In turn, these advocacy groups either attend many of these events or ask their members to attend. However, advocacy groups often do not represent the dissenting voices from the sector.

Many organisations, also those that are connected to advocacy groups, take part in EU funded projects. Many of the EU funded programmes like Horizon 2020 work with consortia of industry players, regulated entities and regional authorities. Collaborations are numerous. The increasing amount of conferences for ES serve as a good platform to initiate collaborations.

### *4.1.5 Stage of development*

Different technologies are at different stages of development. However, as this research focuses on the socio-technical system of the services that ES can provide, the leading technologies (with the highest TRLs) should be considered. Several of the leading technologies have TRLs higher than 8, which makes them commercialisable. Moreover, there are plenty of commercial applications (EASE and EERA, 2017; Delta-ee and EASE, 2019). Accordingly, it should be concluded that these leading, most mature ES technologies are in the take-off phase (Hekkert et al., 2011).

## 4.2 Functional analysis

*4.2.1 Entrepreneurial activities*

When looking at the relevant actors in the electricity sector as a whole, as also described in section 4.1.1, the vast majority are to some extent invested in ES. Most interviewees agree that the amount of firms investing in ES is sufficient for the development of ES (MAJ).

It is clear that the amount of projects has rapidly increased over the last few years, without signs of slowing down. Figure 8 shows the annual amount of *energy storage* installations globally. Pumped hydro storage, represented under the electromechanical storage, has only grown marginally; it is a well-established technology and growth has stabilised over the years. Particularly battery and thermal storage are on the rise. Hydrogen, while receiving a great deal of attention and research funding, is evidently not in its deployment phase.

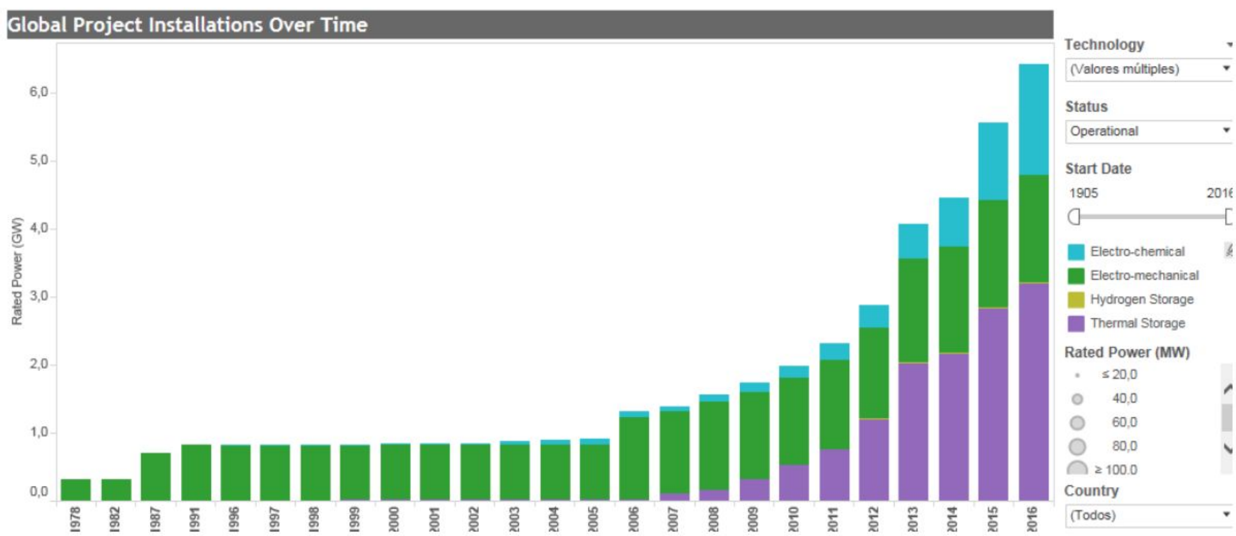


*Figure 8: Globally installed energy storage projects. Source: US Department of Energy (2017).*

Some projects have been granted the Projects of Common Interest (PCI) status, which means they are considered "(...) key cross border infrastructure projects that link the energy systems of EU countries" (EC, 2019). Fourteen of these projects were specifically for ES (EC, 2017). PCI projects for ES for the coming years are also projected in large numbers, but this cannot be stated with certainty pending their approval by the EU.

The level of commercial projects, however, is considered to be insufficient by the majority of stakeholders. The explanation is overwhelmingly pointing towards the poor business case (MAJ). Costs are high with too few possibilities to make money. In turn, regulatory uncertainty and poor markets mechanisms are causing the poor business case (NAT1; TSO2; UTI1). The latter two points are originating in SF5 and SF4 respectively and are therefore more extensively discussed in sections 4.2.4 and 4.2.5. This is aggravated by Europe's strong grid as it delays the immediate need for storage, and thus curbs its value (BAT2; EUR2; RES1). Uncertainty revolving the interaction with different sectors is also a limiting factor for entrepreneurial activity, as emerging technologies in the transport sector, most notably Vehicle-to-Grid (V2G)[9] technologies, puts the necessity of stationary storage into question (RES1). Actors from other sectors may very well enter the power sector in the future (GOV1). This links strongly to the sectoral interactions from SF8.

Despite the poor business case, the amount of actors is sufficient. One respondent argued that in the EU overall it were mostly the utilities that were looking into ES (OTH2). Some bigger utilities are still installing projects, at a loss, on a commercial scale; simply to gain experience for the future (UTI2). More broadly, many established players in the sector engage in storage merely for the sake of diversification (EUR2). But above all, this argument highlights an actor group that is struggling: startups and smaller players. For installing projects without the possibility to be remunerated well, financial reserves are needed for survival that smaller firms are unable to stomach. Because of this poor ability to earn revenues, investments in ES are deterred (BAT2; DSO1, TSO2, UTI1), which affects smaller firms relatively harder. While there are plenty of startups out there, many go bust as the financial threshold to enter the market and to subsequently survive is very high (EUR2; NAT1; OTH1). Therefore, mainly the bigger players win the tendered contracts in the balancing market (NAT1), which is one of the few options to make money.

The lack of an evident supply chain is also named as a cause of a lacking amount of projects (DSO2). Some of the respondents even indicated that there is no substantial *battery* manufacturing industry in Europe at this point. This is confirmed in Table 5. While stationary and EV batteries are not the same (OTH1), the manufacturing capacity has many overlaps; cells are often produced for both appliances in the same factories.

*Table 5: Total lithium-ion battery manufacturing capacity per region. Source: Lebedeva et al. (2016).*

[9] V2G technologies make use of bidirectional electricity flows in the batteries of electric vehicles. This means that when the vehicles are plugged in into the grid to charge, their batteries can be used to store electricity, but when the grid needs more electricity those same batteries can be used to feed peak electricity to the grid when the need is high. In effect, this means that a plethora of cars replaces and offset the need for new stationary batteries. In addition to saving money, it saves additional resources. Another added value of investing in V2G rather than stationary storage is that more V2G means more EVs, and more EVs will result in cleaner air, while stationary storage does not have such an added benefit. However, V2G only works for short-term storage services, as the application is currently limited to the lithium-ion battery technology.

| | Fully commis-sioned (GWh) | Partially commis-sioned (GWh) | Under construc-tion (GWh) | Announced (GWh) | Total manufacturing capacity* (GWh) | Share of total global capacity* | Automotive manufacturing capacity* (GWh) | Share of global automotive capacity* |
|---|---|---|---|---|---|---|---|---|
| **China** | 16.704 | 3.576 | 18.730 | 12.847 | 39.010 | 51 % | 11.240 | 41 % |
| **Japan** | 10.778 | 0 | 1.200 | 0 | 11.978 | 16 % | 5.750 | 21 % |
| **Korea** | 16.059 | 0 | 0 | 0 | 16.059 | 21 % | 4.600 | 17 % |
| **U.S.** | 3.770 | 0 | 1.200 | 35.0 | 4.970 | 7 % | 4.600 | 17 % |
| **EU**** | 1.798 | 0 | 0 | 0 | 1.798 | 2 % | 1.300 | 5 % |
| **Rest of world** | 2.440 | 0 | 0 | 0.564 | 2.440 | 3 % | 0 | 0 % |
| **TOTAL** | 51.549 | 3.576 | 21.130 | 48.412 | 76.255 | 100 % | 27.490 | 100 % |

The absence of a European battery manufacturing industry is due to the fact that it is virtually impossible at this time for European companies to be cost-competitive with Asian firms, most notably from China, Japan and South Korea (BAT2; EUR1; RES1). This is partially caused by the knowledge advantage of Asia (BAT2). However, the EU has launched the European Battery Alliance (EBA250) in 2017, which pursues the "establishment of a complete domestic battery value chain" (InnoEnergy, n.d.). According to some forecasts, the European battery industry will grow from a current market share of 4% to 11% in 2025 (Bloomberg New Energy Finance, 2019). Production capacity in Europe is expected to surpass that of the USA, South Korea and Japan by 2023 (Australian Trade and Investment Committee, 2016).

### *4.2.2 Knowledge development*

While many still believe that energy cannot be stored, research into the maturity of ES technologies proves otherwise. For batteries specifically, many of the technological development is driven by the push for batteries in the EV market (DSO1). The strong research activity is reflected in Figure 9, which displays the number of ES projects in thirteen EU countries and is categorised by project stage, type of technology, and where it is applied. Respondents argue that research projects are still far more prominent than those of a commercial nature (BAT1; DSO2; EUR1; NAT1; RES2), confirming that the ratios of Figure 9 most likely have not radically altered.

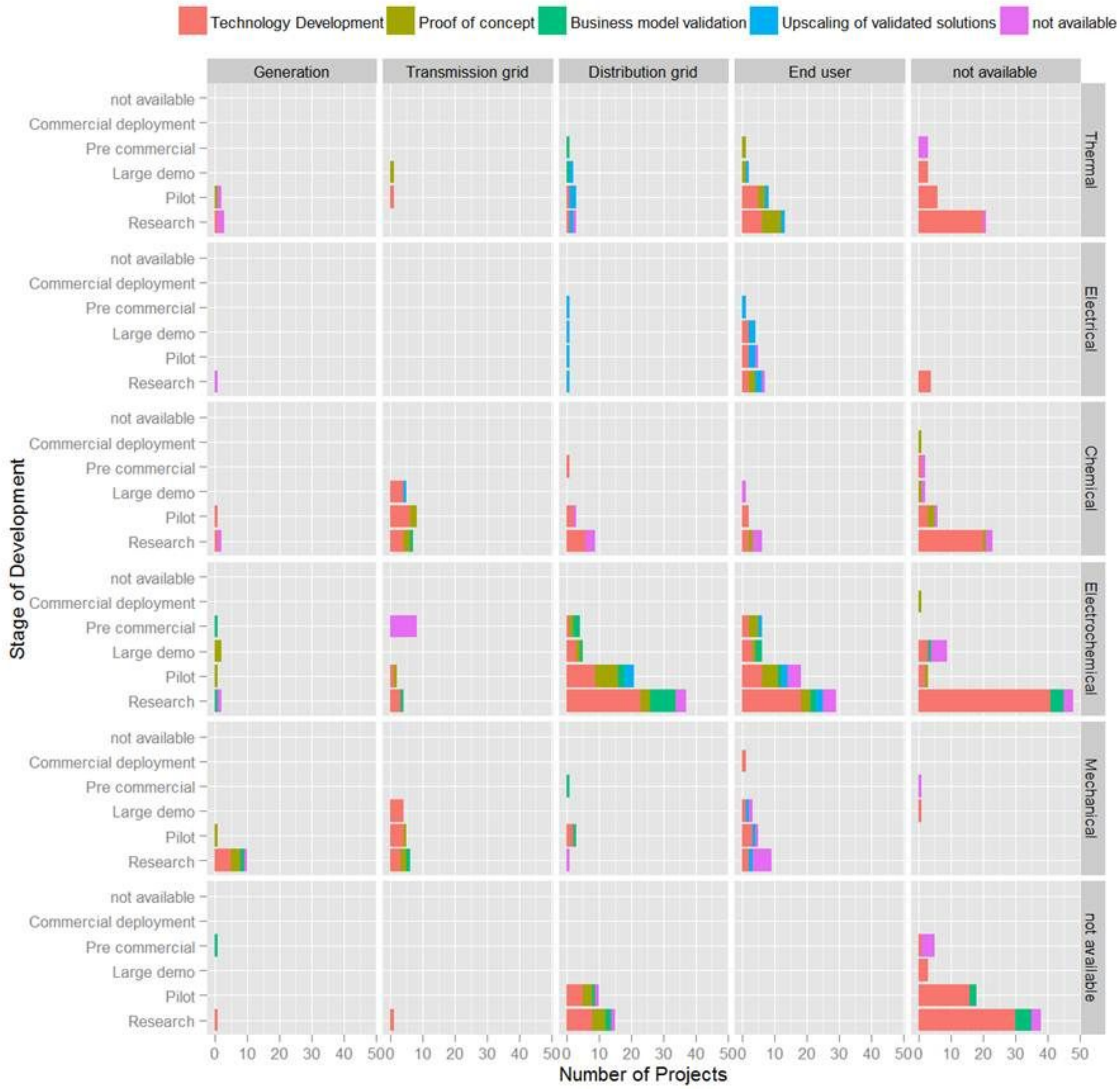


*Figure 9: The number of ES projects co-funded by the EU during the period 2009-2013. The chart distinguishes between the categories of ES technologies. Source: Strategic Energy Technology Information System Magazine, EC (2013).*

However, as this figure dates from 2013, some of the research projects may by now have been developed and potentially moved up the line towards demonstration or commercialisation. No recent quantitative data could be found that distinguishes the categories in the same manner as Figure 9. Nevertheless, progress can be implicitly derived from increased R&D investments, as further discussed in section 4.2.6. In addition, most respondents were moderately optimistic about technological progress and how ES is understood (MAJ). Some interviewees argued that R&D activity is good, despite the fact that there is strong knowledge competition from Asia (NAT1; NAT2; RES1). Particularly, a lot of R&D

activity is put into technological development (BAT1), but it is lacking for research into practical applications and business models for storage (NAT1; NAT2; RES2). However, in the deployment phase the knowledge gaps become evident (OTH1; RES2); how to integrate storage technologies (BAT2; GOV1; NAT1; TSO2) and how ES technologies perform in the long term is understood significantly worse (UTI1).

The EU also funds a considerable amount of projects. Between 2014 and 2018, the EU's Horizon 2020 programme funded projects with a total of 1.34 billion euros for grid storage or low carbon mobility (ECA 2019). Horizon Europe, the successor of Horizon 2020, launches in 2021. ES is explicitly named as a topic under the "Climate, energy and mobility" cluster, as proposed by the European Commission. It is unclear what share of this money will go to ES. In contrast to many other storage projects, many of the Horizon projects between 2018 and 2020 are also aimed at other technologies than lithium-ion and are sometimes specifically designated for stationary appliances (EC, 2019). There are several projects and goals that are directly relevant to large-scale ES. An overview has been made of those projects relevant to large-scale ES, including the grants provided, and is added in Appendix III. It cannot be stated with certainty that the data are exhaustive. Smaller-scale storage projects are not listed as they are not included in the scope of this research.

Figure 10 illustrates the patent trend in electrochemical storage over the last few years. Lithium-ion is responsible for the vast majority of patents (Müller et al., 2014). Further searches into patent information for all storage technologies cannot be visualised, as the database limits the search to the first five hundred results in that category. However, the amount of patents is impressive. This trend shows that R&D into storage, at least battery technologies, is advancing quickly.

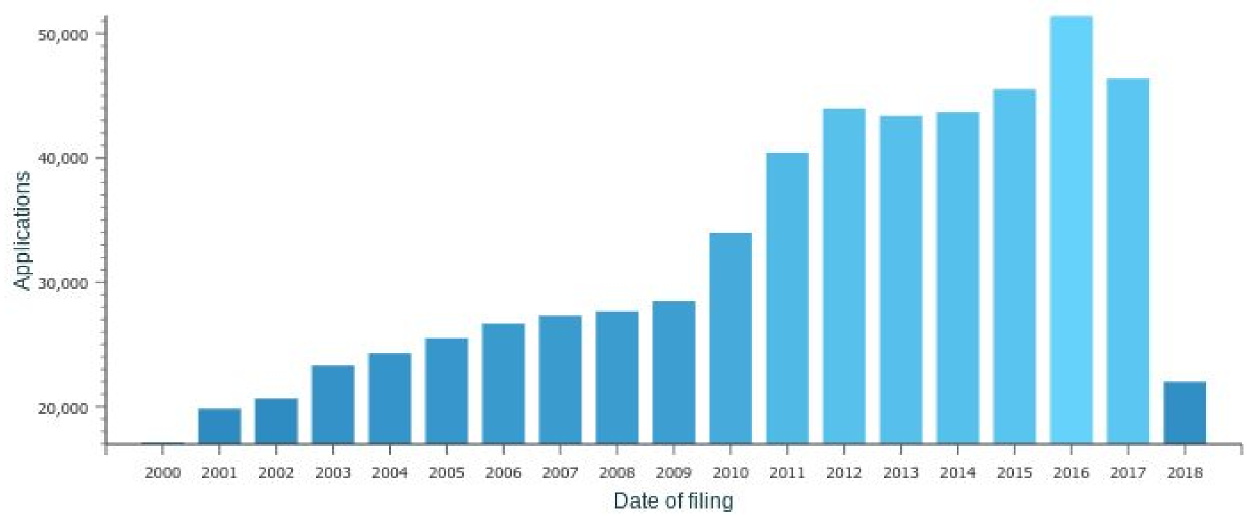


*Figure 10: Trends in patent applications for electrochemical storage between 2000 and 2018. Based on data from the European Patent Office.*

In terms of academic literature, a search for "electricity storage" in Scopus results in eight hundred and eight publications. A clear, upward trend can be identified in the number of articles per year. However, an overwhelming majority of articles is in the field of engineering. Publications in the field of social sciences, business or economics are falling behind significantly, as is reflected in Figure 11.

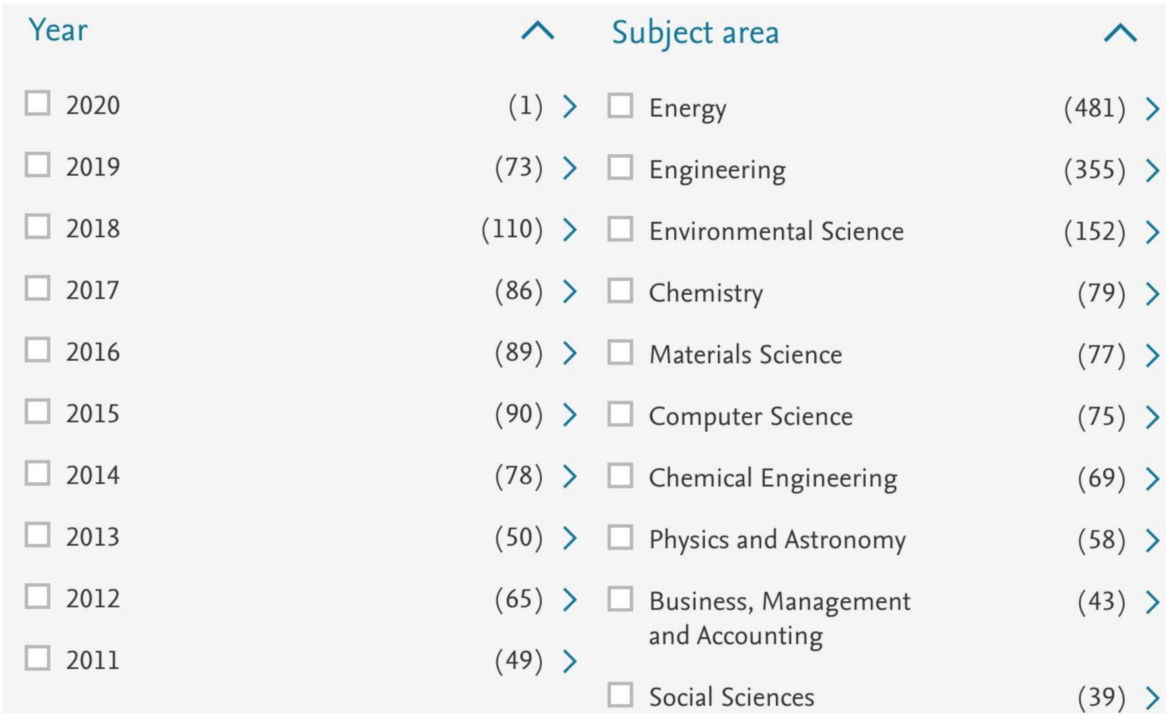


*Figure 11: Academic articles with "electricity storage" in their abstract, categorised in numbers by publication year and subject area. Source: Scopus.*

While it is difficult to draw definitive conclusions from this number, it does support the findings by respondents that non-technical aspects deserve more research.

Many respondents argued, once again, that regulatory uncertainty (BAT1; EUR1) and lacking investment incentives are inhibiting more knowledge development (OTH1; TSO2); the lack of prospects for better remuneration reduces R&D investments (TSO1). However, the sharp public focus on batteries is also reflected in R&D activity (EUR1). Only time will tell if this will turn out to be a wrong strategic decision. It does reveal the direction in which the future is headed and it could paralyse the development of lesser known, or yet uninvented, ES technologies. Section 4.2.4 will elaborate on this point.

### *4.2.3 Knowledge exchange*

Many ES projects are executed by consortia of players from the energy sector; governments, businesses and regulated entities. All the projects listed in Appendix III are all projects executed by a variety of stakeholders across the energy system. Established players work together frequently, even though there is no truly developed community; utilities, DSOs and TSOs have also been working together for years through sector-specific events (EUR1).

Many energy events are taking place in Brussels, of which some are specifically about ES. Among the wide variety of exchange platforms between all stakeholders is the European Technology & Innovation Platform on Smart Networks for the Energy Transition (ETIP SNET), which operates in the framework of the European Strategic Energy Technology Plan (SET-Plan). The SET-Plan was set up in 2007, revised in 2015 (ECA, 2019), and promotes and coordinates research, innovation and deployment efforts for low-carbon technologies. It contains three action points that are relevant to grid-scale storage: "Action 4: development and operation of resilient, reliable, and efficient energy systems, able to integrate variable renewable sources; Action 6: continue efforts to make EU industry less energy intensive and more competitive, e.g. by developing thermal *energy storage* technologies; Action 7: batteries for electric mobility and stationary *energy storage*;..." (ECA, 2019, p. 13). In addition, the SET-Plan has released an implementation plan for its plan, including those relevant to storage (EC, 2018). ETIP SNET's Working Group 2, established only in 2016, focuses on storage technologies and sector interfaces. It therefore follows a technology-neutral approach. All relevant actors are represented. The working group's aims are creating shared visions, identifying challenges, monitoring progress in research and innovation, promoting knowledge exchange (ETIP SNET, 2016).

For batteries specifically, the EBA2050 is the most well-known initiative. It is driven by the European Institute of Innovation and Technology (EIT) InnoEnergy. Established in 2017, the EBA is mainly aimed at setting up a European sustainable battery industry for EVs. Nevertheless, the EBA serves as a platform that also aims to distribute knowledge for stationary batteries. ETIP BatteRIes, also under the framework of the SET-Plan, launched in June 2019 and is also specifically directed at batteries. ETIP BatteRIes " creates a bridge between the different actions related to the battery industry, especially in relation to research and innovation (R&I), and ensures that the relevant stakeholders have the possibility to discuss, and agree upon common R&I priorities" (ETIP Batteries; EERA, 2019). The ETIP SNET has a working group on storage technologies and sector interfaces. Hydropower Europe, a collective of hydropower operators in Europe, was established through EU funds,

There are several conferences for ES. Nearly all are dedicated to the broader term "*energy storage*". EASE organised their third Energy Storage Global Conference in 2018, that has been organised with an interval of two years and is thus fairly new. The Energy Storage World Forum will be held in October 2019 for the tenth time since 2009. The Energy Storage Summit will be held in 2020 for the fifth time since 2016. In addition, storage is increasingly being put on the agenda of broader energy conferences, like the European Utility Week. While this is not an exhaustive list, it show that new storage conferences are picking up.

A clear trend can be identified in the amount of exchange platforms, research and innovation coordination efforts, and many similar initiatives that promote the knowledge exchange in ES. However, quantifying the effectiveness of such initiatives is very challenging. Accordingly, interviewees had very differing responses when asked about knowledge exchange. Few would simply agree to there being a sufficient amount of knowledge exchange (BAT1; DSO1; OTH1; UTI1). It is generally agreed that the information is available, but there are flaws with the actual exchange process (MAJ). In addition, it is argued that there is no level playing field among stakeholders in Europe in terms of knowledge (NAT2). Policymakers are often not well informed and are presented with fragmented information (DSO2;

GOV1). Utilities possess large amounts of knowledge (EUR2; OTH2). TSOs are increasingly looking into it (EUR1), but are not yet as knowledgeable as utilities (OTH2).

The flaws in question are numerous. Some relate to the quality of information availability. The amount of conferences are plentiful (NAT1; TSO1; UTI1), although they are often reserved for the renewables/storage niche, both in terms of attendees and information (OTH2; RES1); conventional energy players are not always willing to embrace storage. Consequently, there is still a lot of disbelief of the potential of storage in the conventional branch of the energy sector based on faulty or outdated information (RES1). Respondent BAT2 even argues that large branches of the sector are reluctant to be properly educated. This shows connections to SF7. Difficulties are also encountered in finding information (TSO1) or being able to filter proper information, as "those who make the most noise get heard" (OTH1). This challenge distorts information flows.

This lack of reach on information exchange also affects the capabilities of policymakers to acquire accurate and up-to-date information on storage. This could potentially be exacerbated by a general lack of transparency in the electricity market (OTH2). EASE members exchange a lot of information on storage technologies and applications, but little on financial numbers (UTI2); some information is not exchanged because it is competition sensitive (TSO2). Financial information, on costs and business cases, unsurprisingly is the weakest link in knowledge exchange. Smaller firms are more eager to share information, whereas larger business are more often secretive and trying to protect their markets in more conventional areas (NAT2).

### *4.2.4 Guidance of the search*

*Policy*

While the Clean Energy Package is not very concrete on ES, there are still many public programmes that either directly or indirectly support storage. The Clean Energy Package now contains a definition of ES, which was absent before, which is a good start (EUR2). The REDII obliges there to be "at least 32% renewable energy in gross final energy consumption by 2030". While there is indeed no specific target for storage, REDII does clearly refer to additional investments in flexibility to support greater renewable integration, in which *energy storage* is explicitly mentioned. It also includes recognition of the need for a non-discriminative market design for storage. However, a vision document has in fact been released in late 2018, called "A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy" (hereinafter: EU long-term strategy). In this document, specified targets are given for expectations of storage capacity. In the EU long-term strategy, there are quantified expectations regarding the technologies that will play a part in the *energy* system in 2050. This is depicted in Figure 12.

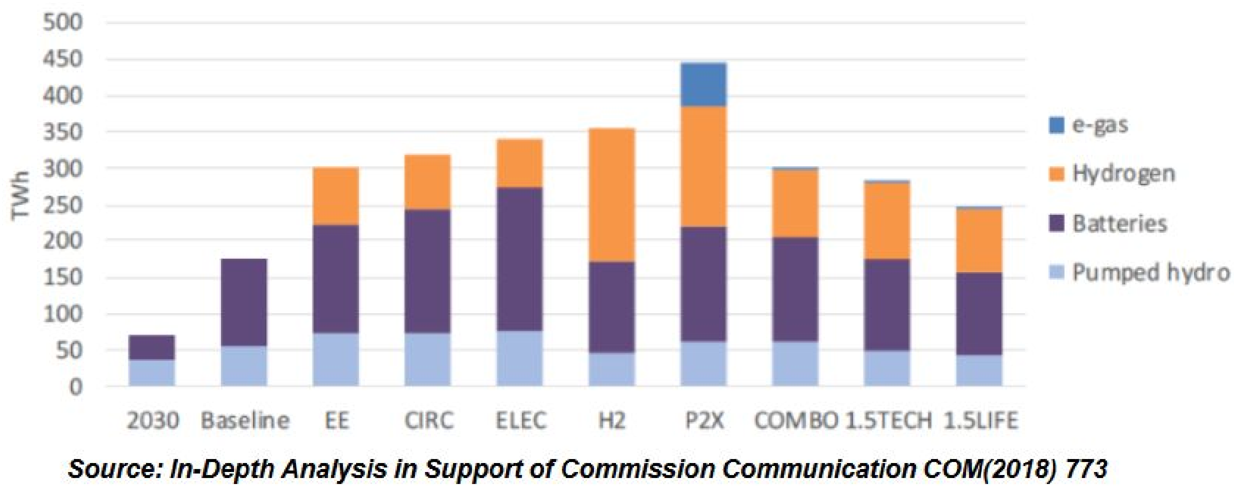


*Figure 12: EU projections on the storage technologies with corresponding capacities that will be a part of the energy system in 2050. Source: EU long-term strategy (EC, 2018).*

The scenarios in Figure 12 represent different energy transition pathways. Energy efficiency (EE) and circular economy (CIRC) are demand-driven GHG reductions, where electrification (ELEC), hydrogen (H2) and Power-to-X[10] (P2X) are GHG reduction scenarios driven by decarbonised energy carriers. 1.5TECH and 1.5LIFE refer to the more ambitious 1.5 degrees limit of the Paris Agreement, with a focus on negative emission technologies and sustainable lifestyles respectively.

More concretely on how to achieve these goals, more R&D and innovation support for ES technologies are proposed, increased domestic support by "...seizing the first-mover advantage..." (EC 2018) by creating the necessary conditions for this. In addition, it is mentioned that investments in the power sector to reach 80% decarbonisation must amount to 1.33 trillion euros a year in the period between 2031 and 2050. The document is clearly aimed at the energy transition at large, but at times is specific on storage in its scenarios. Regulation (EU) 2018/1999, or the Regulation on the Governance of the Energy Union, also contains provisions that focus on increased shares of flexibility. Article 4c and Annex 2.4 of this regulation require member states to include measures to increase flexibility, and particularly storage, in their energy system and by supporting non-discriminatory participation of storage in the energy market.

Many players recognise that large-scale ES, except for batteries in conjunction with renewables, will probably only be needed from 2030 onwards (RES2). All presented scenarios divide the different storage technologies between pumped hydro, batteries, hydrogen and, to o a lesser extent, P2X. An interviewee echoes that there is a strong focus on lithium-ion (McKinsey, 2016), which is mostly reserved for short-term applications, and that hurts the development of other technologies (OTH1). In addition, there is also a misunderstanding that batteries for EVs and stationary batteries are the same technologically speaking (OTH1). Figure 13 depicts the current distribution of allocated funds between

[10] Power-to-X technologies refers to either Power-to-gas or power-to-liquid. More specifically, it refers to the collection of technologies that convert surplus electricity into gases of liquids that can be used as fuels. Some of these technologies are highly renewable: surplus renewable electricity can be used for water electrolysis to produce green hydrogen.

ES technologies. While the budget for hydrogen and fuel cells is even higher than for batteries, we can see that within the batteries lithium-ion counts for more than 50% of the budget.

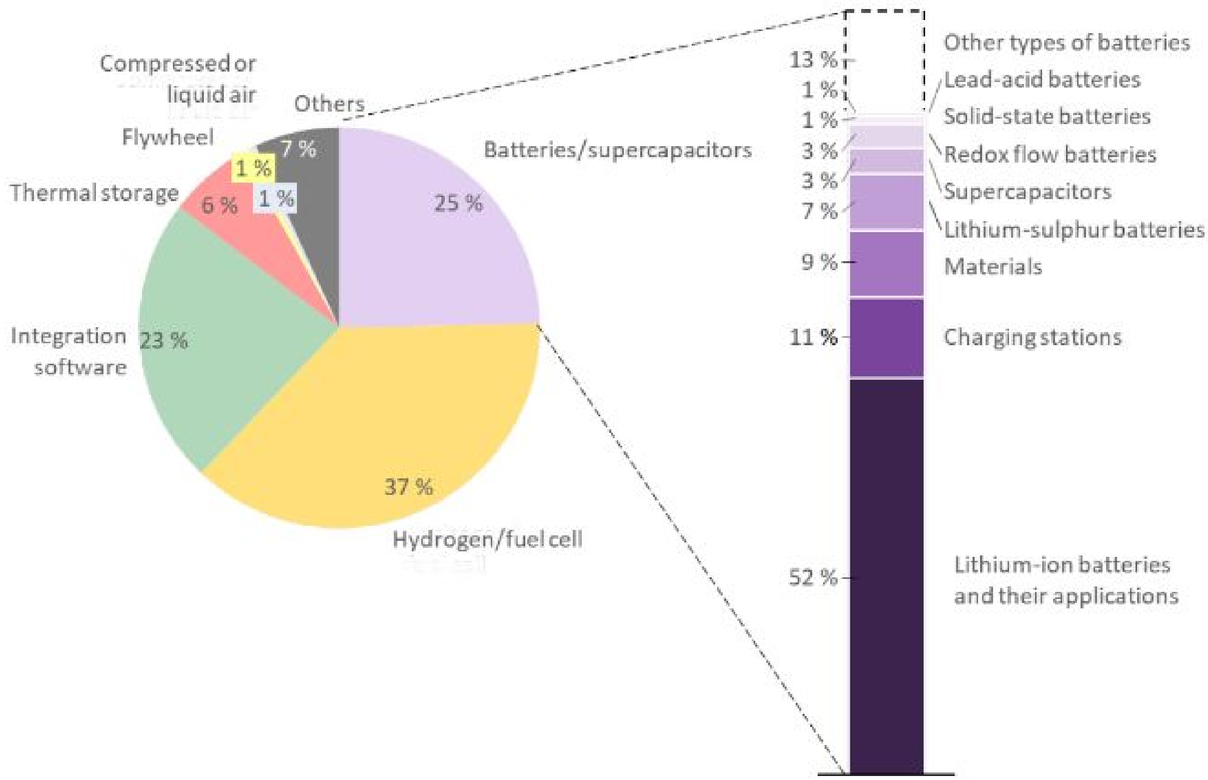


*Figure 13: Distribution of Horizon 2020 funds for ES projects. Source: ECA (2019)*

The focus on lithium-ion batteries is not based on it being the only available technology. Figure 14 illustrates how lithium-ion has only been on the rise since the beginning of this century. As discussed under section 4.2.2, lithium-ion also outperforms other battery technologies in terms of patent registrations. Lead-acid batteries were previously the unequivocal choice for automotive batteries or stationary batteries for the purpose of emergency power. This recent preference for lithium-ion, which can indeed partially be attributed to its decreasing price and its versatility in terms of its applications, is clearly a technology that has been deemed a winner technology by many. However, the positive mood revolving lithium-ion says little about the effectiveness of the all-in strategy.

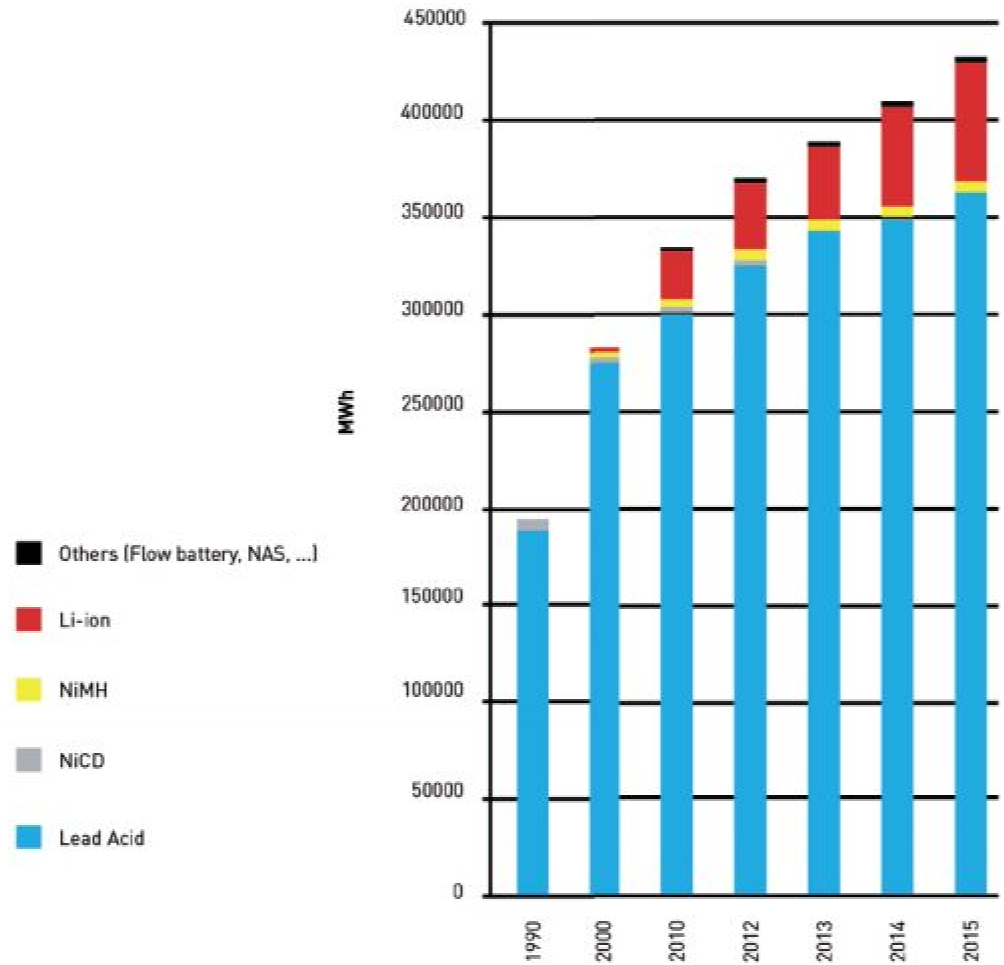


*Figure 14: Global battery market growth between 1990-2015 and market shares between technologies. Source: EASE and EERA (2017).*

Both lithium-ion batteries and hydrogen have cross-sectoral applications, which adds to the logic of its preferential status. Some argue, however, that large-scale, stationary applications require higher energy density than lithium-ion can provide (Bini et al., 2015). This argument is repeated by an interviewee who stated that increasing energy density of lithium-ion batteries should be the main research priority (BAT2). To that end, lithium-sulfur and lithium-air batteries may be more suitable (Bini et al., 2015). Figure 13 also reveals that EU funded projects are not just financing lithium-ion and hydrogen projects. Even lithium-sulfur projects are funded, which can be considered a minor upside considering the aforementioned point on energy density. Figure 13 thus carefully embraces the concept of a "cluster of ES tech" in the literal sense by spreading out funding on a variety of technologies. However, the forecasts for market share in the EU's strategy of Figure 12 does not reflect any coordination in that regard.

InnoEnergy, supported by the EU, has released a report in which they do not merely assess the TRL of ES technologies, but complement that by societal readiness (SRL), consumer readiness (CRL), market readiness (MRL) and intellectual property readiness (IPRL), to form the Innovation Readiness Level (IRL). Table 6 reveals that all the listed technologies are largely on comparable levels. If any, it is hydrogen that is behind, yet it is still one of the favoured technologies when looking at the EU's strategy or research budget. Table 6 also illustrates that market or societal/consumer acceptance is hardly an argument to consider as it would apply equally to lithium-ion and hydrogen technologies.

*Table 6: Innovation Readiness Levels of some major ES technologies broken down per segment. Maximum values range between 0-9 for TRL, 0-3 for IPRL, 0-12 for MRL, 0-6 for CRL and 0-5 for SRL. Source: InnoEnergy, 2017.*

| Technology / Dimension | Li-ion | Flow battery | Super-capacitor | CAES | Hydrogen |
|---|---|---|---|---|---|
| TRL | 8.7 | 8.3 | 8.4 | 8.7 | 8.0 |
| IPRL | 2.8 | 2.4 | 2.6 | 3.0 | 2.8 |
| MRL | 10.1 | 8.8 | 9.2 | 7.4 | 7.1 |
| CRL | 4.5 | 4.3 | 4.5 | 4.8 | 3.3 |
| SRL | 3.9 | 4.6 | 4.6 | 4.2 | 4.7 |
| *IRL (SUM)* | *29.9* | *28.4* | *29.3* | *28.0* | *25.7* |

For renewables' integration, other technologies than lithium-ion and hydrogen (through P2X) will play a role, as Figure 15 demonstrates. This strengthens the case for the EU to consider more technologies.

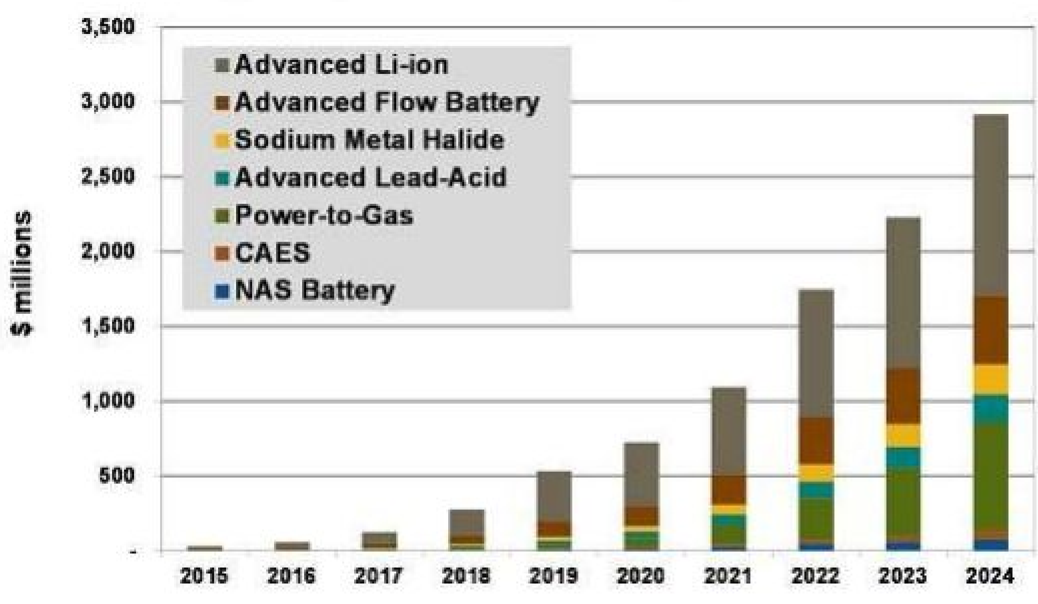


*Figure 15: Projected share of ES technologies used for the integration of wind and solar renewable energy. Source: InnoEnergy, 2017.*

The Clean Energy Package and the EU long-term strategy still lack information on how the objectives should be achieved (RES2; UTI1). There are also no specific targets for storage (DSO1; DSO2; EUR1; NAT1; OTH1). However, as storage is so closely connected to renewables, indirect targets can be deducted (NAT1; NAT2; RES2). Specific targets for storage for the sheer sake of more deployment would not make sense if there is no corresponding need in the energy system (DSO1; NAT2). In addition, anticipating on an integrated sectoral approach complicates establishing a detailed strategy. Therefore, targets for flexibility would make more sense (EUR1). Several respondents argue that there is a gradual shift towards more long-term thinking as the effects of climate change unfold (RES1; UTI1). However, many established players in the sector engage in storage merely for the sake of diversification (EUR2), to gain experience with the technologies even without the presence of a business case (UTI2). However, the regulatory uncertainty revolving storage makes it difficult for market players to deploy long-term projects (DSO2).

*Long-term outlook*

The need for ES in a future decarbonised electricity system is becoming increasingly clear (Deloitte, 2018; Denholm et al., 2010; EASE and EERA, 2017; EC, 2018; Taylor et al., 2013). In order to keep global warming under the projected 2°C, the IEA has estimated that the global ES capacity needs to increase from 140 GW[11] in 2014 to at least 450 GW in 2050 (IEA, 2014).

The previously mentioned EBA2050, while it largely focuses on EV batteries, still contributes to a long-term perspective of where the battery industry should move towards. or batteries specifically, the EU has, through the introduction of the EBA2050 programme, set expectations that the battery market will amount to up to 250 billion euros by 2025 (EC, 2019). Similarly, the SET-Plan, which is based on the EBA2050 framework, also contains (mostly research-related) targets for different storage technologies.

There is more activity in the field of, particularly battery, storage than initially meets the eye. Through the Clean Energy Package and several storage (research) initiatives, regulations, expectations and long-term perspectives are most definitely available to a certain extent. EU policy does in fact show a more proactive approach in terms of vision creation and long-term perspective than many of the respondents would argue. Admittedly, there does not seem to be as much detail on how, where and when storage would find a way into the grid. Yet, this has largely been attributed to the member states and is yet to be revealed in the coming years.

With absolute consensus, the respondents agreed that there was no shared vision of how ES should develop. There is, however, agreement on the fact that more storage will be needed in the future (GOV1; UTI1; UTI2). The question of how this should be achieved causes division between the stakeholders; which technologies, stationary storage vs. mobility, the sustainability of - most importantly - batteries, established players or new entrants, centralised vs. decentralised are among the divisive

[11] This figure gives an over-optimistic image of the current installed capacity. The vast majority (97%) of the installed capacity is pumped hydro storage. While this is perfectly feasible for longer duration flexibility, the technology is older and is being installed for decades. In addition, it has considerable geographic limitations. The uptake of new ES will mainly have to come from different technologies that can be installed more locally.

topics (EUR1). Moreover, there is no agreement within the energy sector, but also differences between different markets and players of certain technologies (DSO2; EUR1; UTI1; UTI2;). Actors have different focus areas, like either cost reductions or sustainability (BAT1). These differences are also caused by poor knowledge exchange. The role of batteries is slightly better aligned (BAT2; UTI2). With the plethora of stakeholder events that are organised, the lack of shared visions can prove challenging in directing resources and activities efficiently. Considering that lacking regulatory incentives are often considered a barrier in other SFs, unharmonised visions will only aggravate that problem.

*Standards*

Lack of standardisation is often named in combination with a better regulatory framework as essential conditions to stimulate ES markets (ECA, 2019; Energy Post, 2018; Energy Storage Forum, n.d.; NAT2; PV Tech, 2014; TSO1). In the US, there is already a uniform standard, but Europe has yet to catch up. Nearly all academic articles, reports and similar data is based on US initiatives. However, DNV GL, an independent consultant group and certification body, has tried to fill the gap in European standardisation by releasing the GRIDSTOR initiative, a set of recommended best practices. These recommended practices cover a broad range of energy storage technologies, instead of one or more battery types, have a system-level approach, instead of being limited to one or two key components, and have a comprehensive and structured approach (DNV GL, 2015). The fact that it covers a broad range of technologies is important, as only covering a select few technologies could further contribute to the aforementioned EU's limited storage focus (NAT2).

Before the Clean Energy Package, ES used to be considered a generation asset, while it is not; storage devices do not generate electricity but store it. Therefore, regulated entities, the DSOs and TSOs, were previously under no conditions allowed to own and operate storage. This debate about this classification has caused division between the regulated entities and the other stakeholders, particularly on the question of whether regulated entities should be allowed to own and operate storage (DSO1; TSO1; TSO2; UTI1). This question has eventually been resolved in the Clean Energy Package: regulated entities can, when there is a market failure, own and operate storage to use it for services merely intended for grid maintenance/improvement insofar they are "fully integrated network components".[12] Storage devices that are not fully integrated network components, are still forbidden. According to Article 40 of the Electricity Directive, TSOs are required to procure balancing services and non-frequency ancillary services.

The Clean Energy Package has introduced a definition of ES in Art. 2(47) of the Electricity Directive, and mandated ES to be incorporated into the network codes in Art. 55(1)(n) of the Electricity Regulation. These network codes are a detailed set of rules, standards and guidelines that determine the requirements of assets of the electricity system. The network codes are heavily influenced by ENTSO-E, the European TSO organisation, and the Agency for the Cooperation of Energy Regulators, the organisation for European energy regulators (EC, 2019). This development should encourage more standardisation, but its execution cannot be predicted. However, the institutions that are setting

[12] Art. 37 and 54 of the recently adopted Electricity Directive that states that - if there is a market failure - regulated entities can own and operate storage insofar it is an "fully integrated network component".

standards should be wary that standard-setting could favour certain ES technologies and create a lock-in of its own; safeguarding technology neutrality should be considered (NAT2).

Moreover, some interviewees argued that increased standardisation *between* ES products can enhance transparency for potential buyers and tendering parties to make it easier to compare technologies that meet their needs (NAT2; TSO1).

Furthermore, the Batteries Directive 2006/66/EC sets minimum recycling efficiency targets for battery technologies. Moreover, the European Commission has issued a stakeholder consultation on sustainability requirements for batteries in 2019, reflecting the interest of the EU to pursue a sustainability approach to battery technologies. This is consistent with the introduction of the EBA2050, which seeks to sets apart the European battery market by setting sustainability targets to oust the reign of short-term, unsustainable batteries from Asia (EUR1). Standard setting can prove to be a tool for competitiveness. However, so far the EU is lagging behind on standards.

*4.2.5 Market formation*

*Available markets*

Many interviewees indicated that there are positive market prospects for ES (BAT1; BAT2; DSO1; EUR2; RES1; TSO1; UTI2). Differences between countries will still be obvious, as markets in Germany, the UK and Ireland are pulling ahead; Germany's political commitment to form a market for storage and the UK's and Irish' geographical situation, being an energy island, explain the difference (EUR1; EUR2). The prospects for markets are confirmed by estimations by Bloomberg New Energy Finance, as depicted in Figure 16.

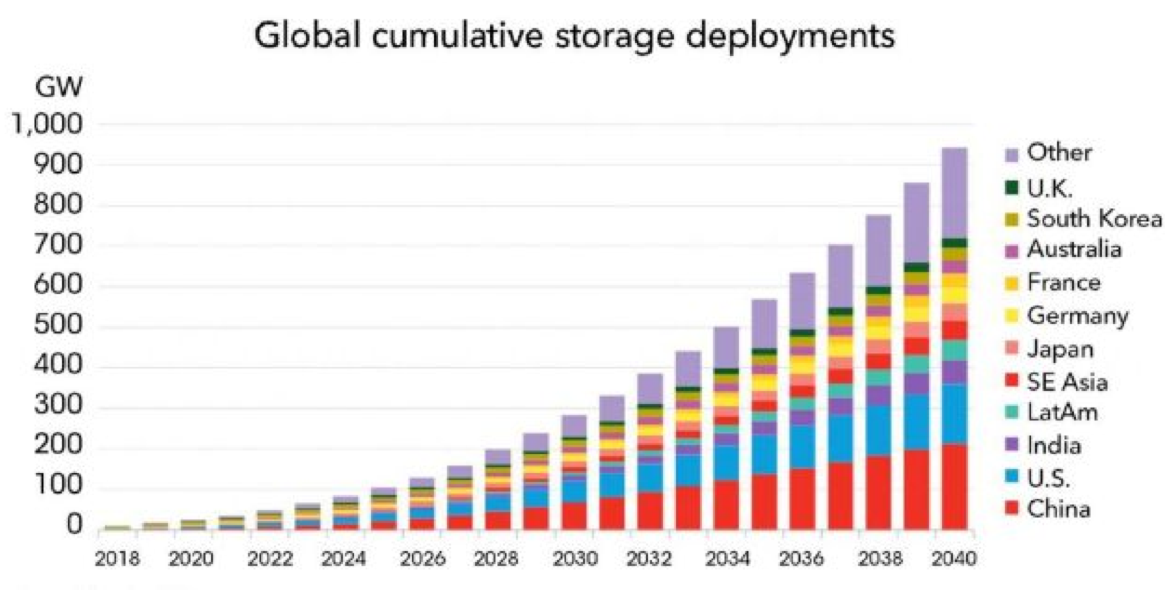


*Figure 16: Forecasted global cumulative storage deployments. Source: Bloomberg New Energy Finance (2018).*

There are not many places where there is much installed capacity apart from pumped hydro storage (GOV1; IRENA, 2017). Others argued that as the need for flexibility in the system will grow, rather than a market for storage, a market for flexibility can be formed; ES can be one of those technologies (RES2; TSO2). However, it is unclear whether it will be mostly stationary ES, or, for example, a mix of stationary and V2G technologies (RES1). Dissenting (minority) voices argue that the market prospects (at least in the short term) are meagre and depend entirely on climate scenarios (OTH1; OTH2). In addition, the regulatory uncertainty, that still has not fully been taken away by the Clean Energy Package, slows down investments (EUR1). The European Market Monitor on Energy Storage report by Delta-ee and EASE presents an accurate overview of growth per year, as displayed in Table 7.

*Table 7: Annual increase in ES installed capacity and market value. This includes all ES technologies. (f) stands for forecasted. Front-of-meter refers to storage devices placed directly in the transmission network. Source: Delta-ee & EASE (2019)*

| | | **2015** | **2016** | **2017** | **2018** | **2019 (f)** | **2020 (f)** |
|---|---|---|---|---|---|---|---|
| Annually installed capacity (in MWh and MW | Front-of-meter | 163.27 / 53.47 | 218.648 / 156.73 | 251.03 / 222.16 | 528.3 / 601.1 | 555 / 559 | 454.5 / 488 |
| | Commercial & Industrial | 0.5 / 0.45 | 11.5 / 19 | 41 / 33 | 153 / 122 | 211 / 171 | 250 / 202 |
| Annual added market value | Front-of-meter | € 187 m | € 207 m | € 230 m | € 485 m | € 455 m | € 363 m |
| | Commercial & Industrial | - | € 13.4 m | € 40 m | € 140 m | € 187 m | € 220 m |

It deserves mentioning that, as the year 2018 shows stronger growth than 2019 and 2020 in terms of added market value, some major capacity that was only expected in 2019 or 2020 has arrived earlier than expected (Delta-ee and EASE, 2019).

*Market policy*

The electricity market design, manifested in the updated Electricity Directive and the Electricity Regulation, comprise of the rules governing the market mechanisms. The market rules are now recognising storage explicitly as a technology to participate in the balancing market. This recognition was absent until the revision of the electricity market design.

It is notable that the new market design emphasises market-based solutions and creating a level playing field for ES (Delta-ee and EASE, 2019). According to Article 51 of the Electricity Regulation, a newly established European DSO network should facilitate the integration of ES in distribution networks. DSOs must be neutral market facilitators using market-based procurement procedures in which ES must be able to participate (Article 31(5) Electricity Directive). Furthermore, DSOs should be incentivised to procure flexibility services and standardisation. TSOs should take into account ES rather than system expansion (Article 51(3) of the Electricity Directive). However, long-term contracts are still only present to a limited extent. Article 5(9) of the Electricity Regulation states that at least 40% of contracts may be no longer than one day, and 60% up until one month unless the TSO requests the regulator to extend the contract up to a maximum of 12 months. Yet, this is not the long-term contract that many of the interviewees refer to. The European Commission has a strong preference for market solutions in the EU energy policy rationale (DSO1). Including long-term contracts would imply putting up a price-cap which would hinder market functioning. High prices caused by scarcity will also incentivise investments. The goal should just to provide a level playing field, and incentives are left to the market. Balancing of options (GOV1).

While there have most certainly been made gains in the new Clean Energy Package, it is still questionable whether it meets the concerns of the stakeholders involved. For instance, it is still widely considered by stakeholders that poor market mechanisms kill the business case (MAJ). The energy transition will most likely not happen without artificial support (BAT1; OTH2). While no additional funding might be needed, there are cries for an attractive investment framework (UTI1). Some argue that there is lacking policy support for ES because it conflicts with support for renewables (DSO2; EUR1); capacity markets for renewables disincentives efficient use of electricity and can make a lot of electricity go to waste (Ugarte et al., 2015). Adequate policy for storage might follow when it is better understood (NAT1). In addition, it often takes a long time to make market policy on a national level, which makes it hard to keep up with developments (NAT2).

While storage is mentioned several times throughout the Clean Energy Package, it is only considered to be a short-term service, while storage needs a longer-term perspective in order to generate revenues (OTH1). There are still no long-term contracts (EUR1); short-term procurement hurts deployment (OTH2). There is no framework for high-CAPEX technologies that will last for a long time, like many storage technologies (OTH1). In addition, stacking revenues from different services, which is difficult under current regulation, is essential for securing investments and fixing the business case (DSO2; OTH2; UTI1). Securing revenues is very difficult (OTH1). However, the business case might pick up as players realise it is a market-based framework (EUR1).

The question of ownership does not just create division in terms of vision, but is also hampering development from a market perspective. Market players argue that with ownership for regulated entities, they are not able to form a market (UTI1), whereas regulated entities are astonished by why they should not be able to use a product that can help execute their role. This division has been excellently resolved in the Electricity Directive.

*Competitiveness of ES as a flexibility provider*

The flexibility services that ES provides can also be offered by demand-side response, grid reinforcement or international grid interconnections, and flexible generation. However, all of these options work in vastly different ways and do not directly compete. Instead, they can complement each other well. Grid extension may in some cases be desirable, particularly with a larger share of wind energy compared to solar (Scharber et al., 2012), but generally, a combination of all flexibility providers will be most practical.

Despite the fact that ES cannot be easily compared in a financial sense to its flexibility "competition", costs are considered a major issue for ES (DSO1; DSO2). There is strong competition between different ES technologies, which carries the risk that it could cannibalise each other's share of the pie (UTI1). The markets for ES that exist now do not function very well, as poor market design still inhibits the business case (UTI1; NAT2). However, over the years the costs of different ES technologies have been decreasing. Lithium-ion batteries have experienced dramatic price drops (McKinsey, 2012). Figure 17 reflects the potential of additional cost reductions for several battery technologies.

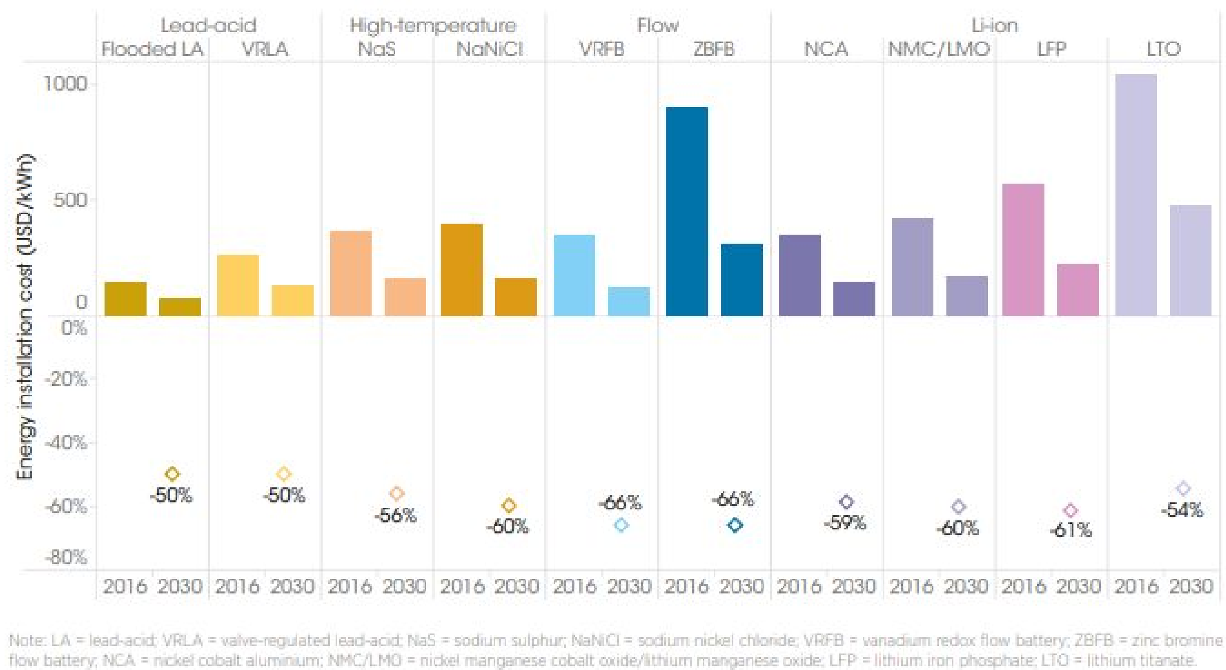


*Figure 17: Cost reduction potential of several battery technologies. Source: IRENA (2017)*

One of the main reasons for the perceived high costs of ES technologies is that much research focuses on the CAPEX, or investments costs. Measured in levelised costs of storage, "(...) the total lifetime cost of the investment in an electricity storage technology divided by its cumulative delivered electricity" (Schmidt et al., 2019, p. 82), are significantly more optimistic: these costs could drop by a third by 2030 and a half by 2050 (Schmidt et al., 2019).

An interviewee argued that if ES was actually competitive, there would have been more projects (TSO1). ES is often not competitive with conventional flexibility solutions like a standby diesel plant, but in that case, there is still an environmental trade-off to consider (NAT1). In addition, environmental policy is getting increasingly stringent. Moreover, some argue that ES is not very competitive at the time, but it shows confidence in becoming so in the future (OTH2; UTI2) and that the levelised costs of storage are sometimes cost-competitive with natural gas power plants already (RES1). There is agreement on the competitiveness of ES, but that depends on individual circumstances (DSO1; NAT1; NAT2; OTH1; RES1; TSO2; UTI1). It also depends on which application/service it involves and how other flexible technologies will develop (BAT1; BAT2; RES2). ES could be made more competitive by better integration with renewables (DSO1). Competitiveness of large-scale, stationary ES is also put at risk by technologies like V2G, and this might affect the storage market (TSO1).

In comparison, residential ES systems are also found to be unprofitable in many instances (Goebel et al., 2017; Schopfer et al., 2018). However, in contrast with large-scale ES, the business cases are much less complicated when used for increasing self-sufficiency and to deter having to purchase more expensive electricity from the grid (Baumgarte et al., 2019). The Dutch TSO TenneT has recently published a tool that determines the profitability of large-scale ES projects. As business case information is scarce and regulated entities have to rely on market players to develop storage devices, such tools are an excellent start into creating business models for large-scale ES. It does not increase the competitiveness of ES by itself but can take away investors disinformation or insecurity.

Ultimately, it should be up to the market to decide if ES technologies are going to play a major role (NAT2). ES could win if it is economically and technologically viable (TSO2), but there is currently no level playing field to find out (NAT2; Ugarte et al., 2015).

### *4.2.6 Resource mobilisation*

*Financial*

According to a European Parliament issued research, the annual storage investment needs in Europe will have to reach between 1.3 and 2.9 billion euros (Van Nuffel et al., 2017).

The EU funds a considerable amount of projects. Between 2014 and 2018, the EU's Horizon 2020 programme funded projects with a total of 1.34 billion euros for grid storage or low carbon mobility (ECA 2019). In 2019 alone, 114 million euros has been reserved for next-generation battery projects (INEA, 2019). Horizon Europe, the successor of Horizon 2020, launches in 2021. The European Commission has proposed to allocate 15 billion euros to the "Climate, energy and mobility" cluster, of which ES is explicitly named as a topic. It is unclear what share of this money will go to ES. However, in line with the general increase in Horizon funds and the increased attention for ES in EU policy, this amount is expected to go up. In contrast to many other storage projects, many of the Horizon projects between 2018 and 2020 are aimed at other technologies than lithium-ion and are specifically designated for stationary storage (EC, 2019).

Aggregate data on investments in all ES technologies hardly available. However, Figure 18 reveals the upward trend of investments in battery storage in Europe, particularly for large-scale storage.

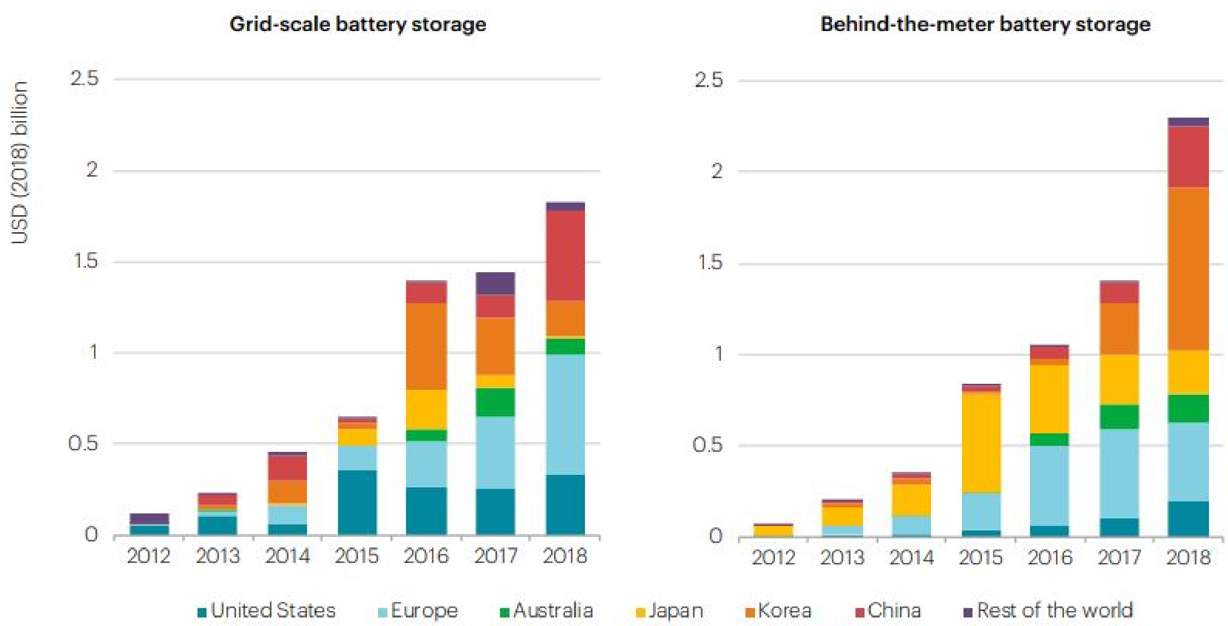


*Figure 18: Investments in battery storage. Source: IEA (2019).*

For hydrogen, investments are also experiencing an upward pattern. Private investments are increasing steadily by about 7% annually (Fuel Cell and Hydrogen Joint Undertaking, 2013), while public spending remains more or less constant. The latter point is illustrated in Figure 19.

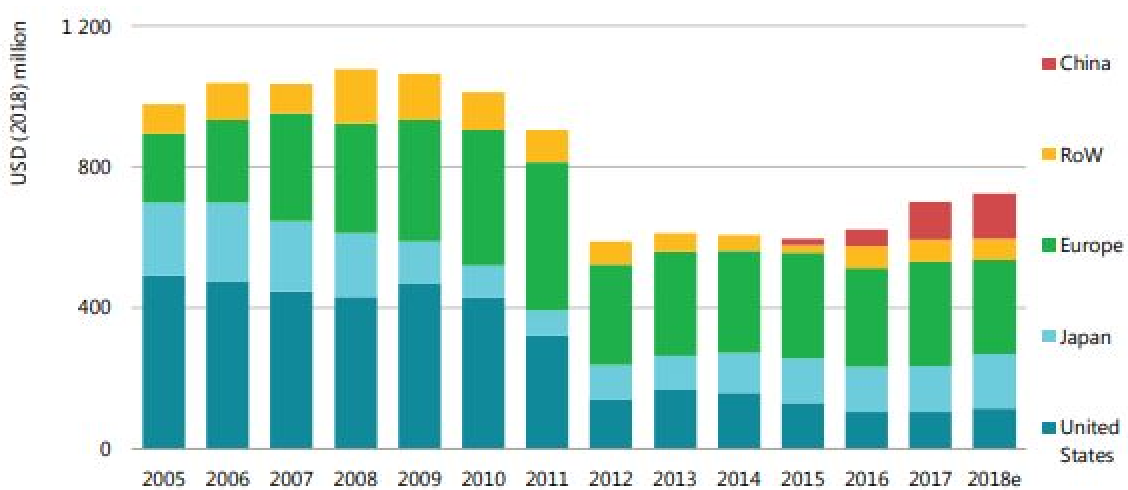


*Figure 19: Public R&D spending on hydrogen. Source: IEA (2018).*

Interviewees mostly responded in agreement. There is not a lack of interested investors (BAT2), but there is an unwillingness to make financial resources available (MAJ). There is not a lack of resources, but lack of revenue streams (EUR1; EUR2; OTH1; OTH2). The remuneration schemes and the regulatory framework are holding back the amount investors are willing to spend (NAT1; NAT2; RES2; UTI1; UTI2). ES is currently just too expensive (DSO1). There is no high return on investment (BAT2), so it is a risky business (EUR1; NAT2; OTH1). This deters investment. One interviewee argued that if the incentive to make the financial resources available would have been there, there would have been more projects (TSO1). The lack of investments is also exacerbated by the lack of a vision for storage (RES2).

Another specific regulatory constraint hindering ES investments is the conflict with capacity subsidies for renewables (DSO1). The favourable tax regimes also only apply to renewables and not to ES (OTH1). This disincentivises utilities or other organisations responsible for renewable generation to treat renewable electricity efficiently, as they will get compensated for their generation capacity rather than the electricity they provide.

*Human*

On human resources, results are divided. Many argue that human resources are not a barrier (BAT2; DSO1; EUR1; GOV1; OTH1; RES1; UTI1). Conversely, others argue that there is an incredible shortage of engineers (BAT1; NAT2; RES2; TSO1). Particularly the manufacturing side is lacking human resources, as it virtually is a missing link in the European chain (EUR1). The issue of finding a sufficient amount of engineers is not limited to ES (RES2). There will be a large demand for engineers that are not currently available (UTI2). Competition for recruiting engineers is so fierce, that it has been alleged to lead to cancellation of collaborations as storage engineers are often finding new jobs at the collaborative partners (NAT2). This might explain why the spread of human capital is unevenly divided; utilities possess far more human capital than regulated entities or regulators (OTH2). As demand for storage is projected to go up, the shortages may intensify.

However, in the Strategic Action Plan for Batteries, one of the major policy objectives is to develop a highly-skilled workforce (ECA, 2019). This is promising as it recognises the problem for batteries but offers little constellation to other ES technologies.

*Material*

In terms of raw materials and material resources, it depends very much on the technology (NAT2). However, the question is most relevant for batteries. The growth projection of batteries, combined with their specific appetite for material resources, are to blame. Battery materials, at least for lithium-ion batteries, are imported from outside of Europe, which might pose a problem (EUR1; RES2; UTI1). The availability of resources is strongly linked to the EV market. For large-scale storage, it depends very much on the market growth (also that in the EV market) and how well EV batteries can be recycled (RES1). Loads of batteries from EVs will become available that could potentially be repurposed (DSO1). Raw materials, therefore, could be a limiting factor for growth in batteries (BAT1; BAT2; NAT1). While it may not pose a significant barrier with the current market size, it will most likely be when the deployment rate takes up (NAT1; OTH2). It depends how gradual the growth will be (GOV1); a boom in the EV market might cause a material shortage in the short-term (UTI1). It is even argued that batteries in EVs will not make sense after 2030 because materials will be more difficult to source, so prices are likely to go up (BAT2). The Strategic Action Plan for Batteries also addresses the availability of and access to raw materials (ECA, 2019).

Additionally, the IT infrastructure is not developed well enough to integrate large-scale storage (TSO1). Simultaneously, Europe's grid is strong and has a lot of smart meters, which helps (EUR1). There is a lot of attention for reusing infrastructure, but not specifically for storage (RES1).

### *4.2.7 Legitimation*

The question of legitimacy is challenging as there are some contradictions that neither prove support or resistance. Some argue that there even is support in the electricity sector (TSO1; UTI1; UTI2), but that the support is mostly driven by the transport sector (UTI2). While supportive, there is still little enthusiasm to be very proactive with projects because it is still financially risky (BAT1; NAT2; TSO1).

Incentives like the EBA2050 demonstrate the direction of support the EU is headed (UTI2). In terms of lobbying power in favour of ES, there are several organisations that make a stand. Most notably EASE, who gather loads of information and communicate a lot to governments (GOV1). Both EASE and the industry are praised for being very good at lobbying in favour of ES (DSO1). Specifically for batteries, EUROBAT represents the battery manufacturing industry. Hydrogen Europe is the major hydrogen storage lobbyist. The International Bromine Council lobbies for bromine technologies, SmartEN for decentralised energy solutions; much of storage-related lobbying is niche. Looking at lobbying budgets, there is also a vast disparity between storage lobbying and conventional players in the power sector. According to Lobbyfacts[13], all these associations combined had a collective lobbying budget of €2 million in 2017. While this figure has increased significantly compared to earlier years, it still dwarves compared to the budgets of conventional sector players, which often have the same lobbying budget per company as all the storage-related associations combined. However, the latter does not say anything about the budget that is attributed to either helping or fighting storage, nor does it say anything about the effectiveness of lobbying activities.

In general, many argue that there is either no, or little resistance against the development of ES (BAT2; DSO1; GOV1; NAT1; NAT2; TSO1; UTI1). The few players that are resisting are primarily incumbent utilities that are trying to protect their markets, but this is not an usual phenomenon (BAT1; DSO2; EUR1; EUR2; OTH2; UTI1). Lobbying power in the electricity sector is strong and the urgency of storage is sometimes downplayed arguing that the European grid is strong; interconnection, which is indeed strong in Europe, competes with ES (RES2).

While storage finds relatively much support in the renewables and green niches, the conventional power sector is less convinced and is often led by outdated information (RES1). The conventional power sector is not embracing ES and thereby resisting. As Table 6 illustrates, the innovation readiness of the major ES technologies, including societal and consumer acceptance, are high. This means that the conventional power sector is most likely resisting ES out of the self-interest of protecting conventional markets rather than anything else.

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[13] LobbyFacts is a platform providing the essential data on lobbying in the European institutions. LobbyFacts provides handy tools to search, sort, compare and analyse official EU lobby data – from both present and past – to help journalists and researchers track lobbyists and their influence at the EU level that uses information from the EU Transparency Register (text adapted from the website www.lobbyfacts.eu).

It is noted that an increased amount of sector coupling, in which gas actors could start playing a role in electricity markets and vice versa, and technological synergies may reduce resistance from incumbents (EUR1). Consequently, the following lack of understanding of storage further diminishes the sense of urgency (NAT1; RES2). This lack of understanding also causes resistance (BAT2). In addition, one interviewee argued that the public sector itself to be resisting as it denies storage a lot of opportunities, or the sector itself as it focuses too much on the short-term (OTH1). Even the security services are mentioned, due to the environmental and fire hazards of certain battery types (NAT2). However, these claims find little support in desk research.

*4.2.8 External transition orientation*

*Landscape pressures*

The landscape pressures that fuel the main driver of change, the energy transition, must align with those relevant for ES. Grünewald et al. (2012) displayed the landscape pressures in the electricity system relevant to *distributed* ES in the UK, in Table 8. These landscape pressures have not altered, but the pressure from public perception and political will has intensified with stronger political and media attention for decarbonisation.

*Table 8: Landscape pressures that influence the ES system in the UK. Adopted from Grünewald et al. (2012).*

| Category | Origin of pressure | Relevance to EES |
|---|---|---|
| Public perception | Public awareness of climate change and willingness to accept and undertake changes in response. Brown-outs and black-outs as a result of increased network demands shift willingness to accept additional measures | Selection of storage technologies that directly interfere with the public, especially relating to visual impact, perceived health and safety concerns and spatial impact; potential to mitigate impact on the public as a result of deep de-carbonisation (such as additional transmission lines or plant capacity) |
| Political will | Government commitments to meet national and international targets for emissions reductions and promotion of low carbon energy sources | Strong impact on the key rationale for the need for storage |
| Market structure | Ideological commitments to liberalised energy markets | Challenge of valuing common good characteristics of storage |
| Energy security | Concerns over security of primary energy supplies, external factors leading to high oil and gas prices | Greater storage capacities with long time constants to provide reserve |
| Affordability | Concerns about energy affordability and fuel poverty | Requires strategic investment and operating strategy to reduce system costs with a mechanism to pass on savings to consumers |
| Supply security | Factors which threaten physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.) | Requires large storage capacity and capacity held in reserve |
| Financial | Changes in the international economic and financial situation | Capital intensive long term investments critically depend on affordable finance |

Much of the content of Table 8 is equally relevant in the EU scope. In terms of public perception, ES technologies indeed pose fewer visual objections than grid extension. However, one interviewee argued that in the Netherlands, security services are hesitant at embracing batteries due to the risk of chemical fires (NAT2). While far from perfect, the political will is becoming increasingly present, as the results of section 4.2.4 also reveal. The EU has committed itself to deep decarbonisation and the role of storage therein is recognised to the extent that it is included in energy policy. In terms of energy and supply security, ES in combination with renewables provides the tools to step away from imported fossil fuels while allowing constant access to supply. However, if the focus on lithium-ion will continue, potential shortages in materials may jeopardise security of supply, as the required metals are both finite and imported. Affordability and financial concerns are of course essential as well. Long-term thinking in business culture, however, is on the rise (UTI1).

As Grünewald et al. (2012) established, there is an ideological commitment to the liberalised energy market. While initially designed to make the electricity system more competitive and reduce prices, the developments the sector has seen since the energy transition has incepted are considerable enough to reevaluate that ideological position. The challenges of a liberalised electricity industry are not unknown, most notably the need for sufficient generation capacity to stimulate competition, as low capacity pushes prices up (Newberry, 2002). It has already been argued that "Ensuring adequate capacity and contestable entry without the normal pattern of long-period commodity price swings needs good long-term contracts, possibly combined with capacity payments" (Newberry, 2002, p. 926). As this research has found, this assessment clearly poses a challenge for the energy transition. First of all, such long-term contracts are lacking. Secondly, incentive schemes for renewables are negatively affecting ES. Moreover, "capacity" is no longer equivalent to centralised generating capacity alone. Capacity in the age of the energy transition refers to the ability to provide clean energy, which requires more than raw electricity generation by wind turbines or solar panels: it requires flexible capacity as well for its integration.

In addition, the lacking business case of ES is a recurring barrier for most SFs. This is starting to change for renewables, which are progressively getting more competitive with fossil generation. However, storage is dependent on renewables, and renewables still rely on policies and subsidies for the greatest part, which makes competition with fossil fuels a difficult choice for the financially-oriented business (OTH2). One interviewee argued that a liberalised electricity market has created the conception that electricity is a market rather than a public good (OTH1). The public good character of electricity as an essential need for society is also fiercely exacerbated by the public good character of what happens when the effects of climate change are not mitigated. State-controlled electricity markets may or may not provide cheaper electricity, but it could surely alleviate some of the challenges in the market design, of which the right to own and operate storage is a prime example.

A liberalised or monopolised electricity system design is an ideological choice and discussing which is best belongs to the economic realm. Still, as sections 4.2.4 and 4.2.5 have shown, the liberalised electricity market so far is not working well for ES. It is very unlikely that the liberalised electricity market will cease to exist and it is perhaps also not desirable, but the EU may have to pay extra attention to the weaknesses of their ideological choice in the upcoming gas market design revision and other future legislation.

The interviewees were clear in how the role of ES in the energy transition should be articulated. However, the view of the storage niche, even present within conventional firms, does not necessarily reflect the view of the whole sector (RES1), as emphasised in section 4.2.7. Nevertheless, the opportunities of ES in the energy transition are generally recognised (DSO1; DSO2; EUR1; TSO1; UTI1; UTI2), but there is not always a sense of how to materialise it (TSO1; UTI1). Not all advantages of ES, e.g. grid stabilisation, are fully understood (BAT2; NAT1; NAT2). A definition of *energy storage* in the Clean Energy Package is already a step in the right direction (OTH2).

When looking at the individual landscape factors, the system actors are responding taking advantage of them. However, the visual element of public perception is not a regular argument in favour of storage. The political will is becoming increasingly evident, as the importance of storage is not only recognised, but ES has found its way into policy. In terms of energy security, the installed capacity is growing significantly every year. Affordability is pursued, through sector coupling and stakeholder consortia like the ETIP SNET, by a holistic, more cost-effective energy transition approach rather than silo-thinking. Supply security is one of the main pillars of the European energy transition, and storage fits well into that goal (Azzuni and Breyer, 2018). Enabling supply security is propagated as one of the main arguments for ES. On the financial side, solutions need to be found for long-term investments scheme and the recognition of the common good characteristic of storage. For the latter, EASE has proposed the "Multi-service business case", in which several services can be provided with one storage device, easing the financial investment burden of CAPEX-intensive storage devices. However, it is up to the legislators to enact market design rules that enable ES technologies.

*Regime change*

In terms of changes in the status quo, the energy transition is based on three pillars: decarbonisation, digitisation and decentralisation (Di Silvestre et al., 2018). The electricity regime must, therefore, change accordingly. As displayed in Figure 20, ES touches on the sub-regimes of generation & supply, network and consumption simultaneously (Grünewald et al., 2012). Therefore, these sub-regimes need to change for storage to find its way into the energy transition.

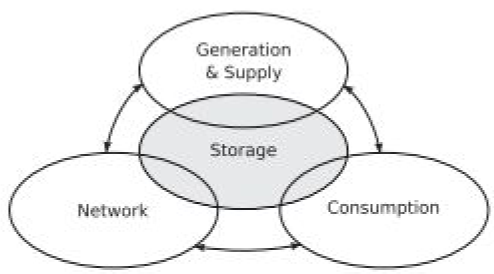


*Figure 20: Sub-regimes in the electricity system that are relevant to distributed ES. Adopted from Grünewald et al. (2012).*

According to interviewees, ES is not considered to be the driving force behind the destabilisation of the current regime. Instead, renewables are driving regime change (DSO2; TSO1; TSO2); ES is one of the solutions that *enable* radical change (BAT1; DSO2; NAT2; TSO2). It has been argued that ES technologies do have the potential to disrupt current electricity regimes (Winfield et al., 2018). Yet, it considered more often that ES will not be a motive force behind the energy transition, but instead can decide the fate of alternative energy transition pathways (Taylor et al., 2013).

Some argue that ES, at least battery storage and hydrogen, can disrupt the transport sector more fundamentally than the electricity sector (UTI2). Nevertheless, whether ES is the motive force or not, the electricity regime needs to change regardless. In addition, regulated entities in some member states are introducing smart tariffs to incorporate the disruptive changes in the other sub-regimes (DSO1).

European energy policy and regulation is still based on old the paradigm (BAT1; BAT2; DSO2; EUR1; NAT2; OTH2; TSO1), but eventually, that whole paradigm will shift (EUR2; RES2). Policy instruments that change economic incentives, e.g. tax incentives and consumption quotas, can put pressure on existing regimes (Kemp and Grin 2009; Turnheim and Geel, 2012). There are no such favourable tax incentives or consumption quotas for ES technologies, even under the new Clean Energy Package.

Tax incentives, feed-in-tariffs, feed-in-premiums, quotas and tenders, however, do exist for renewables, albeit on the national level. Still, member states are in principle free to choose what kind of incentives they operate, as long as they are in line with the “Guidelines on State aid for environmental protection and energy 2014-2020” (The Council of European Energy Regulators, 2018). This leaves open the possibility for member states to set up supportive incentives for ES. Consumption quotas for renewables are clearly codified on the European level in the Clean Energy Package; there are tight targets for mandatory shares of renewables in the REDII.

Consequently, regime change is pursued for renewables and not directly for ES. This means that renewables are mainly responsible for weakening the existing regime. It also means that the paradigms of the regime are shifting, regardless of whether this is caused by ES; it offers an opportunity for technologies with a “network effect” that fit into the system architecture (Taylor et al., 2013). Despite some policy incoherence between different elements of the energy transition, ES fits within a decarbonised system architecture and thus is benefitted by regime change pushed by the renewable sector. This helps explain why many of the actors active ES are also pushing for more renewables.

ETIP SNET, which focuses on many aspects of the energy transition and has a working group on ES, has some of the same actors participating in other, non-ES working groups. All sub-regimes of “Generation & Supply”, “Network” and “Consumption” of Figure 20 are covered in ETIP SNET and participated in by actors that are also relevant to storage. However, there is still a strong lobby against radical changes (RES2), mainly by utilities that seek to protect their conventional markets; utilities also participate in these stakeholder groups, which may affect the rate of regime-destabilising activity in favour of storage. Nevertheless, it is likely that the system will move towards embedded storage (DSO1; NAT1). While the pace in which regime-destructing action is taking place could be much better, particularly with the focus on ES, the status quo is clearly shifting (OTH2; RES1).

Ultimately, costs are driving the transition, favouring economies of scale (UTI2). Renewables are also created at a larger, centralised scale. The centralised nature of the electricity system is therefore not changing entirely (TSO2). Incumbents will most likely still exist, albeit in an altered role (EUR1). In addition, change will most likely be gradual (GOV1). This means that where home storage systems and V2G technologies challenge the system’s paradigms to a stronger extent, large-scale storage may synergise better with gradual, moderate changes in the electricity regime.

*ES and intersectoral interactions*

It is repeatedly stated by interviewees that developments in technological understanding as well as costs, primarily of batteries, are strongly related to developments of automotive batteries (DSO1; RES1). While differences between EV and stationary batteries are observed (OTH1), closer integration between sectors can reduce total system costs while yielding added societal benefits. More concretely for the energy sectors and other areas heavily affected by climate action, sector coupling can provide a new paradigm that contributes to achieving the Paris targets. However, it is noted that capacity remuneration schemes for renewables on a national level disincentivise the search for synergies with ES technologies (EUR1). Renewable generators get paid for their potential generation capacity irrespective of the demand in the electricity grid to take away the uncertainty of securing revenues. Generators of renewable electricity, therefore, lack a financial stimulus to treat electricity in an efficient manner by storing it. This is a clear example of an outdated silo-approach between different segments of the energy transition that needs more integration by holistic policy.

Four building blocks of sector coupling can be identified: infrastructure planning; system and market operation; regulatory framework; and research, development, demonstration and deployment. Most notably, further integration of the gas and electricity markets is often considered to be of interest for ES; P2X technologies lie on the interface between gas and electricity (Olczak and Piebalgs, 2018). These technologies qualify as ES, but its outputs can be used for heating, electricity and transport. V2G technologies link the electricity and transport sector (UTI1), even if it the vast majority of effort comes from the transport sector and the electricity sector is not putting in the effort (UTI2). The development of technologies like V2G, even when originating mostly from the transport sector, still showcases opportunities and can help contribute to decarbonisation in the electricity sector just like ES does. While from a transition perspective sector coupling is desirable as it can decrease system costs by up to 28%, it also has the potential to decrease the business case of large-scale, stationary ES almost entirely (Brown et al., 2018).

Through several stakeholder consortia and even in governmental programmes, the term sector coupling is either recognised or being looked into by system actors. A SET-Plan stakeholder dialogue document for an integrated approach has an objective which reads: “Unlocking the potential of energy storage and conversion of electricity to other energy carriers” (Joint Research Centre to the European Commission, 2014). Having already been published back in 2014, this objective lays out a vision in how P2X technologies could benefit the electricity sector while increasing its applications far beyond electricity. Currently, the European Commission is preparing a new package of gas legislation, which is likely to be published in early 2020. This will include definitions related to P2X technologies such as definitions for blue and green hydrogen, which is of tantamount importance for establishing the sustainability of these technologies. This research is also looking into using current gas infrastructure.

At the request of the European institutions, research has been conducted into how sector coupling can enhance grid stability and flexibility. More specialised policy research is being conducted as well, which will be published late 2019 (GOV1). The interviewee from the European Commission recognises the need for a holistic approach and expects players in the gas and electricity markets to overlap (GOV1). The EU institutions are actively looking into the possibilities of holistic, cross-sectoral policies, which is a promising step. The last Madrid Forum in June 2019, the European Gas Regulatory Forum, has focussed on new technologies, like P2X, and upgrading current infrastructures to incorporate new gases like hydrogen (Delta-ee and EASE, 2019). Just like with V2G technologies, such developments with sectoral overlaps are increasingly on the stakeholder forum agenda. Even in its main regulation, the EU has carefully mentioned linking sectors: Article 25 of the REDII calls for more ES as a link between the electricity and mobility sectors.

Interviewees were moderately positive on synergies. In combination with renewables, it is often considered as relatively well understood (TSO1; TSO2; UTI1; UTI2). A lot is being done in terms of system integration (BAT2; RES1). In general, there is increasing attention between industry and governmental players for cross-technology and cross-sectoral interactions, but these collaborations have room for improvement both in quality and quantity (DSO1; NAT1; NAT2; RES2). Still, it is expected that more sector collaborations will be made in the future (UTI1). Conversely, dissenting voices point to an overly inward orientation (BAT1; OTH1), but a majority of interviewees is more positive. In conclusion, there is increasing attention for sector coupling and attempts are being made throughout the system to establish more connections.

*4.2.9 Summary functional analysis*

As discussed in the methodology, the final SF scores were calculated as a combination of interviewee grades and the researcher's interpretation. This lead to the final scores as depicted in Figure 21.

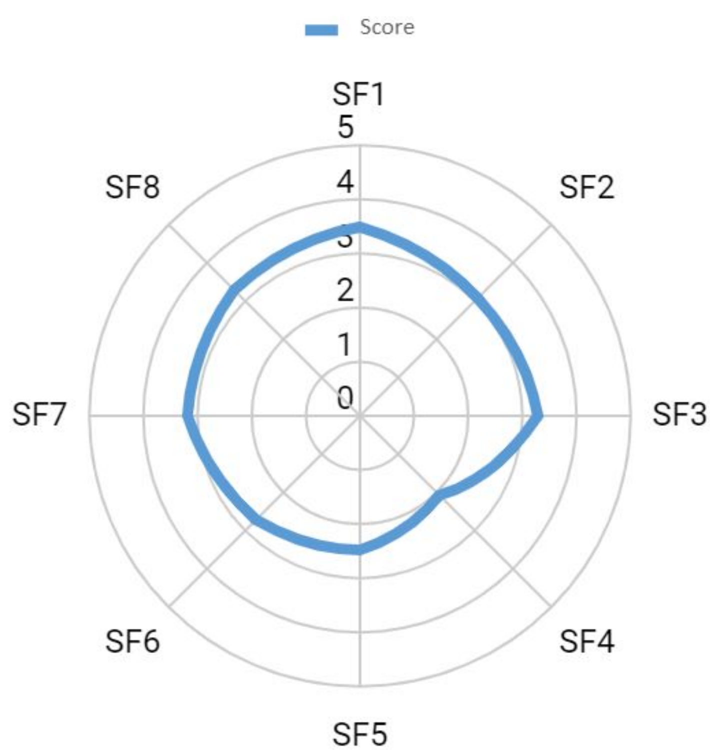


*Figure 21: The final SF scores.*

It can be observed that all SFs are performing between 2,1 and 3,5, which is a small margin. There were discrepancies between the researcher's interpretation and the scores assigned by the interviewees. The in-depth score sheet as used in this research is attached in Appendix V. The score calculations have been added as Appendix IV. However, it is clear that Guidance of the Search and Market Formation, and to a lesser extent Resource Mobilisation, are the weakest SFs.

### 4.3 Barriers

In addition to the functional questions of the interview, the interviewees were also asked directly what they considered to be the biggest barriers. Quite remarkably, they were almost unanimous in expressing the most pressing barriers. Costs, the lack of a business case, regulation built on an outdated paradigm, lack of being able to secure revenues, lack of awareness of technological possibilities and the lack of a long-term perspective are identified with an overwhelming majority as the biggest barriers. Secondly, the state of technology was the only barrier that was also named by more than one actor (GOV1; TSO1). Unsurprisingly, those barriers align well with the conclusions from the structural-functional analysis and translate to poor performing SF4 and SF5.

However, more barriers were identified. It leads to a set of twenty-five barriers, which are all depicted in Table 9. The table includes their interconnected causes, if applicable. Table 9 is a direct result of the conclusions from the interviews and the structural-functional analysis.

*Table 9: The barriers and interconnected causes.*

| System function | Barriers | Interconnections |
|---|---|---|
| SF1: Entrepreneurial activities | Too few projects as regulatory constraints hinder the business case | SF4; SF5 |
| | Lack of competitive European battery manufacturing industry | SF2; SF4 |
| | Market entry barrier for storage services for smaller players | SF5; SF6 |
| SF2: Knowledge development | Too little R&D activity due to lacking investment incentives and regulatory uncertainty | SF4; SF5; SF6 |
| | R&D activity too focused on batteries | SF4 |
| SF3: Knowledge exchange | Information not widely dispersed amongst laggards, policymakers and regulated entities | SF7 |
| | Lacking information exchange on competition- sensitive financial information | x |
| | Fragmentation of information | x |

| | | |
|---|---|---|
| SF4: Guidance of the search | Lack of shared visions among different stakeholders on future dominant technologies and rollout plans | x |
| | Poor long-term thinking in business, not encouraged by market design | SF5 |
| | Weak concept of technology neutrality: focus on lithium-ion and hydrogen | x |
| | Lack of detailed strategy for the implementation of ES | SF3; SF8 |
| SF5: Market formation | Electricity market design lacks price signals | x |
| | The CAPEX costs are too high to be competitive | x |
| | No level playing field for competitive storage due to market design | SF3 |
| SF6: Resource mobilisation | Too little investment due to unattractive regulatory conditions discouraging investments | SF4; SF5 |
| | Lack of qualified engineers | x |
| | Lack of future raw materials for lithium-ion batteries hinders growth prospects | x |
| SF7: Legitimation | Lack of lobbying power compared to conventional sector | x |
| | Niche status; ES not fully accepted by the entire sector as it is not understood and conventional markets are protected | SF3 |
| SF8: External transition orientation | Liberalised electricity markets without access to affordable finance complicate funding | x |
| | Lack of initiative from electricity stakeholders for cost-effective synergies with other TIS | SF1; SF4 |
| | Regulation is based on the old paradigm; no radical shakeup of the regime | SF4; SF5 |

## 4.4 Interconnections

As this chapter has outlined, many of the causes underlying the systemic barriers have their roots in other SFs. Figure 22 depicts the interconnections in a graphical form.

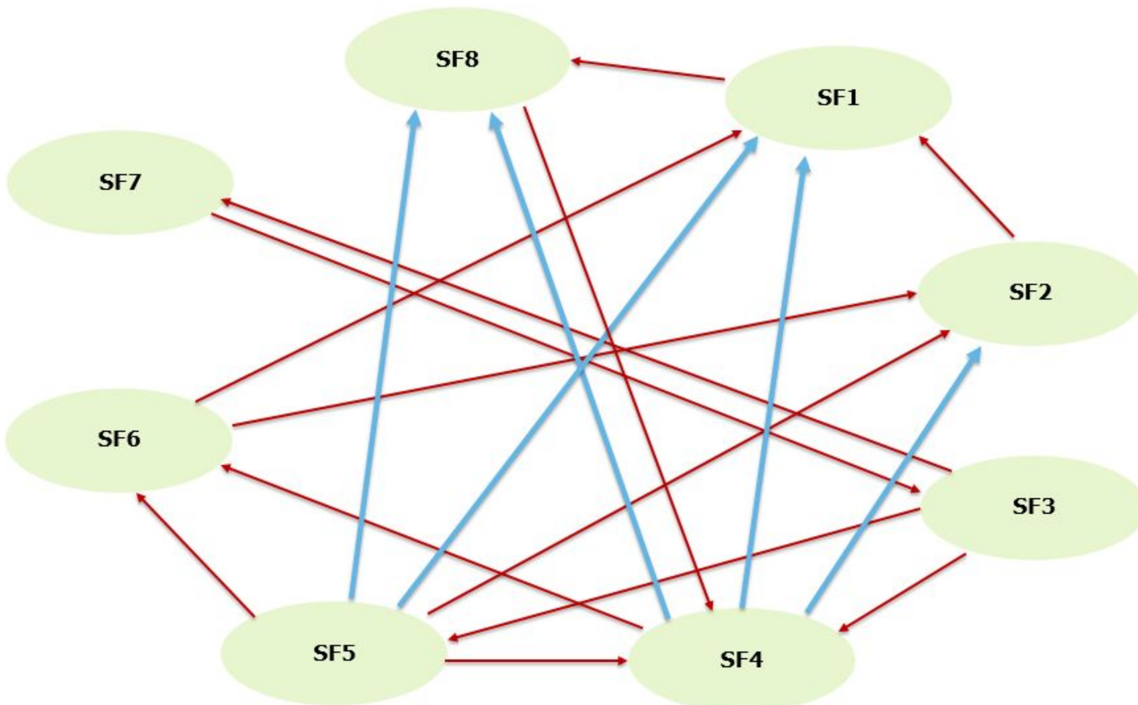


*Figure 22: The interconnections found in the results. A red arrow represents an interconnection of one barrier, a blue arrow of two barriers.*

As is clearly evident, many systemic problems have their roots in systemic problems from different SFs. More specifically, the lack of detailed visions and strategies from SF4, and the incompatible market design from SF5 are the main contributors. To a lesser extent, poor information flows between stakeholders from SF3 also contributes to the poor performance of other SFs. The data behind Figure 22 is added as Appendix VI.

The lacking business case is one of the major challenges of the system. The fact that there are too few projects (SF1), the market entry barrier for smaller players (SF1), mediocre R&D activity (SF2), and the unwillingness to invest in ES (SF6) are all attributable to the lacking business case. Projects are not being launched without prospects of remuneration. Smaller players cannot fully enter the market because storage is CAPEX-intensive and without the possibility to make money, financial reserves are needed to stay afloat (OTH1). Smaller players often do not have this luxury, which is why the market is dominated by larger players. R&D activity is also slowed down by pessimistic prospects of ES; R&D activity is ordinarily rewarded by prospective financial gains. From the investor point of view, it is perhaps most evident why the poor business case is a dealbreaker; investments need to be justified in terms of a certain payback time, which is difficult to establish for ES.

The lacking business case, in turn, is caused by regulatory uncertainty and poor market design, pointing towards SF4 and SF5. However, these barriers are exacerbated by bad information exchanges towards policymakers and, to a lesser extent, regulated entities. Those responsible for making the rules and setting the standards are not presented with the information necessary to formulate policy that takes into account the technical and operational complexities of storage. This is echoed by many interviewees who suggest educating policymakers should be a first step (BAT2; NAT1).

This research reveals that a few barriers are effectively slowing down the entire system. Attempting to address malfunctioning SF2 by linear TIS policy would, therefore, have little use before its underlying systemic causes are addressed. Rather, priority should be given to alleviate the barriers of SF4 and SF5 and see what the effects on the entire system will be before proceeding to target the other SFs. Insecurity about policy/market prospects is discouraging market players to spend more money on R&D, not a hypothetical lack of financial support from governments. Increasing subsidies and/or grants would be an ineffective policy choice. Instead, R&D spending can most likely be stimulated by announcing brighter prospects for ES. Policy interventions should be designed accordingly.

# 5. Discussion

In this section the results will be critically discussed, adequate policy instruments will be proposed, and the limitations of this research are outlined.

## 5.1 Policy recommendations

As discussed extensively in previous sections, this research formulates a set of policy instruments that are likely to be the most effective, rather than provide all possible suggestions. Furthermore, it is important to note that the fact that a proposed policy instrument may very well yield its envisioned result, it most certainly does not mean that such a policy intervention is either feasible or justified in the greater scheme of things (Markard et al., 2015). The EU could play a role in nearly all aspects of the development of ES, but there are some that consider this neither necessary or desirable (DSO1). Interviewees from DSOs, TSOs and utilities, while having different interests, were often in agreement that policy intervention was not justified and it should be left to market forces. In addition, challenges in the markets, e.g. lacking remuneration, investment and thus a poor business, do not automatically constitute a societal issue (DSO1). A market challenge could constitute a societal challenge, but this assessment should be heavily scrutinised before policy interventions. In recent years, the EU has explicitly articulated the importance of ES in the energy transition. This could be interpreted as recognising supportive ES policy as societally relevant, thus justifying policy intervention.

Interviewees are divided on the topic of justifying policy intervention. Some interviewees argued that public financial assistance may be appropriate as ES is fundamentally important and investment certainty is needed (OTH2; RES2). Others suggest that it should be left to the market to find cost-efficient solutions. Utilities are favouring market approaches, which is unsurprising considering their stakes in preserving the status quo. However, regulated entities are also reticent on policy interventions. This means that it is not just financial interests that are withholding support for policy interventions. It further strengthens the rationale for limiting policy recommendations to the most pressing barriers in the system.

The research of Grünewald et al. (2012) echoes that many actors prefer to leave it up to the markets to resolve barriers. Nevertheless, as the results section has clearly indicated, SF4 and SF5 are most in need of improvement. The case for policy intervention in these SFs increases further when incorporating the implications of the interconnections; improvement of SF4 and SF5 will most likely benefit most other SFs.

Interviewees were also asked to give policy recommendations to overcome the barriers they identified. Interviewees often suggested i.a. formulating vision documents, decreasing regulatory uncertainty, and increasing market (remuneration) mechanisms for addressing a wide variety of barriers in other SFs, e.g. for the lack of projects. This means that interviewees suggested addressing the barriers in SF4 and SF5 rather than proposing policy that would directly intervene the barrier at hand. While this is an unconventional approach, it contributed to the establishment of the interconnections. Once the interconnections had been established, the interviewee suggestions for policy recommendations further increased the understanding of how to design the limited number of policy recommendations in such a way that they influence the entire system the most. Appendix VII contains the results of the policy suggestions made by the interviewees.

*A more specific and quantified, strategic vision*

A recurring, underlying obstacle, indicated by interviewees, of all system failures, flows from lack of quantification; visions are not expressed in enough quantified detail, just as many of the targets in regulations. The EU Long-term Strategy could be supplemented with more quantitative detail, with very specific targets and pathways (EUR1; NAT2; RES1; RES2; TSO1). This is in line with the trend towards mission-oriented innovation policy that is gradually finding its way in the EU. Mission-oriented innovation policy focuses on wide societal relevance, clear and measurable direction, ambitious research and innovation actions, bottom-up solutions and cross-sectoral, cross-disciplinary and cross-actor innovations (Mazzucato, 2019).

In the United States, such targets have already helped (DSO2; TSO1; UTI2). The EU Long-term Strategy could also be extended with an investment roadmap for decarbonisation in 2050; there is a precedent for such a concept under the banner of reaching a societal goal, as the capital-intensive nuclear energy industry in its early stages required longer-term investments as well (OTH1). There should be a comprehensive evaluation of all flexibility options (OTH2), including the costs perspective; how much do different options (centralised vs. decentralised etc.) cost (TSO1)? This should include in-depth viability assessments of all ES technologies. Such a vision document, ideally created by regulated entities as they are most aware of the system's needs (OTH2; TSO1), would take away a lot of the uncertainty that actors are experiencing. This suggests a greater leadership role for DSOs and TSOs.

Creating direction in the development of ES sends a clear long-term signal to the sector (GOV1). Setting more quantified, strategic targets indicates that ES will play a critical role in the future electricity system, and therefore give investors more certainty of the prospects of these technologies in the long run. Therefore, it is likely to benefit the number of investments in ES altogether, as well as stimulating cross-sectoral initiatives and R&D activity. In addition, it may help to steer away from short-term thinking in business.

*Financial signals in market design*

Policy would need to focus on securing longer-term revenue streams in order to secure a business case for ES. Short- and long-term objectives should be reconciled (OTH2). More coordination on a European level helps to speed up the adoption of national market policies for ES, as energy policy usually takes long to devise (NAT2).

Difficulties in generating sufficient revenues are one of the major struggles; the inadequate solution to providing long-term contracts in the balancing services markets is still problematic to guarantee long-term revenues for ES. Clearer price signals and revenue stacking should be made possible. The electricity market design also does not allow for the efficient use of storage devices by allowing for several different services to be used simultaneously (European Academies' Science Advisory Council, 2017). A solution could be provided by the previously mentioned "Multi-service business case". In addition, tools developed by regulated entities to assist with determining the business case of large-scale ES projects is a helpful way to create more transparency and security for investors.

Creating financial signals will most likely lead to more investments in storage, more projects, and reduce or take away the market entry barrier for smaller players, as better remuneration prospects increase the business case significantly. It will also help in steering away from short-term thinking in business and increasing R&D activity.

*Level playing field and standardisation in the market*

Furthermore, the existing ancillary services should be rethought to take advantage of fast, new storage technologies (CIGRE, 2018; EUR2). While this is already promoted in the Electricity Directive, it is yet to be seen if this will happen in a harmonised way. TSOs could provide technological and market standards to promote further integration (ENTSO-E, 2016). Addressing this issue will help provide a level playing field in the market, which will not favour one technology. Admittedly, ES is not formally discriminated against in the current market design. However, the requirements necessary to participate in the markets are built around a paradigm in which ES does not fit, effectively making it harder to compete. In addition, policy support and market conditions should be harmonised as much as possible in member states, even if that is challenging (EUR2; NAT2).

Creating a level playing field and standardisation in the market may, once again, improve the business case and thereby particularly take away the market entry barrier for smaller players, as well as stimulate investments and projects in ES.

*Educate policymakers*

Policymakers are not properly informed, despite the existence of many exchange platforms. Measuring the quality of knowledge exchange is challenging, but in this case it becomes clear that the quality and the fragmentation of information flows hinders proper education of policymakers.

In order to make these recommendations feasible, policymakers need to be educated on ES first, after which better policy can follow (BAT2; NAT1). An increased leadership role for regulated entities would, first and foremost, imply that they too are fully educated on ES and its implications for the grid, as they currently are not leaders in terms of knowledge (OTH2). Accordingly, education/knowledge exchange channels should be strengthened in which policymakers, regulated entities and ES experts exchange information on how policy can address the challenges of the system. .

Figure 23 illustrates the overall impact of the given policy recommendations on the system, and what effects would take place.

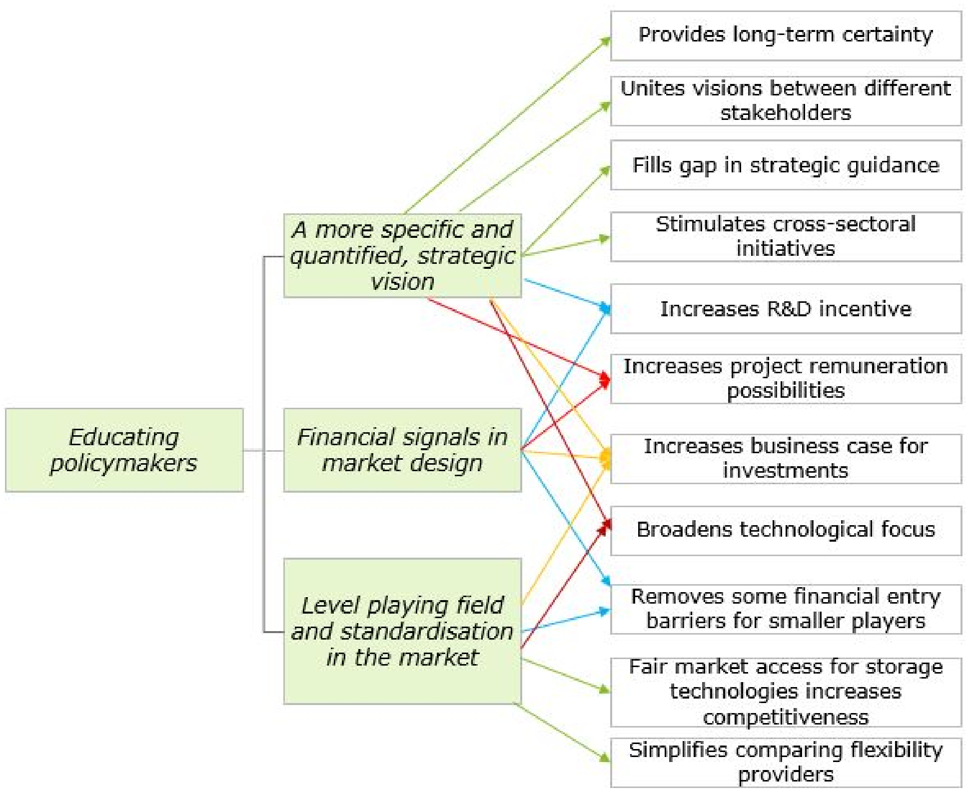


*Figure 23: Expected effects of the policy recommendations.*

## 5.2 Evaluation of results

The research question entailed identifying the barriers to the development of large-scale, stationary ES in the EU. This question has been answered by identifying the poorly performing SFs, finding what causes these performances, and subsequently giving appropriate policy recommendations on the most effective intervention points. The system showed many interconnected barriers.

Even though one of the main findings of this research is that there should be more long-term certainty for ES, stakeholder behaviour and expectations are not reflective of this barrier. In spite of lacking regulatory guidance and market conditions, there are plenty of actors willing to engage in storage. In addition, nearly all interviewees were positive on the market prospects, despite complaints about the paralysing effect of poor financial incentives. Consequently, the poor performance of SF5 is attributable to the sub-elements of the market design and the high costs, not the available markets. The barriers deriving from SF5 are therefore implicitly *supply-side* barriers and have little to do with demand for the services that ES can provide. This assertion is important as it confirms the direction of the policy recommendations, which focus on stimulating supply.

From a strategic angle, the focus on a few ES technologies has several implications. Firstly, strong positive signals for one or several "winning" technologies may be justified, but also risk leading to a self-fulfilling prophecy. More signals for, e.g. lithium-ion, storage may further steer investments and research focus as subsidies or certain market setups may favour the chosen technologies over others, creating a lock-in for the chosen ES technologies (NAT2). Secondly, security of supply and energy independence are main pillars of the EU's energy transition policy. As the vast majority of fossil fuels are imported from outside of the EU, it is understandable to seek more independence. However, batteries still require large amounts of elements, e.g. lithium and cobalt, which are also imported. Some of these elements, ironically, would have to be imported from China, which increases rather than decreases the dependence on resource-based diplomacy. Recycling batteries is challenging and academic research on the matter is in its early stages (Li et al., 2010). Moreover, hydrogen from P2X, when generated from water electrolysis from renewable energy would suit that purpose, but not when extracted from natural gas, as the majority of natural gas is imported from another geopolitical liability.

Policy incoherence can be identified within the market-based policy rationale of the EU. As has already been established in section 4.2.8, an ideological choice has been made by the EU for liberalised energy markets. However, the REDII, which sets the main energy transition targets, works with a top-down approach by setting fixed percentages of renewables in the grid. No such top-down target exists for flexibility, despite its essential role in renewables' integration. This could lead to further coherence troubles as the electricity market design focuses on a bottom-up approach. Moreover, it is aimed at grid stability rather than decarbonisation. As Articles 36 and 54 of the Electricity Directive clearly state, the Clean Energy Package focuses on finding market solutions. Yet, no such price signals are available for ES, which still makes it troublesome for market players to be profitable and thus enter the market. TSOs and DSOs, parties that are eager to develop ES when they see fit, are still discouraged to own and operate because of the preferential treatment of market players. Market players are expected to lead the charge but are unwilling to do so because of lacking remuneration schemes, while the regulated entities that are willing to engage are in many instances not allowed to.

Furthermore, it is also important to recognise that it is too early to determine or even predict how homogeneous the Electricity Directive and the REDII will be transposed in national laws. If not done so with the desired effect, the performance of SF4 and SF5 may be worse than anticipated in this research, as optimal implementation has been assumed.

## 5.3 Limitations

While the data is gathered from various stakeholders in the electricity system, two important stakeholders were not represented: startups and national energy regulators. All but one respondent were from larger firms. Their view might have proven valuable as one respondent argued that startups and smaller companies are being pushed out of the market by the inability to make money (NAT), while larger firms have sufficient financial reserves to survive the game (OTH1). However, the EU scope posed a challenge in this regard as the smaller players are not organised in the same centralised fashion, including with collective advocacy groups,  as the other stakeholder groups, which made finding the right startups that would represent a European sample very arbitrary. Still, one of the respondents, with code OTH2, is employed by a smaller growth-stage firm, which may in part make up for the missing stakeholder. In addition, the national advocacy interviewees include the startup perspective due to their membership. National energy regulators were approached, but the researcher has been unable to secure an interview.

Some of the interviews yielded unsatisfactory results. This may in part have been caused by interviewees' misunderstanding of the intention of the question or the question itself. This has led to the situation that not all answers were useful. Overall, the occasions in which this occurred have been spread out reasonably well. Nevertheless, this could be damaging to the legitimacy of the newly introduced SF8. There is no reference for this SF and diagnostic questions had to be compiled by the researcher. The diagnostic questions for SF8 on the regime interactions lacked sufficient attention for the role of agency, which indeed is an often-cited criticism of the MLP in general (Geels, 2011). The question about landscape pressures was not comprehensive enough. A brief introduction to the interviewees on the relevant landscape pressures could likely have averted an overly simple and short response. Nevertheless, much data provided in other questions still led to utilisable answers to SF8.

In terms of the implications, the essence of SF8 was that it provided the establishment of a contextual window of opportunity in the energy transition at large. The sectoral segment yielded some interpretation challenges. The sectoral interactions are most certainly positive for the energy transition, as they increase the areas in which market players can operate, namely in between sectors, which can increase the efficiency of investments if technologies can be used cross-sectorally. Simultaneously, it also poses the possibility that large-scale, stationary ES will face increased competition from V2G technologies, increased residential storage systems, or from increased gasification. Good performance of TIS-sectoral interactions, therefore, is potentially a threat to ES technologies in their large-scale applications, but beneficial to the flexibility services that ES can provide.

This research has focused on grid-scale applications in the electricity sector, but this would not have been a limitation if the scope of this research would have been broader and would have included V2G technologies. In the hypothetical situation that grid-scale applications in the electricity sector indeed become less competitive, the financial and institutional advantages of sector coupling will be external to the scope of the research. In spite of what went wrong, the aim of SF8 was to show the window of opportunity of ES in light of the overall transition benefits, and it has successfully done so.

In addition, there was some confusion with interviewees regarding the scope of the research. Many used *energy storage* and ES interchangeably, so that their answers may have included heat storage. Others may have been referring solely to batteries whilst answering a question on ES in general, which is a considerable risk of studying a cluster of ES technologies. Moreover, it cannot be established to what degree the interviewees were knowledgeable on the contents of the Clean Energy Package, which was released only a few months before the interviews took place. The Clean Energy Package contains an important set of regulations that greatly influenced the results of this research. All these points may affect the validity of this research.

When conducting desk research, the researcher faced a recurring issue in narrowing the data down to the scope of this research. Data on projects, markets and other quantifiable topics were rarely given for grid-scale ES separately. Instead, aggregate data for all ES, including residential, was often the starting point. Therefore, the researcher had to make constant assessments of the data to adjust it to the scope, which meant that some findings had to be excluded because it could not be assured that it was referring to the chosen scope.

In conclusion, while data quality sometimes proved challenging, it often occurred evenly spread-out, so that other sources of data largely alleviated unclarities in data. Even for SF8, the desk research proved fruitful to compensate for the unsatisfying interviewee results. Regarding the stakeholders that were not questioned, this is largely mitigated by the fact that some of the interviewees have had experiences beyond their current employers and the fact that a governmental actor/European regulator was interviewed. Therefore, while these limitations are to be taken seriously when interpreting the conclusions of this research, it does not render its validity compromised.

## 5.4 Contribution and future research

This study builds on previous integration efforts. The newly introduced SF made another attempt at capturing the context of the TIS, as previously attempted in Bergek et al. (2015), as well as integration efforts from Meelen & Farla (2013). This study differed because it not only incorporated the context into the interpretation of SFs, it added on the work of Bergek et al. (2015) and Kieft et al. (2017) by adding an analytical means of operationalising the window of opportunity that the context offers. Specifically, the energy transition is such a broad topic that just including the context without adding SF8 would have made a delineation between the SFs challenging. Guidance of the search, in particular, would have virtually no boundaries. In that respect, it is also more analytically feasible than the integrated framework of Meelen & Farla (2013), particularly considering the fact that transition management faces scrutiny for its unclear analytical approach (Loorbach and Verbong, 2012).

The barriers that were found under SF8 would most likely not have been found by a conventional TIS analysis. The combined landscape, regime and sectoral analysis offered an assessment of whether or not there was a contextual window of opportunity to which the system acted, which exceeds even a broad interpretation of the TIS approach. The role of agency in these contextual elements, as well as clear analytical boundaries, set this research apart.

Sector coupling was rarely mentioned and would neither have fallen under SF4 or SF5, as all sectoral topics are treated individually in regulatory and policy documents. The identified barriers are therefore the result of the theoretical novelty of this research. Unsurprisingly, SF8 encountered some infancy challenges. As the limitation section has already outlined, the analytical implications of the sectoral segment of SF8 should be more developed and the scope must be more carefully established. The results of SF8 in this research could be used indicatively for future researchers to determine the scope of similar research more coherently.

The scope of this research was unique. The absence of previous studies with such a European scope may be easily explained by the fact that it cannot be done without facing many challenges. It has not been executed flawlessly in this research either; it was an experiment to broaden the scope to enable TIS analyses to remain applicable in an increasingly centralised and transition oriented Europe. Setting the boundaries of an EU scope is challenging on a conceptual level, but equally challenging in the methodological sense as data is fragmented, often decentralised and unspecific. Future research could narrow down the EU scope and make a stronger delineation between the centralised aspects of the EU and the decentralised aspects of EU member states. Researchers are also encouraged to incorporate data from national institutions when centralised or unspecific data on the EU level is insufficient.

As more large societal sustainability transitions are likely to be necessary for the upcoming decades, and Europe is becoming increasingly harmonised in its policies, similar research should be encouraged, as it captures an area that was not as prevalent as it is today and in the future.

# 6. Conclusion

This research aimed to identify the barriers to the diffusion of large-scale, stationary ES in the EU. While it is evident that ES faces significant challenges, notable progress has been made over recent years. However, none of the key innovation processes, reflected in SFs, performed very well. Guidance of the search, market formation and resource mobilisation are performing particularly poorly.

There is a lack of shared visions between the relevant stakeholders on rollout trajectories and the selection of technologies and insufficient quantitative detail in strategies relating to flexibility in the energy transition. In addition, lithium-ion and hydrogen are receiving the lion's share of the attention, which may lead to a premature lock-in. Moreover, the electricity market design is flawed. Legislators favour market operation of storage devices, while market mechanisms make it virtually impossible for market players to be remunerated for storage services. There is no level playing field for disruptive technologies, including ES, to participate in the flexibility market. As the CAPEX costs of ES devices are high, the lack of remuneration possibilities significantly reduce the business case of ES and thus the interest of investors and other industry players. Yet, interviewees are divided on the need for policy interventions, despite the obvious flaws in the system. The results demonstrate that the barriers in SF4 and SF5 are largely responsible for many of the insufficiencies found in the other SFs. As many barriers were identified, the establishment of interconnections between these barriers allowed this research to formulate a narrowed down set of policy measures that are rendered both most effective, as well as politically feasible, and takes into account the reluctant stance of various stakeholder groups towards European policy interventions.

First and foremost, information exchange channels between policymakers and ES experts should be strengthened to make well-informed policy. Subsequently, a detailed and quantified strategy for flexibility should be formulated by either the EU or, perhaps more realistically, by regulated entities. This strategy should go beyond the required capacity and desired technologies and include how flexibility is going to be delivered in conjunction with targets for renewable electricity. With regards to the market design, rules to participate in the flexibility markets should be revisited in order to allow fair access to non-established technologies, to which ES still belongs. Moderate price signals should be incorporated to allow for proper remuneration. In both areas, it would be wise to incorporate the developments in sector coupling.

Despite its various challenges, ES is far from an outsider. It is on the radar of nearly all stakeholders in the electricity system and is receiving increased attention on all fronts. As noticeable gains have been made over the years, it seems likely that ES will follow an upward trend despite the current state of the TIS.

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# Appendix

## Appendix I: Interview guide.

The interviewees were asked several general questions about ES and the energy transition, after which they will be questioned about the specific functional performances. They will be asked what the structural causes of these functional weaknesses are, and how they propose that the EU (through policy) could resolve this. The questions will be rephrased in a more appealing manner to reduce repetitiveness and make it more interesting for the interviewees.

*General opening questions*

- Could you tell me a little bit about yourself and about your organisation's role in electricity storage?
- How do you see the role of electricity storage in the energy transition?
- What do you think are the biggest barriers to the large-scale deployment of electricity storage?

*Functional*
*SF1*

- Do you feel like there are a sufficient amount of actors for the development and large scale diffusion of electricity storage? What score would you give it on the scale of 1 to 5 (1 meaning very low – 5 very high)?
  - If not: Why do you think that is?
  - If not: Could you give a recommendation on how the EU could address this?
- Do you think there are enough launched projects/is enough entrepreneurial activity?
  - If not: why do you think that is?
  - If not: you think that can be stimulated by EU policy?

SF2

- Is the amount of generated knowledge of electricity storage sufficient for its development? What score would you give it on the scale of 1 to 5?

- If not: Why do you think that is?
- If not: Could you give a recommendation on how the EU could address this?

SF3

- Do you think enough knowledge is being exchanged about storage between all actors in the system? In other words, do all the actors along the value chain know enough about (the state of the art of) this technology for it to become a commercial success? What score would you give it on the scale of 1 to 5?
    - If not: Why do you think that is?
    - If not: Could you give a recommendation on how the EU could address this?

SF4

- Do you think there is a shared vision about the development of electricity storage? Are all actors looking for the same type off electricity storage technology, or is there a lot of deviation?
- Do you feel like there are sufficient long-term targets? What score would you give it on the scale of 1 to 5?
    - If not: Why not?
    - If not: Could you give a recommendation on how the EU could address this?

SF5

- Do you think there is or there soon will be a market for electricity storage?
- Is the technology already competitive with existing solutions? If not when?
- Is there enough policy support at the EU level?
- What score would you give it on the scale of 1 to 5?
    - If not: Why not?
    - If not: Could you give a recommendation on how the EU could address this?

SF6

- Do you think there are enough financial, human and material resources available for large-scale diffusion of electricity storage? What score would you give it on the scale of 1 to 5?
    - If no: Why do you think that is?
    - If not: Could you give a recommendation on how the EU could address this?

SF7

- Do you think there is a lot of resistance to the development of electricity storage? Who is resisting?
- How would you rate the level of support for electricity storage on a scale from 1 to 5?
    - If yes: Why do you think that is?
    - If yes: Could you give a recommendation on how the EU could address this?

SF8

- Do you think that the opportunities for storage in the energy transition are adequately recognised? What score would you give it on the scale of 1 to 5?
    - If not: Why do you think that is?
- Do you think that both industry, research and policymakers are looking at synergies between electricity storage and renewable technologies? And how storage can be applied in other sectors than the electricity sector?
    - If not: Why do you think that is?
- Do you think the established order in the electricity sector is changing? In other words, do you think policymakers and industry are pushing for change in the established companies and the way we will look at infrastructure and institutions in the electricity sector in light of storage?
    - If not: Why do you think that is?
    - If not: Could you give a recommendation on how the EU could address this?

- What score would you give it on the scale of 1 to 5?

*Closing question*

- Is there anything that we may not have discussed that is either a driver or barrier to electricity storage?
- Do you have anything else you would like to add?

## Appendix II: The services of ES in the electricity system. Adopted from EASE (2017)

| Generation/Bulk Services | Ancillary Services | Transmission Infrastructure Services | Distribution Infrastructure Services | Customer Energy Management Services |
|---|---|---|---|---|
| Arbitrage | Primary frequency control | Transmission investment deferral | Capacity support | End-user peak shaving |
| Electric supply capacity | Secondary frequency control | Angular stability | Contingency grid support | Time-of-use energy cost management |
| Support to conventional generation | Tertiary frequency control | Transmission support | Distribution investment deferral | Particular requirements in power quality |
| Ancillary services RES support | Frequency stability of the system | | Distribution power quality | Maximising self-production & self-consumption of electricity |
| Capacity firming | Black start | | Dynamic, local voltage control | Demand charge management |
| Curtailment minimisation | Voltage support | | Intentional islanding | Continuity of energy supply |
| Limitation of disturbances | New ancillary services | | Limitation of disturbances | Limitation of upstream disturbances |
| | | | Reactive power compensation | Reactive power compensation |
| | | | | EV integration |

## Appendix III: Overview of projects relevant for large-scale, stationary ES. Compiled from the BRIDGE projects and the CORDIS database.

| Project name | Year | Grant number | Topic | EU funding | Total budget |
|---|---|---|---|---|---|
| BATTERY2030+ | March 2019 - February 2020 | 854472 | Community building and roadmapping for high performance and smart electrochemical energy | € 499 456 | € 499 456 |

| | | | | | |
|---|---|---|---|---|---|
| | | | storage | | |
| Compile | November 2018 - ongoing | 824424 | Integrated local energy systems (Energy islands) | € 5 431 906,25 | € 6 933 605 |
| CROSSBOW | November 2017 - ongoing | 773430 | Demonstration of system integration with smart transmission grid and storage technologies with increasing share of renewables | € 17 287 742,88 | €22 048 478,75 |
| CryoHub | April 2016 - ongoing | 691761 | Large scale energy storage | € 7 045 594,38 | € 8 269 770,99 |
| EU-Sysflex | November 2017 - ongoing | 773505 | Demonstration of system integration with smart transmission grid and storage technologies with increasing share of renewables | € 20 279 863,72 | € 26 489 895,25 |
| Flexitranstore | November 2017 - ongoing | 774407 | Demonstration of system integration with smart transmission grid and storage technologies with increasing | € 17 008 101,88 | € 21 399 588,39 |

| | | | | | |
|---|---|---|---|---|---|
| | | | share of renewables | | |
| FutureFlow | January 2016 - ongoing | 691777 | Transmission grid and wholesale market | € 12 985 233,50 | € 12 985 242,50 |
| GoFlex | November 2016 - ongoing | 731232 | Demonstration of smart grid, storage and system integration technologies with increasing share of renewables: distribution system | € 6 826 393,13 | € 11 234 125 |
| GRIDSOL | October 2016 - ongoing | 727362 | Developing the next generation technologies of renewable electricity and heating/cooling | € 3 421 447,50 | € 3 421 447,50 |
| InteGRIDy | January 2017 - ongoing | 731268 | Demonstration of smart grid, storage and system integration technologies with increasing share of renewables: distribution system | € 12 329 013 | € 15 743 171,43 |
| INTENSYS4EU | October 2016 - September 2021 | 731220 | Support to R&I strategy for smart grid and storage | € 3 998 284,95 | € 4 325 785 |

| | | | | | |
|---|---|---|---|---|---|
| Invade | January 2017 - December 2017 | 731148 | Demonstration of smart grid, storage and system integration technologies with increasing share of renewables: distribution system | € 13 273 626,88 | € 16 305 987,50 |
| Merlon | January 2019 - December 2021 | 824386 | Integrated local energy systems (Energy islands) | € 5 739 471,25 | € 7 382 308,75 |
| MuseGrids | November 2018 - October 2022 | 824441 | Integrated local energy systems (Energy islands) | € 5 877 577,26 | € 7 430 784,50 |
| Naiadas | January 2015 - December 2018 | 646433 | Next generation technologies for energy storage | € 6 492 262 | € 6 492 262,50 |
| Osmose | January 2018 - December 2021 | 773406 | Demonstration of system integration with smart transmission grid and storage technologies with increasing share of renewables | € 21 852 098,69 | € 28 316 380 |
| React | January 2019 - December 2022 | 824395 | Decarbonising energy systems of | € 8 974 327,88 | € 10 764 405 |

| | | | | | |
|---|---|---|---|---|---|
| | | | geographical Islands | | |
| SMILE | May 2017 - April 2021 | 731249 | Demonstration of smart grid, storage and system integration technologies with increasing share of renewables: distribution system | € 12 106 046,95 | € 14 058 908,54 |
| STORE&GO | March 2016 - February 2020 | 691797 | Large scale energy storage | € 17 937 358,63 | € 27 973 369,75 |

**Appendix IV: Score calculation SFs.**

| Scores | Interviewees | Researcher | Desk research | Average | Average cut off |
|---|---|---|---|---|---|
| **SF1** | 3,428571429 | 3,1875 | 4 | 3,538690476 | 3,5 |
| **SF2** | 3 | 2,9375 | 3,5 | 3,145833333 | 3,1 |
| **SF3** | 3,038461538 | 2,90625 | 4 | 3,314903846 | 3,3 |
| **SF4** | 1,977272727 | 1,8125 | 2,3 | 2,029924242 | 2,1 |
| **SF5** | 2,423076923 | 2,520625 | 2,3 | 2,414567308 | 2,4 |
| **SF6** | 2,916666667 | 2,759375 | 3 | 2,892013889 | 2,9 |
| **SF7** | 3,166666667 | 2,9375 | 3,5 | 3,201388889 | 3,2 |
| **SF8** | 3,309090909 | 3,20625 | 3,3 | 3,271780303 | 3,3 |

**Appendix V: Score sheets.**

*Interviewees*

| SF1 | Actors | Projects | SF2 | SF3 | SF4 | Shared vision | Long-term target | SF5 | Market available | Competitivenes | EU policy suppo | SF6 | Financial | Human | Material | SF7 | SF8 | TIS-Landscape | TIS-TIS | TIS-regime |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | - | - | 2,5 | 2,5 | 1,5 | - | - | - | - | - | - | 3,5 | - | - | - | 3 | 3,15 | 5 | 3,5 | 2 |
| 3 | - | - | 3 | 4 | 2 | - | - | 4 | 4,5 | - | - | 4 | - | - | - | - | 3 | - | 3 | - |
| 3 | - | - | 2 | 1 | 2 | 3 | 1 | - | - | - | - | 3 | - | - | - | 2 | 3,3 | 5 | 4 | 2 |
| 3 | 4 | - | 3,5 | 3,5 | 1,5 | 2 | 1 | 1,75 | - | - | - | 2 | - | - | - | 4 | 3,5 | 4 | - | 3 |
| 4 | 4 | - | 5 | - | - | - | - | 1,5 | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | - | - | 2 | 3,5 | 1,5 | 2 | 1 | 2 | - | - | - | 2 | - | - | - | 4 | 3,5 | 4 | - | 3 |
| 4 | - | - | 3 | 4 | 2,4 | 2,75 | - | 2,5 | - | - | - | 2,5 | 3,5 | 3 | 1,5 | - | - | 4,5 | - | - |
| 4 | 4 | 4 | 4 | 4 | 3 | 3 | - | 3 | - | - | - | 3 | 4 | 4 | 2 | 4 | 4 | 4 | 3 | 4 |
| 4 | - | - | 2 | 4 | 1,75 | 2,5 | 1 | 2 | - | - | - | 2 | 3 | 2 | 1 | - | - | 5 | - | - |
| 3,25 | - | - | 3,5 | 2,75 | 2,3 | 2,3 | 1 | 3 | - | - | - | 2,8 | 4 | 4 | 3 | 2,5 | 3,5 | - | - | - |
| 3,5 | - | - | 4 | 2,5 | 3,5 | 3,5 | - | 4 | - | - | - | 3,7 | 4 | 4 | 3 | 3 | 4 | - | - | - |
| 3 | - | - | 3 | 3 | 1 | 1 | 1 | 2 | - | - | - | 2 | - | - | - | 2 | 3 | - | - | - |
| 4,25 | - | - | 3 | 5 | 3 | - | - | 3,5 | - | - | - | 2 | - | - | - | 3 | 3,3 | - | - | - |
| 4 | - | - | - | - | - | - | - | 3 | - | - | - | - | - | - | - | 3 | - | - | - | - |
| 4,5 | 5 | 4 | 3 | 5 | 3 | 3 | 3 | 4 | 5 | 4 | - | 2 | - | - | - | 3 | 3,3 | 4 | 2 | 4 |
| 3 | | | 2 | 2,5 | 1 | | | 2 | - | - | - | 3,5 | | | | 3,5 | 2,65 | | | |
| 2 | - | - | 3 | 2 | 1 | 1 | 1 | 2 | - | - | - | 3 | 3 | 2 | 4 | 3 | 3,3 | 3 | 2 | 5 |
| 4 | 5 | 3 | 1 | 3 | 1 | 1 | 1 | 2 | 2 | 2 | - | 4 | - | - | - | 4 | 2 | 1 | 3 | 2 |
| 3 | 3 | - | 3,5 | 3,5 | 2 | 2 | - | 2 | - | - | - | 4 | - | - | - | 3 | 4 | 4 | 4 | - |
| 3 | 3 | - | 3 | 3 | 2 | 2 | - | 2 | - | - | - | 4 | - | - | - | 3 | 4 | 4 | 4 | - |
| - | - | - | 4 | 4 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3,5 | - | - | - | 2,25 | - | - | - | 2,25 | - | - | - | 3,15 | 3 | 1 | 3 | 3,5 | 3 | 2 | 3 | 4 |
| 3 | 4 | 2 | - | 2,5 | 2 | - | - | 2 | - | - | 2 | 4 | - | - | - | 4 | 3,5 | - | 3 | 4 |
| 4 | - | - | 3 | 2 | - | - | - | 2 | - | - | - | 2,3 | 3 | 1 | 3 | 3 | 2,5 | 2 | 3 | - |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | | | | | | | | | | | | | | | | | | |
| 3,42857143 | 4,166666667 | 3,25 | 3 | 3,03846154 | 1,97727273 | 2,2 | 1,285714286 | 2,42307692 | 3,5 | 3 | 2 | 2,91666667 | 3,4 | 2,6 | 2,6 | 3,16666667 | 3,30909091 | 3,555555556 | 3 | 3,428571429 |

*Researcher's interpretation of interview data*

| SF1 | Actors | Projects | SF2 | SF3 | SF4 | Shared vision | Long-term target | SF5 | Market available | Competitiveness | EU policy support | SF6 | Financial | Human | Material | SF7 | SF8 | TIS-Landscape | TIS-TIS | TIS-regime |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3,25 | 3,5 | 3 | 2,5 | 3 | 1,75 | 2 | 1,5 | 2,9 | 3 | 2,5 | 3 | 3,7 | 4 | - | 3,5 | 3,3 | 3,15 | 3,5 | 3,5 | 2,5 |
| 3,5 | 4 | 3 | 3 | 4 | 2 | 2 | 2 | 3,7 | 4 | 3 | 4 | 4,3 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 3 |
| 3 | 3 | 3 | 2 | 2 | 1,5 | 2 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | - | 3 | 2,5 | 3,3 | 4 | 4 | 2 |
| 2,75 | 3,5 | 2 | 2,5 | 3,5 | 1,75 | 2 | - | 2,7 | 3,5 | 2 | 2,5 | 2,5 | - | - | - | 3 | 3,5 | 3,5 | 4 | 3 |
| 3,5 | 5 | 2 | 3 | 3,5 | 2 | 2 | - | 2,7 | 4 | 2 | 2 | 3 | - | - | - | 3 | 3,7 | 4 | 4 | 3 |
| 2 | 2 | 2 | 2 | 3,5 | 1,5 | 2 | 1 | 2,7 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3,3 | 3 | 4 | 3 |
| 3,5 | 3,5 | 3,5 | 3,25 | 4 | 2 | 2,25 | 1,75 | 2,5 | 3,5 | 2,5 | 1,5 | 3,1 | 3,5 | 3,5 | 2,25 | 3,5 | 3,7 | 4 | 4 | 3 |
| 4 | 4 | 4 | 3,5 | 4 | 2,5 | 2,5 | 2,5 | 3 | 4 | 3 | 2 | 3,85 | 4 | 5 | 2,5 | 3 | 3,7 | 3 | 4 | 4 |
| 3 | 3 | 3 | 3 | 4 | 1,5 | 2 | 1 | 2 | 3 | 2 | 1 | 2,3 | 3 | 2 | 2 | 4 | 3,7 | 5 | 4 | 2 |
| 3,5 | 3,5 | 3,5 | 3 | 3,3 | 1,75 | 1,75 | 1,75 | 2,7 | 3,5 | 2,5 | 2 | 2,85 | 3 | 3 | 2,5 | 2,5 | 3,2 | 2,5 | 3,5 | 3 |
| 3,5 | 4 | 3 | 3 | 2,5 | 2,5 | 2,5 | 2,5 | 3,5 | 4 | 3 | - | 3,7 | 4 | 4 | 3 | 3 | 3,7 | 3 | 4 | 3 |
| 3,5 | 3 | 4 | 3 | 4 | 1 | 1 | 1 | 2,3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2,7 | 2 | 3 | 3 |
| 3,75 | 5 | 2,5 | 3,5 | 3 | 2 | 2 | 2 | 3,15 | 4,5 | 3 | 2 | 2,35 | 2 | 3 | 2 | 3 | 3 | 2,5 | 3 | 3,5 |
| 3,5 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 3 | 2 | 2,7 | 2 | 4 | 2 | 3 | 3 | 2 | 4 | 3 |
| 4 | 5 | 3 | 5 | 4 | 2 | 2 | 2 | 3,3 | 5 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 4 |
| 3 | 3,5 | 2,5 | 2,5 | 2,5 | 1 | 1 | 1 | 1,85 | 2 | 2 | 1,5 | 3 | 2,5 | 3 | - | 2,75 | 2,5 | 2,5 | 2 | 3 |
| 2 | 2 | 2 | 3 | 2 | 1 | 1 | 1 | 1,7 | 2 | 2 | 1 | 3 | 3 | 2 | 4 | 2,5 | 2,7 | 3 | 1 | 4 |
| 4 | 5 | 3 | 2 | 3 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 2 | 4 | - | 3 | 2,3 | 2 | 3 | 2 |
| 3 | 3 | 3 | 3,25 | 2,25 | 2 | 2 | 2 | 2,5 | 3,5 | 2 | 2 | 2,4 | 2 | 2 | 3 | 3 | 3,85 | 4 | 4 | 3,5 |
| 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2,33 | 3 | 2 | 2 | 2,3 | 2 | 2 | 3 | 3 | 3,7 | 4 | 4 | 3 |
| 3 | 3 | 3 | 3,5 | 2,5 | 2 | 2 | - | 2,7 | 4 | 2 | 2 | 2,5 | 2 | - | 3 | 3 | 4 | 4 | 4 | 4 |
| 3,5 | - | - | 3 | 2,5 | 2,25 | 2 | 2,5 | 2,2 | 2,5 | 2,5 | 1,5 | 2,75 | 3 | - | 3 | 2,5 | 2,75 | 2 | 2,75 | 3,5 |
| 3 | 4 | 2 | 3 | 2,5 | 2 | 2 | 2 | 1,7 | 2 | 2 | 1 | 3,5 | 4 | - | 3 | 3 | 3 | 2 | 3 | 4 |
| 4 | - | - | 3 | 2,5 | 2,5 | 2 | 3 | 2,7 | 3 | 3 | 2 | 2 | 2 | 1 | 3 | 2 | 2,5 | 2 | 2,5 | 3 |
| | | | | | | | | | | | | | | | | | | | | |
| 2 | 2 | 2 | 3 | 2,5 | 2 | 2 | 2 | 2,7 | 3 | 2 | 3 | 3,3 | 2 | 4 | 4 | 4 | 3 | - | - | - |
| | | | | | | | | | | | | | | | | | | | | |
| 3,1875 | 3,533333333 | 2,733333333 | 2,9375 | 2,90625 | 1,8125 | 1,875 | 1,714285714 | 2,520625 | 3,1875 | 2,3125 | 1,933333333 | 2,759375 | 2,6 | 2,833333333 | 2,75 | 2,9375 | 3,20625 | 3,066666667 | 3,366666667 | 3,133333333 |

*Researcher's interpretation of desk research*

| SF1 | Actors | Projects | SF2 | SF3 | SF4 | Shared vision | Long-term target | SF5 | Market available | Competitiveness | EU policy support | SF6 | Financial | Human | Material | SF7 | SF8 | TIS-Landscape | TIS-TIS | TIS-regime |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | | 3,5 | 4 | 2,5 | | | 2,5 | | | | 2,5 | | | | 3,5 | 3,5 | | | |

*Final scores*

| | Interviewees | Researcher | Desk research | Average | Average cut off |
|---|---|---|---|---|---|
| **SF1** | 3,428571429 | 3,1875 | 4 | 3,538690476 | 3,5 |
| **SF2** | 3 | 2,9375 | 3,5 | 3,145833333 | 3,1 |
| **SF3** | 3,038461538 | 2,90625 | 4 | 3,314903846 | 3,3 |
| **SF4** | 1,977272727 | 1,8125 | 2,5 | 2,096590909 | 2,1 |
| **SF5** | 2,423076923 | 2,520625 | 2,5 | 2,481233974 | 2,5 |
| **SF6** | 2,916666667 | 2,759375 | 2,5 | 2,725347222 | 2,7 |
| **SF7** | 3,166666667 | 2,9375 | 3,5 | 3,201388889 | 3,2 |
| **SF8** | 3,309090909 | 3,20625 | 3,5 | 3,33844697 | 3,3 |

## Appendix VI: Counted interconnections.

This table counts the interconnected barriers per SF. Every number counts as one interconnected barriers. This means that SF4 has seven barriers in other SFs to which it is interconnected.

| | SF1 | SF2 | SF3 | SF4 | SF5 | SF6 | SF7 | SF8 |
|---|---|---|---|---|---|---|---|---|
| SF1 | x | 1 | 0 | 2 | 2 | 1 | 0 | 0 |
| SF2 | 0 | x | 0 | 2 | 1 | 1 | 0 | 0 |
| SF3 | 0 | 0 | x | 0 | 0 | 0 | 1 | 0 |
| SF4 | 0 | 0 | 1 | x | 1 | 0 | 0 | 1 |
| SF5 | 0 | 0 | 1 | 0 | x | 0 | 0 | 0 |
| SF6 | 0 | 0 | 0 | 1 | 1 | x | 0 | 0 |
| SF7 | 0 | 0 | 1 | 0 | 0 | 0 | x | 0 |
| SF8 | 1 | 0 | 0 | 2 | 2 | 0 | 0 | x |
| Total | 1 | 1 | 3 | 7 | 7 | 2 | 1 | 1 |

## Appendix VII: Results on policy solutions.

This Appendix gives an overview of the policy instruments categorised per SFs that could address poor performance.

*SF1: Entrepreneurial activities*

Policy on this issue is contentious. Some argue that the business case will gradually come (GOV1). Others admit that it is hard to find a proper business case, but that it does not mean that it should justify policy intervention if there is no articulated benefit for society (DSO1). The latter point should be taken into account. Nevertheless, policy solutions offered by respondents refer to taking away the regulatory uncertainty, for example by allowing several revenue streams on one storage device - also known as revenue stacking (TSO1). Others agree that the EBA is a good policy measure to create a battery industry in Europe (EUR1; RES1). In addition to creating sustainable batteries, such an initiative also helps with one of the major energy objectives of the EU: security of supply. Increased demand in lithium-ion (which is imported) or imported storage devices leads to a similar energy dependence as is currently experienced in fossil fuels. On the flip side, others question the efficiency of investing in a domestic market when Europe is already so far behind (BAT2; UTI1). Instead, Europe could focus on new technologies without trying to outcompete Asia (UTI2).

Others refer to creating vision documents for the future in which it is clearly outlined what the flexibility needs will be in the future, and which services will be required (GOV1; OTH2). Also, more awareness needs to be created (OTH2).

*SF2: Knowledge development*

On policy recommendations, there was little consensus among the respondents. Some of the respondents propose conducting further pilot projects and investing in R&D (NAT2; UTI2). In addition, the environmental impact and reusability should be considered in further research (OTH1). Long-term investments should be incentivised, as this is also a barrier to knowledge development (OTH1). As some of the respondents point to regulatory uncertainty, strengthening a long-term vision and setting market conditions are named as means to stimulate knowledge development (EUR1). It is also proposed to set standards in policy so that storage technologies can be compared by market parties and this would stimulate technological development (TSO1). Lastly, communicating regulation better would take away some of the regulatory uncertainty, as one of the major challenges of current regulation is its unclarity (BAT1).

More should be invested in R&D to achieve competitiveness (Ugarte et al. 2015); costs must go down and business models should be researched. The R&D strategy of Europe should also promote smart grid developments, incorporating smart vehicle charging and vehicle-to-grid technologies (smart mobility), but also recognise and realise chances of future smart cities. A regular exchange of experiences from past projects and activities, including stakeholders along the energy value chain and across storage technologies, could help to sharpen such a strategy. The EC has suitable instruments to promote R&D on all different storage technologies.

*SF3: Entrepreneurial exchange*

While the challenges of knowledge exchange are diverse, the suggested policy solutions are more aligned. All policy suggestions are related to educating the stakeholders - and most notably policymakers - and raising awareness. The creation of communication programmes (BAT2; DSO2) belongs to the solutions. Awareness needs to be created with the support of quantified facts (RES1). More concretely, a vision document for the electricity sector, once again supported with quantified numbers, needs to reveal on what is expected and how that will be achieved. Along with this, transparency should be promoted (OTH2). To combat the secrecy and the difficulty of achieving such quantified facts, a platform should be created in which “stakeholders feel comfortable sharing information” (RES2). In addition, there should be more focus on storage at European bodies for regulated entities, EDSO and ENTSO-E (NAT1), organisations that are both legally mandated. Lastly, comparative research should be conducted to market design and subsequently stimulate exchange between EU member states (OTH2).

Alternatively, one respondent suggested a common methodology for regulated entities to assess the value of different options (OTH2). This shows resemblances to the suggestions for SF2, namely standardisation.

*SF4: Guidance of the search*

A strategy for development should be formulated, including quantified and very specific targets and pathways (EUR1; NAT2; RES1; RES2; TSO1). This could, for instance, be done as a roadmap based on success stories (GOV1). Such a vision document, ideally created by regulated entities (OTH2; TSO1) would take away a lot of the uncertainty that actors are experiencing, as the creation of a vision document was proposed by many respondents for different SFs. Creating direction in the development sends a clear long-term signal to the sector (GOV1). In addition, policy support and market conditions should be harmonised as much as possible in member states, even if that is difficult (EUR2; NAT2). For now, it is too early to know how homogeneous the Electricity Directive will be transposed in national law. While some actors state that setting targets should preferably be left to the market (UTI1). It is also recognised that for such a stringent issue like the energy transition there are just too many variables. Certainty is needed and this justifies policy intervention (OTH2). In the United States, such targets have already helped (DSO2; TSO1; UTI2). In addition, focussing on more exchange of knowledge is proposed (NAT2).

*SF5: Market formation*

Policy would need to focus on securing longer-term revenue streams. Short- and long-term objectives should be reconciled (OTH2). In addition, regulatory uncertainty must further be removed by creating a long-term vision and investment scheme for decarbonisation in 2050; financing for nuclear energy in its early stages could be taken as an example (OTH1). There should be a comprehensive evaluation of all flexibility options (OTH2), including the costs perspective; how much do different options (centralised vs. decentralised etc.) cost (TSO1).

More coordination on a European level could speeden up national progress (NAT2). Policymakers need to be educated on ES, and also on sector interfaces (BAT2; NAT1). Lastly, smarter network tariffs might resolve much of the problems posed by lacking regulation (DSO1).

Difficulties in generating sufficient revenues are one of the major struggles, and by not adequately addressing long-term contracts this is also difficult. There need to be clearer price signals and revenue stacking should be made possible. The electricity market design also does not allow for the efficient use of storage devices by allowing for several different services to be used simultaneously (EASAC, 2017). A solution could be provided by allowing for a so-called Multi-Service Business Case, which allows several operators to use one device for several services to spread the costs and maximise revenues (EASE, 2019a).

Once again, there should be no technological discrimination in the procurement of ancillary services. Furthermore, the existing ancillary services should be rethought to take advantage of fast, new storage technologies (CIGRE, 2018; EUR2).

Flexibility services should be standardised entirely. While this is already promoted in the Electricity Directive, it is yet to be seen if this will happen in a harmonised way. TSOs could provide technological and market standards to promote further integration (ENTSO-E, 2016).

*SF6: Resource mobilisation*

Clear regulation helps attracting investors (GOV1). Cost-competitiveness should be increased to that the investment case goes up (BAT2). This could also be achieved by financial support and tax incentives for green technologies other than renewables (BAT1). The incentive schemes for certain stakeholders could be altered to make ES more favourable (OTH1). Formulating a clear vision with quantified targets could also help (RES2).

The market mechanisms should be strengthened, to allow ES to secure revenues (NAT2). The existing services in the energy system should be revisited as they are designed in a way that disadvantages storage (EUR2). However, some argue that it should be left up to the market entirely and that intervening should be discouraged (DSO1; UTI2).

It should be incentivised to train people to become ES engineers (UTI2). More specifically, ES could be taught at universities. Potentially, EU member states could exchange engineers (NAT2).

There should be a recycling market (RES2).

*SF7: Legitimation*

Proposed policy measures are not linked directly to this SF. Once again, it is suggested to formulate a vision with quantified targets for flexibility (RES2). Storage will not always be most cost-competitive, but it also does not have to be. Other regulatory uncertainty also needs to be removed (BAT2), as the lacking business case and investment incentives are also still named as resisting factors. Lastly, educating the incumbents/conventional sector about the possibilities of storage, with up-to-date quantified information (BAT2). The same should happen for policymakers (NAT1).

*SF8: External transition orientation*

Education is required to make people see the added value of ES in conjunction with renewables (NAT1). Comparable to creating investment incentives through the creation of a vision document, it could also help players recognise the financial and technological opportunities in the energy transition.

More cross-sectoral, cross-stakeholder and cross-business events should be organised to facilitate the search (BAT1). Policy targets for collaboration may help (NAT1). Once again, a shared vision on the development of ES and the energy transition at large may stimulate the search for such synergies (OTH1; OTH2). Alternatively, it is argued that it would be more efficient to invest heavily in V2G rather than stationary batteries; it has the added benefit of cleaning up the air, EV charging infrastructure is expensive and needs support, plus it allows for cheap flexibility in the electricity system which allows for more renewables integration, which in turn would make EVs more renewable (UTI2). This would serve several purposes at once and would arguably require less capital than separate investments without focus on the synergies.

Economies of scale should be utilised to make centralised cheaper than decentralised, so that it does not completely change the paradigms but just the instruments (UTI2). Support schemes like in Norway should be taken as an example (BAT2). The market design should be altered in such a way that it allows for disruption (NAT2). This is a recurring policy suggestion. Also, once again, formulation a vision is suggested (RES2).