REEEM Innovation and Technology Roadmap

Energy Storage Application

July 2017

About this report

In the framework of the REEEM project the development of three technology and innovation roadmap is planned to highlight the role of innovation and technologies in the transition pathways. The first roadmap, presented in this report, is dedicated to energy storage application. The primary findings of this roadmap were consolidated in a stakeholder workshop held on 19 May 2017 in Brussel. The inputs are incorporated in this report.

This report will be complemented by IRL reports, assessing and evaluate innovation readiness of 5 storage technologies (to be published on July 31st) 2017, and a report on evaluating techno-economic parameters of storage technologies (to be published on February 28th 2018). The outcome of the current report will result in the aforementioned data which in turn, will be used as input in several of the modelling exercises of the REEEM project.

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REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

The REEEM project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739. This publication reflects only the views of its authors, and the European Commission cannot be held responsible for its content.

Summary

*In order to deal with the probable consequences of **climate change**, there is a need to reduce the amount of Green-House Gas (GHG) emission in the energy sector. While estimations show that the amount of energy-related emission of carbon dioxide globally will double by 2050, the European Union plans to reduce its emissions about 80% as compared to 1990 by 2050.*

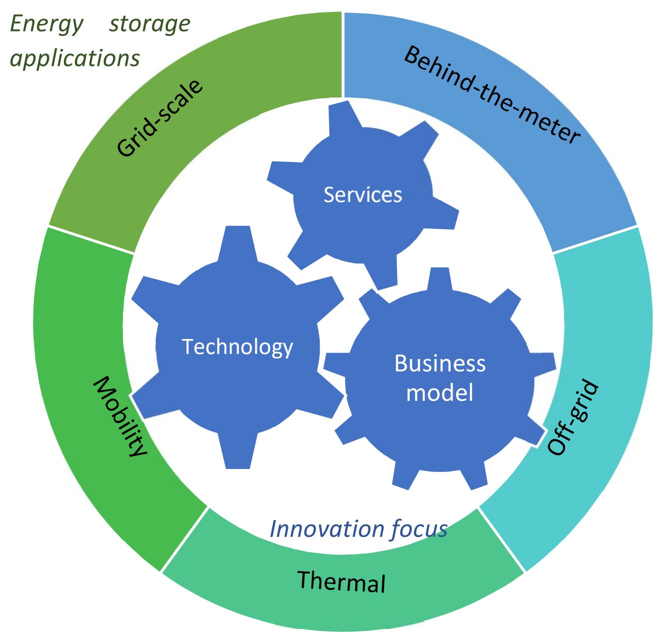
***Energy storage** could play a crucial role in this energy transition, by enhancing the reliability, flexibility and security of the European energy industry. The potential position of energy storage in the future energy industry could be particularly significant, given the ambitious targets for the development and deployment of renewable energy. Energy storage could be a key component of this development in supporting the renewable energy integration. Accordingly, the development and deployment of energy storage is placed at the top of the Energy Union's priorities, and gained the attention of major European countries and industrial sectors.*

*This **roadmap** explores the potential role and position of energy storage in the transition of the European energy industry, by shedding light on different applications of energy storage. The analyses of this roadmap identify five main applications, namely grid-scale, behind-the-meter, off-grid, mobility and thermal.*

*The roadmap further characterizes market and technologies for each application in order to shed light on the current status of the energy storage markets and to explore **innovation** potential in three categories of services, technologies and business models. Innovation in services will contributes to the business cases of energy storage, in technologies would improve the system performance, and in business models would lead to successful integration and corporation of actors, all necessary for successful development and cost reduction of a market.*

*The roadmap's **findings** unveil the market challenges and drivers of different storage applications in the current and expected market environment, based on plausible scenarios for the energy system. Successively, recommendations are made on actions that could accelerate energy storage development.*

*The overall **aim** of this roadmap is to inform policymakers and investors by shedding light on decisions that can lead to competitive and timely actions accelerating the development of energy storage. The actions are suggested within a timescale based on their importance and effectiveness.*



Content

List of Figures

List of Tables

I. Introduction

The European Union has taken the first step toward to the development of low-carbon society. The Energy and Climate Package, or so-called 202020 Directive, set decarbonisation and energy efficiency targets for EU, which were shared by Member States and are being complied with. Further policy packages were then issued, which impose targets for the EU energy market of at least 40% reduction in greenhouse gas reduction, 27% renewable energy sources, and 27% improvement in energy efficiency by 2030, compared with 1990s level [1]. The plans for 2050 are even more ambitious; and consist in reducing green-house gas emissions by 80%, increasing the share of renewable energy sources in the energy market to about 50%, and eliminating almost totally the carbon emissions of the power industry [2].

Energy storage can act as an enabler in achieving these targets and successively contribute to the decarbonisation of the energy industry in several ways, by providing flexibility in the market (see Figure 1). First, energy storage can facilitate integration of renewable energy sources (RES), by storing the energy when produced during low demand time, and enhancing the quality of the power supply. Currently, in the market, the cost of renewable energy has dropped significantly, a 80% reduction for solar panels (PV) between 2009-2015, and a 30-40% reduction for wind turbines in the same period. Yet, successful penetration of these energy sources relies on finding a solution for RES reliability and stability. Energy storage can play a significant role in that.

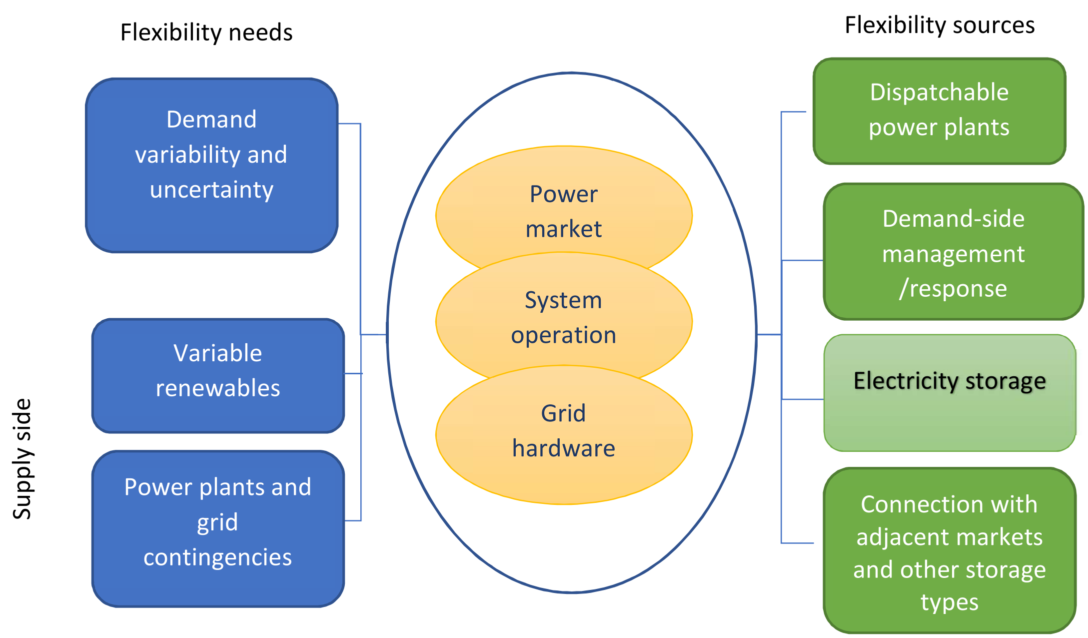


Figure 1- Energy storage position in the market [3]

Second, storage can delay or reduce the need for investment in new production plants by meeting the demand during peak time and improving energy time-of-use. Enhancing the grid flexibility through the adjustment of supply and demand and maintaining energy system reliability through a cost-effective manner is among the multiple roles that energy storage can play in the future energy system.

Furthermore, energy storage empowers self-production and self-consumption in the energy industry. Importance of consumers empowerment has been highlighted in the European winter package, and consumers could play a crucial role in the future low carbon energy system.

In spite of their known advantages, storage technologies yet play a minimal role in the energy industry. The grid-connected storage capacity worldwide in 2014 was estimated to be 171 GW, out of which 98% is pumped hydro storage. In Europe the installed storage capacity is higher than 50 GW, 95% of which is pumped hydro storage [4] [3]. This marginal role owes to several barriers, including uncertainty about the regulatory systems, low cost-competitiveness, limitation to monetizing the value of storage projects, low society acceptance, critical material use, performance and safety issues [5,6]. Besides, storage technologies need to compete with other alternative options such as demand response and grid infrastructure expansion in electricity sector and with Internal Combustion Engine (ICE) cars in mobility sectors.

In Europe, the potential role of storage technologies would depend on how the future European energy system operates. On one hand, the European energy system can move toward an integrated energy system and on the other hand, toward local energy markets empowered by smart grids and demand side management. In both cases energy storage can enhance the flexibility and reliability of the system [4], and offer several services in the market given increasing share of RES. While disagreement persist, the need for storage capacity is estimated to be about 20-60% of renewable energy share to support the energy industry [7][5,8] as a possible mean for flexibility option.

This roadmap explores the potential role of energy storage in the future energy industry by exploring different applications of energy storage, and services relevant for that application. It further shows that different ranges of technologies can lead to success of the energy storage applications, but choosing the right storage technology is essential for an effective and cost competitive application. The findings aim to inform investors and policy makers decision; by shedding light on different drivers and challenges in the energy storage market and recommending competitive and realistic actions for the development of the storage applications.

In this roadmap, the applications of energy storage are divided into the following five groups**:**

- **Grid-scale** encompasses stationary electrical storage implemented at a specific location on grid.
- **Behind-the-meter** refers to stationary storage implemented at consumers location and not on the grid. This application is for the consumers who are still connected to the grid.
- **Off-grid** includes energy storage installed at off-grid and remote areas for homes, telecom towers or mini-grids.
- **Mobility** focuses on energy storage system used for mobility and four wheel individual and fleet vehicles.
- **Thermal** incudes storage of thermal energy for heating, cooling or power generation purposes.

This roadmap is structured as follow, Chapter II describes the applications of energy storage. For each application, it further explains related services (see Table 1), technology and market characteristics (Figure 1 and 2) and market drivers and barriers in details.

Chapter III summarizes the main market drivers and challenges of the energy storage market, and presents a list of action that can accelerate the development of energy storage market. Full technical details of storage technologies are provided in fact sheets in Appendix I.

Table 1 – Energy storage applications, services, and technologies identified in this roadmap

Application	***services***	***Potential technologies***
Grid-scale	*1. Upgrade deferral* *2. Energy arbitrage* *3. Black-start* *4. Load leveling* *5. Capacity firming* *6. Congestion relief* *7. Reserve capacity* *8. RES integration* *9. Frequency regulation and system balancing* *10. Power quality control*	*Li-ion* *Flow batteries* *CAES* *Supercapacitor* *PHS* *Fuel cell* *TES* *Flywheel* *NaS* *(other batteries)*
Behind-the-meter	*1. Decentralized electricity generation* *2. RES integration* *3. Energy cost management* *4. Energy arbitrage* *5. Peak shaving* *6. Backup power* *7. Provision of ancillary services to upstream grid*	*Li-ion* *Lead-acid* *LAES*
Off-Grid	*1. Off-grid supply* *2. Diesel generation replacement* *3. RES integration* *4. Microgrids* *5. Telecom towers*	*Lead-acid* *Li-Ion* *CAES* *Flow batteries* *Supercapacitors*
Mobility	*1. EVs* *2. FCVs* *3. Vehicle-to-grid*	*Li-ion* *Hydrogen* *Flow batteries* *Supercapacitors*
Thermal	*1. Seasonal storage (heating or cooling)* *2. Peak-shifting* *3. Concentrating solar power (CSP)* *4. Storage and integration of RES heat* *5. Power-to-heat* *6. Heat-to-power* *7. Waste heat management* *8. Buffering* *9. District heating services*	*Heat tanks* *Molten salt* *Underground (aquifer, cavern and borehole)* *Surface (steel tank and pit)*

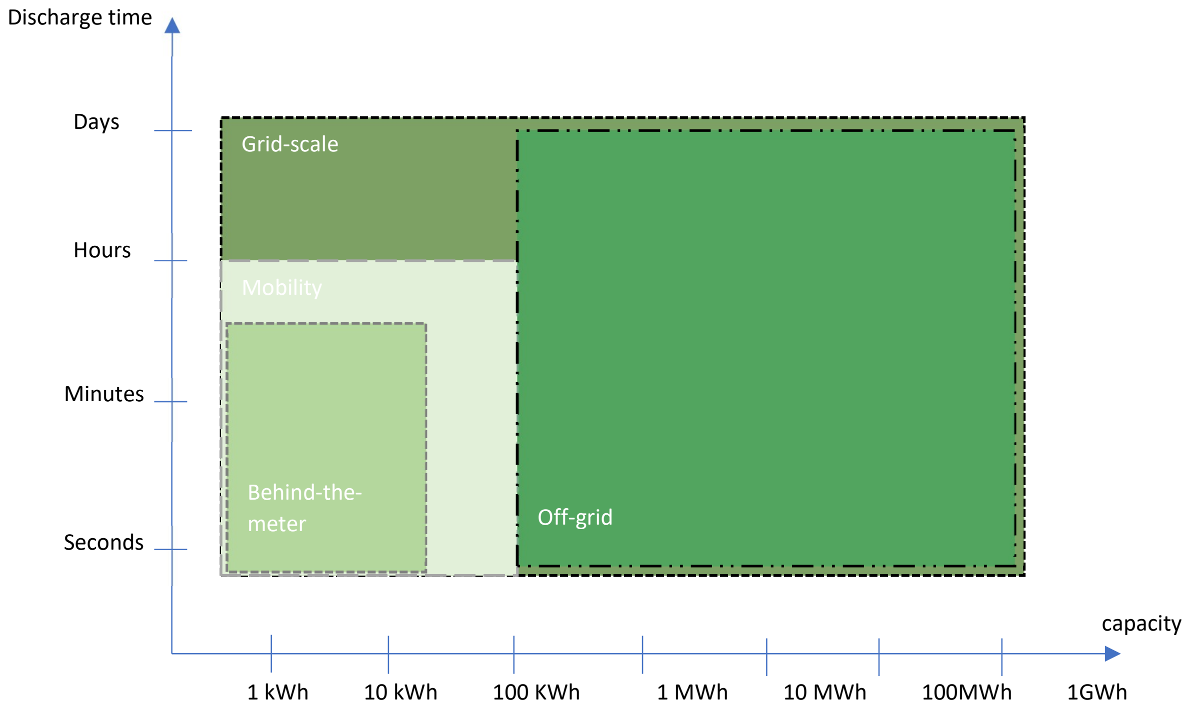


Figure 2 – Energy storage application overview and their energy capacity

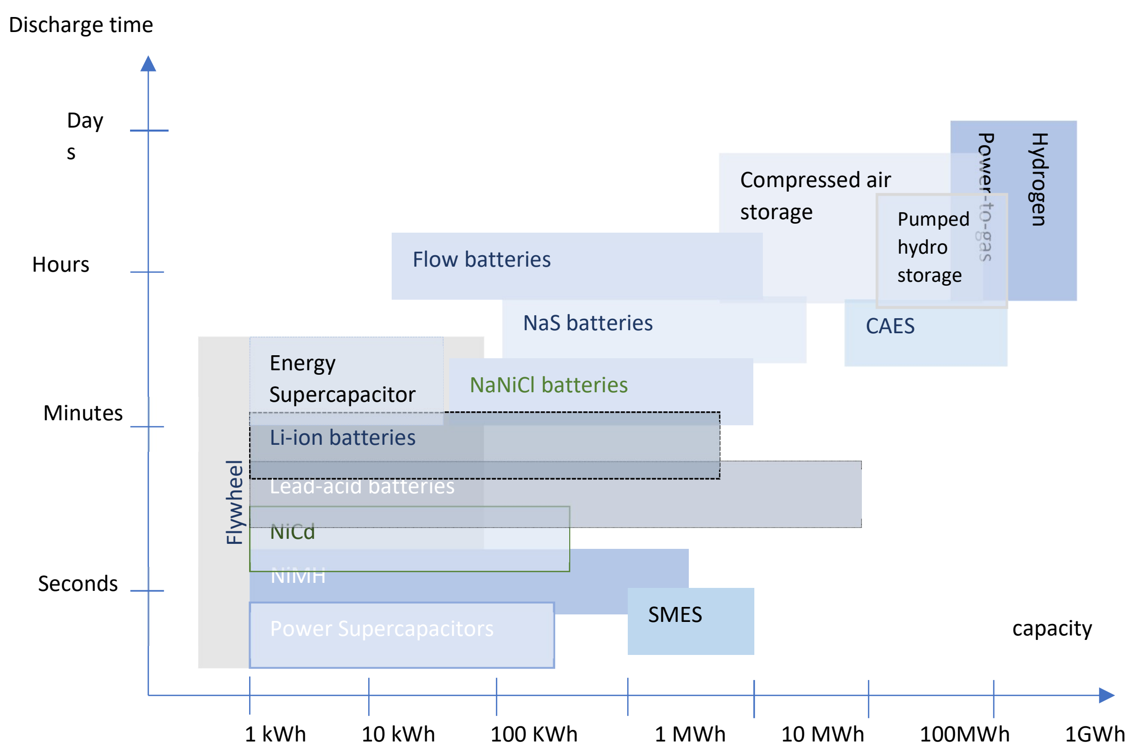


Figure 3 – Overview of energy storage and their energy capacity and energy storage (Team analysis, ARUP, 2010; SBC Energy Institute, 2013)

II. Storage Applications

II.1. Grid-scale

II.1.1. Application services and benefits

This application encompasses stationary electrical storage implemented at specific locations on the grid. The application aims at delivering local support to transmission and distribution networks. Development of energy storage on grid will allow advanced energy and distribution management system. With the decreasing costs of storage technologies, storage assets are more regarded as viable alternatives, for example for TSOs (Transmission System Operators) and DSOs (Distribution System Operators), to support the grid.

The key services of storage technologies in the grid-scale application are:

- **Upgrade deferral:** Due to major changes in spatial distribution of energy generation or high peak demand, large investments in transmission and distribution networks will be required in Europe. This is in order to improve interconnectedness of the network. Storage technologies can delay the need to replace or enhance equipment within grid, for example by meeting the peak demand. As an illustration, specific amount of energy storage can defer the need for investments in the system upgrade when there is an almost overloaded transmission and distribution node [9]. Several projects are under development in USA in order to provide transmission upgrade deferral benefits [10]. This includes for example the Charleston Energy Storage Project which in the short term aims at curbing current local capacity constraints and service reliability issues [11].
- **Energy arbitrage:** In the energy system, there are extra charges for transmission capacity during the peak demand. In this situation energy storage could be used for energy arbitrage, to store energy when the price is lower, and sell that energy at a higher price during the peak demand period.
- **Black-start:** energy storage can be used to support the energy system and meet the demand when there is an outage due to lack of supply. Energy storage can provide energy during the outage, or creates an orderly shutdown of processes, and provide time to transfer to onsite generation resources [12].
- **Load Levelling:** The difference between the electricity supply generation (primarily generation) and end user demand (load) within a region or area can influence power output. The grid-scale storage could be utilized to level their load curve, particularly when there is a higher demand.
- **Capacity firming:** energy storage can support among other things conventional and nuclear power plants in several ways. This support includes covering generation load if the generation does not function, balancing strong and fast load variations, and eliminating imbalance charges.
- **Congestion relief:** Storage systems, when strategically placed on the grid, can help defer energy production or demand and thus reduce the load on critical lines and avoid congestion [12].
- **Reserve capacity**: storage could be utilized as reserve capacity when there are sudden and unexpected supply shortages for a short time. It therefore can contribute to the reliability of the system.
- **RES integration:** Renewable Energy Sources (RES) supply a notable share of the European electricity needs. This share is expected to grow in the coming years. However, they may produce energy during off-peak times, when there is low demand or the energy is prices low. Energy

storage allows storing RES energy and to use that energy when it is more valuable or needed. Storage could also balance the short duration of intermittency of RES energy and make their output more reliable.

- **Frequency regulation and system balancing:** Storage could be used to support transmission and distribution systems to maintain the necessary frequency, and stability of the system. Benefits from storage in this service are specific to situation and site.
- **Power quality control:** Energy storage can support the grid against short-duration events that affect the quality of power delivered and therefore support the stability of the system. Some examples of poor power quality are:
    - Variations in voltage magnitude (e.g., short-term spikes or dips, longer term surges, or sags).
    - Variations in the primary 60-Hz frequency at which power is delivered.
    - Harmonics (i.e., the presence of currents or voltages at frequencies other than the primary frequency).
    - Interruptions in service, of any duration, ranging from a fraction of a second to several or even many minutes.

II.1.2. Technology characterization

There are several storage commercial and mature technologies for grid-scale applications. Pumped hydro storage (PHS), Compressed air energy storage (CAES), secondary batteries (such as lead-acid and Li-ion), and flywheel are some of the storage technologies deployed for grid-scale services. With a global installed capacity over 125 GW, PHS is 97% of the deployed electricity storage capacity worldwide. In Europe, over 42 GW PHS has been installed, mainly for nuclear capacity forming in 1960-1990 [13]. Limitations in siting and environmental permitting has been one of the obstacles in further development of PHS in Europe. The Huntorf CAES in Germany is the first and one the two existing plants worldwide. The low efficiency and the need for supplementary fuel has led the research towards advanced adiabatic CAES [14].The use of batteries for grid-scale applications has recently attracted more attention in Europe. modularity and little site requirements of batteries have made them favourable technologies for future developments. Moreover, batteries can offer a wide range of services due to their short response and relatively acceptable efficiency range. In 2015, the largest battery in the EU was a 10 MW Li-ion technology in Feldheim in the north eastern Germany for stabilizing the grid of the respective TSO (50 Hz) [15]. Based on the current market condition and technology development, Lithium-ion energy storage is expected to play a significant role for the grid-scale.

Table 2 shows the necessary technical characteristics of storage technologies for this application.

Table 2 - The technical requirements of different grid-scale services (own analysis and [16,17][18]*)*

Services	Capacity scale	Discharge duration	Response time	Potential technologies
Upgrade deferral	10-100 MW	Up to a few hours	Mins - hours	Batteries, PHS, LAES CAES, flow batteries, fuel cells
Energy arbitrage	100-2000 MW	Hours to day	>1 hour	NaS, CAES, batteries
Black-start	Up to 10s of MW	Minutes - hours	Milliseconds to seconds	Batteries, Fuel cells, CAES, flow batteries
Load levelling	1-100 MW	Minutes - hours	seconds to minutes	PHS, CAES, batteries, fuel cells and TES
Capacity firming	1-100 MW	Minutes - hours	seconds to minutes	PHS, CAES, batteries, fuel cells and TES
Congestion relief	Up to MW	Minutes-hours	Milliseconds to seconds	Batteries, flywheel, flow batteries, SMES
Reserve capacity	Up to 100 MW	30 minutes – few hours	< 10 minutes	Batteries, PHS, CAES, Fuel cells
RES integration	1kW – 400 MW	Minutes - hours	Seconds – hours-days	Flywheels, batteries and supercapacitor, SMES, fuel cells, CAES
Frequency regulation and system balancing	1-400 MW	Minutes- Hours	millisecond-seconds	Batteries, flow batteries, SMES, supercapacitor, flywheels
Power quality control	<20 MW	Millisecond to minutes	Millisecond, Seconds	Flywheels, batteries, SMES, supercapacitor, LAES

Several factors, including the location on the grid, load profile, and service specifications influence the technical requirements for each storage technology. Overall, the voltage must be based on the power of the line and on the expected growth of the load. Storage assets located more upstream on the grid would need to be more powerful (several tens of MW for transmission grid support). Long periods of uninterrupted congestions need energy intensive technologies to perform efficient congestion relief.

Different services also demand different frequency of use and response time. For example, the frequency of use of storage assets for congestion relief is much lower than for other services such as frequency regulation, or arbitrage. The response time required for congestion relief is less stringent than for other services such as frequency regulation. Parameters such as power density play a less significant role for this application as the space is not an issue for installation of storage technologies on the grid.

II.1.3. Market characterization

Market sizing for grid-scale support application is highly difficult, even for a designated area. It is expected that more opportunities become available for this application since half of the projects developing or extending European power grids are delayed or cancelled [19], and often require long term planning [20]. According to ENTSO-E's Ten Year Network Development Plan (TYNPD) 2012, more than one third of the investments in grid upgrade in Europe is delayed compared to the initial schedule (Figure 4) [19] and this is not isolated to certain countries or regions. The main reasons for the delays are due to issues related to permitting processes, leading to financial issues, or public acceptance, as population are not yet used to grid building [19]. Other reasons are lack of economic profitability, complicated cost benefit analysis or ownership establishment.

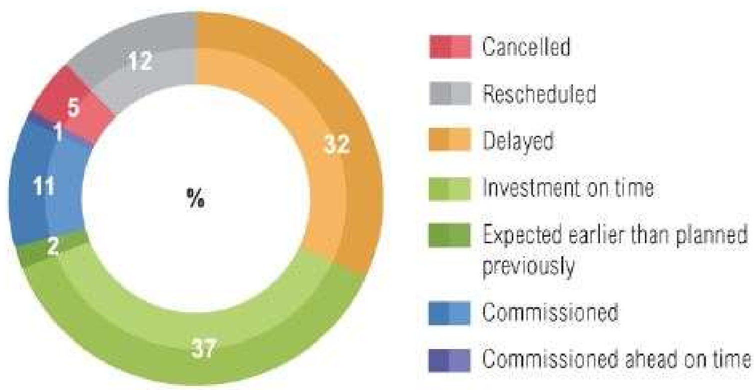


Figure 4- Evolution of ENTSO-E's Ten Year Network Development Plan 2012 portfolio [19]

In Europe, the network is currently redundant and highly developed, but this is expected to change given delays in the grid development projects. For example, in France, the current investment strategy of the TSO aims inter alia to relieve anticipated congestion through equipment upgrades [20].

II.1.3.1. Policy and legislation analysis

Political commitments to develop solar and wind electricity generation are strong and trigger massive investments in new RES generation capacity. Globally, continued political commitments to develop renewable energies should translate into significant shares of intermittent electricity generation in the generation mix on the long term. In addition to this, RES energy generation are changing the location of generation capacities, as they are located in circumscribed areas favourable to deployment of these assets. These locations could be far away from areas with high energy demand. For example in Germany, there is large power supply by wind farms in north and high demand in south. This has created a supply demand mismatch [11]. Also, with raising number of households with installed PV panels, the number of prosumers are increasing and that create challenges for distribution networks.

One approach to overcome these challenges is to improve integration of European grid facilitating electricity import and export. However, the existing delays in grid expansion combined with the commitment to increase the share of RES create opportunities for the development of storage technologies [21].

Political decisions can influence the storage market also through operation and ownership permits. For the development of grid-scale storage projects, one fundamental question is whether a TSO or DSO – as one of the main beneficiary of storage implemented on the grid – can build and operate energy storage assets, and seek cost recovery through regulated as well as unregulated revenues. Currently in the market the system operators are not allowed and this is reflected in Directive 2009/72/EC under Article 9 stating

TSO cannot contribute to supply and generation of electricity, as it could interference with their responsibilities. This delimits application of large scale storage on the grid [22].

The unbundling principle is not a showstopper for grid-scale storage. One of the few European examples is the Italian system operator TERNA that built and now operates “movable storage systems” to perform grid support (legislative decree 01/06/2011, n°93, also applying to DSOs). This concession to the European unbundling policy has a limited scope of application and is only when: the system must ensure the security of the national electricity system and its proper functioning, maximum use of renewable energy sources and procurement of resources for dispatching services. For now, the regulatory framework has been adapted by the Italian regulatory agency (AEEG) for the purpose of TERNA’s grid-scale battery trials. On the other hand, TERNA has not been authorized to operate PHS plants.

The regulation regarding pumped hydro storage (PHS) is different across different European member state countries [23]. For example, in eight member-states (Czech Republic, Spain, Italy, Lithuania, Poland, Portugal, Slovakia and the United Kingdom) there is no grid fee for storage plants, while three member states (Austria, Belgium and Greece) and Norway impose a fee for storage charging and discharging. Germany made an exception for both new and capacity extension of existing PHS for 20 and 10 years, respectively (see Figure 5) [24].

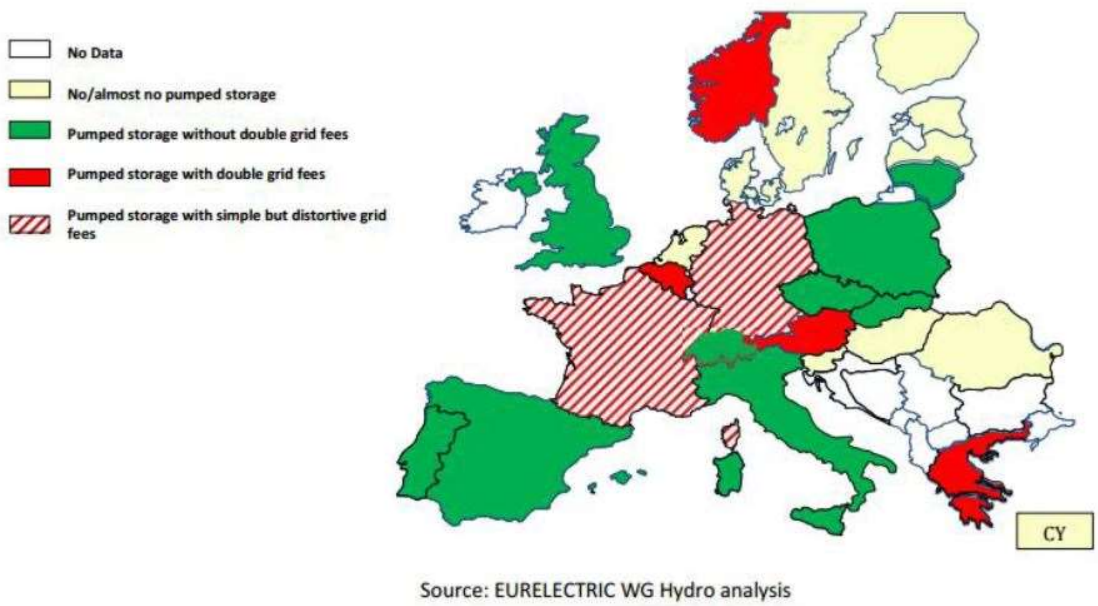


Figure 5- Pumped Hydro Storage: Treatment of grid fees

Furthermore, in some European countries the access of energy storage is taxed twice, both as consumer in charging and producer in discharging power to the grid, which is attributed to the lack of clear asset definition of storage[23][25]. This double feeing is recognized as a barrier by [23][25].

II.1.3.2. Market acceptance

New grid infrastructure constructions face increasing oppositions and acceptance hurdles from a wide range of stakeholders. These opposition, lead to long permitting process and construction delays. The resulting delays in the construction of new infrastructure may then favour compact solutions with smaller footprint such as storage since its implementation process is expected to be shorter[11]. Furthermore, the deployment of storage technologies on grid network affects society and consumers to a lesser degree.

However, the deployment of some storage technologies such as PHS also have faced oppositions in some European countries and in accordance their permission processes are slow [11]. In addition, safety concerns linked to storage systems still are issues and may threaten storage implementation. For instance, in the case of electrochemical storage systems:

- Some battery technologies include hazardous or even toxic materials (e.g. zinc-bromine or lead-acid batteries).
- Some technologies may feature industrial risks (explosions, fires, etc.)
- Some technologies use rare materials (e.g. lithium-ion)

All of the above points are exposed to environmental and social debates. Estimating the negative impacts of these phenomena is complicated and therefore hard to compare with the alternative solutions.

II.1.3.3. Storage operators and business models

For energy storage to play a significant role in the future energy industry, potential operators need to make long-term commitments and investments in R&D and technology deployment. Any return from storage technologies indeed takes time to become profitable. Different business models are available to system operators:

- **The System operator owns the storage asset and captures network value only.** In this model, the investment is made by the TSOs and DSOs to provide network services only, i.e., services which are today already provided by the operators with other technologies and infrastructure. The energy storage asset is integrated in its regulated assets base, and so is eligible for cost recovery through regulated revenues. The transmission or distribution network operator can keep the whole control of the system, regulating the dispatch of stored energy in case of congestion or reliability events or subcontracting it to a third party (e.g. stakeholders with specific skills for optimizing and managing energy storage devices). This business model presents two main features:
    - On one hand, it is expected to be easier to implement and less subject to regulatory constraints as has been shown by Terna in Italy, since only regulated revenues are captured (investment deferral, network reliability). This indeed does not threaten the unbundling principle.
    - On the other hand, the revenue base is limited to regulated revenues only, which could hamper the economic viability of this storage application and demotivate the investment decisions of TSOs and DSOs.
- **The system operator owns the storage asset that captures both network and market values, potentially with the help of a third party intermediary**. In this model, the investment is made by the transmission or distribution network operator to provide network services as in the previous

case, but also seek for unregulated revenues from market services, i.e., new services that generate revenue such as arbitrage,). The storage system then requires a specific regulatory status in unbundled markets. The TSO or DSO have then a partial control of the system, at least for the dispatch in case of congestion or reliability events. In unbundled markets, one or several third parties are likely to take the market dispatch responsibilities. This business model presents two main features:

  - On one hand, it is expected to be more complex than the other models to implement and subject to regulatory constraints, since both regulated and unregulated revenues are sought for; this requires third parties to be involved in order to capture unregulated services.
  - On the other hand, the revenue base is larger than for the above model, which could strengthen its economic viability.

- **A third party owns the asset and captures both network and market value.** In this model, the storage asset is owned by an independent party, which can be registered as a generator and/or a customer on the market. The third party has a contractual agreement with the TSO or DSO to value the network services. The expenses of the TSOs and DSOs then qualify as OPEX and can be recovered through the fee charged for using the network. The third party keeps the control of the storage system and can optimize the use of the system according to its own interest (market operations, etc.) as well as the requirements of the TSO or DSO.
  This business model presents two main features:
  - On one hand, it is expected to be more complex to implement due to different contractual agreements and revenue streams. The legal feasibility of this model is moreover not clear.
  - On the other hand, the revenue base is larger than for the first model and this could strengthen its economic viability. In this case, it is important to consider that TSOs and DSOs may cooperate with the third party
- **The System operator owns the storage asset to only captures network value and third party own assets to capture the market value.** In this model, the storage assets are owned by DSOs and TSOs provided that it allows them to conduct their network services with energy storage. The third party then invest in energy storage and own assets that are deemed for market services. In this model, the third party can control the system and market operations according to its interests as long as it complies with the requirements of DSOs and TSOs.
  - On one hand, this business model is more complex to implement since the third party and the system operators needs to align their work together and could influence each other markets. Also, this business model necessitates enactment of new policies.
  - On the other hand, this business model could generate revenue for the system operators, provided that energy storage technologies become cost competitive. Also new market players can enter the energy landscape and lead innovation.
  -

II.1.3.4. Value chain

An illustration of the value chain decomposition is shown in Figure 6. As explained in the previous sections, the most critical actors in the value chain are currently storage operators for which legal uncertainties remain in unbundled market.

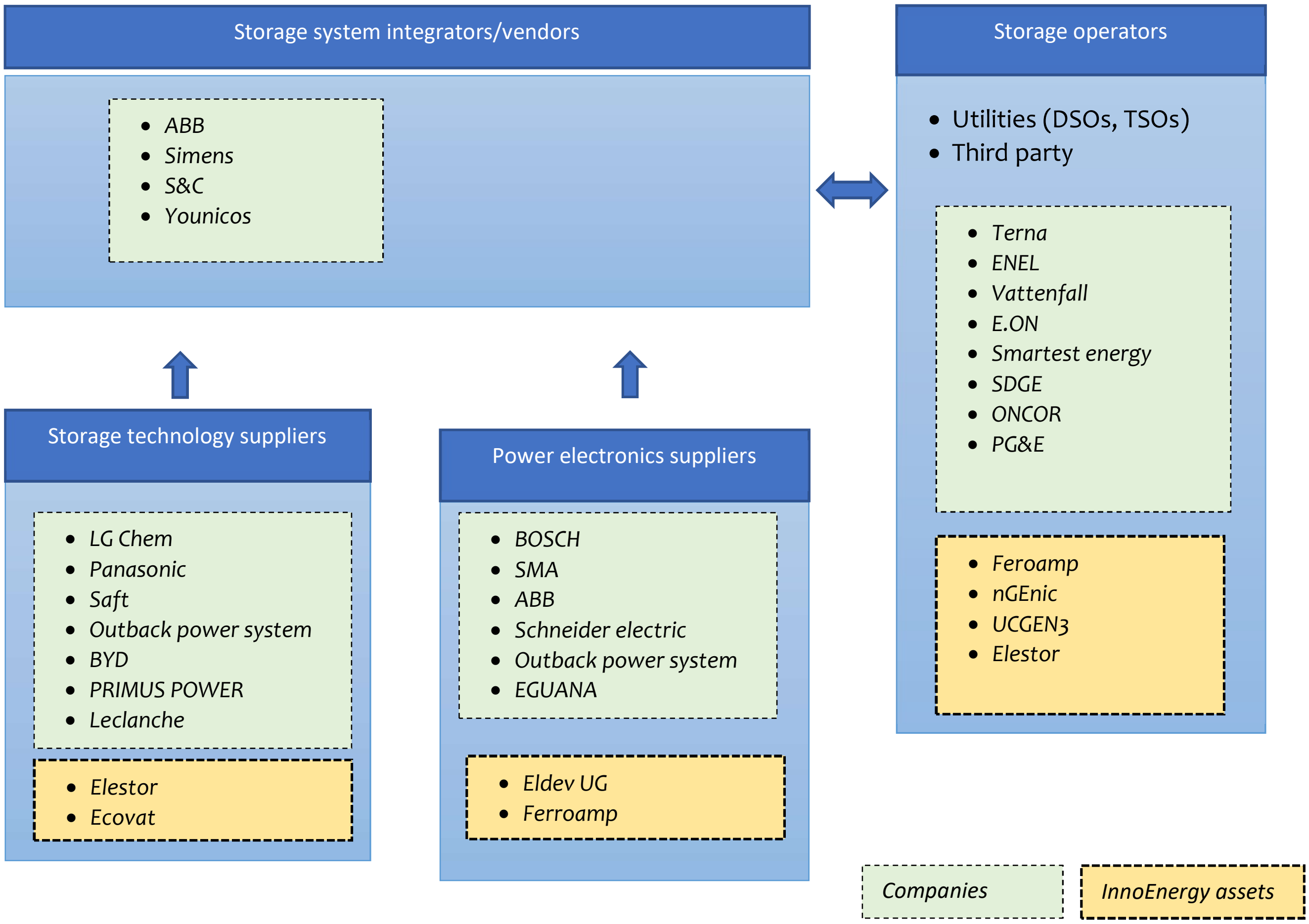


Figure 6– Value chain and main actors of grid-scale application, non-exhaustive list

II.1.4. Market challenges

In Europe, the development of storage projects for transmission and distribution grid support is currently hindered by several parameters, as listed below:

- **Local operators of storage and regulations implementing the unbundling principle:** For the development of grid-scale storage projects, one fundamental question is whether or not a TSO or DSO – as one of the main beneficiary of storage implemented on the grid – shall build and operate an energy storage asset, and seek cost recovery through regulated as well as unregulated revenues. Currently. This policy hinders the development of storage as an alternative to other existing technologies and infrastructure (e.g., the choice between storage versus the construction of new lines) and creates uncertainty about the legal owners of storage assets delimiting the interests of potential investors.
- **The development of smart grids and demand management:** the opportunities for grid-scale storage is reduced because of the development of smart grids and demand-side management, which are alternative flexible options.

- **Social resistance:** Negative perspective regarding safety of energy storage technologies thereby long authorization procedures. They are causing delays in energy storage deployment across different European countries.
- **Lack of robust energy storage evaluation:** Over-evaluation of storage (economic) value due to regulated prices makes storage technologies a less favorable option. Indeed, in Europe many countries have regulated electricity prices that do not necessarily reflect neither the wholesale price of electricity nor the constraints on the grid, from which the owners of energy storage can benefit.
- **High cost of grid-scale storage technologies**: If the cost of technologies does not decrease during the coming years, the full potential of the market is unlikely to be realized. Gas fired turbines are cheap substitute grid-related services of storage.
- **Raw material sustainability**: Some storage technologies are made of rare materials (e.g., li-ion), the exploitation of which may have severe environmental impact. Besides, dependency on rare materials question production sustainability of the technologies.

II.1.5. Market drivers and scenarios

Several drivers can influence cost, affordability and status of storage technologies for the grid-scale applications:

1) **Investments deferral in grid infrastructure:** Lack and delays of investments in the construction of new grid network infrastructure favour development and deployment of storage technologies. This is because the storage technologies could provide alternative solutions with (in some cases) lower cost, shorter implementation time and smaller footprint. Grid expansion results in more overhead transmission lines over farms and landscape, which destroys the view and also needs digging the ground and cutting trees and some hills, and all this happen throughout the line from generation to consumption node. Storage can be nicely built near the consumption node in a small space, and alleviate the need for lengthy transmission lines. Currently in the energy market there are more incentives for utilities to invest in grid infrastructure. With increasing the CAPEX intensity of network upgrades, storage technologies find better opportunities. The opportunities are dependent on different factors including, a high peak to average demand ratio, modest additional load and/or expected demand growth [11].
2) **Regulation for storage operators**: Regulatory clarifications should be made regarding the operators of storage assets on the grid. There is a room for clarifications about who can earn regulated and unregulated revenues from the assets. Any delays in modifying the existing regulations can be lead to delays in investments in storage assets.
   This roadmap recommendation is for the fourth business model namely, the System operator owns storage assets to captures network value and third party own storage assets to capture the market value. This model fosters innovation in the market with the entrance of new business players. It also allows the system operators to benefit from storage assets and therefore delimit their change resistance. The business model enhances economic viability of energy storage, by bringing new players into the landscape of the energy industry, whose business is dedicated to energy storage. The plays could make long term planning to find a position in the market and generate revenue.
3) **Integration of RES and balancing supply and demand:** RES is expected to produce a large share of energy in order to meet the European energy demand. These sources of energy not only produce intermitted energy but also, they are not always located in areas with highest energy demands. The aim at increasing share of RES and imbalance between regional supply and demand drive investments in energy storage technologies that can positively contribute to the market flexibility. This already has been the case in some European countries such as Italy.

4) **Economic values of energy storage:** There is a need to show actual business cases for energy storage to illustrate economic values of storage technologies on grid. The reduction in wholesale power purchases during peak demand, or the creation of a more reliable energy system while decreasing operational costs and outages are examples of major economics saving due to the application of storage on grid. In another example when nodal pricing applies, with storage assets on grid it would be possible to gain additional revenue streams. Lack of considering these parameters may result in over-looking the value and revenues generated from energy storage.
5) **Standardization of storage system:** there is a need for establishment of standards for connecting different component of energy storage systems. Examples of these standards are for system installation, product safety, performance or recycling. Standardization of these aspects could effectively bring the cost of the energy system at grid down and spontaneously enhances the performance of the system.
6) **Supply chain**: Strengthening the European supply chain can effectively alter the penetration of energy storage applications. Two examples of necessary changes in supply chain are:

   Availability of raw material: there are concerns about the availability of resources for energy storage technologies, especially for large scale application. Upon findings substitute material for energy storage technologies, sustainability of technologies' production could be assured.

   Human resources: There is lack of human resources for construction and operation of energy storage technologies and this hampers the development and deployment of the technology. This happens for instance in the battery manufacturing plants or operation sites.

   European manufacturers: currently in Europe there is lack of local manufacturers producing storage technologies, while other countries such as USA or Japan are becoming stronger in this field. This results in lack of European competitiveness in the energy storage market which could delimit the interest of local industry for investment in storage assets.
7) **Technological innovation:** Innovation could contribute to the reduction of the cost of storage technologies. The technology cost remains a great barrier for the deployment of grid scale storage. Cost drivers can be summarized as (see Figure 7) [26]:

   Technology structural changes and evolutions: A dramatic improvement in the technology together with a sharp growth in the learning rate can result in cost reduction. For example, if the promise of new liquid metal battery chemistries, or the use of organic materials in flow batteries would be realised. Advanced manufacturing methods and the use of recycled material may improve the final cost as well. the efficiency of storage technologies will be improved with further research and development of the technologies, including making them suitable for longer term storage.

   Market-related forces: This can cause a large influence when learning curves would be constructed using price rather than cost data. For example, in high demand for a product and existence of few suppliers, the price may remain high, leading to a presumed decrease in the learning rate.

   Government policy related to research and development (R&D) expenditure: When there is government support for demonstration projects of some technologies, it can act as a driver to help new technologies emerge and move beyond the demonstration phase.

   Compound or component learning: it happens when technologies are a combination of different elements, each of which has a different rate of learning. In this case, if the learning rate is saturated in one component, the learning rate for the technology as a whole reduces.

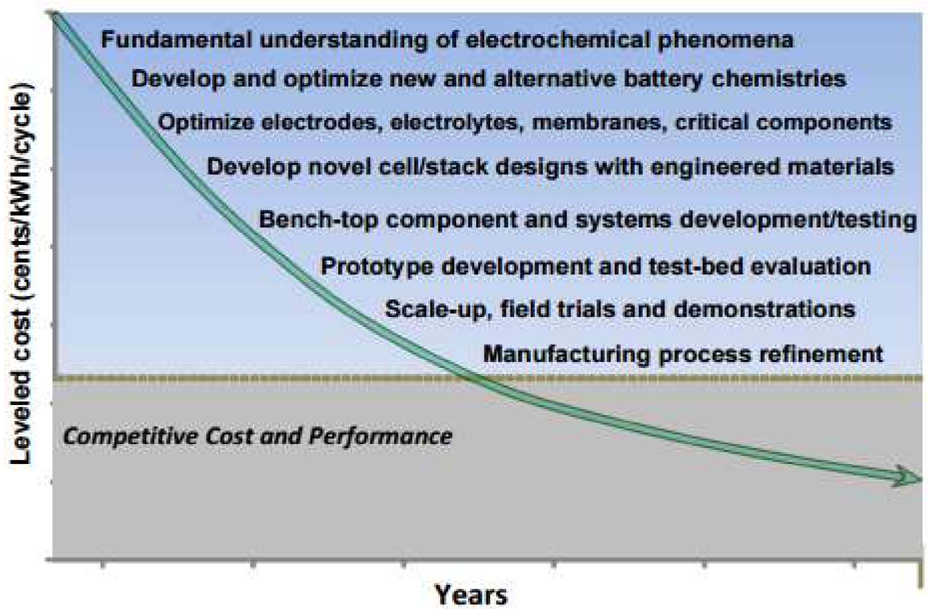


Figure 7- Steps to drive down cost in technology development [25: P. 46]

Table 3 - Market drivers and scenarios for grid-scale storage application

Vision for storage deployment to 2050			Time frame
Drivers		Scenarios	
Transmission and distribution grid support	Investment deferral in Infrastructure	Investments will be made in energy storage technologies to compensate for delayed/cancelled investments in European grid infrastructure. In addition, electrification of areas with low population density will be proceeded through investments in energy storage, instead of long grid infrastructure. This inclusion necessitates large governmental support.	2025-2030
	Regulation for storage operators	Governments will make clarifications about the ownership of energy storage for different applications and services. This will improve the existing business models in the market and motivate prospective storage owners to make large investment in energy storage.	2020-2025
	Integration of RES and balancing supply and demand	Investments will be made in energy storage to compensate for intermittent renewable energy and to facilitate balancing regional supply and demand. The investments will be supported by government and industry and lead to the enhancement of the market flexibility.	2020-2025
	Economic value of energy storage	Estimations will be made on the economics of energy storage (revenue generation), and cost of transforming the energy market through large installation of storage technologies. Public databases on actual installation cost of energy storage and their long-term saving will further provide evidence on the energy storage's values. Investors contribute to this process by sharing their knowledge with each other. This illustrates successful business cases of energy storage and positively contribute to their development.	2020-2030
	Standardization of storage system	Initiatives will be made to publish standards on energy storage's installation, safety and performance. This will reduce the cost of storage services and increase their market share.	2020-2025
	Supply chain	The European supply chain will be strengthened and local European suppliers become more competitive in production of storage technologies (e.g., li-ion) and meeting the market demand. Entries and exits of different companies throughout the supply chain will be improved. In addition, programs and courses will be offered to train expert workforce and improve their knowledge about the technologies for safe installation and operation of storage technologies.	2020-2030-2040
	Technological innovation	The development of the storage technologies will be supported through government and industry funded R&D program, technological structural change, and learning curves. Researcher and scientists will find innovative solutions for improving technologies' materials, performance and efficiency. This in turn will increase the industry motivations to invest in further deployment of storage technologies.	2020-2025-2030

II.2. Behind-the-meter

II.2.1. Application services and benefits

This application is related to stationary electricity storage implemented at the consumers' location and not on the grid. It encompasses storage dedicated to both non-residential consumers (industrial and tertiary) and residential consumers (individual and collective) and creates a value transfer from the utilities (mainly DSOs) to the end-users. Political incentives (e.g. subsidies, rebates) and favourable economic environments (e.g. high feed-in vs. retail prices differentials, high demand charges) create viable business cases for this application. These incentives coupled with the responsiveness of end-users to surplus value proposition spurs the storage markets.

The services included in the behind-the-meter storage application, could be summarized as below.

- **Decentralized electricity generation (self-production & consumption)**: behind-the-meter storage application can realize a transition from a centralized to a decentralized electric energy system where consumers contribute to production of electric energy [4] and could consume from that energy. This means that behind-the-meter storage is closely linked to the production of domestic power generation and self-consumption which result in value creation for end-user.
- **RES integration**: Energy storage used in conjunction with RES generation allows the consumers to produce, store and use energy to offset their other energy purchases. Paired with renewable energy generation, electricity storage can contribute to the reliability of power supply and allow higher integration of intermittent RES in the system.
- **Energy arbitrage**: when dynamic pricing applies, consumers can store energy when the price of energy is low and use that energy when the price is higher during peak demand[12].
- **Energy cost management**: This service allows end-users to decrease their overall electricity bill through several approaches, such as diminishing peak charges.
- **Peak shaving:** This service allows the peak demand to be decreased, as the consumers can use stored energy during peak times.
- **Backup power:** This service allows end-users (including both industrial users and households) to meet their own demand during black-outs and shortage of electricity. Emergency back-up power is among industrial users' initial value proposition for energy storage.
- **Provision of ancillary services to upstream grid:** behind-the-meter storage can provide ancillary services such as regulation and frequency control to grid when it is integrated.

II.2.2. Technology characterization

Technologies for behind-the-meter applications can have different requirements depending on the type of end-user and main targeted value proposition. As storage assets are installed at customers' premises, the *energy density of installed technologies* is among the most influential parameters. This feature is even more meaningful in dense (urban) areas where the residential floor space per household is smaller. Currently in the market the most common storage technologies for this application are batteries, especially Li-ion. For example, the recent Powerwall battery packs from Tesla Company aims at providing storage services in residential and commercial buildings. The ease of use, operability, maintenance, costs, accident risks and hazards, space, and noise, are some of the main concerns of residential end user in choosing a storage system. According to German advisory group Team Consult, the installed capacity of batteries in Germany alone is to three-fold in 2017, from 60 MW to almost 200 MW [28]. This is mostly due to the ever-increasing need of the households to absorb more onsite generated solar PV electricity. Table 4 summarizes the key technical characteristics of storage technologies for behind-the-meter application.

Table 4 – Technical requirements of different behind-the-meter services (own analysis and [16–18])

Services	Capacity scale	Discharge duration	Response time	Potential technology
Decentralized electricity generation	Up t0 100 MW	Hours-days	Seconds-minutes	Batteries
Renewable energy integration	1kW – 20 MW	Minutes-hours	Second-minutes	Batteries, supercapacitors
Energy cost management	20 MW	Hours-days	Second	Batteries, flywheels, fuel cell
Energy arbitrage	Up to MW	Hours	Hours	Batteries
Peak shaving	Up to 1 MW	Hours	Minutes	Batteries, TES
Back up power	Up to 5 MW	Minutes- hours	Seconds	Batteries
Provision of ancillary services to upstream grid	Up to several MW	Seconds to hour	Millisecond, Seconds	Batteries, flywheel, fuel cell, supercapacitors

As shown in Table 4, the discharge duration mainly depends on the type of clients and also on the main value proposition. For example, for services such as black-out and outage the consumers require longer discharge duration. The number of cycles of storage technologies should be proportional to consumer's usage, as the consumer do not opt for frequent replacement of storage technologies.

Power rating is useful for peak shaving services, and it typically depends on the peak demand rating of the household or the facility. It can range from a few kW for households to hundreds of kW for facilities or companies. For behind-the-meter applications, the response time is also an important feature, especially if the assets are used for peak-shaving, or to back up outages. From milliseconds to hours could be required for end-uses to meet their demand, for example for critical electrical devices. Lastly frequency of use is daily for peak shaving and weekly or monthly for continuation of power supply.

In addition, several issues arise from the storage facilities being close to consumers. Among these, *safety issues* are of the utmost importance. Storage technologies should be safe to avoid domestic fire and not pose any danger to the end-users. The safety issues have a major influence on consumers' willingness to adopt these storage technologies. Furthermore, *ease of use, installation and maintenance* is also key for a wide scale adoption by residential end-users. The user interface needs to be simple enough for the customer to perform basic maintenance operations.

II.2.3. Market characterization

Estimates of the current and future market size for behind-the-meter storage are limited and in Europe they are largely focused on Germany, due to its particular market structure. In Germany, domestic PV systems are already widespread, leading to the emergence of electricity prosumers. New business models and financing schemes are emerging in the market. Benefiting from high levels of subsidies, Germany is currently dominating installation of PV plus storage systems [29]. Nearly 2% of households with PV systems had battery storage installed in 2014 [30]. In Europe, in addition to Germany, Sweden has introduced hourly billing which enables benefiting from behind-the-meter storage assets through energy arbitrage and load levelling. However, as the price of electricity is low in this country, the financial benefits are low and that weaken financial values of storage technologies.

According to different analyses [29,31,32], behind-the-meter storage is expected to take-off in the next few years, pushed by the deployment of distributed solar PV systems, both for the residential and commercial sub-segments.

The IEA projects in its New Policies Scenario that the solar PV installed capacity in buildings will grow worldwide from 87 GW in 2013 to about 250 GW in 2020, with Europe, China, India, Japan and the US contributing the largest shares of this [33]. In another projection by IRENA, the growth of rooftop solar PV would increase potentially to 480 GW in 2030, when it was 3 GW in 2010 [34]. This illustrates a large market potential for energy storage for behind-the-meter application.

II.2.3.1. Policy and legislation analysis

The behind-the-meter application of storage technologies can benefit from the political actions supporting renewable energies due to two reasons:

- behind-the-meter storage is closely correlated to domestic solar PV system and therefore promoting a larger share of investments in PV would create a more competitive business case for energy storage;
- Development of renewable energies is coupled with a growing share of intermittent energy in the system. This motivate investments in energy storage at behind-the-meter where distributed RES are installed, as it could enhance the flexibility of the system.

In this line there are policies that could demotivate installation of storage asset at behind-the-meter [11]:

- There is need for hourly billing in order to further financially value from storage assets. This is however only the case in only a couple of European countries. The tariffs structure and tariff level along with technology costs are the key parameters of the business case for an end-user. Energy cost management using varied grid tariff at different time of the day is the most important identified value stream for behind-the-meter storage. The energy cost management involves a value transfer from the DSOs to the customers and will undoubtedly cause a transformation in utilities business models or tariff structure.
- If net metering tariffs are applied for PV panels, this would reduce the business case for self-consumption,
- Often lower tariffs are more common than maximum power level.

Moreover, behind-the-meter storage can be closely related to distributed energy resources and its development partly supported through policies favouring the use of distributed energy resources. In Europe, Germany has subsidized over 10,000 power storage systems since 2013, totalling € 163 million Euros [35].

The German development bank (KfW) supports battery storage systems as of May 2013 by offering low-interest loans and repayment subsidies for solar PV plus a fixed battery storage system installation. This support scheme only applied to solar systems of maximum 30 kWp, with effective power reduction to 60%. As the result of this scheme the installed systems grow from 8.000 systems in 2013 to above 15.000 end 2014 [11]. These incentives have led to the development of energy storage and it is facilitating the penetration of RES to reach the Germany's 50% renewable electricity target set in the *Energiewende* for 2030 [30].

In addition, legal issues related to ownership of storage assets can influence the development of energy storage. Storage ownership is a significant factor for behind-the-meter application as the distributed storage development has a direct impact on the revenues coming from demand charges. This in particular will affect the revenue and position of DSOs in the electricity system.

In Europe, if behind-the-meter storage expands, DSOs need to decide whether to extend their scope of operation or focus on traditional regulated activities. Further legislations are expected in Europe to clarify this legal aspect about what DSOs can or cannot do. The evolution of this market segment is thus unclear for the moment.

II.2.3.2. Market acceptance

Social acceptance with regards to the development of behind-the-meter application is expected to be positive and influential. This is because European customers are sensitive to climate concerns and aware of existing climate challenges. Many early adaptor, for example in Germany, consider both PV and energy storage as a solution for the future environmental problems. This particular mindset will be an important factor for the early development of behind-the-meter storage in European markets.

The position of customers in the development of this application will be significant as it requires Business to Customer (B2C) interactions, and therefore an enhanced effort on ergonomics and customer-centered marketing. One convincing example of storage technology for customers is the launching of the Tesla Powerwall battery marketed as "Beautifully Functional". This trend shows that the development of behind-the-meter application requires the seduction of the end-users that will have to accept and buy the product for their own house. Safety issues are another factor that influence end-user's willingness to adopt storage systems. The quality standards by manufacturers and distributors are crucial to address these issues.

Another factor that can influence the society's view about the behind-the-meter storage application is tariff structure. Moving towards coincident or critical peak demand pricing or time-of-use tariffs provides greater incentives for demand-side management, and hence consumer-level energy storage.

II.2.3.3. Storage operators and business model

Business models for behind-the-meter application are numerous and actors' activities can greatly vary from one to another. Four main models appear for this segment.

Consumers owned assets not capturing market value. Consumers invest in the energy storage system and seek to optimize their electricity bill, for both network and energy charges. Depending on locally applied grid tariffs and potential arbitrage revenues, the revenues from the storage could globally recover the costs of the system. A consumer has a partial control of the system. He/She decides the right level of control delegation according to the operational constraints of the technology. The consumer can be assisted by a third party for the day-to-day operation optimization. The third party can have a partial control of the storage via remote monitoring systems. Technology providers may offer this type of services. The DSO has no control on the system in this case. However, it can include conditions in the incentive scheme for the consumers (e.g. peak shaving target).

Consumers owned assets capturing market value through aggregators. As in the previous case, the consumer invests in the energy storage system and seeks to optimize the electricity bill, for both network charges and energy charges. Additionally, the consumer has a contractual agreement with an aggregator who is registered on the market, to increase the arbitrage revenues. The aggregator takes the market operation responsibilities. It can either have a direct control on the system or just send orders to the consumer or another third party. In any case, market operations are limited by the consumer's operational constraints. This model strongly depends on a suitable aggregator which can bid on the market. The distributor still has no control on the system in this case. However, it can include conditions in the incentive scheme for the consumer (e.g. peak shaving target).

Distributors own storage assets for network services. The investment is made by the distributor. The distributor keeps the ownership of the energy storage device, which is maintained on the consumer's premises. Thus, the storage system is "embedded device" of the distribution network.

The storage system is designed to provide network services. It shall be aggregated by the distributor with a set of distributed storage devices over the network. All storage devices are integrated in the distributor's Regulated Assets Base, and so are eligible for cost recovery through regulated revenues. In some cases, the consumers can also benefit from the storage system through its retail tariffs (gains on both network charges and energy charges). If so, the consumers can contribute to the investment (e.g. paying the installation costs).

The distributor keeps the whole control of the distributed storage devices. The devices are dispatched remotely, in case of congestion or reliability events. The distributor defines the adequate level of control (e.g. feeder, substation, storage device, etc.) to manage efficiently the network. To make this control feasible, the target application must have minimal operational constraints. The storage device should for instance not be "invasive" in the operational processes of industrial customers. At last, the consumer can be assisted by a third party for operation optimization. The third party can take the control of the storage on behalf of the distributor. Technology providers may offer this type of services.

Storage as a service - third party owned assets capturing market value. The investment is made by an independent third party company. The company keeps the ownership (total or partial in case of a lease) of the device, which is maintained and operated on the consumer's premises. Thus, the storage system is a "beyond-the-meter" asset but the consumers only sees the service of storage: the end consumer sees no upfront costs and only a share of the savings.

The third party company seeks to optimize the consumer's electricity bill, for both network charges and energy charges; it can also act as an aggregator to increase revenue streams. The consumer and the company have a contractual agreement to share the benefits coming from the operation of the storage.

Storage-as-a-service is therefore expected to become the most attractive business model from the consumer point of view. This is because the consumers can benefit from storage services, while do not need to gain the expertise to manage and control the storage assets, and they do not endure upfront cost.

However, as explained earlier DSOs may react to the expansion of distributed storage assets that could affect their activities.

II.2.3.4. Value chain

Value chain of behind-the-meter storage system is depicted in Figure 8 and is largely based on the German examples. In these markets, types of actors and associated business models are numerous and associated range of activities can greatly vary from one actor to another. However, the main identifiable trends are:

- Storage system integrators and vendors are responsible for client relationship and work with suppliers to pro-pose a packaged and efficient storage system.
- The level of proprietary technologies in these systems can vary greatly among vendors. As an example, Tesla works with Panasonic to develop their own system whereas other companies focus on the energy management systems and financial offers to customers.
- Storage system vendors are entering partnerships with solar systems providers to offer customers a global package offering optimized performances.

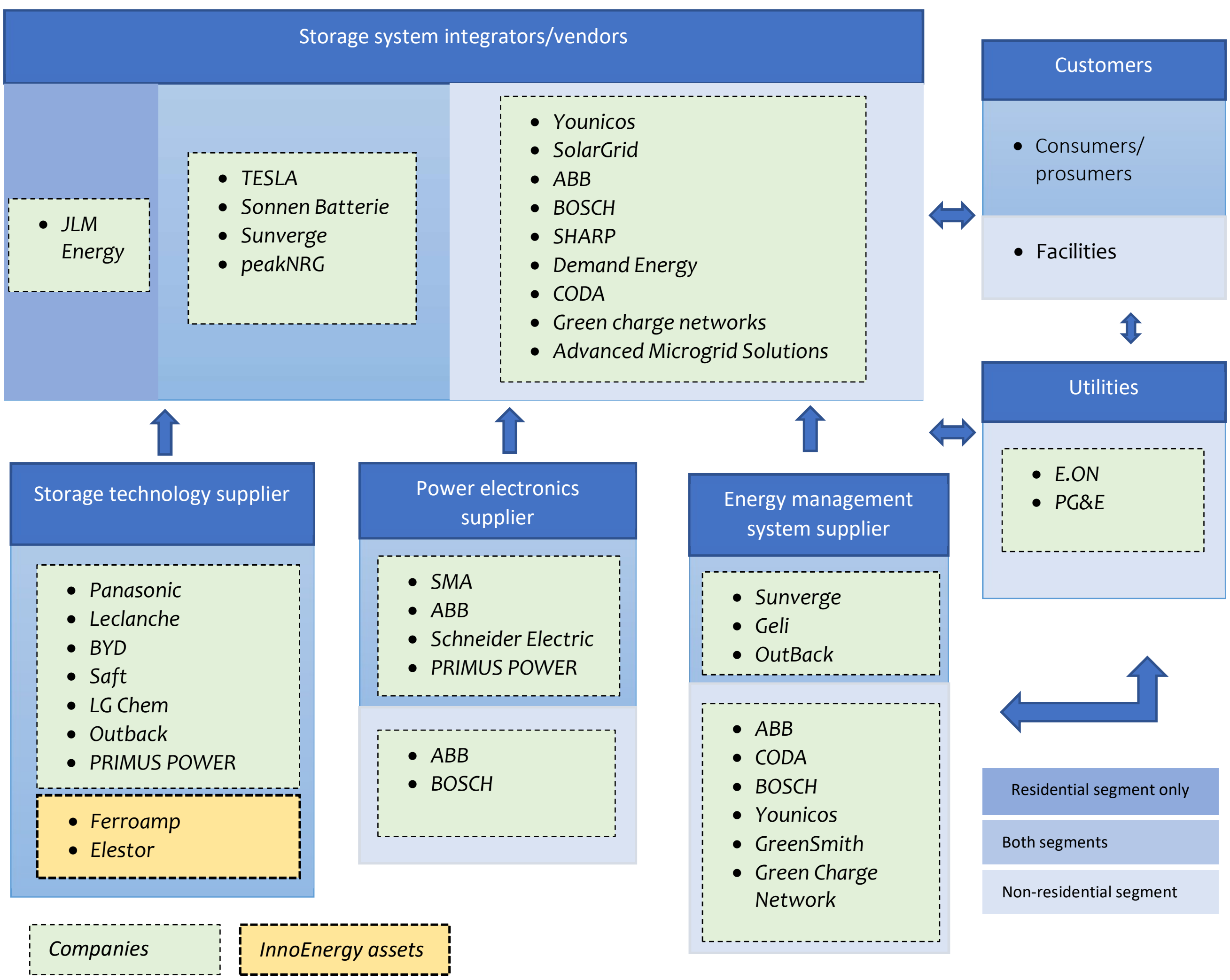


Figure 8 - Value chain and main actors of behind-the-meter application, non-exhaustive list

II.2.4. Market challenges

There are several challenges hindering the deployment of behind-the-meter application:

- **The complexity of electricity bill charges**: Solar PV plus storage systems allow consumers to reduce their demand and energy charges, but the fixed costs associated with the consumer connection to the grid do not decrease and are still borne by the DSO. Repartition of the bill between these three types of charges is key to understand the business case of behind-the-meter storage.
- **Economic viability of energy storage:** The economic viability of these projects is still vulnerable to how "cost reflective" electricity pricing will be implemented by DSOs. The design of retail tariffs for end-users will directly impact the business case for pairing solar PV with energy storage. The future attitude and role of utilities and corresponding regulatory frameworks (incentives vs. taxes) will greatly influence this development. Current market analyses show that governments would support application of energy storage. However, some regulatory changes, such as the recent announcement of a tax on auto-consumption in Spain, show that the evolution of regulatory frameworks might lower the competitiveness of energy storage.
- **Energy storage upfront cost**: currently, it is not yet clear who should own storage assets and endure upfront costs for behind-the-meter application. High upfront cost and long (and uncertain) payback time is a challenge for potential customers, especially household consumers.
- **Lack of commitment to invest in energy storage:** Currently potential energy storage investors, including utilities, distributors or consumers for the behind-the-meter application do not fully commit to the development of storage asset at behind-the-meter.
  When it comes to utilities, today, the problem – known as the "utility spiral of death" – is largely experienced by German utilities that see the grid maintenance costs going up and the capital cost of renewable energy moving down, encouraging a lower reliance of consumers on the network. In turn, that pushes grid costs even higher for the remainder of customers, who then have even more incentive to become self-sufficient. To face this "spiral of death", the utilities will have to adapt, for instance through owning and operating behind-the-meter storage asset. Otherwise, new tariff structures or taxes will have to take into account the impact of behind-the-meter storage on utilities costs recovery. The willingness of utilities to take part or not in the market shift will be an important factor for the expansion of these resources, but the future evolution of the regulation on both their scope of action (e.g. ownership of storage equipment) and their level of flexibility on pricing will be the starting point of any utilities decision for energy storage.
  Ownership of storage assets at behind-the-meter by DSOs faces similar issues. Because, the development of distributed storage has a direct impact on DSOs revenues coming from demand charges. Behind-the-meter storage requires the DSOs to adapt their business models. If behind-the-meter storage expands, DSOs will necessarily have to clarify their position and decide whether to extend their scope of operation or to refocus on traditional regulated activities. Further legislations are expected, in Europe to clarify this legal aspect about what DSOs can or cannot do. For the consumers, as explained in the last point, energy storage cost is still a barrier.
- **The role and position of aggregator.** To accelerate the development of behind-the-meter application, the role and responsibilities of the aggregators in many cases need to be further clarified in Europe. An aggregator consolidates or aggregates a number of individual customers and/or small generators into a coherent group of market players and aims at optimizing energy supply and consumption both technically and economically.

Without an aggregator or retailer, it would be difficult to monetize revenue streams of energy cost management, utilization of variable renewables or consumption offset from the grid. As illustrated in Figure 9, the actual status of aggregators differs from country to country. The aggregation ranges from a legal status with the possibility to participate in different markets in the UK to undefined status in Spain. As noted in this study, aggregators are expected to further develop thanks to an evolving regulatory and technical framework in Europe.

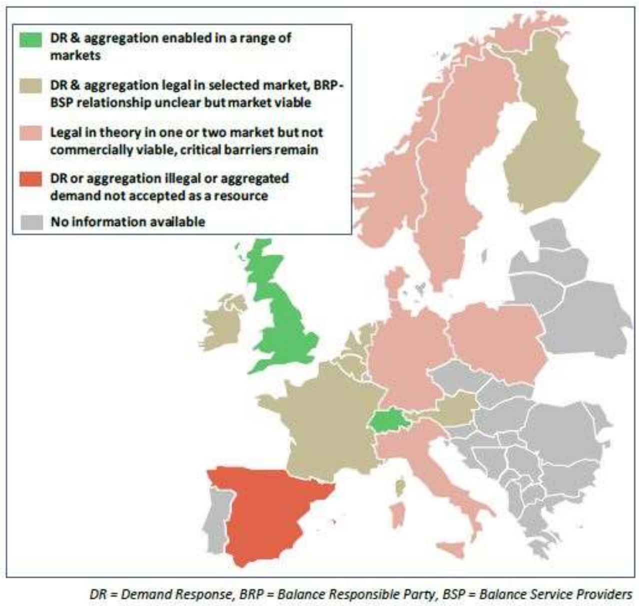


Figure 9- Mapping aggregation and demand response in Europe [36]

II.2.5. Market drivers and scenarios

1) **Policy supports (related to RES, storage, net metering).** It is expected that the policies supporting the deployment of distributed electricity generation, including RES generation, and national targets for RES penetration to positively influence the development of the behind-the-meter application. Likewise, policy supporting or restricting storage (e.g., double taxation on storage) can affect future cases of the energy storage. Another group of policies that can boost this application concerns the application of net metering. It is notable that while often the regulations are discussed at EU level, some countries such as Germany or Sweden are early adaptors and have already subsidies for this sector.
2) **Tariff structure and levels:** When dynamic pricing applies, tariff structure and levels along with technology costs, are the key parameters influencing the end-user's final energy cost. Accordingly, regulations on tariff structure will make energy storage attractive to end-users and are triggering factors for the implementation of behind-the-meter storage.
3) **Society acceptance and awareness:** Public acceptance and awareness about the benefits of energy storage can contribute to the deployment of behind-the-meter applications [37]. For example, consumers could be interested in using RES or favour energy independency, both of which support the position and role of storage technologies for the behind-the-meter application. Also, consumers may have concern about the maintenance and control processes for storage assets at their residential buildings, which should be addressed.

4) **System integration:** As the storage assets for behind-the-meter applications are installed at the behind-the-meter thereby consumption points, system integration is essential to enable benefiting fully from the storage assets. Energy storage at household level could be integrated with the grid and enhance the reliability and stability of the system.
5) **Storage plus RES (PV) cost:** as discussed earlier, one of the growing cases for behind-the-meter application is when storage is combined with PV installations in residential locations. This means the combined cost of PV and storage installation is a decisive factor on the consumers' investment decisions. Supportive policies motivating installation of RES and storage assets could hence contribute effectively to the installation rate of storage.
6) **Standardization of storage system for behind-the-meter**. Standardization of storage system through predefined storage installation, safety, recycling can decrease the cost of storage services effectively and therefore is a driver for the development of these systems.
7) **Regulations for storage operators.** The business model that outlines who should endure the upfront cost of storage assets and is responsible for maintenance and controlling of the storage system is an important market driver. Currently due to uncertainty in the market there is lack of commitment to investments in storage assets.
   This roadmap recommendation is for storage as a service business model, because the consumers of storage assets are often not energy experts hence their understandings of the storage and its benefits are limited. A third part can assure functionality of the system, and create value for itself and consumers. This business model could influence the performance and value generation of DSOs and therefore may faces their opposition.
8) **Advances in e-mobility sector**: stationary storage technologies, particularly batteries, are currently dominating the behind-the-meter application. This means that any improvements in stationary batteries, could result in a larger deployment of the behind-the-meter application. In recent years, the e-mobility sector and the large production of electric vehicles have contributed to improvement in price and performance of batteries. Future co-evolution of mobility and behind-the-meter storage applications is expected to remain a driver for both applications.
9) **Black-out:** Changes in electricity systems and global environment could lead to a higher chance of black-outs in the future. In that case, the consumers may gain interests in having energy storage to avoid outages. This incentive is particularly important in organizations and companies whose services are significantly affected by electricity outages, such as hospitals or financial institutes.
10) **Technology innovation:** as the behind-the-meter applications of storage assets depend on consumers, the cost and energy density of the technology, and its safety remain the most important factors for the application development.
   Technology innovation will directly affect technology cost and motivate further application of energy storage. For example, the technology cost could be reduced through finding substitute materials for storage technologies. This in particular can be reached through research and development in new chemistries for liquid electrochemical batteries, deployment of environmentally benign and more abundant organic materials for flow batteries, and the use of recycled materials. Different innovation approaches leading to technological innovation are discussed in section II.1.5.

Table 5 - Market drivers and scenarios for behind-the-meter

Vision for storage deployment to 2050			Time frame
Drivers		Optimistic	
Behind-the-meter	Policy support	Policymakers enact supportive policies that promote a larger share of RES, storage or net metering all boosting the development of storage. Policymakers provide incentives both in form of financial and technical supports for end-users to install storage in their private residence. These policies increase the share of energy storage in the market	2025-2030
	Tariff structure and levels	The billing of energy will become more transparent and that will inform consumers about the cost of connection to the grid, and also time-of-use pricing schemes. In this situation, the consumers become aware of tariffs costs and therefore consider investments in energy storage as a mean to avoid high tariff costs. This create a stronger business case for energy storage technologies installed at behind-the-meter.	2025
	Society acceptance and awareness	Investments will be made in educations and programs to increase the awareness of end-users about the benefits of energy storage. Development of further safety and performance standards, and informing consumers about who will be in charge of the maintenance and controlling of the storage system address consumers' safety concerns.	2025
	System integration	The storage systems installed at residential or industrial consumption points will be integrated into the grid for optimizing the use of energy storage applied at behind-the-meter. Based on the emerging business model, TSOs or third party could be involved in the system to utilize the excessive energy in the storage.	2025
	Storage cost plus RES (PV) cost	Policies and subsidies will be introduced in the market to reduce the cost and increase the competitiveness of investments in storage plus PV. This will gain the interests of society to contribute to storage plus PV installations.	2020-2025
	Standardization of storage system	Initiatives will be made to publish standards on energy storage installation, safety and performance at behind-the-meter. This will reduce the cost of storage services and increase their market share.	2020-2025
	Regulation for storage operators	Regulators will clarify who should be the main owners of energy storage technologies and operate the system at behind-the-meter. The recommendation is to foster storage as a service as the main business model, which can create value both for the third party and the consumers. This business model also will address consumers concerns about the storage services and maintenance.	2020-2025
	Advances in e-mobility sector	Larger production of electric mobility will bring down the cost and enhance the performance of batteries. This will also reduce the cost of storage systems installed at behind-the-meter.	2020-2025
	Black-out	Changes in the weather condition and/or imbalance between energy generation and consumption could lead to a more frequent black-out and outage in the European energy system. This increase the interests in storage system in order to avoid the black-outs and outages.	2020-2025
	Technological innovation	The development of the storage technologies will be supported through government and industry funded R&D program, technological structural change, and learning curves. Researcher and scientists will find innovative solutions and substitute for technologies' materials, performance and efficiency. This in turn will increase the industry motivation to invest in further deployment of storage technologies.	2030-2040-2040

II.3. Off-grid

II.3.1. Application services and benefits

Off-grid applications of energy storage range from individual off-grid energy systems for homes, telecom towers to any remote / isolated consumer to mini-grids. This market segment includes a variety of situations, from households without access to electricity, to communities and facilities located in remote areas (e.g. small islands) as well as off-grid and remote telecom towers. This application is not common in Europe, because most of the inhabited areas are electrified. The application excludes nomad applications dedicated to specific usages such as solar lanterns. The application provides following services:

- **Off-grid supply**: The off-grid energy storage can decouple electricity generation from the load, thus ensure continuity of supply for electricity consumers in off-grid areas.
- **Diesel generation replacement:** Replacement or hybridization of existing diesel generation motivates the off-grid application of energy storage. Diesel generation has traditionally been used as the most accessible and cost-effective solution for off-grid energy production, but there are currently other generation sources available (e.g., RES) that together with storage are more reliable and sustainable.
- **RES integration**: Renewable electricity generation is becoming increasingly competitive with diesel generation in many remote areas. This is especially since RES are becoming cheaper, while providing a clear and reliable source of energy. Energy storage allows storing the energy of intermitted RES and using that energy throughout the day when needed. Therefore, energy storage would facilitate integration of RES in remote and off-grid area by contributing to their reliability and stability.
- **Microgrids:** rural areas necessitate to deploy microgrids in order to satisfy their needs. There are several strategic locations, such as hospitals and military facilities that would be the first to benefit from microgrids. Microgrid will foster development of several technologies including storage, and energy and distribution management systems. Today most islands and many off-grid areas, also in Europe, are powered by diesel generation, often sized to meet peak demand [7,38]. For these sites, microgrid storage systems can be a good substitute, especially since price, remoteness, fuel transport cost, and lack of infrastructure related to diesel generation results in supply security risks.
- **Telecom towers:** In off-grid locations, several telecom towers are located. These towers often do rely on diesel generators. However, storage-based solutions integrated with solar power options could provide a more efficient, environmental and economically viable options. The growing demand for connectivity has resulted an expansion in the telecom towers network. This create a big business case for energy storage as they can reduce the cost of telecom towers extensively[39].

II.3.1. Technology characterization

Requirements for technologies dedicated to off-grid storage applications depend on types and needs of targeted off-grid consumers, and also types of energy sources used for energy production. Generally speaking, off-grid systems serve fewer and less diverse consumers than national grids [40]. The energy usage by consumers connected to off-grid system could be simultaneous and daily load profiles are often more volatile. The most commonly used technologies are battery technologies. This comprises a wide range of sizes and battery technologies, from secondary batteries like lead-acid, Li-ion to flow batteries such as Vanadium-Redox batteries [41]. Off-grid solar systems in tropical islands and remote areas are among the fast rising markets for residential-scale batteries.

Table 6 summarize the main technical character for this application.

Table 6 – Technical characteristics of different off-grid services (own analysis and [16–18]*)*

Services	Capacity scale	Discharge duration	Response time	Technology
Off-grid supply	10s of Watts to several 10s of MWs	Hours	Seconds - minutes	PHS, TES, Fuel Cell, Batteries, CAES, supercapacitors
Diesel generation replacement	Up to 10s of MWs	Tens of hours	Millisecond to second	Batteries and supercapacitors, PHS
Renewable energy integration	10s of Watts to several 10s of MWs	Tens of hours	Seconds - Minutes	Batteries, supercapacitors, SMES, fuel cells, CAES
Microgrids	10s of MWs	Tens of hours	second	PHS, TES batteries
Telecom towers	Up to 10s of MWs	Hours	Milliseconds to seconds	Batteries, Fuel cells, flywheels

Off-grid energy storage systems should keep a balance between supply and demand at the level of a household or mini-grid. Typical variations in terms of supply and demand cover a day period, resulting in a daily frequency of use and a discharge duration of tens of hours. This discharge duration should allow for an autonomy of several days depending on the associated load profiles. The storage technology should have enough energy capacity to meet demands of a household or mini-grids. Power rating for off-grid energy storage depends on the maximum load of the consumers served by the system. As a consequence, it may vary from as low as 10 W for households using few and low-consumption appliances (e.g. some LEDs, one radio) to around 100 MW for large mini-grids and energy-intensive isolated facilities. Response time depends on the criticality of the system and equipment served. For household and community applications, the response time could be in the order of seconds, whereas it may be as low as milliseconds for more critical off-grid consumers (e.g. telecom towers).

Furthermore, off-grid energy storage systems shall be robust, easy and safe to install and use, because in remote areas, often there are limited opportunities of emergency interventions, and operational constraints exists (e.g. environmental conditions). Besides, energy storage for the off-grid application should be securely installed given the higher risks of theft in many remote locations.

II.3.2. Market characterization

The development of off-grid storage application is supported by strong international commitments to provide sustainable and universal access to modern energy. Off-grid energy storage together with intermitted RES energy generation could be an option for the replacement or hybridization of existing off-grid diesel-based energy systems.

Off-grid energy systems would be more popular in remote and isolated areas with penetration of energy storage [7]. This includes mainly islands and areas far from national grids. Therefore, the main market potential for this segment remains where the current grid infrastructures are least developed, i.e. in emerging and developing countries, particularly Asia, Sub-Saharan Africa or sparsely populated areas (e.g. Australia).

IEA estimates that the number of people without access to electricity was 1.3 billion in 2010. This number should decrease to 1 billion in 2030. Renewable energy integration together with energy storage can play a significant role in that. To store only half of the supplied solar energy daily, there is a need for a minimum of 21 GWh of energy storage off-grid African systems by 2040.

II.3.2.1. Policies and legislation analysis

International commitments to provide sustainable energy access for all is gaining a momentum. Both international and national initiatives worldwide consider the off-grid system as a solution for electrifying rural areas. This could be translated into a favourable environment for investments in off-grid energy storage.

In Europe for off-grid and mini-grid storage application the enacted legal and regulatory frameworks should clarify unbundling policies, since for off-grid energy storage application owners need to generate, transmit, distribute and sell electricity.

II.3.2.2. Market acceptance

Consumers often have poor perception of off-grid energy solutions. They often believe that off-grid markets offer poor-quality or basic products and/or services. This poor perspective is also emphasized by policies that support grid-electrification. This is an issue at the global level and as mentioned first Europe is widely electrified and second, European consumers are more concerned about environment. Accordingly, European consumers may consider investments in energy storage, if it provides them with a more environmentally friendly solution.

II.3.2.3. Storage operators and business models

Storage for off-grid applications is a component of stand-alone systems, which comprise both generation and distribution assets. The business models for off-grid application therefore cover the whole energy systems. Multiple ownership models exist for this segment, which depend on a number of factors including: (1) The size of the system: the smaller the system, the more likely it is owned and operated by the final electricity consumer; (2) The regulations in place: while less important for individual systems, regulations have a great influence on mini-grids ownership models. The following types of business models can be distinguished[40]:

Individual systems- equipment sales: These types of models have been historically applied for individual systems, where a company designs, manufactures, distributes and/or sells a storage system to final electricity consumers. These business models usually face challenges in addressing the issue of high upfront cost, finding finance for equipment, and in building finding the right distribution channels to reach their customers.

Individual systems- leasing & pay-as-you-go models: In these models, the offer can be referred to as "energy-as-a-service", with companies proposing to install simple energy systems at their customer location at no cost or with a small, sometimes refundable, deposit. In turn, the customers pay for the energy they consume from the installed system. These models become increasingly popular with the fast deployment of mobile use and especially mobile payments that enable efficient prepayment.

Mini-grids- utility operator model: In this model, the government or the national utility manages all the aspects linked to the mini-grids. Hence, the investment is made by the national utility that operates and maintains the mini-grid including the storage asset. The national utility develops and collect electricity bills depending on the pricing system in place. This model is expected to be easy to implement and less subject to regulatory constraints, since it is based on regulations applying to the national grid. However, the national utilities do not consider mini-grids as their core business and their management structures are not adapted to the smaller projects.

Mini-grids- community-based models: In this model, the community members own the storage assets and manage generation and distribution. This model often requires assistance from an NGO or a company since insufficient local human capacity and knowledge (technical and management) on energy system (including energy storage) is a clear bottleneck. In Europe, there has been interest in this business model.

Mini-grids- private operator models: In these models, a private entity plans, builds, manages and operates the mini-grid system. The funding depends on private equity and commercial loans as well as public support through grants, subsidies, etc.

Mini-grids- hybrid operator models: In these models, different entities may build, own, operate and maintain the system. This basically covers the different forms of public-private partnerships, in particular the rural energy services companies where the government owns the system while a private entity builds, operates, maintains and collects revenues from energy sales. It can also take the form of concessions, where governments grant exclusive rights or beneficial terms to companies for a certain area or a period of time. These models can be more attractive in the sense that they build upon the strength of different actors. However, they may be difficult to implement.

II.3.2.4. Value chain

An illustration of the value chain decomposition is shown in Figure 10. Compared to the other segments, the following points shall be noted:

- Most off-grid storage systems are integrated into stand-alone energy systems comprising generation and distribution. Mini-grids also feature integrated generation systems.
- Mobile network operators are often key to the deployment of these off-grid solutions since they provide innovative mobile pre-payment solutions and enable remote operation and monitoring of the system.
- With regards to individual systems, most distributors and installers are small, multi-products actors located close to the final electricity consumers. Some systems integrators may also act as product wholesalers though.

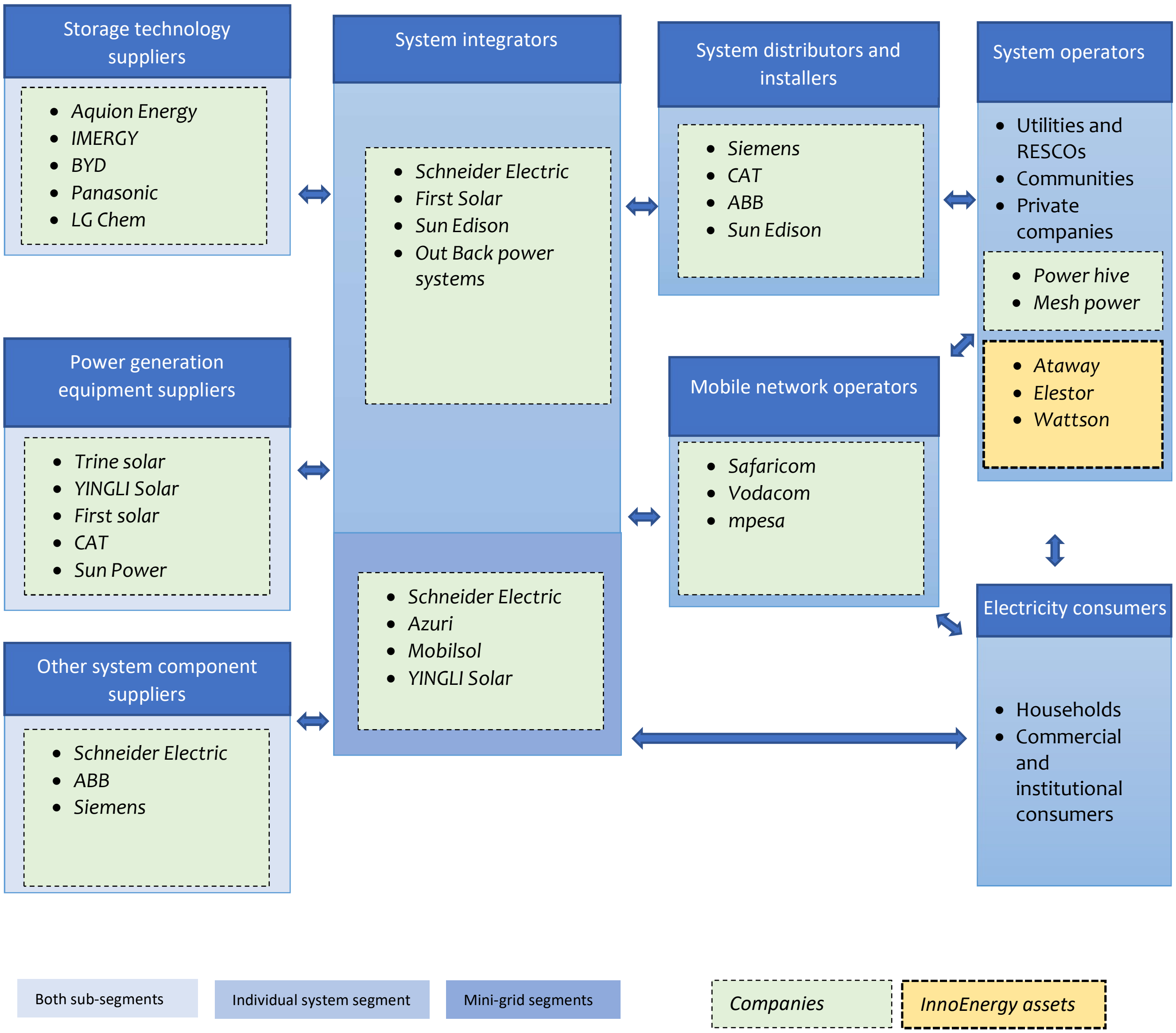


Figure 10 - Value chain and main actors of off-grid storage segment, non-exhaustive list

II.3.3. Market challenges

The following challenges hinder the development of energy storage technologies for off-grid applications.

- **Lack of supportive national policy**: Supplying electricity to individuals is often challenging, with long, complex and numerous regulatory processes. Lack of coordination between off-grid storage application and existing policies (especially when the priority is given to grid extension) and agencies lead to a confusing environment for investors. National energy policies and planning still lack a clear framework for off-grid solutions as compared to grid development, in spite of recent changes. There are legal constraints for individual off-grid systems, and also for the development of mini-grids.

- **Capital intensity:** Access to finance is vital to support the deployment of off-grid storage systems, due to two reasons: (1) the systems tend to be more capital-intensive than the alternative options such as diesel and (2) limited experience and remoteness often translate into higher risks for investors. Off-grid systems, especially when functioning with RES generation plus storage, are competitive compared to diesel generation, but they are generally more capital-intensive due to country risk premiums and technical risk premium.
- **Negative customer perspective:** Early off-grid deployment initiatives were largely labelled as “energy for the poor” and sometimes featured poor-quality products and services. Therefore, customer experience and perception of products and services is not always positive.
- **Uncertainty about grid infrastructure:** The development of grid infrastructure is often surrounded by great uncertainty. It is expected that grid extension will remain the priority where demand levels and density are high. The average cost of supplying grid-based electricity will remain below the cost of the alternatives due to economy of scale [38]. As a consequence, even though off-grid solutions can act as an important stepping stone to grow demand and improve the viability of grid connection at a later date, their long-term potential remains focused on islands or scarcely populated areas.

II.3.4. Market drivers and scenarios

1) **Financial support (by government, industry):** Access to finance emerges as a key enabler for the deployment of off-grid systems that include storage. The upfront costs of storage have resulted emerging leasing business models in order to make off-grid systems more affordable. Through further installation of off-grid energy storage, a track record will be available and that successively can facilitate and increase knowledge about finance sources.
2) **Grid extension deferral:** Grid extension has been a preferred solution for enhancing energy access in the remote areas, where currently are often supported by diesel generators. Recently, the off-grid individual systems and mini-grids have been recognized and highlighted as alternative solutions. For example, in north of Sweden there are flats available that are not electrified and are supported by diesel generation. Investments by the Swedish government in grid extension will delimit investments in off-grid energy storage in these areas. The decision for investments in energy storage or grid extension depends on which solution is more cost efficient.
3) **Grid cost:** when the cost of investments in grid is less efficient than energy storage, it could drive investments in off-grid energy storage assets. In some regions, investments in storage plus RES could offer a more cost competitive project than building several kilometers of grid for a limited number of consumers. The price of energy storage in compare with grid extension could become more competitive in the future.
4) **Local perspective:** Most companies serving the off-grid market are now putting an emphasis on improving the customers’ experience. For instance, they adapt their product and service based on different customers’ needs; they raise their quality standards by switching to higher performance energy storage technologies; or monitor customers’ use to address their need. These investments in customers’ experience may result in higher acceptance of the technology by them.
5) **Diesel and gasoline fuel’s subsidies:** Diesel or gasoline are subsidized in some countries [38]. Pressure for phasing out or reducing these subsidies is increasing, primarily as a result of their

burden on the public budget [33]. Reduction of these subsidies may shift the interest of segments of the market to energy storage, which when is coupled with RES energy, can provide an alternative solution for electrification of remote areas.

6) **Diesel and gasoline fuel's transportation cost:** In many countries transportation of diesel and gasoline are costly, due to the expenses and challenges such as risk of theft or safety concerns. Higher cost of transportation would result in more motivation for installation of energy storage in remote areas.
7) **Technological innovation:** technological innovation through approaches and processes mentioned in section II.1.5 and II.2.5. can reduce the cost of energy storage also for off-grid energy storage application. Please note that for this application, there is a special need for innovation in technologies that can allow long term energy storage.

Table 7 - Market drivers and recommendations for off-grid

Vision for storage deployment to 2050			Time frame
Drivers		Scenarios	
Off Grid	Financial support	Governments financially support the consumers in off-grid (rural) areas to install energy systems powered by RES plus storage. This support will motivate new investments in and larger share of energy storage. New finance model such as leasing will decrease the upfront cost of off-grid systems and pave the path for further installation of energy storage.	2025-2030
	Grid extension deferral	The market focus will shift from a centralized energy system and investments in grid to decentralized generation and consumptions. Large investment will be directed in RES generation and energy storage to provide rural areas with access to sustainable and reliable energy.	2020-2030
	Grid cost	The cost of investments in energy storage assets will become more competitive when compared with the cost of grid extension. This competitiveness motivates investment in off-grid energy storage.	2025-2030
	Local perspective	Programs and campaigns will help increasing the awareness of society and consumers about the off-grid energy solutions. This in turn will gather their support (both financially and socially) for further expansion of off-grid energy system, thereby energy storage. Knowledge on energy independency and cost management will contribute to storage deployment.	2025
	Diesel and gasoline fuel's subsidies	The subsidies for diesel and gasoline fuel will be reduced. This will enhance cost competitiveness of energy storage in off-grid areas when is compared with alternative solutions (e.g., diesel). Accordingly, the technology's share increases due to larger market interests.	2025
	Diesel and gasoline fuel's transportation cost	The transportation of gasoline and diesel fuel will remain costly and risky due to long distances and lack of road safety. This barrier further motivates investments in energy storage in off-grid areas as a cheaper and safer solution.	2025
	Technological innovation	The development of the storage technologies will be supported through government and industry funded R&D program, technological structural change, and learning curves. Researcher and scientists will find innovative solutions and substitute for technologies' materials, performance and efficiency. This in turn will increase the industry motivation to invest in the deployment of storage technologies.	2020-2030-2040

II.4. Mobility

II.4.1. Application services and benefits

This application focuses on storage systems used for mobility in on-road four wheels individual and fleet vehicles. It includes **electric vehicles (EVs)** with plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) and **hydrogen vehicles powered by fuel cells (FCVs)**. These systems are powered by an external source of energy and then disconnected before motion occurs, and the energy is stored in the vehicles until its use by an electric motor. This type of vehicles requires storage systems, whether electrical or chemical, and their uptake will hence foster demand for storage devices.

Another service of energy storage mobility application is **vehicle-to-grid**, which refers to when plug-in EVs, both BEV and PHEV, contribute to demand response services by discharging their electricity to grid or throttling the charging rate.

Mobility in all its forms, including private and public transport, accounts for 20% of all GHG emissions in Europe (See figure 10), of which 75% are in roads. Accordingly, electrification of this sector can help achieve decarbonisation. However, this is only reached when electricity and hydrogen are produced with renewable energies or with fossil fuels integrating CO_2 capture. Depending on the electricity mix, the impact of large uptake of EVs and FCVs will be different on the overall impact of mobility greenhouse gas emissions.

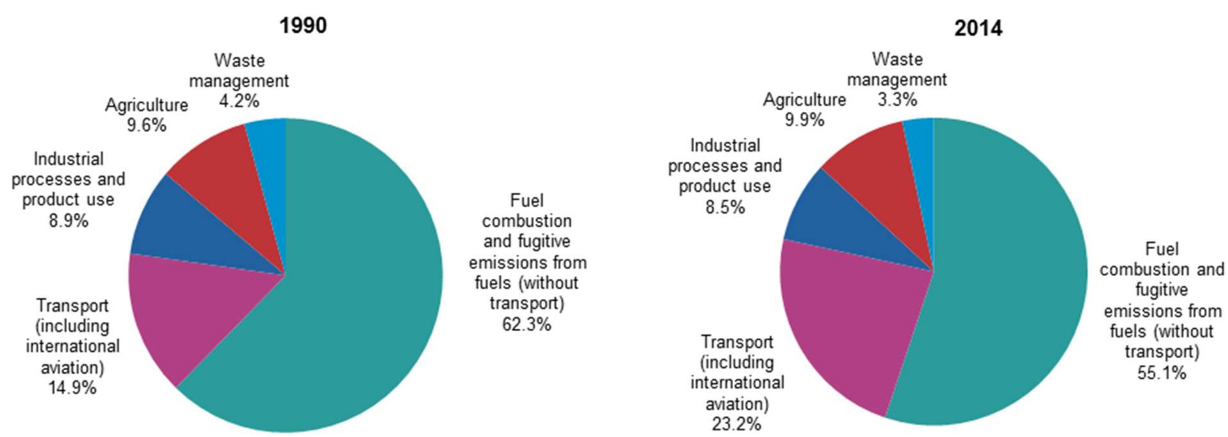


Figure 11 - Greenhouse gas emissions, analysis by source sector, EU-28, 1990 and 2014 [42]

Alongside of dimensions such as environmental protection and energy security, the electrification of the European transport system can contribute to the competitiveness of the European car industry [43]. Today most (>95%) car production for the European brands is in Europe, but when it comes to electric mobility a high percentage of vehicles production or montage is in Asian countries. This provides evidence on lack of competitiveness in Europe in the growing electric car industry.

Today, the market of EVs appears more mature than FCVs market, and EVs are much more competitive as far as the total cost of ownership, and recharging station cost is concerned. However, fuel cell technologies are expected to undergo cost decrease, making FCVs increasingly competitive in the long term.

II.4.2. Technology characterization

In Electric mobility, traction battery is considered as the key enabling technology [44]. Li-ion chemistry currently makes up a large share of traction batteries, but in the future a large contribution of non-lithium based chemistries are expected. The design and characteristics of the storage technologies are of the utmost importance for the performance of the electric vehicle. Vehicles with higher energy capacity and thus higher driving range are costlier. Table 8 summarize the technical requirements of of electric vehicles storage.

Table 8 – Technical requirements of different mobility services (own analysis and [16–18]*)*

Services	Capacity scale	Charging time	Discharge duration	Response time	Potential technology
EVs	Large with high density	0.5- 8 hours	Second-hours	Milliseconds	Batteries, especially Li-ion
FCVs	Large with high density	As quick as for gasoline	Second-hours	Milliseconds	Fuel cells, solar fuel cell
Vehicle-to-grid	Similar to EVs.				

The recent focus of battery development has shifted toward a higher energy system specifically suited for PHEV and BEV. Technology requirements are different for BEVs and PHEVs. As electricity is the unique source of power in BEVs, the amount of stored energy needs to be higher than for PHEVs. Energy capacity is the most important parameter for BEVs as it directly influences the vehicle's driving-range which currently needs to be increased to compete with other vehicles.

Discharge duration of typical EVs is about 20 minutes. As storage systems seldom run at nominal power in normal driving conditions, discharge duration is lower than the number of driving hours (typically one or two hours). The operating range depends more heavily on the energy content of the storage system than on its discharge duration. As an example, the Nissan Leaf (80 kW of power and 24 kWh of energy content) and the Tesla-S (280 kW of power and 85 kWh of energy content) both have a discharge duration of 18 minutes but the Tesla-S that has three times more energy content and operating range three times longer (270 vs. 81 miles) [45]. Charging time is also important for EVs and can go from less than one hour (fast charging) to more than eight hours (slow charging). Response time normally is in the order of milliseconds.

FCVs present clear advantages compared to EVs, especially BEVs. For example, the new Toyota Mirai has a theoretical driving-range of 500 kilometres (312 miles) against 130 kilometres (81 miles) for a standard EV such as the 2015 Nissan leaf [45]. Although some BEVs such as the Tesla-S can reach theoretical driving ranges of 430 kilometres (270 miles), the low energy density of batteries compared to fuel cells implies heavy cars with costly and large batteries. The driving-range of an EV is directly correlated to its price due to the considerable cost of batteries [46]. This advantage of FCVs over EVs is not true for PHEVs that have an even longer driving-range thanks to the ICE motor, but this comes are at greater price as the end-user needs to pay both the battery and the engine.

Power rating is fairly similar for PHEVs and BEVs, it must be sufficiently high to propel the car. Small cars dedicated to urban areas typically have power of 50-80 kW, whereas higher standard cars often have more than 100 KW of power. Higher power rating will induce better accelerating performance.

Finally, the durability of vehicles is important and it can be largely influenced by usage. For EVs, the typical lifetime achieved by current technologies is less than 10 years which is less than gasoline cars. For FCVs, durability of fuel cells stacks is about 120,000 km (75,000 miles) [45] and still needs to improve to compete with gasoline cars. This feature will be critical for the choice between EVs and FCVs.

Furthermore, EVs and FCVs both need to respect safety standards present in the automotive industry. These technologies may raise new challenges to prevent fire or explosion in case of important shocks during traffic accidents. This may require costly add-ons to protect the already expensive storage and propulsion systems, altering even more the cost performance balance.

Also, to promote electric Transport application apart from technologies innovation, there is a need for improving recharging infrastructure. Different archetypes of the infrastructures are described below [47]:

- **Hydrogen refuelling station for FCVs:** similar to natural gas refuelling, it takes around five minutes. Very limited availability in Europe.
- **"Wired" charging for BEVs**: plugging into a charging station using a cable and a plug. Slow charging takes 4 to 8 hours using ~ 5kW power. Fast charging takes 20 to 30 minutes with a 50 kW charging power. However, not all BEVs are suitable for fast-charging and these infrastructures are less available than slow charging stations. Currently, there is about 1 fast-charging station for every 20 low-charging stations in Europe. Overall, the availability of public charging stations is still limited in Europe.
- **Battery swapping for BEVs**: replacing a battery for a fully charged one at a special swapping station. This operation takes only five minutes but needs special suitable BEVs (such as Renault Fluence) and has very limited availability. One of the first companies selling battery charging and swapping services, Better Place, filed for bankruptcy in 2013. The future of battery swapping and associated business models is still being shaped [48] and might be inspired by companies such as Gogoro or Nomadic.
- **Induction charging for BEVs**: the battery in the car is charged by wireless induction charging during 2 to 8 hours. This technology is still at the development stage and suitable BEVs are not available yet (few pilots are in progress). Even if this technology will not replace plug charging in the near future, it might be an alternative for charging infrastructure.

II.4.3. Market characterization

The European market has shown a willingness to make a shift from a transport sector dominated by fossil fuels towards a new kind of transportation powered by energy sources emitting less greenhouse gases and harmful substances. This willingness in the European car manufacturing companies could be noticed in investments made in research and innovation in order to decarbonize the transport sector and speed up energy efficiency [49].

Estimation show that although the market for individually owned passenger vehicles is and will continue to be largely dominated by ICE cars in the next coming years, usage of EVs, and to a lesser extent of FCVs will increase. UBS report estimate that by 2025 EVs will be 30% of the total sold cars in European market [50].

To have an accurate assessment of the market, unfortunately the uptake of FCVs on a commercial scale is not sufficient today. Data provided by Navigant research, which are in line with IEA estimations, predict that FCVs sales will not exceed 100,000 vehicles by 2020.The market of EVs is more mature, with a significant number of new registrations in 2014 and regular growth expected in the next five years. Figure 10 displays the uptake of electric vehicles in Europe from 2011 to 2013, showing the predominance of Norway and Netherlands, two markets benefiting from high levels of incentives.

Globally, the IEA [51] states that Japan, the US, China and then France was the main market for BEVs in 2012 in term of volumes. Norway is still the leader when comparing the sales of EVs to the total passenger vehicles sales with more than 6% of new registration being EVs [47]. It is worth noting than PHEVs sales are popular in the Netherlands and Sweden, when BEVs sales are dominated in France, Denmark, Austria, etc.

Figures 12 for EVs annual sales show that there would be about 8-9 million EVs on the road by 2020, but targets and timelines vary widely by member states [47]. France, for example, has a goal of 2 million EVs on the road by 2020; Germany aims at 1 million by 2020; the Netherlands has set its 2020 EV target at 200,000, followed by an ambitious 1 million EVs just five years later in 2025. These targets are ambitious and may be difficult to achieve in most countries, but they signal strong commitment and support for large-scale EV adoption from national governments.

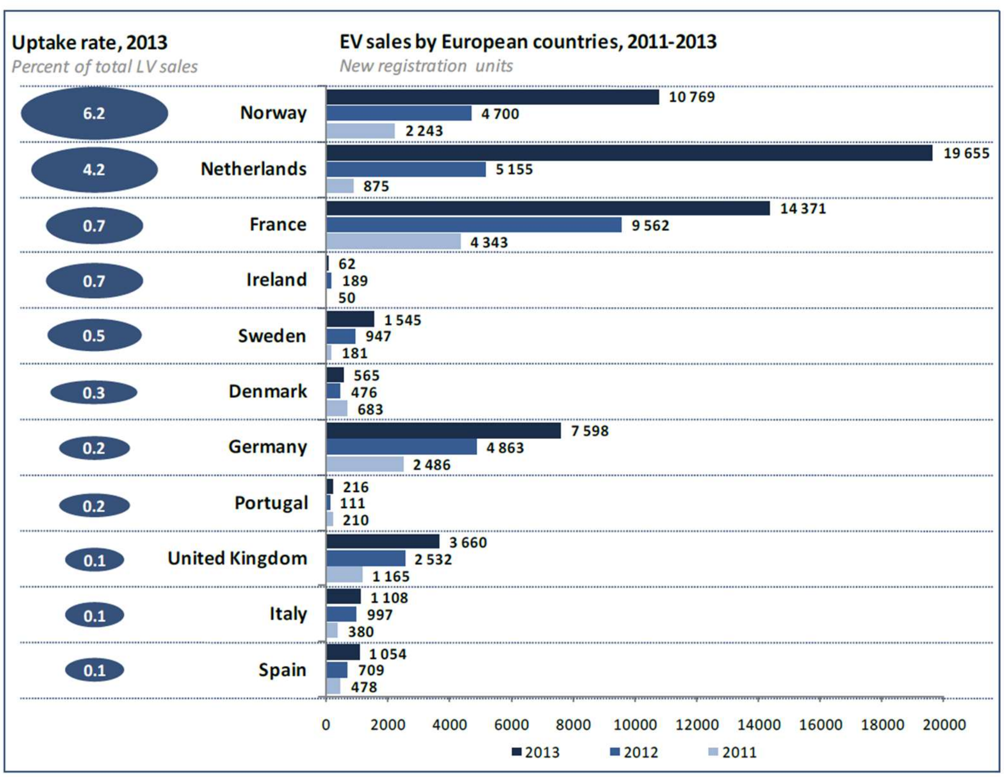


Figure 12- Market share of EVs in European countries [47]

These numbers also illustrate the growing market of storage batteries. In Europe, the annual storage need for EVs is expected to be about 100 GWh in 2020 and 200 GWh in 2030 [47]. Only the market for li-ion batteries is expected to double every 5 years in the electric vehicle industry [52]. Europe aims at developing a competitive and secure battery manufacturing role [49]. The European Union already possess a notable role in the lead-acid battery industry. Europe also contributes to the development of Li-ion cells, and other chemistries that are advantageous for the electric mobility [49]. However, further actions are necessary before Europe attains a dominant position in storage manufacturing industry.

II.4.3.1. Policy and legislation analysis

Governments, motivated by long-term targets for climate change mitigation and reduction of petroleum use, have set goals to increase the share of electric mobility in transportation sector. To support the development of EVs, government also support mobility programs, foster supply, and incentivize demand through financial enticements. Today, without subsidies, EVs and FCVs are significantly more expensive than ICE (see Figure 13). With incentives, consumers might be drawn to these solutions that offer a competitive and environmentally friendly mobility solution.

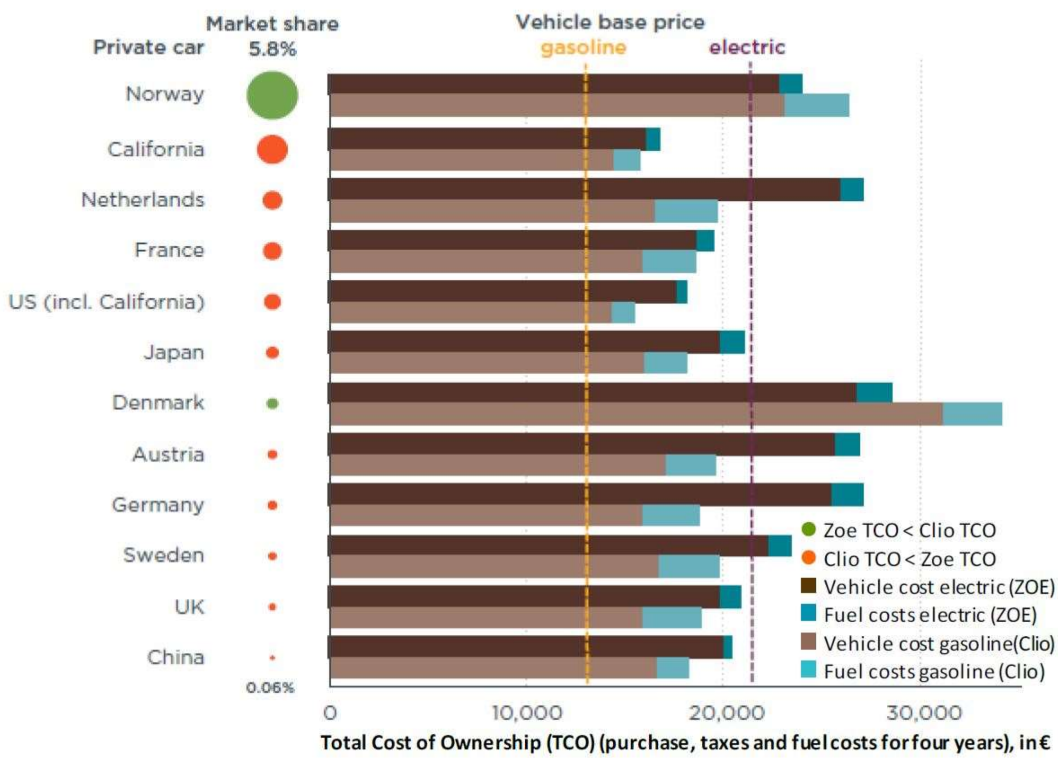


Figure 13 - Comparison of vehicle purchase price and fuel costs [53]

For example, in Norway, EVs are more attractive than ICEs as a result of subsidies that include exemption from purchase tax, VAT, toll road charges, registration tax, and annual circulation tax [53]. Similarly, many European governments (e.g. Denmark, the Netherlands, France, UK) and cities (e.g. Oslo, Amsterdam, Paris, and London) are incentivizing consumers to opt for electric mobility, each with their own schemes. Three incentive examples are:

- Direct subsidies, defined as a one-time bonus upon purchase of an EV;
- Fiscal incentives, defined as a reduced purchase and/or annual tax for EVs;
- Fuel cost savings, incentive due to electricity prices being lower than fuel prices as a result of lower taxation and/or lower energy costs, as well as higher efficiency of EVs.

The amount of subsidies for EVs in European countries is displayed in Figure 14. Norway in the first rank offers a broad package of subsidies amounting to almost € 17,000 per car when compared to the purchase of a compact class ICE car; UK pays back to buyers a onetime premium of GPB 4,000-7,000 (based on purchasing price) for all vehicles emitting less than 75 g/km [47].

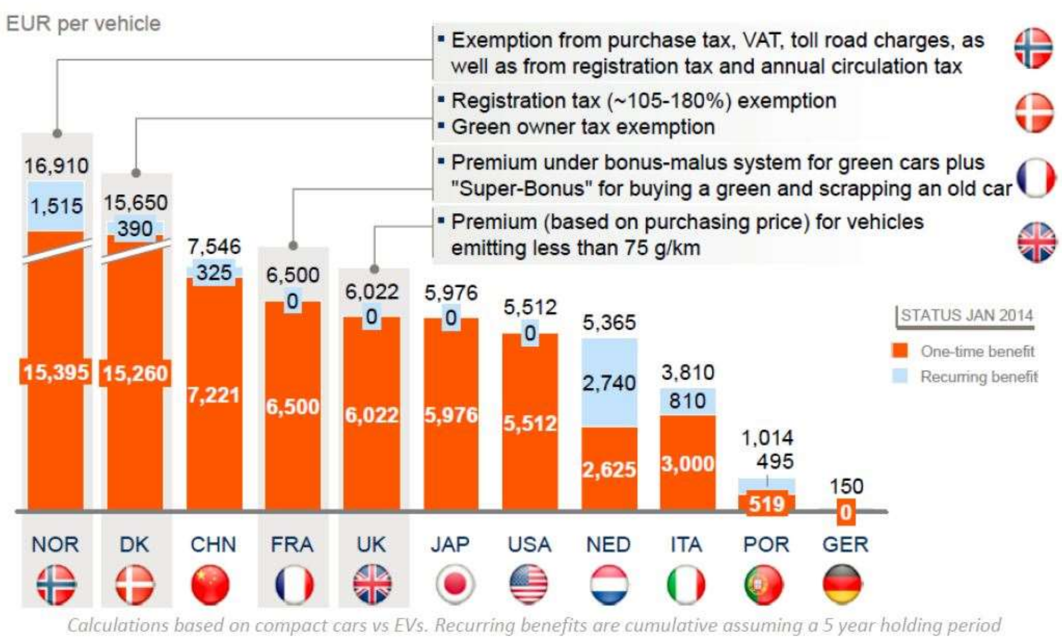


Figure 14 - National purchasing subsidies (EVs compared to ICE cars), from [47]

National incentives deployed with tax schemes or subsidies, local incentives, especially in cities where there are traffic congestions, can add important value for EVs and FCVs customers. City officials often have authority over transport policies for local measures and can play a significant role in promoting alternative vehicles. Main examples are access to car pool lanes, free charging sites or free parking. For example, Oslo excludes parking fees or toll for EVs and grants access to bus and taxi lanes. In addition to this, the government can foster the development of the storage market by investing and supporting electric public transport. For example, currently in Sweden there is large investment in EVs for public transport and that influences the society perspective, while simultaneously contribute to the country’s emission reduction. These incentives decided at local level have a positive impact on the wide scale adoption of EVs and FCVs and are likely to become more common in the future thanks to their reproducibility in densely populated areas.

II.4.3.2. Market acceptance potential

The desire to reduce their carbon footprint is a motivation for environmentally conscious consumers to invest in electric mobility. Some are even willing to pay a premium for the zero- or low-emission alternatives to ICE. For example, 29% of Norwegian EV buyers cite “environment” as their primary reason for purchase [47]. However, the cost, lack of infrastructure, and technical characteristics are still barriers that demotivate the decision of potential customers.

Consumers especially have concerns about limited driving range of electric mobility, what has been referred to as “range anxiety”. This concern could be address by further development of batteries increasing their driving range and vehicle-to-grid technologies that may allow EVs to both draw and return electricity to grid [54]. This means that further development of vehicle-to-grid technologies could be responded positively by the consumers and gain their acceptance.

II.4.3.3. Mobility and operators and charging business models

As far as vehicles are concerned, current business models do not obviously need to evolve for the uptake of EVs and FCVs but major changes are expected on the way refuelling is performed with the development of charging-as-a-service.

Vehicles business models

Proprietary and leasing models will continue to dominate and future of battery leasing is uncertain. The higher upfront cost of vehicles may advantage leasing models over proprietary models but these two models will largely dominate the market. In order to lower the hurdle of a higher purchase price of EVs for potential buyers, some car manufacturers are experimenting with the concept of battery leasing, separate from the purchase of the EV itself. The additional benefit to consumers is that they can replace batteries when needed and do not have to worry about its durability and long-term performances.

Few initiatives, such as AutoLib’ in Paris, are developing mobility-as-a service where the traditional model of car ownership is changing. However, the entire shift toward mobility-as-a-service needs more time and the main concerns about business models for the uptake of EVs and FCVs are for charging services providers.

Charging business models- [47]

The installation of charging infrastructure is costly and its deployment at an international scale comes at a cost too high for governments to bear alone. At the same time, the operation of these stations (both slow and fast charging) is quite challenging because of the low margin. It is difficult to generate sufficient revenue solely from the power sales to EV drivers who charge their vehicles, in order to recover the investment in the infrastructure.

Some charging service providers, such as New Motion in Europe, have followed a different approach. They provide both the hardware (i.e. actual charging stations) and back-office services (such as payment and billing services) as a turnkey solution for customers who want to have charging stations installed, such as retailers, municipalities, and businesses with parking lots for their guests and employees. EV drivers pay for a subscription with the service provider and can get access to the network of all publicly accessible stations connected to the network.

Municipalities and businesses are paying for hardware and installation of charging points. As a result, the actual infrastructure is funded by numerous parties, which have the freedom to set their own pricing scheme for the charging stations that are installed, and decide whether they are public or private. Some retailers might want to attract additional customers by offering two hours of free charging and then including a premium for any additional charging time. Businesses might want to offer completely free charging to their employees. Given that some customers might receive additional benefits from setting up the charging stations, they do not necessarily need to recoup the complete investment from the power sales to EV drivers. For the charging services provider, revenues are generated by the hard-ware sales and the subscription fees from EV drivers, as well as the fees for the back-office services delivered to customers.

As a potential solution to infrastructure and charging time issues, battery swapping could also be a quick recharge alternative for EV drivers. However, this solution still requires elaboration before a wide scale adoption.

II.4.3.4. Value chain

An illustration of the value chain decomposition for mobility application is shown in Figure 15:

- The central position of car manufacturers that play the role of developers, integrators and system vendors. They work with independent battery suppliers to develop EVs but for FCVs, Hyundai and Toyota have their own proprietary technologies as far as fuel cells are concerned.
- The parallel value chain of charging infrastructure needs to interact with car manufacturers and storage technology suppliers but is mainly composed of independent entities developing new business models. These business models usually aim at shaping the relationship between utilities and vehicle owners. For FCVs, actors involved in the construction of hydrogen refuelling stations are mostly conventional actors of the refuelling sector.

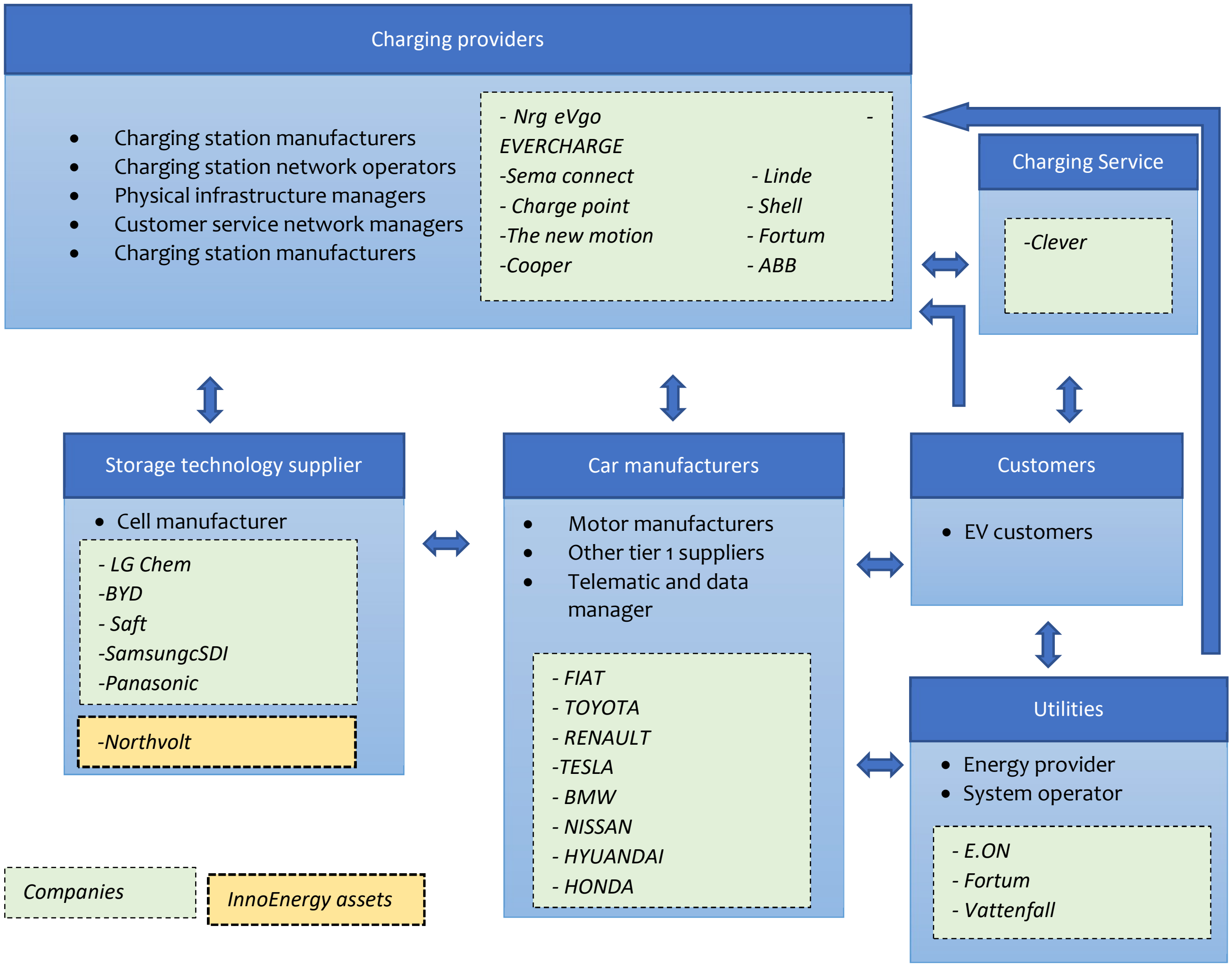


Figure 15 - Value chain and main actors of mobility storage application, non-exhaustive list

II.4.4. Market challenges

The following challenges hinder the development of electric transport application:

- **High vehicle's cost:** cost of fuel cell and electric mobility options hinders the development of the relative market, since the customers need to bear the upfront investment (see figure 13). Even if expected savings on fuels might lead to a greater net present value for an EV or FCV compared to an ICE car, the savings are small compared to the vehicle cost and people do not always have this calculation in mind and are not willing to pay a premium. It is remarkable that EVs exhibit important fuel cost savings that are not sufficiently high today in most countries, but will be an important driver for future expansion.
  FCVs uptake also depends on the price of hydrogen versus gasoline and electricity. The costs of hydrogen produced with the main production pathway – natural gas using SMR (Steam Methane Reformer) – are not expected to decrease [55]. Alternative hydrogen production pathway, for example from grid electricity, is still costly compared to the conventional pathway. For cost-

effective renewable hydrogen, the availability of low-cost surplus electricity would be a prerequisite. However, this surplus will also constitute cheap electricity available for EVs.

- **Limited technical characteristics**: the performance of vehicles and batteries is also decisive for a wide-scale adoption. Future vehicles will be compared to ICE cars in terms of driving-range and durability. Therefore, lack of technical competitiveness of available electric transport options is a barrier for the storage deployment in this market.
- **Competitive alternatives**: There are types of cars that are in competition with EVs and FCVs and other clean mobility options. Two potential alternatives are biofuels and natural gas that can restrain the uptake of cars with an electric engine. In addition, ICE cars have a long sell history with extensive maintenance and services which could make consumers reluctant to switch to electric mobility options.
- **Lack of suitable infrastructure:** Future availability of charging infrastructure is a key parameter for the uptake of electric transport. the simultaneous deployment of charging and refuelling infrastructures requires high level of funding and adapted business models. Today, this is a major concern for both EVs and FCVs, but EVs are well ahead in term of current and expected installed capacity and charging solutions (home charging, public charging, charging as a service, etc.). The convenience of home charging is one of the most attractive attributes of EVs, but does not easily apply to drivers living in apartment buildings or other multi-unit dwellings that either lack garages or do not have the ability to install charging stations easily. In addition, EVs suffer from the long charging duration. Even if fast charging infrastructure is used, their small driving-range constitutes an important loss of earnings for businesses and it might prove deterring.
  Uptake of FCVs is less challenging as they necessitate fewer charging points. Hence, provided that these vehicles come at an affordable price, customers can fully benefit from their services.
  With regards to fleet vehicles (buses, delivery vehicles and other captive fleets), the refuelling infrastructure for FCVs is less problematic, since these fleets can be served by dedicated fuelling stations and maintenance depots.
- **Weak European supply chain:** in Europe, a large share of battery cells used in electric automotive industry are imported from Asia. There is no significant European automotive cell manufacturing capacity for traction battery cells, especially Li-ion and NiMH. This is while Europe has strong car manufacturing industry and has the potential to play an important role in the EV industry [49]. Hence, the European security of supply chain is weak and there is a risk of high cost due to delay, relinquish of quality control, value loss of parts during transportation, and design option [44,56].
- **Incompatible national policies:** national policies in different Member States are affecting the development of electric mobility. However, not all the member states are supporting the development of electric mobility. Accordingly, there is need for further harmonization and enactment of supportive policies for these vehicles.
- **European unbundling policy**: The unbundling policy can affect the electric transport industry, because it hinders the use of electric vehicles for grid services or in combination with smart grids. If EVs reach large-scale market penetration and smart grid systems become more commonplace, EVs could become part of the solution through providing services to the grid and electricity market thanks to their important storage potential. This would be possible for example if utilities own the storage and utilize the "vehicle-to-grid" concept. On the other hand, the charging of EVs at a large scale can also create challenges for local distribution grids and their operators, if not properly managed.
- **Core technology possession and development:** in the electric mobility industry, it is not clear who should own the batteries that are used in EVs. Provided that it is the consumers, they need to

endure a cost in order to change or fix the batteries. Alternative option would be if a third party owns the batteries and lease that to consumers [see, 47]. Currently in the market, commonly consumers are the owners and therefore responsible persons for the batteries.

- **Recycling the 2nd life business model:** There are benefits in recycling batteries that are used in EVs. In EVs the batteries need to maintain high performance. Often the efficiency of the battery decreases after a certain number of charge/discharge cycles. In such case, the batteries could be still used in other applications such as behind-the-meter. Furthermore, batteries consist of materials and elements that could be recycled. Yet, lack of developed processes and plans for recycling and 2nd usage is a challenge for further applications of electric mobility.

II.4.5. Market drivers and scenarios

1) **The fuel cost:** one main driver behind the uptake of electric mobility is the potential fuel costs savings [47]. In many European countries, taxes on fossil fuels are much higher than on electricity. Nonetheless, still fuel cost saving is low in comparison with vehicles costs [47]. Further decreases in electricity costs and real-time pricing may increase fuel cost savings and further drive investments in electric mobility.
2) **Recharging/refuelling infrastructure**: The availability of charging and refuelling infrastructure is key for the development of EVs or FCVs in the near future. If recharging stations or hydrogen refuelling stations do not become widely available to support the use of these vehicles, end-users will not make the switch and keep using ICE cars.
   Individual EVs also need to get the possibility to be charged at home or at the office location, enabling the end-users to benefit from low electricity prices during off-peak and curtailments periods. Vehicles are parked several ours of the day, usually at home or work. This fact represents an opportunity for charging points to be deployed where cars are most often parked rather than where it is easiest to permit and build charging infrastructure.
3) **Investment in market value chain:** The SET-plan highlights the importance of investments in the value chain related to electric mobility products [49]. Europe can improve its battery value chain, by exploiting new uses for batteries beyond EVs. Examples of such applications are the use of static batteries for households or for utility scale grid connected assets. This relevant to Key Actions 3 and 4 of the SET Plan on “consumers, smart cities and energy system ”as well as Action 7 on “batteries for e-mobility and stationary storage” [57].
4) **Strengthening supply chain**: Europe needs to exploit its competences in disruptive battery technologies and scale-up its batteries production (e.g., Li-ion) to meet short-term and long-term goals of the market. The higher production scale will result in improvement and innovation in the batteries and will help reduce the production cost of these technologies.
   To enhance European competence in disruptive battery technologies, two approaches are possible: (1) to develop a national or European for cell production capacity, or (2) to establish foreign investment in manufacturing plants in Europe, as Japanese and Korean companies already did [49]. However, due to EU dependency on the raw material complete independency will remain an issue (e.g., graphite for li-ion) [56,58].
5) **Policies and targets:** governments can contribute to the battery business cases through several approaches. First, they can require installation of charging infrastructure in Member States, as mentioned in Directive 2014/94/EU. The availability of recharging/refuelling infrastructures is the key for the development of EVs or FCVs in the near future.

Second, there are set emission targets available for car manufacturing companies in Europe. The set target for 2021 is 95 grams of CO_2 per kilometre. Extension of this targets, with more ambitious number, could promote investment in electric mobility.
In addition, governments can set different forms of incentives for the electric mobility application. Main examples are access to car pool lanes, free charging sites or free parking. These incentives can be decided at local level and will have a positive impact on the wide scale on EVs and FCVs adoption.

6) **Local perspective:** In the electric mobility markets, local perspective could influence positively the development of the electric transport market. The government can influence the local perspective in at least in two ways: (1) motivating the uptake of new low-carbon transport alternatives by public services (buses, garbage trucks, etc.). (2) inciting companies to adopt these vehicles for social purposes. For example, silent vehicles could be allowed to deliver at night in urban areas, thus creating flexibility for operations in specific areas. Overall, local incentives will spur the development of this market.
7) **Technological innovation:** to improve competitiveness and reduce the cost of electric mobility, technical innovation is necessary. In addition to the technological innovation approaches mentioned in sections II.1/2/3.5, other technical improvements related to the mobility application are:
   Improvement in technical features such as energy density and power capacity. The hybridization of storage technologies can contribute to this development of electric transport sector.
   Also, research and innovation should explore alternative materials for batteries, or production processes to reduce technologies' cost and substitute the rare materials.
   The current and projected battery prices are mapped in Figure 16. For automotive batteries, some of the key targets regarding technical characteristics of batteries for 2030 published by European Commission [1] are: (i) gravimetric energy density above 250Wh/kg at pack level, (ii) a battery pack cost of EUR 75 per kilowatt-hour (kWh) and (iii) a battery cell production in EU of 50 GWh/year. For stationary batteries, the key targets for 2030 are (i) an energy storage system based on a high-efficiency (>90%) battery with cost below EUR 150/kWh (for a 100kW reference system) and (ii) a lifetime of thousands of cycles. The European commission prioritize R&I effort in advancements in battery technologies for mobile applications due to their importance [1].

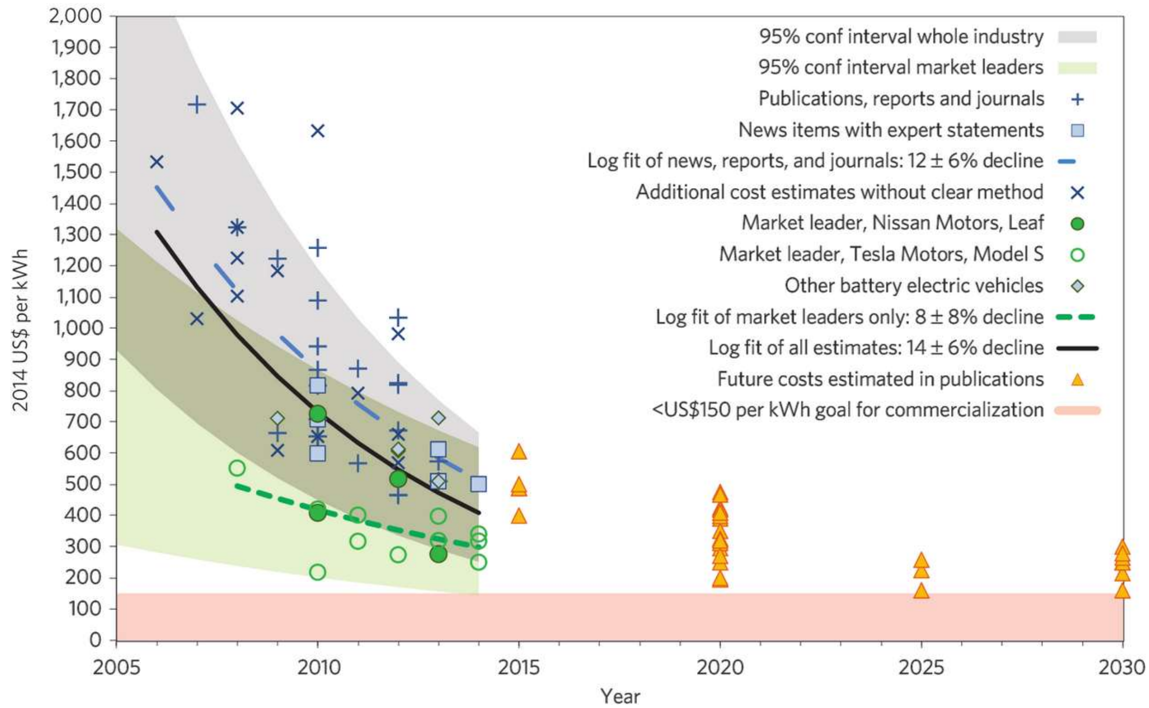


Figure 16 - Cost estimates and future projections for electric vehicle battery packs, measured in US $ per kilowatt hour of capacity. Each mark on the chart represents a documented estimate reviewed by the study [59]

Table 9 – Market drivers and scenarios for mobility

Vision for storage deployment to 2050			Time frame
Drivers		Scenarios	
Mobility	The fuel cost	Large investment in RES will be made. Larger share of RES with no fuel cost results in lower cost of electricity. The cost saving potentials then will motivate the consumers to shift from ICE cars to EVs. Larger market shares of EVs and FCVs are the outcomes of this scenarios.	2030
	Recharging/refuelling infrastructure	Large investment will be placed in recharging/refuelling infrastructure of EVs and FCVs. These investments are made by different parties, including private companies, customers, or institutes and are supported by government. Larger and more advanced infrastructure will enhance the user experience of EVs and FCs and thereby motivate further investments in the electric mobility. The services of EVs and FCVs accordingly will be improved. Another possibility is when autonomous cars enter the market. These cars can benefit from driving outside of the city toward charging stations in the nights.	2025-2030
	Investment in market value chain	European industry and research institutes will support and invest in the value chain by exploring different applications of storage technologies (beyond EVs for batteries) and improving technologies' cycles. This will improve the business cases of storage technologies.	2020-2025
	Strengthening supply chain	Investments will be made to enhance Europe battery production capacity. Also, efforts will be invested to attract foreign investments in European manufacturing plants. This will motivate car manufacturers to contribute to EV industry due to their trust on local supply chain.	2020-2030
	Policies and targets	Targets will be mandate installation of certain number of charging infrastructures and production of EVs and FCVs in different European countries. Emission targets (95 grams of CO_2 per kilometre) will continue and will be tighter in Europe for Automotive industry. The targets are supported by policies facilitating transportation and parking of EVs and FCVs. Accordingly, both industry and customers will gain interest in electric transport options and energy storage in transport will be exploited with a higher rate.	2025-2030
	Local perspective	the society perspective and their interests in electric mobility will lead to a larger share of EVs and FCVs in the streets. The positive perspective will increase the sales of these cars.	2025
	Technological innovation	The development of the storage technologies will be supported through government and automotive industry-funded R&D program. Innovations generated from this research enhances technical features of batteries. In addition, technological structural change, and learning curves further decreases the technology price. This lead to development of EVs with better technical feature and thereby stronger performance.	2020-2030-2040

II.5. Thermal

II.5.1. Application services and benefits

This application includes storage of thermal energy and using that energy for heating, cooling or power generation. Thermal storage can reduce carbon emission and energy usage of a country by matching the supply and demand of heat, where gap exists. The gap is temporal or geographic and happens in systems with or without district heating and cooling infrastructure. In district with high population density, heat storage and grid can be a more energy efficient system, with lower CO2 emission. Technologies for this application generally function based on heating or cooling of a storage medium. Given the actual amount of installed thermal energy storage in compare with its potential, this type of energy is currently underutilized [60]. One reason for this low deployment is low heat value, that makes it difficult in the market to make a competitive business case for thermal energy storage.

Thermal storage application provides several services, as is listed below [18].

- **Seasonal storage (heating or cooling):** in this service heat and cold is obtained from different resources and stored to be used when there is a need in the market. Thermal storage can provide hourly, daily or seasonal thermal storage services, for example for heating buildings.
- **Peak-shifting**: This service allows the daily fluctuation of thermal energy's supply and demand to be decreased. Peak shifting and demand management of systems such as heating, ventilation and air cooling (HVAC) increases the economic competitiveness of thermal storage.
- **Concentrated solar power (CSP):** the thermal energy storage in CSP allows generation of dispatchable electricity when sun is not available or heat for district heating. This service is among the most important application of thermal energy storage. Molten salt technology can be used for this service and allows thermal plants to generate heat even after the sunset.
- **Storage and integration of RES heat:** the thermal energy storage can be implemented in the solar power production field and separate solar thermal from solar radiation.
- **Power-to-heat:** thermal energy storage technologies (e.g. molten salt) could be utilized to convert electrical energy to thermal energy or to use it in district heating systems (DHS) [18].
- **Heat-to-power:** thermal energy storage technologies enable storing excess heat and using that heat when electricity is needed. For example, in molten salt technology super-heated steam could be generated to power a conventional steam turbine when electricity is needed.
- **Waste heat management:** Thermal storage enables the recovery of waste heat from industrial processes or buildings, and the use of such heat where there is demand. In Germany, about 12% of the industrial final energy demand is available as waste heat at the temperature above 140 C. In 2010 this number is equal to 86 TWh out of 720 TWh [60].
- **Buffering:** The thermal storage technologies can stabilize the temperature in locations that need constant temperature, for example cleanrooms of pharmaceutical companies, or in swimming pools.
- **District heating services:** district heating systems (DHS) obtain the heat from several sources (e.g., cogeneration plants, nuclear power plants, boiler station) to supply different consumers. Thermal storage technologies can contribute to this process by storing buffer heat and allowing the DHS system to balance the heat demand and supply on an hourly, daily or seasonal basis. DHS can also use thermal storage to overcome heat shortage and plants shutdown. Storage can also allow DHS to store heat when the prices are lower and use that heat during high demand.

II.5.2. Technology characteristics

Several technologies are available for thermal energy storage (TES). It can be segmented in three groups, namely sensible heat storage (SHS), latent heat storage (LHS) and thermochemical storage (TCS) [18]. The principle of SHS is to elevate the temperature of the storage medium in order to store and release thermal energy. While different materials including molten salt, sand or rocks can contribute to SHS storage technologies, water remains to be the most commercial and popular storage medium. SHS is suitable for low temperature application, and is the most commonly used segment of thermal storage technologies. SHS also has the potential to lead the future thermal storage market. SHS can be used as a steel hot water tank at the household level, or in big borehole or cavern storages for community or city level solutions. The use of heat storage connected to district heating (DH) systems is a common practice in Nordic countries, such as Finland and Denmark. Different studies have highlighted the role of heat storage in integration of variable renewable energy (for example see [61]). In this case, heat storage is employed to shift the heat production in time, when the generating plants prefer to ramp up or down their operation. In some plants like Katri Vala in Helsinki, TES is linked with a large-scale heat pump to balance the heat demand in the DH network [62].

LHS, on the other hand, store energy through changing the physical state of the storage medium at constant temperature. This thermal energy segment is in the development phase, but is expected to play an important role in the future given its high energy density. LHS technologies are ideal for applications that require no significant temperature differences.

TCS stores thermal energy using chemical reactions, either through adsorption (physical bonding) or absorption (uptake/dissolution of a material). TCS technologies are common in the building sector (e.g. domestic hot water, space heating, air-conditioning) and industrial sector (e.g. process heat and cold) [63].

Different technologies can contribute to these segments of thermal energy storage as listed in Table 10. So far water tanks and ice and chilled water storage are among the most commonly applied thermal storage technologies.

Table 10 – Thermal storage technologies, categorized based on storage principles

SHS	Small water tanks, hot water tanks, molten salt storage, UTES
LHS	Ice storage, PCM
TCS	Adsorption storage

The necessary conditions for thermal energy services affect the choice of a technology (Table 11). Primarily, it is important to specify the temperature at which the thermal energy is needed. For different temperatures, different types of technologies are available. The technologies for temperatures lower than 10 °C are often cold-water storage tanks, available in commercial and industrial facilities around the world. This technology supplies cooling capacity. At higher temperatures, the most common liquid storage material is molten salt.

Table 11 – Technical requirements of different thermal storage services (own analysis and [18]*)*

Services	Capacity scale	Discharge duration	Response time	Technologies
Seasonal storage (heating and cooling)	A few to tens of KW	Hours-Days	Minutes to Hours	Underground (aquifer, cavern and borehole), and surface (pit) TES
Peak-shifting	A few KW	Minutes-hours	Seconds to minutes	Underground and aboveground TES
Concentrating solar power	Hundreds of KWs to several MW	Hours	Minutes	Molten salt technology
Storage and integration of RES heat	A few kW up to MW	Hours	Minutes	SHS for industrial processes
Power-to-heat	Up to 10s of MW (for Utility scale) Several kWs (end-user side)	Several hours	Seconds	large scale compression heat pumps, electric boilers connected to district heating networks
Heat-to-power	Up to 10s of MW	Several hours	Seconds	Molten salt
Waste heat management	Dependent heavily on source and location of thermal energy. The requirements are fairly similar to other services.			
Buffering	Up to kW	Minutes	Minutes	Boilers, Molten salt, TES
District heating services	Up to 10s of MW	Hours-Days	Minutes	Underground (aquifer, cavern and borehole), and surface (steel tanks and pit), TES

Another important characteristic is storage capacity. It needs to be identified in relation to its use and benefits. Suitable technologies for large thermal storage are technologies having high energy density using LHS principal, and underground thermal energy storage (UTES). UTES can benefit from natural hot and cool temperature resources for large scale thermal storage. In countries such as Denmark, Sweden The Netherlands, and Norway, UTES is commonly used for seasonal storage of heat in centralized and distributed energy systems [64]. These technologies also allow controlling peak load and reducing customers' bills.

In thermal storage, also system efficiency and reliability is important and often a struggle. Currently, the system inefficiency is due to thermodynamic constraints (e.g., the smaller temperature gradient over which the system might be operating) or reliability restrictions.

Response time of thermal storage technologies is important but often slow and their frequency of use is dependent on the provided service and could range from daily to seasonal.

II.5.3. Market characterization

The installed capacity of thermal energy storage technologies across the globe is about 3 GW. Leaders are Spain (over 1 GW of capacity), the US (600 MW), Chile (over 480 MW) and India (over 200 MW) [65].In a study by [66] the market for thermal energy storage worldwide was valued at USD 3.33 Billion in 2016. The estimation indicated that this rate is expected to grow at a compound annual rate growth of 11.0% from 2017 to 2022. The increasing application of thermal energy storage will be mainly due to large CSP installation, and integration of thermal energy storage. Only in 2015, the grid connected molten salt deployment for CSP was larger than 30 GW [18]. As estimated by IRENA, "*the storage of thermal energy (typically from renewable energy sources, waste heat or surplus energy production) can replace heat and cold production from fossil fuels, reduce CO2 emissions and lower the need for costly peak power and heat production capacity. In Europe, it has been estimated that around 1.4 million GWh per year could be saved—and 400 million tonnes of CO2 emissions avoided—in the building and industrial sectors by more extensive use of heat and cold storage*" [62, p. 4]. For example, it is known that thermal energy storage used (e.g., by 2-period meter) in electrical water heaters can reduce a country's peak demand. In France, this thermal energy storage in electric water heater allowed reduction of annual peak by 5% [60]. Currently, more than 1-third of households in France are equipped with a "2-period meter" that allows the water heater to function as distributed storage resources, and empower the customers to respond to peak-pricing structure [60]. While small scale thermal storage are common in Europe, the analysis shows that it is long-term thermal storage will contribute significantly to energy saving.

The end users of the thermal storage application are utilities, commercial and industrial and residential. In 2013, the commercial and industrial sector were the main users of thermal storage technologies. However, this could be changed in the future with the increasing share of RES at residential locations [66].

II.5.3.1. Policies and legislation analysis

There are a number of policies available in Europe that indirectly affect the development of thermal energy storage. The first policy is related to EU Directive 2010/31/EU on energy performance of the buildings (EPBD). In Europe, buildings are responsible for about 40% of energy consumption which is equal to about 36% of CO_2 emissions [67]. Thermal storage can contribute to this directive by enabling better and more efficient energy system in buildings as well as more efficient consumption of heat.

Another policy affecting the development of thermal storage is Energy Efficiency Directive 2012/27/EU (EED), which among others promote improving efficiency of heating systems in buildings and industries [68]. In order to meet the obligations and targets of this directive, installation of heat storage is deemed as valuable. This directive is not yet translated into the national laws

Policymakers also can influence the development of thermal storage by supporting or discouraging investment in electrification of heat grids and systems. This electrification lowers the opportunities for thermal energy storage. Finally, in recent years, motivations for investments in thermal energy storage increased based on policies supporting a larger share of energy generation from RES.

II.5.3.2. Market acceptance

Market acceptance for thermal energy storage is different based on its location and potential consumers. But generally speaking, consumers play an important role in the deployment of thermal storage could be classified often as business to consumers (B2C). For example, in residential building, installation of thermal energy storage and expansion of heat grid, necessitate agreement of all the owners. In this situation, the awareness and acceptance of consumers play a significant role. It is notable that installation of thermal energy storage technologies is more efficient and cost competitive for larger scales applications (see Figure 17)

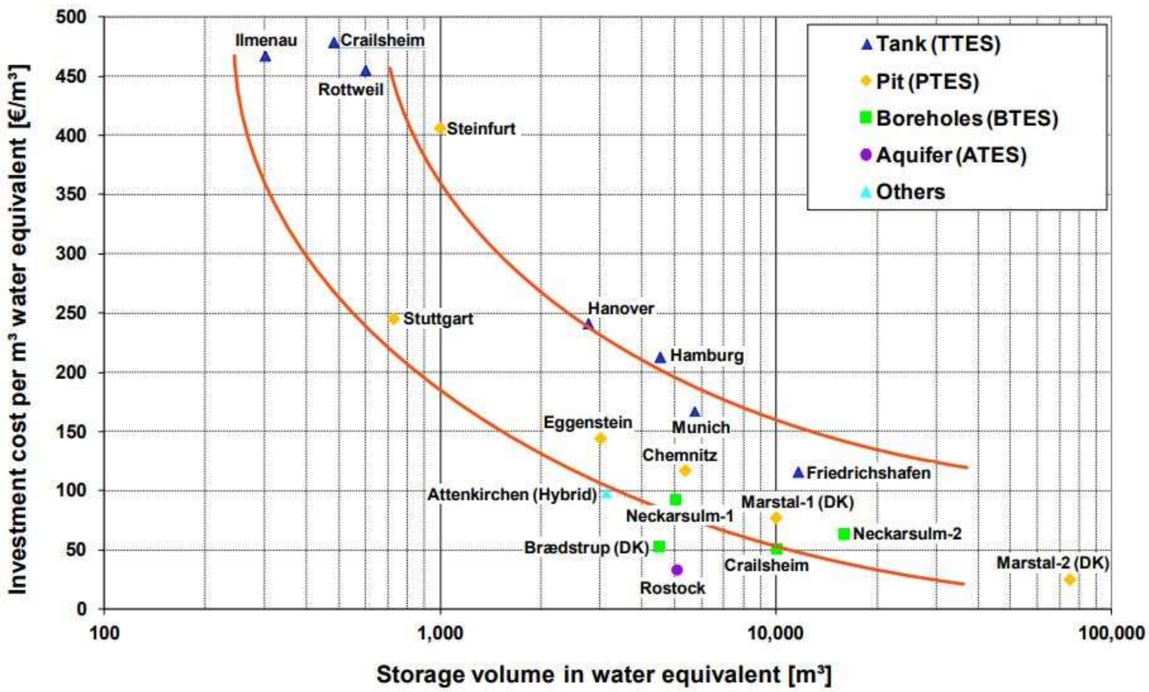


Figure 17- Specific storage cost of demonstration plants (cost figures are without VAT, storage without country code are located in Germany)[70: p. 27]

II.5.3.3. Thermal storage operators and business models

The installation and operation of thermal energy storage is different from electricity storage. In the market, investments and operation of thermal storage is possible by both public and private companies, and often is carried out through Engineering, procurement and construction (EPC) contracts for the complete installation.

II.5.3.4. Value chain

Different thermal storage technologies for different purposes necessitate different value chain. In this roadmap, we suffice to the illustration of UTES thermal storage value chain, presented in Figure 18.

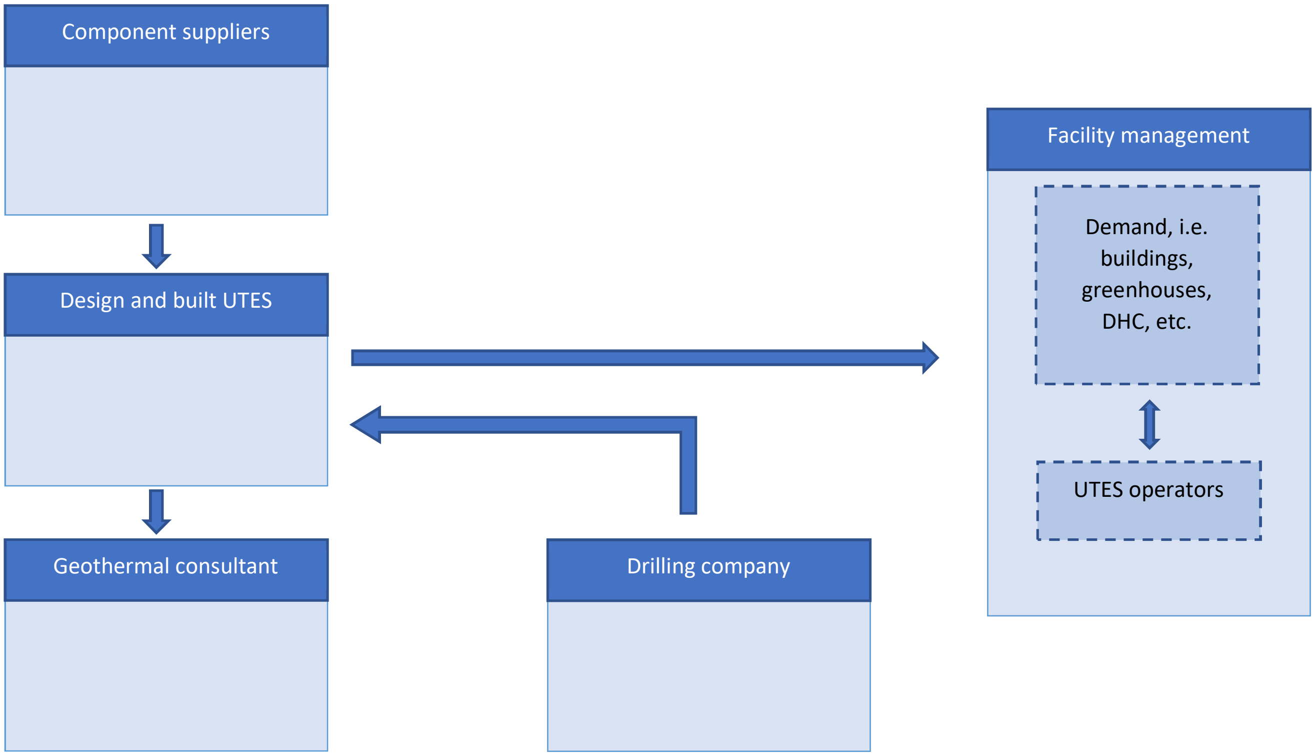


Figure 18- Value chain and main actors of thermal storage segment, non-exhaustive list

II.5.1. Market challenges

The following parameters influence the development of thermal energy storage negatively in the industry:

- **Underestimation of thermal storage potential**: currently the potential influence of thermal energy storage is underestimated, due to lack of consistent data on the available and wasted amount of heat. Such data can provide financial and environmental motivations for the development of thermal energy storage.
- **Technology cost**: Thermal energy store technologies' cost remains one of biggest barriers to their development. The major cost associated with thermal storage technologies is related to heat (and mass) transfer technology (see Figure 17).
- **Technology performance (material properties)**: each storage technology can only respond to defined conditions (e.g., temperature) and requirements. One of the main characteristics lowering the performance of storage technologies is related to the technologies' material properties and stability, in particular technologies within TCS segment. R&D aims to find substitute materials for storage technologies to function in different temperature. Also they need to improve the thermal insulation to improve their efficiency [63].

II.5.2. Market drivers and scenarios

1) **Quantifying energy storage potential**: currently there is no information available on the potential of thermal energy storage in EU28+2. Quantifying this potential in different parts of the energy system could motivate and lower the risk for investments in thermal storage technologies.

2) **System integration**: the integration of storage technologies into existing systems for example in walls or in RES power plants can significantly influence their market deployment and attractiveness and cause a strong case for their application.
3) **System control and maintenance**: In order to optimize integration of thermal storage in buildings and industries, there is need for the improvement of system maintenance and control of storage technologies. This would enable higher energy saving and better energy system management and lead to more investments in storage technologies.
4) **Policies and targets**: policymakers can promote the development of thermal storage by investing in R&D funds especially for technologies that are in the development phase, or promoting integration of thermal energy storage into different systems, such as buildings. National policies also could be enacted to promote thermal storage installation in each member state.
5) **RES heat integration**: the society's interests in integrating RES heat increases, because thermal storage technologies are becoming more mature and market awareness enhances. This would lead to a larger application of thermal storage and a larger integration of RES heat.
6) **Heat grid expansion:** one factor that can influence the position of thermal storage in the market is the decision to electrify the heating system of residential areas or instead invest in heat grid. In densely populated areas heat grid could provide a more efficient system, and that should be considered for making a decision regarding electrification of heating system or expansion of heat grid.
7) **Technology innovation**: like the other applications, innovation in storage technologies can contribute to further development and deployment of the thermal application. Different innovation approaches leading to technological innovation are discussed in section II.1.5. In addition, the following innovations are notable for thermal energy storage:

   *Thermochemical materials***:** one of the long-term plans is to further develop thermochemical energy storage for medium/high temperature applications and services that require high energy density. While demonstration projects have been completed in some countries such as Germany, further development is still needed [70].

   To increase the potential of thermochemical energy storage, a major challenge is to improve stability and containment of storage material. After such improvements, the ideal applications of thermochemical energy storage could be identified and applied. For example, today molten salt is only stable at temperatures above 400°C, while in temperatures below 200°C to 250 °C it solidifies. This means that the salt necessitates significant energy during the night-time when heat is not collected, to prevent solidification and consequent damages. Solidified salt can cause serious mechanical problems. Therefore, improving the storage materials could reduce the cost of thermal storage and improve the technologies efficiency for different applications, for example CSP.

   Overcoming hydrogeological constraints: R&D could also address improvement in system operation and concepts of UTES to overcome hydrogeological constraints and prevent corrosion at high temperature [71].

Table 12 - Market drivers and scenarios for thermal storage

Vision for storage deployment to 2050			Time frame
Drivers		Scenarios	
Thermal	Quantifying energy storage potential	The industry and innovative solutions will allow the identification and estimation of the amount of available and wasted heat resources. This knowledge and information first will highlight the potential of thermal energy storage and also, inform investors' decisions about the existing market gaps. This information would explore where the installation of thermal energy storage could lead to highest energy efficiency while creating economic values.	2020-2030
	System integration	Investments will be made in installation of thermal energy storage in processes and locations where heat is wasted or could be better managed. Examples of such installation is in walls of buildings, or in residential and industrial regions.	2025-2035
	System control and maintenance	New technologies and solutions will be introduced in the market, allowing better control and maintenance of thermal storage. This in turn will optimize the thermal storage management thereby performance and motivate further investments and larger share of thermal storage in the market.	2025
	Policies and targets	R&D funds by policymakers support the development of thermal energy storage and increase their performance in order for these technologies to play a notable role in the future. National policies also provide supportive incentives for improving energy efficiency in different market segment, including buildings and that motivate larger installations of thermal storage.	2025-2030
	RES heat integration	Thermal storage technologies will further develop and become more effective in harnessing RES heat (e.g., solar thermal storage). Besides, society knowledge about these technologies increases. As the result, interest in thermal energy storage technologies for harnessing RES heat increases, and larger investments would be made in these technologies.	2025
	Heat grid expansion	Investments in heat grid will be prioritized in densely populated areas, as it could result in higher energy efficiency. Investments in large thermal energy storage system would reduce the cost of technologies and create a more competitive business case for their further applications.	2025-2030
	Technological innovation	R&D efforts will be made to enhance the technologies' applicability. Based on the innovation efforts, cost of the technologies would be decreased and barriers such hydrogeological constraints (e.g., related to UTES) would be overcome. The technologies' stability would be improved and their performance in different geological conditions would be enhanced.	2020-2030-2040

III. Discussion and recommendation: vision for storage deployment till 2050

This roadmap sheds light on the important role and position of energy storage in the transition of the European energy system, collecting information from literature, a wide network of industrial partners and actors of the market. It explores different applications of energy storage, sheds light on innovation in services, technologies and business models within the application and discusses drivers, and barriers of the storage market. The outcomes aim at informing policy and investments decisions on how to accelerate development of energy storage. Below the main market challenges and drivers for energy storage applications are summarized and in accordance actions that can effectively accelerate share of energy storage are discussed.

III.1.1. Key drivers for the energy storage market

The analysis of this roadmap shows that different applications of energy storage can contribute significantly to **the integration of renewable energy** resources by increasing the flexibility and diminishing intermittency of RES. Renewable energy, both distributed and centralized, will meet a large share of the European energy demand. The objectives for the European energy system in 2050 is to increase share of renewable energy in energy production to about 50% [2]. Investments in RES and the expected increase in the share of RES in the European energy industry consequently propel larger applications of energy storage.

Also, the roadmap discusses that, consumers will play a significant role in the future centralized and distributed energy systems. This can be translated into **consumers' empowerment** and **end-user involvement** during the energy transition toward a more sustainable and efficient energy system. The important role of customers is highlighted in the European clean energy package, "*consumers across the EU will in the future have a better choice of supply, access to reliable energy price comparison tools and the possibility to produce and sell their own electricity*". Energy storage contributes to this empowerment by enabling consumers to concurrently produce, store, and consume energy and effectively manage their energy consumptions and cost.

Furthermore, increasing share of RES and empowering consumers contribute to the development of **distributed energy systems** in the future market. These systems enable meeting the energy demands of industry, residential, commercial and industrial customers with a larger share of RES [37]. The role and positions of energy storage in the distributed systems will be significant, as it enhances the reliability and flexibility of the systems. Given this role, the development of distributed energy systems will motivate investments in energy storage. Similarly, policies, and decisions that increase the share of distributed energy system in the future energy industry would result in larger investments in energy storage.

The role of the consumers in the future European industry also provides evidence of the importance of **society perspective and awareness**. The society perspective can contribute effectively to development and deployment of a new technology. Similarly, positive perspective about energy storage, and understanding of its role in energy and cost management could effectively drive investments in energy storage technologies. Lack of understanding of these technologies could result in consumers' opposition, lack of interest or long permission process for storage application. Education programs and awareness campaign for society offered by government, NGOs or other authorities could raise society awareness and therefore contribute to energy storage deployment.

Technological Innovation will change the future of the energy industry by offering cheaper and more sustainable technologies as well as alternative solutions for existing or new market services. Technological innovation influences the development of energy storage by enhancing performance, creating new services and reducing the cost and footprint of storage technologies. These developments incentivize investments in energy storage technologies. The significance of technological innovation is evident in the battery cost that has dropped about 70% from 2007 to 2014, further reduction of 70% is forecasted towards 2030 (see figure 16) [1,59]. Timely and focused innovation generates competitive advantages for the storage technologies and allow energy storage to gain the full markets' commitment.

Reviewing several cases across European countries pinpoint the influential role of **policy decisions and legislations** during sustainability transitions in the energy industry. Recently, European policymakers have focused on the potential role of energy storage in the future energy market [72]. Policymakers, among others, could steer the innovation in the energy storage market by investing in R&D budgets, supportive legislations, or orienting the market to select the most effective business model.

Stakeholders of a technology significantly affect the development and deployment of its market. When it comes to Energy storage, the stakeholder (e.g., government, consumer, supply chain, customer, industry, and NGOs) also may contribute to the development of storage applications. This is possible especially with **coordination of stakeholders'** actions and decisions. Coordination of R&D efforts and investments in selected storage technologies and services in the future could effectively lead to exploitation of the full market potential.

The roadmap's analyses also discuss about the important role of European **supply chain** in the development and deployment of new technologies. There is a need to further strengthen European energy storage supply chain, to minimize risk of supply, improve supply independency, and enhance operations and maintenance of storage assets. Following a same logic, issues related to supplies of storage elements (in particular rare elements), lack of trained and knowledgeable human resources, or limited manufacturing capacity act as barriers for the development of energy storage.

Lastly, **consistent data sets** could illustrate economics and environmental values of new technologies, and underline the current gaps in the energy industry. So far, there is a lack of such database on energy storage in Europe in order to show their business cases. There is also lack of data identifying the real value of energy storage. Development of a database is therefore necessary to increase the knowledge on energy storage's installation and potential.

III.2. Key challenges to be tackled

While benefits of energy storage and its potential contribution to energy transition are known, several challenges hamper its development. The identified challenges for different applications of energy storage are summarized below:

The first challenge is related to lack of clarifications regarding the **legal owners and operators** of energy storage. Existing unbundling policies in Europe prohibit system operators from owing, operating and/or capturing all the values associated with energy storage services. The policies need clarification in respect to the legal owners and beneficiaries of storage assets (recommendations are presented in Table 13). This in particular is important for the applications that create market revenue. Given the existing policies, currently there is a **lack of commitment** by potential investors in energy storage and that has slowed down the development process of energy storage.

In addition, in traditional energy systems, there is no concrete **definition of energy storage** and thereby rules and regulations for storage are not clear. The assets in the power system are classified either as generation, transmission and distribution, or consumption units. In some cases, storage owners have to pay double fees for receiving/delivering electricity from/to the grid. This is for example the case for PHS in most European countries, as its pays double fees (tariffs) to access network. As shown by [25], in many EU countries there is no regulation recognizing storage as a separate technology.

Another challenge emerges as the result of **competition** between energy storage and other alternative technologies with similar services and applications. To illustrate, for grid-scale application demand response or reinforcement of grid can delimit storage services in the market. For behind-the-meter application similarly demand response could be an alternative option. In mobility application, energy storage needs to compete with hydrogen and ICE technologies [73] .

Furthermore, the current **technical limitations** of some energy storage technologies reduce their favourability for different services in the market. In particular, the following limitations are remarkable: high technology cost, limited lifecycle or low efficiency, long charging duration (especially for mobility application), instability in very high or low temperatures; and intensive dependency on raw materials.

High energy storage **cost,** paid upfront by investors, is the next challenge for the technology deployment. In addition to this, economic viability of energy storage is debated due to lack of data showing the real financial values of energy storage. For example, there is not much of information available on the potential value of storage based on long-term wholesale saving, and demand management.

Also, the analyses show that energy storage development is slow due to the lack of **society acceptance and awareness** about the benefits of energy storage and distributed energy systems. Society's limited awareness about the benefits of energy storage, and lack of knowledge on cost calculations in electricity bill negatively influence the interests of potential investors.

Finally, weak European **supply chain** for energy storage negatively affects the technologies' development and deployment in the market. Dependency on the foreign products and services could limit the interests of European industry in energy storage. This dependency and lack of strong supply chain also could lead to slow development of recycling facilities and competitive 2nd life business model for storage technologies.

III.3. Actions for accelerated development of energy storage

Development and deployment of energy storage could be accelerated through strategic actions that trigger the market drivers and resolve the barriers. Below the action built on the analysis and findings of this roadmap are summarized in Table 13. The recommendations attempt to consolidate the many market drivers and innovation ideas enumerated for each energy storage application. The actions include both long-term and near-term, needed to accelerate energy storage applications. In most cases, a broad range of stakeholders need to participate to realize the actions.

Table 13 – The recommended actions of this roadmap

Action	Proposed timeline
1. Prioritization of investments in energy storage when it provides a more energy efficient solution, or time and scale are important factors for the project which could better justify energy storage services. • In less densely populated areas, investments in electric storage could be prioritized over investments in grid infrastructure as it can provide potential consumers with access to electricity in a short time, with less cost and lower foot print. In addition, electric storage is scalable meaning that its capacity could be increased through the time with increasing population thereby demand. • Investments in energy storage could be prioritized in locations with large share of RES, in order to enhance flexibility and stability of the system. • Investment in energy storage shall be prioritized in off-grid areas as it provides a more environmentally friendly solution over energy generation from diesel. • Investment in thermal energy storage and heat grid could be prioritized in densely populated areas over electrification due to higher efficiency of the system.	2025-2030
2. European rules for storage ownership and operation should be clarified and recommendations for effective business models should be provided. This report makes recommendations for the following business models for each energy storage application. • For grid-scale applications, the recommendation is to allow a third party to invest in services that create market value, while enable TSOs and DSOs to invest and own energy storage for services that create network value. This business model would create a market for innovation in the energy industry, strengthen economic viability of storage assets, and delimit establishment of monopolies in the market (See section II.1.1.3). • For behind-the-meter application the recommendation is to promote storage as a service business model. The reason is that in this application storage assets are often installed at consumers' residential areas, for whom management of storage technology and benefiting from all the services are complex. The third party can aid the consumers to fully benefit from the storage system, while lowing the consumers' cost and creating economic value for the assets. Having the knowledge and expertise, the third party also can assure the utilization of all potential storage services installed at behind-the-meter (See section II.2.1.3). • For off-grid application the optimal business model is dependent on regional condition in which energy storage being installed. In Europe, there are benefits for applying leasing and pay and you go business model. This business model enables establishment of an off-grid energy system by companies with expertise and experience. Also, it assures establishment of a right and fully functioning system for consumers. • For mini-grid all the business models have their own advantages, but recent trend shows the European market interests in community based application. This partly could be explained by European consumers interests in energy independency (See section II.3.1.3). • For mobility, the main business model would be related to charging and services of batteries, since the ownership of EVS and FCVs will follow the existing business models for ICEs. The recommendation for charging business model is for the leasing of batteries, as it could effectively address consumers' concerns about durability and long-term performance of the batteries. In addition, this business model also would enable faster recycling production and reuse of the batteries, provided that recycling facilities or 2nd life business models further develop (See section II.4.1.3).	2020-2025

Table 14 – The recommended actions of this roadmap (continued)

Action	Proposed timeline
3. Policymakers should enact policies targeting effective services of energy storage: • Policies can promote investments in storage plus PV in order to boost development and integration of RES energy. • Policy makers should introduce subsidies for installation of storage in rural areas, in particular when it is energy storage plus PV. This is to motivate substitution of diesel based generation. • Policymakers could introduce incentives for integration of storage systems into the national energy system in order to fully benefit from installed storage capacities. Examples of these cases are integration of storage system at behind-the-meter, off-grid or in the mobility sector. • Policy makers should introduce policies promoting integration of heat storage in building with a large number of consumers, in order to increase the efficiency of the system.	2020-2025
4. Public sources and databases need to be further developed in order to gather and share knowledge on possible business cases, services, and revenue and saving potentials of energy storage assets. • Database should provide data on implemented project sizes, system costs, efficiency and long-term economics of energy storage technologies. Databases also could provide information on the installed and conducted commercialization projects. • Database could provide information on amount of saved heat or electricity through the utilization of thermal and electrical energy storage technologies.	2020-2030
5. There is need to strengthen cost drivers of storage technologies and systems. To reduce the cost of energy storage the following approaches could be taken. Expectedly technology volume and standardization would have the highest impact on storage systems' cost reduction. • *Technology volume*: Investment in project and manufacturing processes that lead to larger technology production and installation in order to bring the cost of the technologies down. • *Standardization*: In the energy storage market initiatives should be taken for standardization of energy storage for different applications, meaning to make standard connections between different component of energy storage systems. The standards can focus on different aspects such as system installation, product safety, performance standards and recycling to reduce the cost of energy storage systems effectively. • *Technology innovation and structural change*: Improvements will be made in the technology and a whole or its elements resulting a sharp growth in the learning rate. An example would be if the promise of new liquid metal battery chemistries would be realized. Note that while R&D efforts and innovation on storage technologies are ongoing, chances of breakthroughs (advanced innovation) are becoming less likely, since the technologies are fairly developed. • *Market-related forces*: this cost driver would happen when the number of suppliers increases, and hence the price of technology decreases. This leads to a larger deployment and sharper learning curves. • *Government policy related to research and development (R&D) expenditure*: When there is government support and R&D investments in for development and demonstration projects of some technologies.	2020-2025
6. Investments should be places in R&D fund to support innovation of energy storage technologies in order to reduce their cost, and improve their performance. • There is a need to facilitate process to set common goals for technology improvement, price, efficiency and recycling • REEEM IRL report makes R&D recommendation for 5 specific storage technologies: li-ion, flow batteries, supercapacitors, CAES and Hydrogen. Complete Technology improvement examples could be found in the report of EASE [18].	2020-2030-2040

Table 15 – The recommended actions of this roadmap (continued)

Action	Proposed timeline
7. Investment should be made in demonstration projects in order to show the actual business cases, technologies' applicability and economic values of energy storage technologies. In some cases, this necessitates granting permission to go beyond the existing policy and market infrastructure.	2020
8. Subsidies should be granted for both end-products and manufacturing processes. This is in order to support European manufacturing capacity and initiatives. Currently most of batteries are produced outside of Europe (mainly in China, Japan or Korea). This means that supporting the end product creates value for foreign suppliers, while supporting production processes would target and promote local manufacturing processes.	2025
9. Cross-cutting investment should be made in European supply chain for energy storage to enhance the manufacturing capacity, train human resources, and establish production capacity in Europe.	2020-2030-2040
10. Investments should be made in facilities for recycling of storage technologies. This could be for example in facilities that enable extracting and reusing batteries' raw material. This would potentially affect the market position of Europe as it is expected that Asian companies dedicate less efforts to the development of recycling facilities. In addition, Europe faces lack of security of supply for some raw materials. Recycling capacity could enhance the security of the supply of these materials.	2025-2030
11. Mapping the availability of raw material in different European countries could enhance the awareness regarding what resources are currently available, highlight the European dependency on raw material, and facilitate the development of a raw material pool.	2025
12. Targets and incentives should be set to promote investments in electric mobility. • Currently there are set emission targets for car manufacturing companies. The targets are set for 2021, i.e., 95 grams of CO2 per kilometer. Extension of these targets, with more ambitious number, is recommended in order to promote investment in electric mobility. • Policymakers promote investments in services for electric mobility. One approach would be to incentivize investments in electric and fuel-cell charging infrastructures, for example by allocating subsidizes to the installations of charging infrastructure. • Promote additional/higher incentives for special areas e.g., islands, remote areas where grid is weak.	2025-2030
13. NGOs and government need to organize education program and campaign to increase the awareness of end-users about the benefits of different energy storage technologies and its contribution to efficient energy consumption and cost management.	2025
14. Investments will be in new maintenance and control services of thermal energy storage systems as they would contribute to the optimization of the systems.	2025-2030
15. Integration of thermal energy storage in locations and areas with high population density or energy intensive processes. This is if it could lead to a more efficient energy system	2025-2035

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Appendix I –Technology Factsheet

The following pages include Fact sheet about storage technologies [3,16,17,74], [75]. The evaluated technologies within this roadmap are illustrated in Table I-1. Development stages of the technologies from ideas to maturity are named research, development, demonstration, deployment and matures. Please note that different resources provided different estimations for the characteristics of the storage technologies (e.g., cost[1]). In those cases, a range has been noted.

Table I-1- Overview of energy storage technologies

	Principal				
	Electrochemical	**Electrical**	**Mechanical**	**chemical**	**Thermal**
Technology	Sodium Sulphur (NaS) Batteries	Superconducting Magnet Energy Storage (SMES)	Compressed Air Energy Storage (CAES)	Hydrogen storage technologies	Sensible heat storage (SHS)
	Flow Batteries (VRB and ZnBr)	Super Capacitors	Flywheels		Latent heat storage (LHS)
	Lead Acid Batteries		Liquid Air Energy Storage (LAES)		Thermochemical heat storage (THS)
	Sodium Nickel Chloride Batteries (NaNiCl2)/ ZEBRA		Pumped hydro storage (PHS)		
	Lithium ion batteries (Li-on)				
	Lithium-sulphur batteries (Li-S)				
	Nickel-cadmium (NiCd) batteries				
	Zinc air batteries				

[1] In most cases the cost was given in USD 2014. Hence, it was converted to Euros using the USD/Euro exchange rate as of June 30th 2014 (0.73). http://www.x-rates.com/historical/?from=USD&amount=1&date=2014-06-30

Flywheel

Flywheel technology uses the electrical energy to spin a flywheel and retrieve that energy in a reverse process by a mean of the motor that accelerated the flywheel acting as a brake. Extracting energy from the rotating flywheel. To reduce friction losses, often the flywheel is placed inside a vacuum with the actual flywheel magnetically levitated instead of using conventional bearings.

Development status
Demonstration and Deployment

Pros:

- Rapid response times
- Low maintenance requirements
- Mature technology
- Unlimited number of charge/discharge cycles

Cons:

- Requires robust containers to keep fragments if the flywheel fails
- Variable speed rotation during energy releases
- High engineering specifications
- High price

Mechanical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	730-3650
Cycle efficiency	90-95%
Power rating (MW)	0.1-20
Storage duration	Short term
Cycling Times	20000+
Self-discharge %	>20% per hour
Energy density (Wh/l)	20 - 80
Power Density (W/l)	1000-2000
Response time	Seconds

Application:

Grid-scale	☑
Behind-the-meter	☐
Off-grid	☑
Mobility	☐
Thermal	☐

Lithium ion (Li-on) Batteries

Lithium ion (Li-ion) batteries high energy density. The technology could be implemented on a large scale. Research and development is on-going in various other chemistries of the battery type with a view to improving performance and reducing the cost. R&D particularly aims to improve battery power capability with the use of nanoscale materials; and increase battery specific energy by developing advanced electrode materials and electrolyte solutions.

Development status
Demonstration and Deployment

Electrochemical

Pros:

- Extremely high energy density
- Considerable discharge cycles
- High efficiency

Cons:

- High cost
- Negative effects of overcharging/over discharging
- Issues related to overheating

Technical character and key data(~2014):

Energy Capital cost (Euro/KWh)	365-1825
Cycle efficiency	85-95%
Power rating (MW)	0.1 - 50
Storage duration	Short-Med. term
Cycling Times	1000 - 10000
Self-discharge %	0.1 - 0.3%
Energy density (Wh/l)	200 - 400
Power Density (W/l)	1500 - 10000
Response time	< Second

Application:

- Grid-scale ☑
- Behind-the-meter ☑
- Off-grid ☑
- Mobility ☑
- Thermal ☐

Lead-acid Batteries

Lead acid battery have several technology types. Flooded lead-acid batteries immerse the electrodes in liquid electrolytes and release gases upon charging. Sealed lead acid batteries have two forms: Absorbed glass mat batteries which create energy by immobilizing electrolytes with a micro fiber glass mat; and Gel cell batteries which have the electrolyte mixed with silica dust to form an immobilized gel. Sealed batteries they have a longer re-charge time and shorter useful life. Advanced lead acid batteries have been developed and are particularly suited to energy storage applications.

Electrochemical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	146-292
Cycle efficiency	70-80%
Power rating (MW)	0-40
Storage duration	Short-Med. term
Cycling Times	500-1800
Self-discharge %	0.1-0.3%
Energy density (Wh/l)	50-90
Power Density (W/l)	10 - 400
Response time	< Second

Development status:
Deployment and Mature

Pros:

- Developed technologies
- Established infrastructure for end of life recycling
- Relatively efficient
- Low self-discharge rates

Cons:

- High depths of discharge
- Low energy density
- Potentially hazardous materials

Application:

Grid-scale	☑
Behind-the-meter	☑
Off-grid	☑
Mobility	☑
Thermal	☐

Flow Batteries

A flow battery consists of external liquid electrolytes and two soluble redox couples. These electrolytes can be pumped from the tanks to the cell stack which includes two electrolyte flow compartments separated by ion selective membranes. During the charging phase, one electrolyte is oxidized at the anode and when another electrolyte is reduced at the cathode. In this process, the electrical energy is converted to the electrolyte chemical energy. The above process is reversed during the discharging phase. Flow batteries can be categorized into redox flow batteries (E.g., Vanadium Redox (VRB)) and hybrid flow batteries, (e.g., Zinc Bromnie (ZnBr)).

Electrochemical

Technical character and key data (~2014):

	VRB	*ZnBR*
Energy Capital cost (Euro/KWh)	110-730	10-730
Cycle efficiency	75-85%	65-80%
Power rating (MW)	0.03-3	0.05-2
Storage duration	Long term	Long term
Cycling Times	12000+	2000+
Self-discharge %	Small	small
Energy density (Wh/l)	16-33	30-60
Power Density (W/l)	<2	<25
Response time	<Second	<second

Development status
Demonstration and Deployment

Pros:

- Less sensitive to higher depths of discharge
- Able to tolerate a large number of charge/discharge cycles
- Long life
- Virtually unlimited capacity

Cons:

- Low energy density
- Not commercially mature

Application:

Grid-scale	☑
Behind-the-meter	☑
Off-grid	☑
Mobility	☑
Thermal	☐

Sodium Nickel Chloride (NaNiCl2) Batteries

Sodium Nickel Chloride Batteries consists of a nickel chloride cathode, a beta alumina separator and a liquid sodium anode. During the charging process the sodium ions are transported through the beta alumina to the anode reservoir. Discharge is the reverse of this process. Sodium ions move easily across the beta alumina but electrons cannot, and accordingly there is no self-discharge. The batteries are often left charged when they are not in use. The operating temperature of the cell is between 270 C and 350°C.

Electrochemical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	900-1200
Cycle efficiency	86-88%
Power rating (MW)	1 - 10
Storage duration	Short-Med. term
Cycling Times	2500-3000
Self-discharge %	15%
Energy density (Wh/l)	100-140
Power Density (W/l)	150-200
Response time	Second - Minute

Development status
Development and Deployment

Pros:

- High energy density
- Long life (20 years)
- Little / no self discharge
- No cooling requirement
- Fully recyclable

Cons:

- Heating sometime is required
- safety concerns about the molten sodium
- Unsuitable for short cycling

Application:

Grid-scale	☑
Behind-the-meter	☑
Off-grid	☑
Mobility	☑
Thermal	☐

Sodium Sulphur (NaS) Batteries

A sodium Sulphur battery is constructed from sodium (Na) and Sulphur (S), where the casing (outside container) is the positive and liquid sodium is the negative electrode. During charging, the sodium ions are transported through the ion selective conductor to the anode reservoir. Discharge is the reverse of his process. The battery cannot self-charge because sodium ions move easily across the ion selective conductor, while electrons cannot. Batteries typically are fully charged, when are not in use.

Development status
Demonstration and deployment

Pros:

- High energy density
- Long life cycle
- Quick response
- Efficient in charge-discharge cycles
- Able to tolerate a high number of charge/discharge cycles

Cons:

- Heating may be required
- Potential safety issues with
- the molten sodium
- Fire issue at a Japan installation
- Relatively high self-discharge rate

Electrochemical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	219-365
Cycle efficiency	75-90%
Power rating (MW)	<8-34
Storage duration	Long term
Cycling Times	2500 - 4500
Self-discharge %	0.05 %
Energy density (Wh/l)	150 - 300
Power Density (W/l)	140 -180
Response time	<Second

Application:

Grid-scale	☑
Behind-the-meter	☑
Off-grid	☑
Mobility	☑
Thermal	☐

Lithium Sulphur (Li-S) Batteries

In lithium-Sulphur (Li-S) cells, lithium dissolution from anode surface during discharge and reverse lithium plating during charge. Each Sulphur atom theoretically can host two lithium ions. This new type of energy storage device can achieve 80% more capacity than Li-ion batteries and be safer. However, it is still in the R&D phase.

Development status
Research and Development

Pros:

- Greater specific energy than LiBs
- Cost-effective
- Similar manufacturing techniques as other major cell chemistries

Cons:

- Short cycle life
- Pure sodium requires system protection from moisture
- Polysulfide can impact charging and discharging performance
- They can catch fire

Electrochemical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	190 (cost target)
Cycle efficiency	95%
Power rating (MW)	kw-MW
Storage duration	min to 1 h
Cycling Times	1500
Self-discharge %	negligible
Energy density (Wh/l)	350
Power Density (W/l)	
Response time	milliseconds

Application:

- Grid-scale ☑
- Behind-the-meter ☐
- Off-grid ☐
- Mobility ☑
- Thermal ☐

Nickel Cadmium (NiCd) Batteries

NiCd battery consist of nickel hydroxide and metallic cadmium as the two electrodes. The electrolyte of this solution is aqueous alkali. The battery requires low maintenance and is robust, but is to some extent hazardous since both cadmium and nickel are toxic heavy metals. Besides, the battery capacity can decrease if it is repeatedly recharged after being only partially discharged.

Development status
Deployment and Mature

Pros:

- function is cold temperature
- low maintenance

Cons:

- Safety concerns

Electrochemical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	365-1460
Cycle efficiency	60 – 70%
Power rating (MW)	0-40
Storage duration	Short to Long term
Cycling Times	2000-3000
Self-discharge %	0.2-0.6%
Energy density (Wh/l)	50 - 150
Power Density (W/l)	80 - 600
Response time	< Second

Application:

- Grid-scale ☑
- Behind-the-meter ☑
- Off-grid ☑
- Mobility ☑
- Thermal ☐

Metal air Batteries

Metal-air rely on water-based electrolytes and the electrolyte of the cell is usually in liquid form or solid polymer, with a good OH-ion conductor. The metal-air family have different types of anode, but Zinc and Lithium are the most advanced anodes, available with a high energy density that release electrons upon oxidation. The cathodes are air electrodes, with porous carbon structure or a metal mesh covered with proper catalysts.

Electrochemical

Technical character and key data (~2014):

	Zinc-air
Energy Capital cost (Euro/KWh)	120 - 130 (cost target)
Cycle efficiency	80%
Power rating (MW)	1-50 MW
Storage duration	6 h
Cycling Times	4200
Self-discharge %	Negligible
Energy density (Wh/l)	700
Power Density (W/l)	
Response time	Milliseconds

Development status
Research and Development

Pros:

- Environmentally benign
- Higher energy densities (~900-1600Wh/kg)
- Potential low cost
- Abundant material content

Cons:

- Inefficient and difficult electrical recharging
- A few hundred cycles
- A relatively low 50% cycle energy efficiency
- Charging voltage is higher than discharge voltage

Application:

Grid-scale	☑
Behind-the-meter	☑
Off-grid	☑
Mobility	☑
Thermal	☐

Compressed Air Energy Storage (CAES)

CAES uses geological underground voids or purpose made vessels to compress and store air in order to store energy. When the stored energy is needed, the released air is heated via combustion using natural gas and is expanded in order to drive a gas turbine to generate electricity. Current installed CAES plants are termed adiabatic storage and dissipate the generated heat as waste to the atmosphere. Compressed air energy storage requires little land, but require extensive water resources and emits greenhouse gases. Note that the emissions are very low and could be avoided in adiabatic and isothermal plants.

Development status
Deployment and Mature

Mechanical

Pros:

- Rapid start up times
- Simple mechanical system
- Long asset life

Cons:

- it requires fuel (gas)
- low efficiency
- requires suitable geological features
- generate heat and emissions (if fossil fuel used)

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	1.5-88 (Large scale) 148-180 (over ground small)
Cycle efficiency	45-70%
Power rating (MW)	10 - 1000
Storage duration	Long term
Cycling Times	8000-15000
Self-discharge %	about 0
Energy density (Wh/l)	2 - 6
Power Density (W/l)	0.2 - 0.6
Response time	Second - Minutes

Application:

- Grid-scale ☑
- Behind-the-meter ☐
- Off-grid ☑
- Mobility ☐
- Thermal ☐

Liquid Air Energy Storage (LAES)

The Liquid air energy storage (LAES) uses liquid air or liquid nitrogen as the energy storage medium in insulated low pressure tanks at cryogenic temperatures. When electricity is required, the stored air in insulated pressure tanks is vaporized and expanded through turbines to generate electricity. Two processes can increase the efficiency of this technology: first if waste heat is applied to the conversion process or cold air is recovered from it.

Mechanical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	190-387
Cycle efficiency	55-80%
Power rating (MW)	10-200
Storage duration	Long term
Cycling Times	-
Self-discharge %	Small
Energy density (Wh/l)	Larger than CAES
Power Density (W/l)	-
Response time	Minutes

Development status

Development and Demonstration

Pros:

- No geographical restriction
- Established supply chain
- Unlimited feedstock

Cons:

- Low efficiency unless waste heat used
- lack of technology maturity
- Mature supply chain
- do not use toxic material
- Long cycle life
- Long duration application"

Application:

Grid-scale	☑
Behind-the-meter	☐
Off-grid	☐
Mobility	☐
Thermal	☐

Pumped Hydro Storage (PHS)

Hydropower storage project function by impounding water behind a dam, forming a reservoir. Water is released through turbine generators to produce electricity. Release cycles can be relatively short, or long. The water could be impounded during high rain seasons and be used over dry years.

Mechanical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	3.7-73
Cycle efficiency	70-85%
Power rating (MW)	100-5000
Storage duration	Long term
Cycling Times	10000-30000
Self-discharge %	~0
Energy density (Wh/l)	0.5-1.5
Power Density (W/l)	0.5-1.5
Response time	Minutes

Development status
Mature

Pros:

- High capacity
- Low cost
- No fuel consumed
- Fast response time

Cons:

- High capex required
- Long construction times
- Dependency on water flow activity and turbine height
- Disruption to natural river flows and habitat
- Land usage
- Environmental permitting and siting

Application:

Grid-scale	☑
Behind-the-meter	☐
Off-grid	☑
Mobility	☐
Thermal	☐

Superconducting Magnet Energy Storage (SMES)

SMES store energy by generating strong magnetic fields. The magnetic fields are generated within a superconducting coil generating a DC current flowing through the coil. The amount of energy available do not depend on the discharge rating, while in batteries discharge reduced the amount of energy output. SMES systems consist of a high inductance coil which can be treated as a constant current source. The superconducting nature of SMES means that energy can be stored for long periods of time and very little energy will be lost. The most commonly used superconducting material is Niobium-Titanium (NbTi) which is operated at -271°C.

Development status
Research and Development

Pros:

- Almost instantaneous recharge
- Almost infinite cycle life

Cons:

- Low energy density
- Parasitic losses associated with the cooling of the superconducting magnet
- High cost of superconducting materials

Electrical

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	730-7300
Efficiency	85-95%
Power rating (MW)	0.1 - 1
Storage duration	Short term
Cycling Times	20000+
Self-discharge %	10 -15 %
Energy density (Wh/l)	0.2-2.5
Power Density (W/l)	1000-4000
Response time	< second

Application:

Grid-scale	☑
Behind-the-meter	☐
Off-grid	☐
Mobility	☐
Thermal	☐

Supercapacitors

Supercapacitors consist of two conductor electrodes, an electrolyte and a porous membrane separator. In supercapacitors energy is stored in the form of static charge on the surfaces between the electrolyte and the two conductor electrodes. The supercapacitors with high-performance are based on nano materials to increase electrode surface area for enhancing the capacitance.

Development status
Demonstration and Deployment

Electrical

Pros:

- Potential unlimited number of charge/discharge cycles
- High current loads
- Rapid cycle times
- High power density
- Not susceptible to overcharging

Cons:

- High cost
- High rate of self-discharge
- Low energy density

Technical character and key data (~2014):

Energy Capital cost (Euro/KWh)	219-1460
Cycle efficiency	85-95%
Power rating (MW)	0.1-0.3
Storage duration	short term
Cycling Times	10000 - 100000
Self-discharge %	20 - 40 %
Energy density (Wh/l)	10-30
Power Density (W/l)	100000+
Response time	< second

Application:

- Grid-scale ☑
- Behind-the-meter ☐
- Off-grid ☑
- Mobility ☑
- Thermal ☐

Hydrogen

In this chemical storage, electrical energy is stored by electrolysing water, producing hydrogen and oxygen. Hydrogen is stored and oxygen is released. Successively and when needed, hydrogen is re-electrified (e.g., via fuel cell) and recombined with oxygen to produce electricity. By product of this process are heat and water. Hydrogen can be stored either as a gas, or liquid at temperature below −253°C or as a compressed gas in storage tanks. Use of Hydrogen in chemical industry is mature and therefore the transport and containment infrastructure for hydrogen is based on well-established technologies within the supply chain.

Chemical

Technical character and key data(~2014):

Energy Capital cost (Euro/KWh)	2-15 (hydrogen fuel cell)
Cycle efficiency	20-50%
Power rating (MW)	<50
Storage duration	Med.-long term
Cycling Times	1000-20000
Self-discharge %	~0
Energy density (Wh/l)	500-3000
Power Density (W/l)	500+
Response time	Sec

Development status
Development and Deployment

Pros:

- No emissions (only water vapors)
- Feasibility of transportation
- No self-discharge
- High efficiency
- Low maintenance
- Long life span
- Low noise volume
- Heat waste recycling capability
- Internal consolidation capability

Cons:

- Low round trip efficiencies
- Low energy density
- Safety concerns
- High prices of fuel cell technologies

Application:

Grid-scale	☑
Behind-the-meter	☐
Off-grid	☑
Mobility	☑
Thermal	☐

Thermal Energy Storage (TES)

TES encompasses a variety of technologies that store available heat energy following three main principle.
Sensible thermal storage (SHS) changes the temperature of a storage medium in order to store or release energy for low temperature applications. Latent thermal storage (LHS) take advantage of melting or absorbing of a material to store heat. The materials in this application change the phase. In LHS the materials have a higher storage capacity within a small temperature range compared to SHS. Thermochemical heat storage (THS) uses a chemical reaction and sorption to store energy. In this technology heat is stored through chemical reactions and bonds.

Thermal

Technical character and key data (~2014):

Capital cost (Euro/KwH)	15-44
Cycle efficiency	30-60%
Power rating (MW)	0.1-300
Storage duration	
Lifetime or cycling	-
Self-discharge	0.05-1
Energy density (Wh/l)	80-200
Power Density (W/l)	-
Response time	Slow

Development status
Development and Deployment

Pros:

- large quantities of energy storage
- low major hazards
- Low daily self-discharge loss is small
- good energy density and specific energy
- low capital cost

Cons:

- the cycle efficiency of TES systems is normally low (30–60%)

Application:

- Grid-scale ☐
- Behind-the-meter ☐
- Off-grid ☐
- Mobility ☐
- Thermal ☑