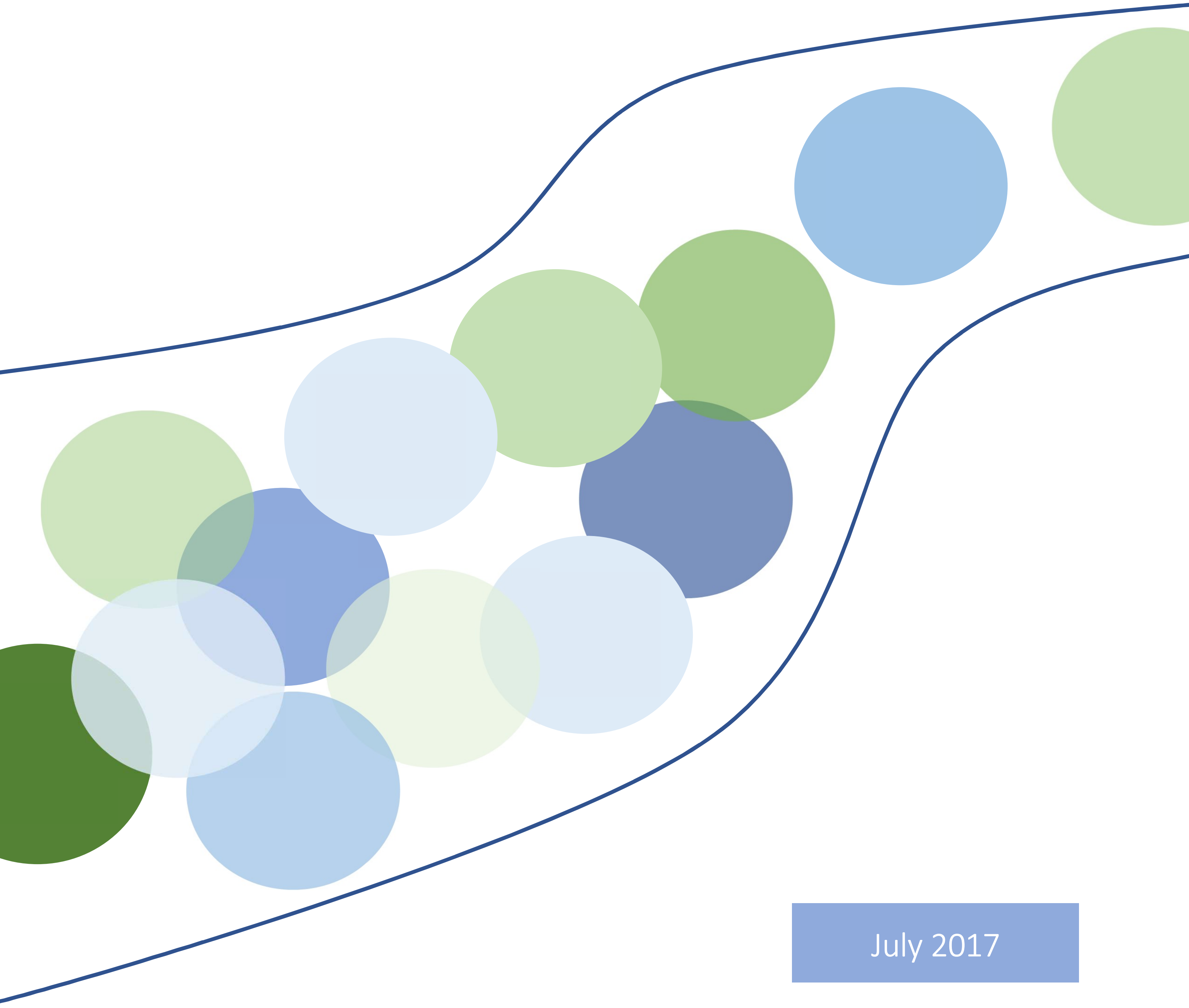
Innovation Readiness Level Report

Energy Storage Technologies



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About this report

In the framework of REEEM project, three innovation readiness level reports will be developed on three different energy technology groups. The first report, presented in this document, is dedicated to energy storage technologies. Five storage technologies are selected and studied in this report, namely Li-ion, flow batteries, supercapacitors, CAES, and hydrogen. The technologies are from different energy storage categories to provide a wider picture on the existing technologies in the market.

This report will be complemented with the REEEM Technology and Innovation roadmap on energy storage applications (to be published on 31st July 2017), and a report reviewing techno-economic parameters of storage technologies (to be published on 28th February 2018).

Authors

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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.

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Summary

Innovation is identified as a key to economic growth and plays an important role in tackling climate challenges. This is reflected in the 5th pillar of Energy Union recognizing research, innovation and competitiveness as "*paramount to address the climate challenge, to accelerate the EU energy transition, and to reap benefits in terms of jobs and growth*". In this context, innovation could be defined as a process of making changes to products, services and technologies or a result from interactions within an (open) ecosystem made of researchers, entrepreneurs, citizens, investors.

As the results of innovation, different **new energy technologies** have entered the energy markets. These new technologies offer new services, or substitute existing one, for instance with lower CO_2 emissions, lower energy consumed, at reduced costs. The generalised adoption of new technologies can successfully to change the competitive market dynamics. resulting in electricity production with almost zero emissions (e.g., wind and solar power), emergence of prosumers, and better management of energy quality and cost.

In spite of their advantages, not all new technologies can successfully **access the energy market** and play a role in it. In order to be successful, several factors and parameters should be considered and evaluated. This does not suffice to the technologies' specifications and competitiveness, but also other socioeconomic factors. Therefore, to assess a technology's innovation maturity and its potential and risk in accessing a market, it is necessary to evaluate all the dimensions affecting innovation readiness of a technology.

For that purpose, InnoEnergy has developed an **Innovation Readiness Level** (IRL) methodology to assess, the innovation readiness of a technology, product or service along 5 dimensions: *technology readiness level, Intellectual property (IP) readiness level, market readiness level, consumer readiness level and society readiness level*. The methodology explores factors and processes that are prerequisites for the technology's development and access to the market. It is used at time of selection and along the management of innovation projects or venture.

This document reports the results of IRL of a number of **energy storage technologies** using an adapted version of the IRL methodology for REEEM purposes. Energy storage technologies have a significant role to play in the future energy industry, given their ability to enhance reliability and flexibility of the energy system. While different storage technologies enter the market, not all are successful due to their limited innovation maturity that lowers their competitiveness when compared with other storage technologies, or alternative options.

The **findings** illustrate potentials and risks of different storage technologies to access the market. It also suggests points in innovation processes of these technologies which can effectively improve their competitiveness in accessing the energy market. The studied storage technologies are: *Lithium ion batteries, flow batteries, compressed air energy storage, supercapacitors and hydrogen*. The results provide suggestions for policymakers, investors and industries about strengths and drawbacks of the innovation processes of the studied technologies.

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I. Introduction

I.1. Energy Union: role of energy storage in the European energy transition

The European Energy Union aims at providing a holistic approach to the transformation of the EU energy system towards a low carbon society. The overall objective is to secure supply of sustainable energy for consumers at affordable price. Innovation is an acknowledged mean for reaching this objective, and hence founds the 5th pillar of energy union titled: Research, Innovation and Competitiveness. The 5th pillar states: "*the transition and disruptions our economy is undergoing to meet climate and energy challenges will require major technological advances, different social organization, new business models, optimized processes and better alignment between the research, innovation and industrial policy priorities.*"[1].

The Energy Union recommends an integrated innovation approach for technology groups that could play a more effective role in energy transition. Energy storage technologies are among the acknowledged technology groups, as they have the capacity to contribute to system flexibility and to facilitate renewable energy integration. As yet, different energy storage technologies are introduced to the market and each of them has its own particular characteristics making it suitable for certain applications and services. Storage technologies also have different levels of maturity and therefore potential to successfully access the market. The potentials are not only bounded by the technology development, but also its maturity and readiness level of other dimensions such as market, consumer and intellectual property (IP).

Therefore, in order to explore the technology's potential to access the market, there is a need to study all the relevant dimensions. Below, first a review of two tools assessing the technology development and deployment potential are presented. Successively, the REEEM IRL methodology is explained in detail.

I.2. Technology development assessments tools: an overview

I.2.1. Technology Readiness Level (TRL)

In 1989 NASA introduced a systematic approach to study the development of a technology, with the creation of the Technology Readiness Level (TRL) tool. The TRL describes the technology maturity level on a 0-9 scale, where 1 is the development of the idea in a laboratory and 9 represents the full technology readiness for deployment in the market. The tool assesses the technology maturity before its integration in the market, and studies asymmetries along the development process. The TRL tool is used widely in economic practice.

I.2.2. Demand Readiness Level (DRL)

To be successful, any new product or services needs to find its demands in the market place. This is because such analysis fails to consider innovation needs of different actors taking part in the market and the process of technology development [2]. Hence, the concept of Demand Readiness Level (DRL) is developed in order to better understand and manage the process of technology deployment by hybridizing market pull and technology push approaches [3]. DRL studies technology maturity by analysing different actors' readiness to adopt innovation, assessing their need for it.

I.2.3. Innovation Readiness Level (IRL)

The Innovation Readiness Level (IRL) tool has been developed by InnoEnergy with the purpose of assessing the level of maturity of an innovative product, service or emerging business (i.e. start up and venture). The tool empowers the assessment of innovation potential of a technology, product or service by analysing all the dimensions that can influence its innovation process. The IRL extends earlier efforts that were focused on TRL and DRL, and assesses a technology's development along 5 different dimensions. Each dimension consists of several levels representing the technology readiness stage in that dimension. Successively, the IRL of a technology is assessed by considering the technology's level in all the five dimensions. The dimensions are (Figure 1):

1. Technology Readiness Level (TRL): it measures the maturity of a given technology, using the nine levels originated within NASA in the 80's. These range from the fundamental research up to the market certification and sales authorization.

2. IP Readiness Level (IPRL): it measures the "freedom to operate" of a technology. This dimension is made up of three levels, which range from the basic research based on IP mapping up to the detailed and complete freedom to operate in a global framework.

3. Market Readiness Level (MRL): it measures the maturity of a need for the technology in the market. This dimension is made up of twelve levels, which range from the identification of an unsatisfied need up to the full commercialization and scaling.

4. Consumer Readiness Level (CRL): it identifies the level of knowledge about the consumers and their need for the technology under study. This dimension is made up of six levels, which range from the identification of the consumer and his/her needs up to the consumer integration in technology development.

5. Society Readiness Level (SRL): it identifies the level of knowledge about the stakeholders' interests in and concerns about the technology. It also estimates how the technology impacts on society. This dimension is made up of five levels, which range from the recognition of the stakeholders up to the involvement of the stakeholders.

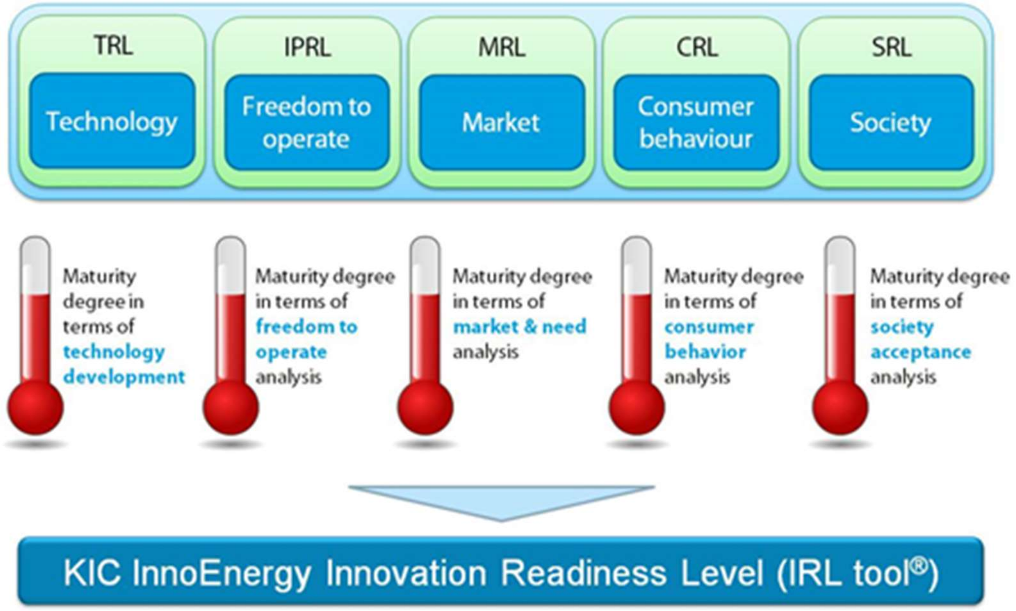

Figure 1 – InnoEnergy IRL tool

I.3. REEEM IRL methodology

For the purpose of the REEEM project, a customised version of the IRL tool is used. The customisation assures that the IRL methodology is applicable to technology level (while InnoEnergy IRL tool is applicable also to products and services) and evaluates all energy system stakeholders. The REEEM IRL assessment has relevance for public and private investors and policymakers as it explores the shortcomings and opportunities of the storage technologies along 5 dimensions of TRL, IPRL, MRL, SRL, and CRL. The dimensions have similar number of levels as the InnoEnergy IRL tool. The higher is the level of a technology in each dimension, the higher is its readiness to access the market.

The first version of the REEEM IRL tool was tested internally through a pilot project at InnoEnergy. Successively, the test results were evaluated and the tool was revised. The data for the REEEM IRL methodology was gathered by means of an extensive questionnaire. The questionnaire includes binary or predefined answers which limit the influence of biases and external opinions on the results. The answers were coded in order to report the questionnaire's results quantitatively reporting the technology's level in each of the IRL dimensions. This means that the answers to the questionnaire are turned into a scale for each dimension. There has been no weighting of the questions, meaning that all the analysed parameters within each dimension were treated equally. The obtained results are consolidated through literature studies and several interviews with experts who were involved in filling the questionnaire. The interviews' results are utilized to provide a more comprehensive picture of the technologies' IRL and understand the logic behind the answers.

Below all the REEEM IRL dimensions are explained:

TRL: this dimension is 9 levels and evaluates the maturity of a technology by exploring its development process from research to sale and certifications. In this process TRL investigates the technology's objectives and studies its production and demonstration processes. In addition, different technical features of the storage technologies are assessed to understand if the technology could satisfy its application and services' objectives. The European SET Plan targets[1] (if available) are presented in order to shed light on the need and prioritization of R&D efforts [4]. The following technical characteristics are studied:

- **Energy storage capacity** (kWh) which refers to the amount of energy that could be stored in a system.
- **Energy density** (kWh/kg) and **power density** (kW/kg) that reflect on the amount of energy per mass and is particularly important in applications where space is important.
- **Specific energy** (kWh/l) that refers to the amount of energy per volume.
- **Charge and discharge rates** (kW) to define how fast energy can be charged/ discharged.
- **Response time** (seconds, minutes, hours) which sheds light on the time needed for the storage system to provide energy on demand.
- **Lifetime** of a storage system is given as the number of cycles or years.
- **Efficiency** that is the ratio of energy discharged by the system to the energy needed to charge it at each cycle and accounts for energy lost in the storage cycle.

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[1] *Referring to Strategic Energy Technology Plan - European Commission (SET Plan)*

IPRL: in this dimension is 3 levels and questions are raised to assess if a technology could freely access and operate in the market, or its deployment is blocked due to established IP and patents. Companies' knowledge about the existing patents in the market is evaluated and it is investigated how and if the companies cooperate together in respect to their IP rights. Data are obtained through several questions in the questionnaire and interviews with the experts.

MRL: this dimension is 12 levels and investigates market parameters influencing the development and deployment of an energy storage technology. The analysis first identifies different potential applications of the technology under study. In this process, the findings of the REEEM Technology and Innovation Roadmaps are utilised. Successively, a technology's value chain, supply chain, and customers are evaluated, and existing competition in the market is assessed. When available, the future technology's market trend is illustrated in order to envision the technology deployment potential. The overall objective is to explore the market need for technology, and the road toward full commercialisation and successful deployment of the technology.

CRL: when end-users of a technology are different from its customers, the analyses of this dimension with 6 levels aims at exploring consumers' readiness and need for the technology. In other words, the CRL estimates the consumers' willingness to engage in the technology development, analyse their needs, routines, resources and abilities. It addition, the CRL explores consumers' contributions to the technology deployment. The answers to the questionnaires and interviews with the experts investigate the significance and the role of consumers in the development and deployment of the technology in the market.

SRL: this dimension is 5 levels and evaluates the technology's stakeholders. The assessment aims to identify if for each technology the stakeholders are identified, informed and involved in the process of technology deployment. Furthermore, through the findings of interviews and the questionnaires, the concerns of the stakeholders are identified and it is explored if and how these concerns are tackled.

The overall IRL of a technology is assessed, by considering the technology's level in all the five dimensions namely, TRL, IPRL, MRL, CRL, and SRL. A technology's level within each dimension is reported as a number, and the IRL is reported as the sum of the technology's level in all the other dimensions (0-35). However, for understanding the IRL level of a technology is it important to evaluate the technology's potentials and risk to access the market along the five dimensions. In other words, IRL could not be understood as a standalone number, but rather a description of a technology's in all the five dimensions. This is because for each technology some dimensions are more important than the others. Note that, IRL provides description of the current status of the technology without making any projection about its future.

I.3.1. Context: Energy storage technologies

The IRL assessments, presented in this report, focus on storage technologies. In the energy market, different categories of storage technologies compete. The technologies are categorised based on the basic storage principle into five main groups of electrical, electrochemical, mechanical, chemical and thermal (Figure 2). The technologies within these categories have different technical characteristics, therefore can provide different applications and services to the market and have different installed share across the world (Figure 3,4,5). The REEEM Innovation and Technology roadmap describes the applications and services of energy storage in details, following a market-driven approach. The findings of IRL assessments in this report complement the roadmap's outcomes by explaining which storage technologies could perform the identified applications and services more efficiently and through a cost-effective manner. The identified energy storage applications are:

- **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.

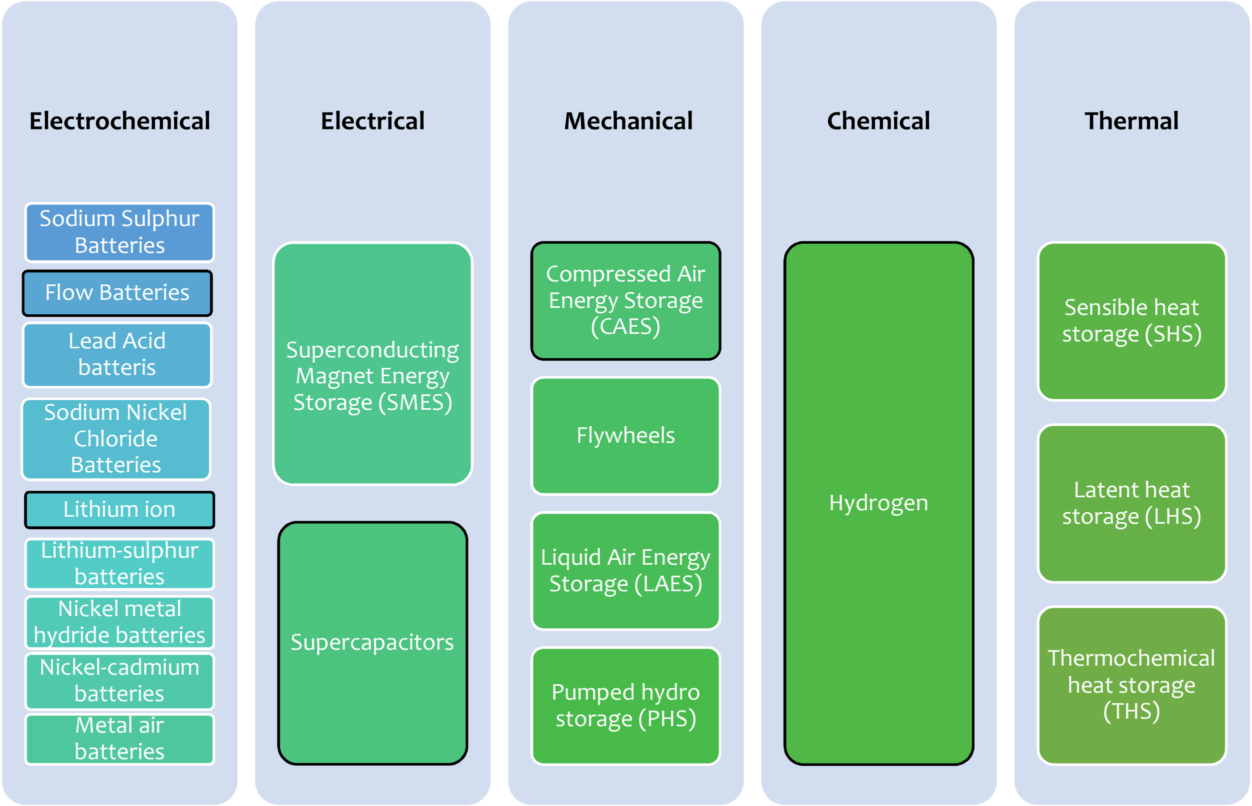

Figure 2 –- Overview of energy storage technologies

In this report, the IRL methodology is applied on of 5 energy storage technologies. The selected technologies are: lithium-ion, flow batteries, supercapacitors, compressed air energy storage (CAES) and hydrogen. The technologies are selected from different principles of energy storage technologies (see Figure 2, the studied technologies are highlighted with black borders), and with different deployment share (Figure 4,5) in order to provide a wider picture of the market. This report did not evaluate any technology from thermal category, due to lack of data. The lesson learnt from the IRL assessments could inform the application of IRL for other storage technologies.

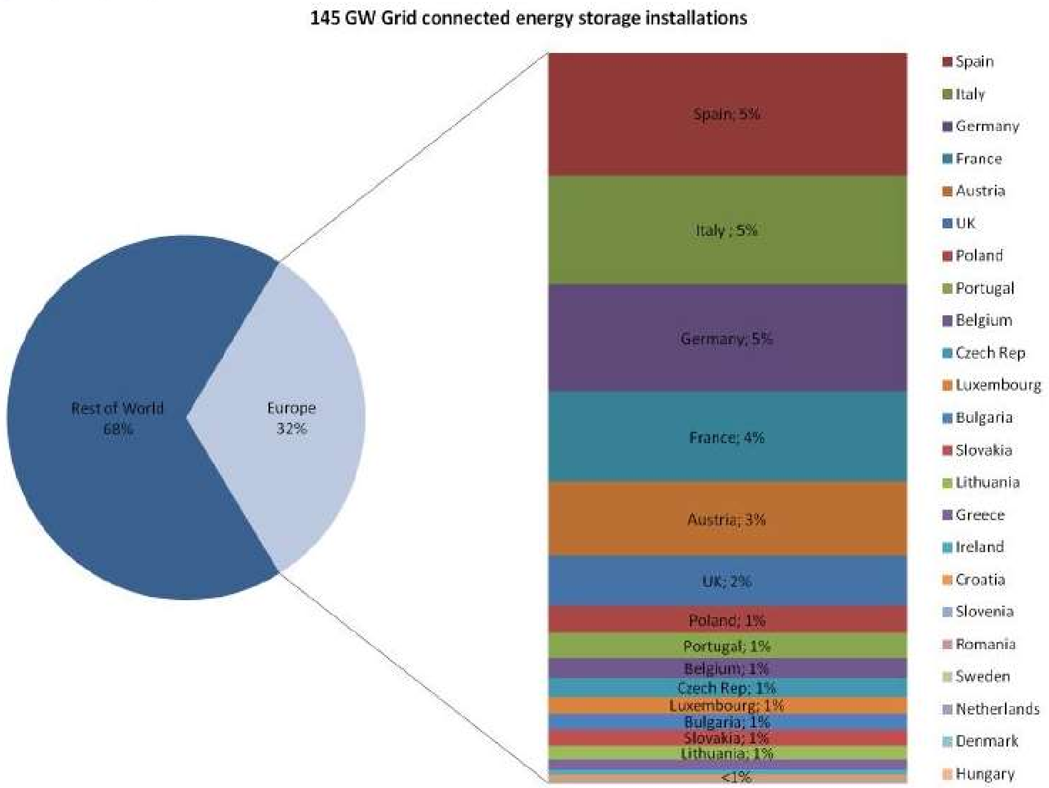

Figure 3- share of grid connected storage in different EU member states

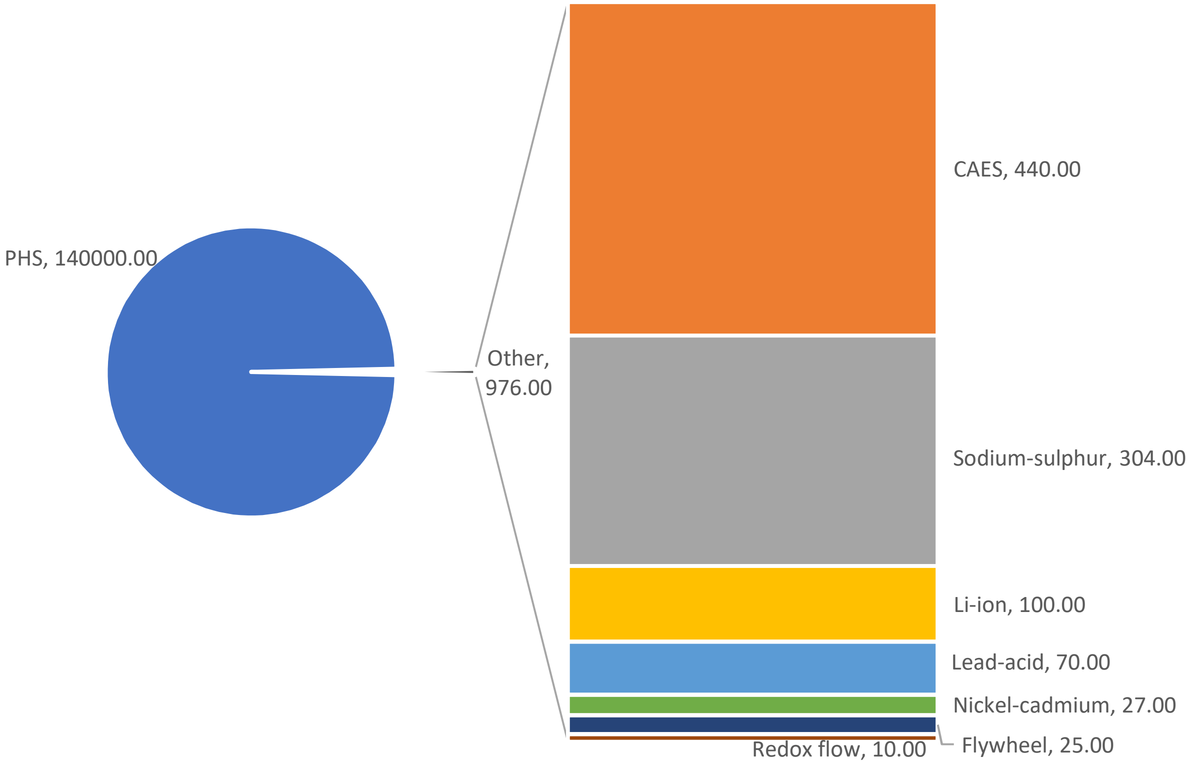

Figure 4- Current global installed grid-connected electricity storage capacity (MW) [5],[6]

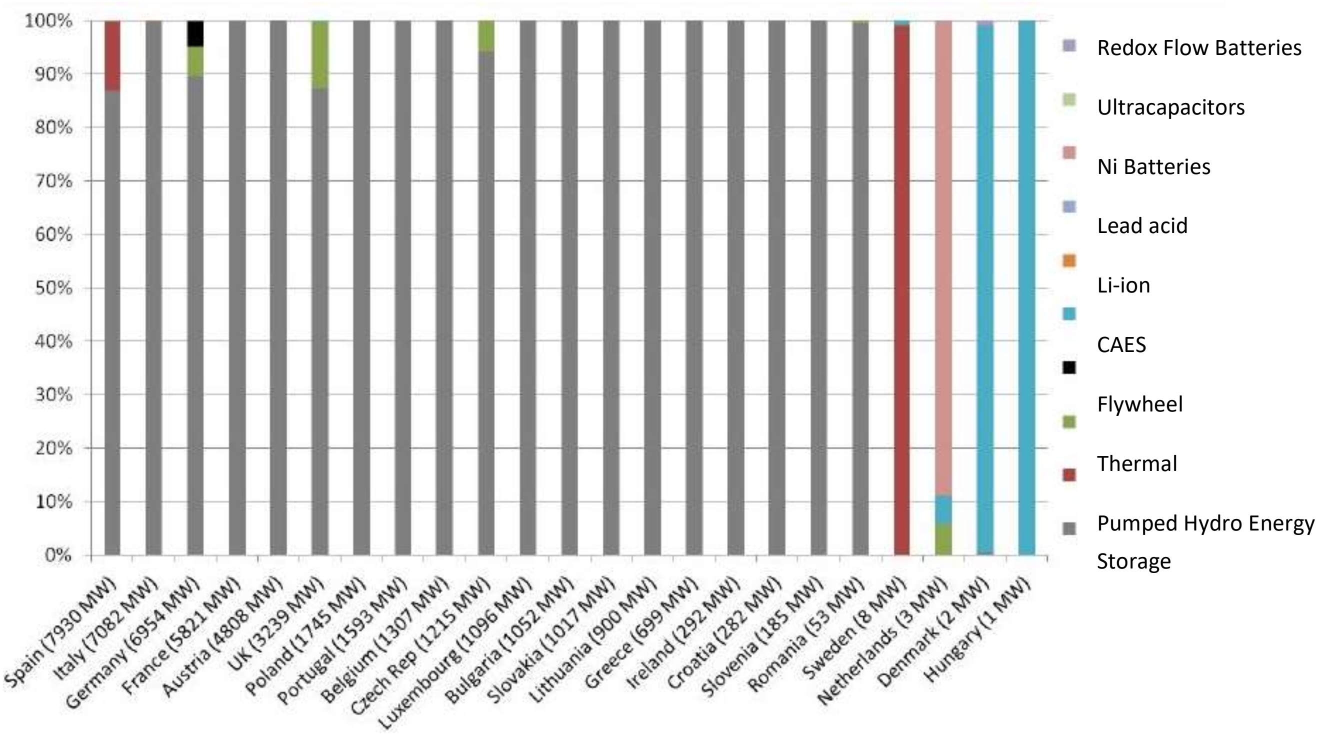

Figure 5- share of grid connected storage technologies in EU[7][8]

II. Innovation Readiness Level assessment: storage technologies

II.1. Lithium-ion

Lithium ion (Li-ion) battery is an electrochemical storage technology with a cathode made of lithium metal oxide (e.g., LiCoO2, LiMO2) and anode made of graphitic carbon. The electrolyte is a non-gaseous liquid which contains lithium salts. In this technology, li-ions move from the negative electrode to the positive electrode during discharge and back when charging. Li-ions are good candidate for applications and services that necessitate short response time and high energy density. Li-ion batteries are among the most developed and deployed storage technologies in the energy market today and contribute remarkably to revenue generations.

Our IRL analysis confirms the readiness of li-ion for entering the market, with number 29.9, and the results illustrate the huge potential of this technology to access different markets. The technologies recorded a high level in all the five dimensions of REEEM IRL tool (see Figure 6).

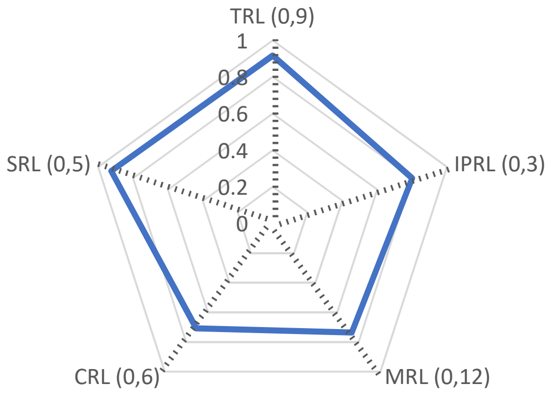

Figure 6- IRL radar chart of li-ion batteries[2]

Technology readiness level: this dimension recorded the value of 8-9, indicating the technology maturity to access the market. The research and development has resulted in extensive understanding of the technology's basic principle. Tests and demonstration projects in the relevant environment have confirmed the applicability of the technology. The services and applications of this technology are identified, and expectedly applications' objectives could be met successfully. In addition, there is a plan to increase the production capacity of these batteries (see Figure 7).

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[2] *The numbers in brackets indicate the number of levels within each dimension.*

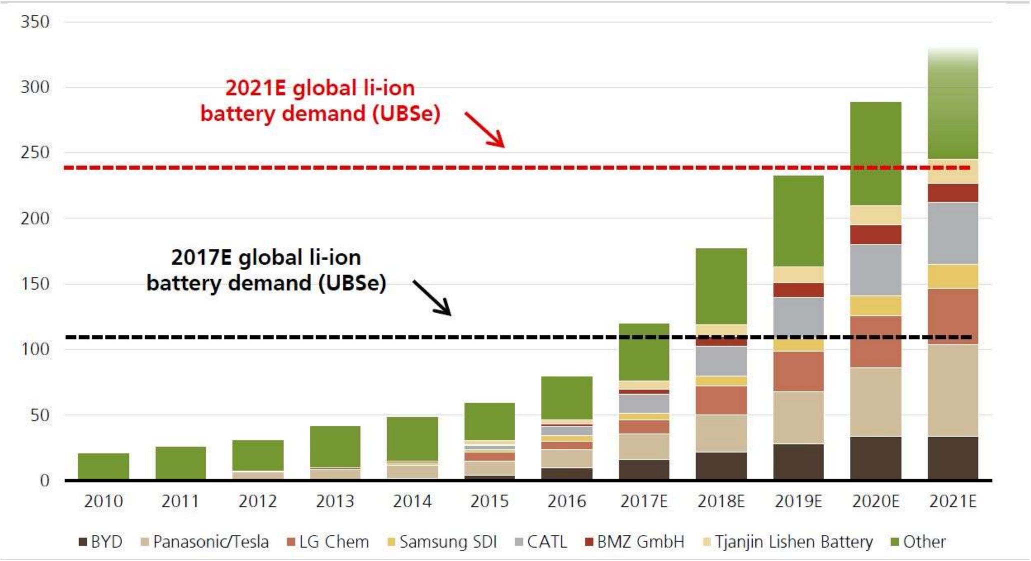

Figure 7- Li-ion battery cell production capacity plans in line with EV sales forecast for the next five years – limited visibility on post-2020 plants at this point (GWh) (includes non-automotive and automotive demand) [6, p. 16]

Currently the main risks affecting the TRL of li-ion are:

- The technology's (marginal) cost: that needs to be lower in order to serve its application objective.
- Batteries' structure: Further research and innovation is needed in order to improve the batteries' structure, notably regarding the use of rare material. Moreover:
    - research and innovation can improve the technologies' energy density and lifetime,
    - finding alternative electrode materials by using lower cost and environmentally friendly compounds. The effort in this direction is stated by [10]:"*Research efforts are being made to satisfy the needs of some of these uses by finding alternative electrode materials based on cheap and environmentally friendly compounds, which will work on principles that are different from the Li intercalation-deintercalation reactions*."
- Value chain: Currently, the market is challenged by limited and scattered supply chain of li-ion batteries activities in Europe. For example, when it comes to the mobility industry, many of the European car manufacturers have made large investments in the production of electric vehicles but, they have made limited investments in battery manufacturing capacity, meaning that they rely mostly on outsourced products. The manufacturing processes of the technology needs to be strengthen, and value chain players need to cooperate more closely together.
- Legal: The technology needs further improvement in certification and permission process, as legal issue is still a barrier for large applications of this technology. For example, installation of li-ion batteries in passenger vehicles needs obtaining safety and environmental certifications. This is not limited only to some countries, but regulations are different in across European countries.

The SET plan targets are set to improve technical characteristics of Li-ion batteries (Table 1). As illustrated in this table the most significant improvement is related to the lifetime and cost of li-ion batteries.

Table 1– SET plan technical targets for li-ion batteries [4][3]

	Li-ion	2011	2030	2050
Li-ion (Energy version)	*Specific energy*	Max. 241Wh/kg-	ca. 180-350Wh/kg –	>350Wh/kg - >
	Energy density	535Wh/L	350-800Wh/L	800Wh/L
	Cost	ca 500-1000€/kWh (or 25c€/kWh/cycle)*	ca 200€/kWh (or 10c€/kWh/cycle)	< 200€/kWh
	Power			
	Life time	ca. 500 cycles	>. 10000 cycles	>. 10000 cycles
	Safety	*Safe*	*Safe*	*Safe*
	Temperature	-20, +60°C	-20, +70°C	-20, +70°C
Li-ion (Power version)	*Specific energy*	50-90Wh/kg-	ca. 80-100Wh/kg –	>100Wh/kg –
	Energy density	105-190Wh/L	170-220Wh/L	220Wh/L ca. 10kW/kg
	Cost	> 1000€/kWh	ca 20€/kW i.e. LTO <10€/kg	< 200€/kWh
	Power	ca. 3kW/kg	>5kW/kg	ca. 10kW/kg
	Life time	ca 10000 cycles	>. 15 years	>. 15 years
	Safety		Safe	Safe
	Temperature	-10, +60°C	-20, +70°C	-20, +70°C

* *The estimates of EASE show that the cost of li-ion cell level currently is about 250 €/KWh, and will be 100 in 2030* [11]

IP readiness level: This dimension recorded number of 2-3 out of 3. The results of the questionnaire and interviews with experts did not indicate any IP barriers for the development of the batteries. Although different companies possess registered patents for li-ion batteries, the patents are licensable and market players can use them. The battery industry is small and according to the companies the issues related to patents become more significant when big companies join together and establish patents for their own use.

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[3] *The SET Plan targets are published in 2011, and accordingly could not perfectly reflect the current technology status. However, the table could highlight the technical characteristics that requires further improvements.*

Market readiness level: The analysis of MRL recorded a level of 10-11 out of 12. The analysis illustrated the existing demand and need for this technology in many European countries. In fact, Europe is among the leading continents in utilizing li-ion batteries [12]. The batteries have been used in Italy for grid-scale application, in Germany for integration and self-consumption of PV power and in France for off-grid applications. Different European policies and research funds acknowledge the role of li-ion batteries and support their deployment in the different markets (see figure 4,5).

Li-ion battery has been applied in different market segments. It is suitable for transmission and distribution grid in order to supply ancillary services and support power quality and to enable the smoothing and shaping of intermittent renewable energy generation and therefore allow larger integration of renewable power plants. The share of li-ion batteries worldwide for grid connected applications is estimated to be 1,134 MW [8].

Li-ion batteries have also entered households for behind-the-meter application (e.g., TESLA power wall). The battery enables time shifting, energy arbitrage, and self-consumption of locally produced solar energy. Moreover, the largest share of produced electric vehicles is supplied with li-ion. Looking at figure 8, it is notable that the markets for li-ion battery are changing. In 2013 the share of li-ion batteries was largest in end-use sectors due to the large application of these batteries in mobile devices such as laptops and mobiles. However, it is expected that in 2020 other applications play a larger role, such as utility application for improving operational efficiency and effectiveness.

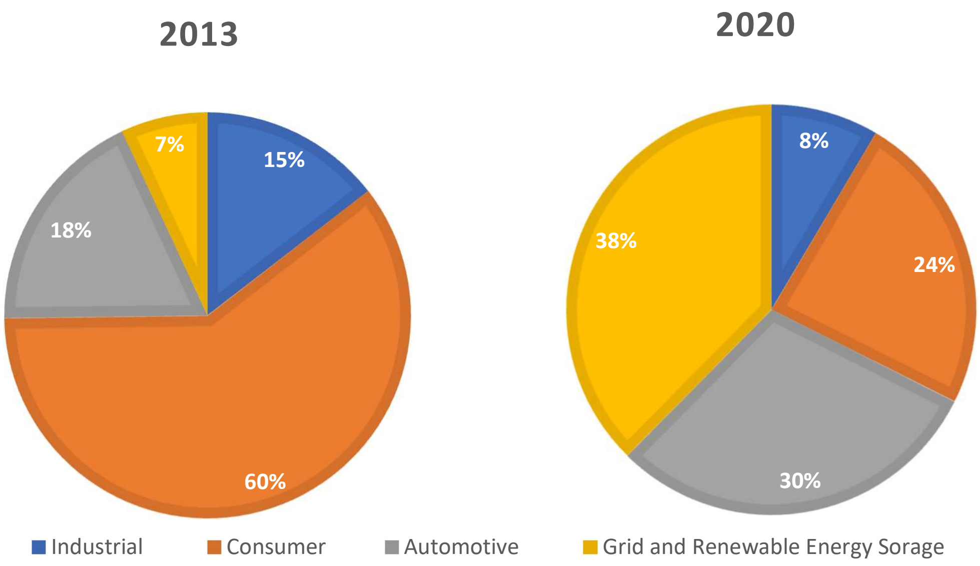

Figure 8- Share of li-ion batteries in different market segments[13]

The IRL assessment identified following parameters lowering the MRL of li-ion batteries:

- Existing legislations bound the application of li-ion in the market due to lack of transparency about the legal operators of energy storage.
- In spite of li-ion's maturity and improved cost competitiveness, the technology still needs to compete with other existing technologies in the market. To illustrate, in the mobility sector li-ion batteries need to compete with Internal Combusting Engine (ICE) cars, and for grid application with flow batteries.

- Current business cases are indicating that the effectiveness and real economic value of li-ion batteries. Further deployment of li-ion batteries will enhance their operational revenue and strengthen their business cases.
- The lack of European suppliers is an issue for the technology development and deployment, as it threatens the sustainability of the supply chain and creates risks regarding market development. Currently most suppliers of li-ion batteries are from Asia, Korea, China and Japan (See Figure 9).
- There is s risk of raw materials availability and especially rare materials.
- There is a need for education of human resources in order to raise market knowledge on how to implement batteries in systems, and supply relevant services.

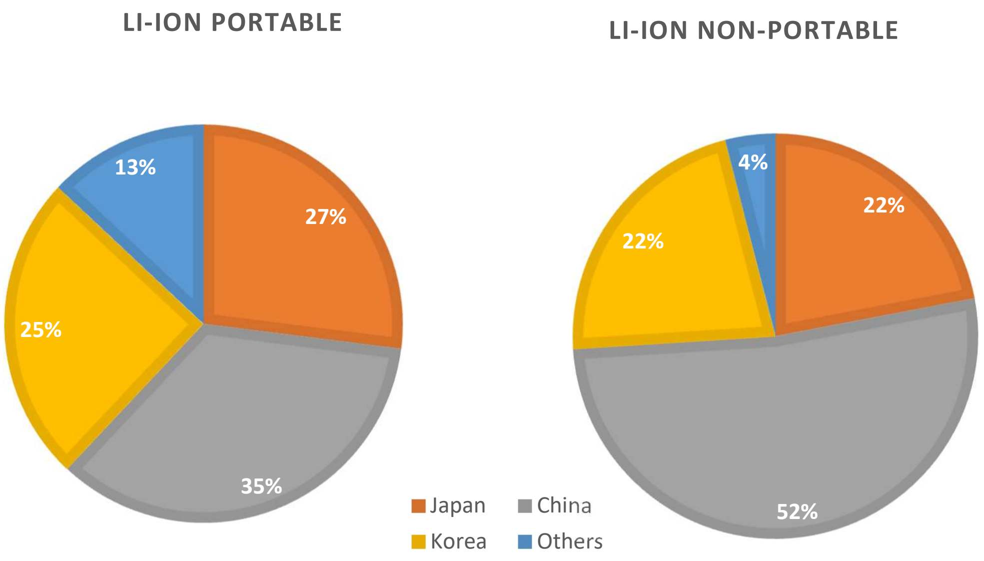

Figure 9- Battery cell production capacity [14]

Consumer readiness level: Potential consumers are identified and are willing to make investments in this technology. This is represented in CRL of 4-5 out of 6. Currently there are two main issues that lower the consumers' readiness for this technology. Firstly, not all the consumers do have the essential resources to invest in and benefit from this technology, due to the technology high cost. For example, the consumers at behind the meter, needs to make investments in purchasing and installing li-ion batteries at their residential household which require them to endure upfront cost. Secondly, they are not always engaged in the development of the technology and often have limited knowledge on li-ion battery and its potential services in the market. Although both would help in the success dissemination of the technology. Especially for behind the meter, li-ion batteries provide Business to Consumer (B2C) services and therefore consumers' knowledge and understanding of these batteries are important.

Society readiness level: this dimension recorded the lowest score in all the five dimensions of the IRL for li-ion batteries, showing 3-4 out of 5. Although the stakeholders of the technology are identified and their concerns are explored, not all the concerns have been addressed and that weakens the technology's SRL.

The main concern about li-ion batteries lowering the SRL is related to the use of rare material and limited European recycling facilities. These issues concern governments, technology developers and supply chains. To address the concern, among others, three approaches could be taken by governments: to directly invest in manufacturing capacity and recycling facilities in Europe, to support the industry and promote their investments in recycling capacity, or to invest in research and development of the technologies and allow technology development.

Furthermore, the consumers or customers, depending on the application, are concerned about the services associated with the technologies. To illustrate, the customers of electric vehicles are concerned about the life time, or charging services of the li-ion batteries in their vehicles. In another example, when li-ion batteries are installed at behind-the-meter, the consumers would be concerned about the services necessary for maintenance and actual applications of these batteries at their household. However, this is not limited to li-ion batteries and often is the vase for new technologies providing B2C services.

Finally, large-scale deployment of li-ion batteries for different applications (e.g., mobility, grid-scale and behind-the-meter) is capital intensive calling for strong investment capacity in Europe to be successfully deployed. Depending on the targeted applications, different part of society may need to endure the investment costs in li-ion batteries. An example of this case has happened when feed-in-tariff were introduced into the German market and raised the electricity bills for the consumers. Possibility of similar situations raises concerns and further limits the SRL for the li-ion batteries.

II.2. Flow batteries

A flow battery consists of external liquid electrolytes and two soluble redox couples. The 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 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. The power rate is determined by the active surface of the membrane and by hydraulic pumps management. The storage capacity could be increased by using larger storage tanks for electrolytes. Flow batteries can be categorized into redox flow batteries (e.g., Vanadium Redox (VRB)) and hybrid flow batteries, (e.g., Zinc Bromine).

Our analysis shows high IRL for flow batteries, with number 28.4 (Figure 10). The lowest recorded dimensions are MRL and CRL and that reflects rather low-cost competitiveness of flow batteries and the high competition between them and li-ion batteries in the market. Below the findings regarding each dimension are discussed.

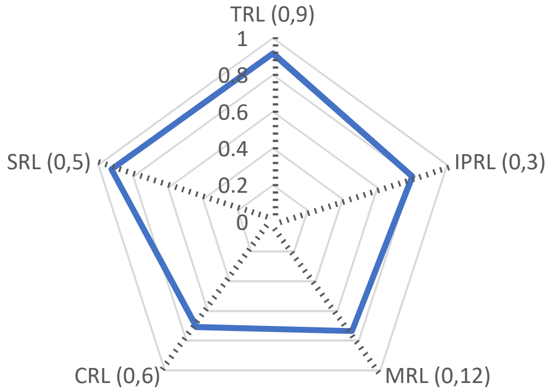

Figure 10- IRL radar chart of flow batteries

Technology readiness level: This dimension recorded a number of 8-9, implying the technology readiness for the deployment in the market. The characteristics of the flow battery are identified, the technology's elements are fully integrated, and tested in a predefined working environment. The technology satisfies its applications' objective and is suitable for different applications. The batteries have a low energy density that makes them only suitable for applications for which space is not a constraint, but are competitive when it comes to life cycle, safety, and reliability for stationary applications.

The parameters constraining the TRL of flow battery are related to the technology cost that needs further decrease before justifying its purpose and services in the market. The high cost is not only due to the material, but also to the system required for application of the technology. In addition, for large scale applications, there is a need for legal permission, which as yet hinders the technology access to the market.

Table 2 illustrates the SET plan targets for the flow batteries at 2030 and 2050. while flow batteries are fairly mature, innovation could improve the technical characteristics of the technologies. In particular, SET plan targets illustrate the need for improvement of cost, lifetime of the membrane and power and energy density of flow batteries.

It is remarkable that the flow battery has the potential to reach an infinite number of life cycles [15] and, its large production and economies of scale could allow a competitive cost to be achieved [11]. Moreover, R&D is going on to use membrane-less and low-cost elements for flow batteries. This can include membrane-less hybrid organic-inorganic battery based on elements like Zinc and Parabenzoquinone [16]. Another effort is to increase the energy density and scale-up possibilities of flow battery. For example, the use of inexpensive and reversible polysulfide and iodide species to offer a high-energy and low-cost all-liquid polysulfide/iodide redox flow battery (PSIB) is being considered [17].

Table 2 – SET plan technical targets for flow batteries [4]

	Features	*2011*	*2030*	*2050*
Redox Flow batteries (Vanadium, ZnBr2)	*Specific energy*	*Vanadium: 10-20Wh/kg ZnBr2: 50-60Wh/kg*	*Gen2 Vanadium Bromie 20-40Wh/kg*	
	Energy density	*Vanadium: 15-25Wh/L ZnBr2:-*		
	Cost	*Projected service cost (Capex and Opex) 10c€/kWh Energy cost 400€/kWh Power cost 600€/kW*	*Projected service cost (Capex and Opex) 7c€/kWh Energy cost 120€/kWh Power cost 300€/kW*	*Projected service cost (Capex and Opex) 3c€/kWh Energy cost 70€/kWh Power cost 200€/kW*
	Power			
	Life time	*10-20 years (>10000 cycles)*	*50.000 cycles*	
	Safety	*Not inflammable*		
	Temperature	*10, +40°C*	*Wider operating T° range (>100°C)*	

Market readiness level: the MRL recorded a number 8-9 out of 12. The flow batteries are suitable for different applications including industrial sector, grid-scale services (e.g., peak shaving and energy time shifting) and off-grid and mini-grid applications. Given their long lifetime and the ability to decouple power and energy [11], flow batteries are suitable for services both requiring high power and energy.

In the mobility sector, flow batteries are not suitable for passenger vehicles, due to their low energy density, but could be applied in heavy duty vehicles, including ships, trains and possibly trucks. Flow batteries have competitive advantages over li-ion batteries in the market due to their independency from rare materials, making them suitable for large scale applications. According to Navient Research [18], the share of flow batteries together with power-to-gas will account for 17% of the total global market for the integration of wind and solar power in the next 10 years. This rate for li-ion batteries is estimated to be 48% (Figure 11) [19].

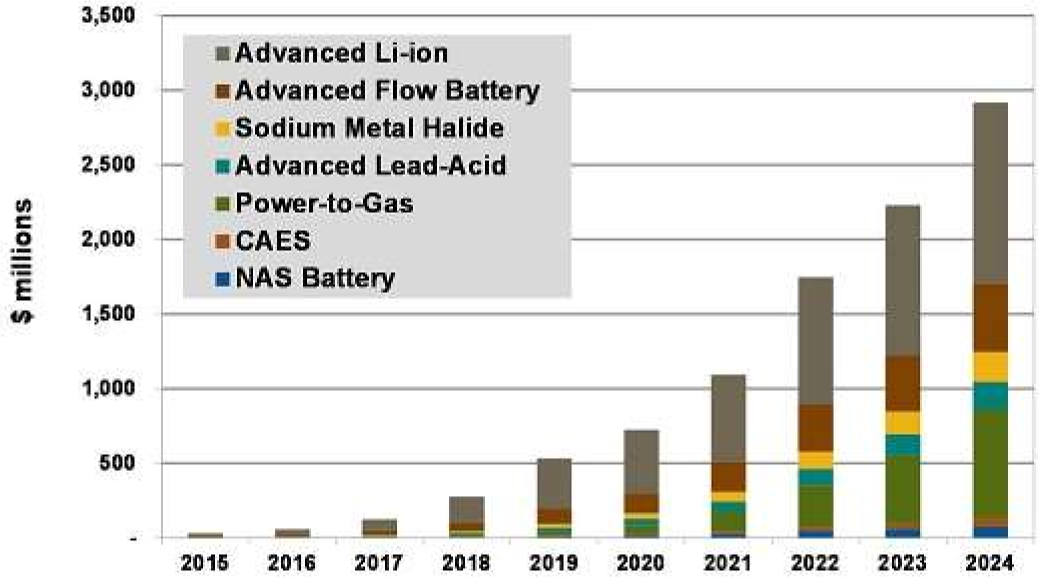

Figure 11- installed revenue, energy storage for wind and solar integration. World markets: 2015-2024 [18]

The following points can summarize the parameters that limit the MRL of flow batteries:

- There is still a need for further policy and legal support for large application of flow batteries. For example, the government could contribute to the technology development process by providing R&D budget and facilitating the technology accessibility to the market through incentives and supporting policies.
- While the society is in general positive about flow batteries, there is a need for customers' awareness on the benefits of flow batteries.
- There is lack of strategic planning and market estimations for flow batteries, due to high competition between flow and li-ion batteries.
- There are other storage technologies available in the market that could provide similar services. Accordingly, there is a high competition between flow batteries and others technologies in the market.
- The price of the technology is too high to justify its position and services in the market to meet the demand.
- When it comes to the supply chain, the companies' knowledge about the market and their experience with different suppliers are important factors as they affect the accessibility to suppliers. Most of the flow batteries development so far is done in the USA, Australia and Asia (Japan and China). Europe has the capacity to develop 10kW to 200kW products [20].

Consumer readiness level: this dimension recorded a level of 4-5 out of 6. Potential consumers for different applications of flow batteries are identified. A group of consumers also has shown interest in flow batteries in order to meet their energy demand more sustainably. For example, consumers' interests have been mentioned for the application of flow batteries at mini-grid for community development. In some European countries (E.g., the Netherlands), in order to facilitate the incorporation of the technology to limit the CO2 emissions consumers are motivated to change their routines. These consumers could be involved in the process of technology development by providing feedback and sharing their experiences about the technology. Overall, the consumers of the technology are identified for different applications, and market acceptance has fairly positive.

Currently, the main problem of consumers is about high technology and system cost. In addition, there are other technologies that can provide similar services to consumers and therefore threaten the competitiveness of flow batteries in the marketplace. Lack of knowledge about benefits and different services of flow batteries, and energy storage in general is another issue limiting CRL of flow batteries.

Society readiness level: this dimension recorded a number of 4-5. The stakeholders of the technology are identified and can influence the development and deployment of the technology. Government, customers and consumers and supply chain are all informed about the technology and engaged in its development. It is notable that the stakeholders of the technology are different for different applications. For example, when the technologies are applied for mini-grid for community, one of most important stakeholders is municipalities.

As the flow batteries do not impose any constraints to the environment, health or safety and they use only abundant material, there are limited concerns about their deployment. The development of flow batteries in the market could be affected by both European and national policies. Harmonisation policies in Europe would be useful for their development, because technology developers could understand better the development and deployment processed of the flow batteries in the whole Europe and accordingly, contribute more effectively to the market.

II.3. Supercapacitors

A supercapacitor consists of two conductor electrodes, an electrolyte and a porous membrane separator. In a supercapacitor, energy is stored in the form of static charge on the surfaces between the electrolyte and the two conductor electrodes. Since this mechanism is highly reversible, supercapacitors could be charged and discharged at high power rate. The power capacity of a supercapacitor could be increased by adding and extracting more electrons, and its capacity is determined by the electrolyte surface area and pore size distribution.

The analysis on supercapacitors recorded the highest parameters was related to the TRL, and SRL of supercapacitors, and the total number of 29.3 for IRL. Below the different dimensions of the IRL are evaluated (Figure 12).

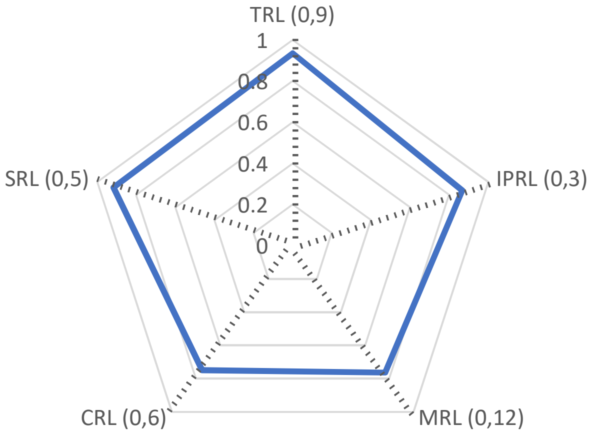

Figure 12- IRL radar chart of supercapacitors

Technology readiness level: the TRL recorded 8-9, indicating the maturity of the technology to access the market. The services of the technology are recognized, the technology's applicability and performance are tested, and the supply chain for the technology are positioned in the market. Supercapacitors could have numerous charge and discharge cycles, which makes them suitable for short term but frequent services. They also are suitable for high power services, having 10-20 kW/kg power rating.

The technical features of supercapacitors are presented in Table 3 and they indicate innovation potentials in some aspects. The following technological innovation are remarkable:

- Enhance energy density of supercapacitors, as currently they are not suitable for long-term applications (energy density (<8Wh/kg)).
- Improve the technology's voltage as supercapacitors are a low voltage technology and retain the same voltage for safe operation
- Improve the technology's operation temperature range (-40 °C – 65°C)
- Find solutions to combine supercapacitors with batteries in order to make use of commentary characteristics of these two technology groups. For example, this would allow the grid to benefit from high energy density of batteries, and high-power capacity of flow batteries. Supercapacitors can allow

instantaneous peak power which prolongs the batteries life and also would reduce the system cost by reducing the number of batteries needed [21].

- Reduce the electrode fabrication cost, as pointed out by ...: ”*An additive-free, cost-effective and scalable successive ionic layer adsorption and reaction (SILAR) method is reported to prepare nickel–cobalt binary hydroxide (Ni–Co–BH) on a reduced graphene oxide (RGO) directing template over a macro-porous conductive nickel foam substrate* [22]."

The SET plan targets for the technical characteristics of supercapacitors are presented in Table 3.

Table 3 – SET plan technical targets for supercapacitors [4]

	Features	***2011***	***2030***	***2050***
Supercapacitors (EDLC, pseudo capacitors like oxides, hybrid or asymmetric systems)	*Specific energy*	<10Wh/kg (close to 5Wh/kg)	>10-15Wh/kg	
	Energy density	4-8 Wh/kg	50Wh/kg	Energy close to power batteries (50Wh/kg)
	Cost	0,3 €/W (cell basis)	0,2€/W (cell basis)	0,05€/W (cell basis)
	Power	10-20kW/kg (1-5s) ca. 1500-2000m2g	»40kW/kg (1-5s)	»60kW/kg (1-5s)
	Life time	>10000 cycles	1.5M cycles	> 2M cycles
	Safety			
	Temperature	-40°C – 65 °C	-40°C – 100 °C	-40°C – 125 °C
	Voltage	3.0 Volt	*4.0 Volt*	Electrolyte stability ca. 4.5-5V
	Specific capacitance	6 F/g	*50 F/g*	Ca. 600 F/g

Market readiness level: the market for the technology exist for the grid-scale, off-grid and mobility applications. The technology is expected to effectively contribute to services requiring high power density. Given its technical characteristics, the supercapacitor is suitable for services and applications that require large power discharge, and limited energy capacity. The supercapacitor can serve transmission lines in order to provide stability to the system. It could be used for frequency control during interruptions (e.g., when a generator fails to work), or when there is an imbalance between supply and demand. The supercapacitors can also respond fast and therefore be suitable for smoothing the renewable energy intermittency.

In mobility applications, the supercapacitors could be utilised in vehicles for starting the engine, where batteries would exhaust fast by providing frequent and high-power services. Moreover, in more recent years supercapacitors have been used in large vehicles, such as public transport vehicles. These vehicles, namely Capa vehicles, drive often in the same regulated path, and could be charged during each bus stop in 30s when the passengers are leaving or entering the bus. The short charging time, long lifetime, lower need for maintenance and almost 95% round-trip efficiency of supercapacitors create competitive advantages for this technology over batteries. Capa vehicles have been deployed in some countries such as China and Germany.

Additional parameters contributing to the MRL of supercapacitors are the reliable supply chain, and the established value chain. Also, the future market share of this storage technology is estimated, strategies for the market development are defined, and its market trend speculated.

What is delimiting the MRL of supercapacitors is the threat of alternative technologies in the market. This is especially since the technology has limited energy density and therefore could lose the market to other technologies. Penetration of supercapacitors in different segments of the energy market and for various applications could overcome this limitation in the future. An example of the emerging market segments is the application of supercapacitors in the mobility industry for large vehicles (e.g., Capa vehicles).

Consumer readiness level: this dimension recorded level of 5 out of 6. It is notable that due to the technical specifications of supercapacitors, the consumers of this technology are often not directly involved in the deployment of this technology. Therefore, the CRL is a less important dimension for the development of supercapacitors in the current market.

The factors lowering the CRL of supercapacitors are due to lack of consumers' awareness about the benefits of supercapacitors in the market and that delimit their interest and contribution to the technology deployment.

Society readiness level: this dimension recorded a level of 4-5 out of 5, indicating the knowledge on stakeholders of this technology and their needs is adequate. The concerns of stakeholders about supercapacitor are limited, as the technology is safe to use, and is built from materials without supply restrictions. The applications of the technology often do not influence the routines and functioning basis of the market, or do not impose environmental risks and concerns. This means that the stakeholders often benefit from the technology, and they have limited concerns about its applicability in the market. Further political and financial supports can strengthen the acceptance of this technology by the society.

II.4. Compressed Air Energy Storage (CAES)

CAES is an energy storage system compressing and storing air in geological underground void, at a pressure of about 100 bars. To discharge electric energy, the released air is heated through combustion process using natural gas and is expanded in order to drive a gas turbine to generate electricity. CAES requires little land, but extensive water resources and emits greenhouse gases. Different types of CAES technologies enter the market with improved technical features, using different thermodynamic processes:

- Diabatic CAES: this technology expands the stored air by the aid of combustion of a supplementary fuel (typically natural gas) to drive the turbine and generate electricity.
- Isothermal CAES: in this technology, the heat from air compression is captured and stored in water. This process delimits the necessity for the combustion and enhances the efficiency of the system to 70-90% [23][24].
- Adiabatic CAES: this technology captures and stores thermal energy, which is generated during the compression of air in a centre. The heat will be reused to heat the air upon expansion. Therefore, there is no need for natural gas to reheat the air during the generation. This process increases the technology's capital cost but enhances its efficiency to about 70% [24]. It is likely that this technology become available on a commercial scale toward the year 2020 [25].

As yet, there are two successfully applied projects of CAES. The first CAES plant was installed in Huntorf, Germany, in 1978 [26] with the capacity of 290MW. The second plant with the size of 110 MW was installed in McIntosh, Alabama, USA in 1991. These plants are utilized for peak shaving, load levelling in grid operation, storing off peak energy and for frequency control [27].

The overall IRL of the technology is fairly lower than alternative technologies (28.0) and that is due to the challenges associated with the MRL and SRL dimensions, discussed below. (Figure 13).

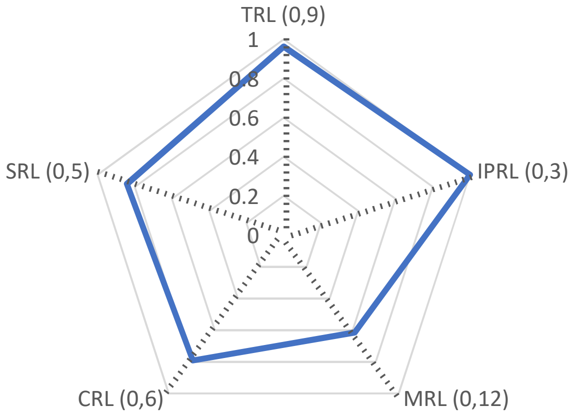

Figure 13- IRL radar chart of CAES

Technology readiness level: It records a number of 8-9 out of 9, showing its maturity. The technology applications and services are predicted, the pilot test and commercialisation process have been conducted. CAES has competitive capital cost (comparative with Pumped hydro storage (PHS)), and a simple technology structure which makes it attractive for development and deployment. CAES have power capacity from a few kW to hundreds of MW. The charging and discharging duration for this technology is from a few minutes to days. The technology has moderate response time and good partial-load performance [11].

Two main issues are influencing the technology's maturity are (1) low efficiency and (2) certification and permitting process, due to CO2 emission associated with the technology. The SET Plan targets for this technology (Table 4) also provide evidence on the need for improvement of efficiency of CAES. Based on the analyses, the following R&D recommendations could be made:

- Recovery of heat losses in charging by the aid of thermal storage to alleviate or minimize the use of fuel.
- Increasing the exergy gain of recuperation by preheating and increasing the temperature of air during the charge mode. This way, the exergy of the stored air is higher and higher efficiency can be retained. Supplementing CAES with solar thermal plants, for example, can provide the additional heat needed [28].

Table 4 – SET Plan technical targets for CAES [4]

	Features	***2011***	***2030***	***2050***
CAES	*Cost*	*200-250€/kWh Capital Cost: €470/kW-€2170/kW (depends on CAES type and sizing)*	*TES unit cost 20 to 30€/kWh (depending on storage capacity)*	*50% cost to meet longer-term TES cost goals (Costs depend on scale and TES)*
	Efficiency	*Adiabatic (with heat storage; 70% efficiency expected)* *Diabatic (need extra heat during discharge; 55% efficiency expected)* *Isothermal (Low capacity & power storages; 70-75% efficiency)* *Liquefied gas (higher cost for similar efficiency but not geographical dependent)*	*Advanced adiabatic materials for high T° thermal storage: stable, resistant, cheap, high heat capacity, good conductivity & low degradation* *Demonstration of huge thermal energy storage with new media and container to resist pressure (>200-300 bars) and thermal stresses (gradients >600°C)* *Liquefied gas systems capital cost/demonstration of thermal*	*Improving efficiency (>70-75%)*

IP Readiness level: the results recorded a level of 3 out of 3, suggesting that this dimension does not delimit the IRL of CAES and on the contrary, it has deepened the existing market knowledge. New patents on CAES are entering the market (see for example: US-based LightSail Energy Ltd [29]), contributing to strengthening the technology performance and functionality in the market.

Market readiness level: This dimension recorded a number of 7-8 out of 12. This MRL level is lower than the other technologies studied in this report. The analysis of the MRL shows that the market need for the technology is identified. CAES is suitable for applications and services for which space is not a restriction. The technology could be used for grid-scale and off-grid applications, and it could provide services such as emergency backup power, load levelling, balancing, arbitrage, peak shaving, power quality control and energy management. The application of CAES technology in the market goes back to 1978 and accordingly, the technology value chain is identified. There is deep knowledge in the market about political, environmental and social parameters, influencing CAES deployment. CAES is the only recognized and proven bulk storage, apart from PHS, available on commercial scale. Accordingly, it could play a role in the future market when the share of renewable energy sources increases and provides demand services and other ancillary services.

The factors delimiting the access of CAES to the market are related to the dependency on fuels, low energy efficiency, its size and immobility. As a result, investments in other storage technologies such as batteries have been prioritized over the CAES.

Consumer readiness level: CAES is large and suitable for applications for which space is not an issue, thereby investments in CAES are expected for grid-scale and off-grid applications. This means that CRL is a less significant dimension for IRL of CAES. Yet, consumer awareness could facilitate the technologies access to the market. This is reflected in the CRL assessment recording the level 5-6 out of 6.

Society readiness level: The SRL of the technology is 3-4 out of 5. The assessment showed that the stakeholders of the technology are identified and their concerns evaluated. However, unresolved issues and concerns of stakeholders lower the technology's SRL. These are associated is associated with the large land use of CAES and its energy storage process that is coupled with CO2 production. Tackling this issue with innovation and introduction of new types of CAES could effectively strengthen the social dimension and therefore facilitate the technology access to the market.

II.5. 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 cells) and recombined with oxygen to produce electricity. By-products of this process are heat and water. Three components of the process to store hydrogen are [30]:

- Electrolyser: three types of electrolysers are currently known in the market:
    - Alkaline Electrolyser (most mature and already commercialised)
    - PEM Electrolyser (today MW-scale at demonstration phase)
    - High Temperature electrolysis (R&D phase)
- Hydrogen Storage:
    - As a liquid at temperatures below -253°C
    - As a compressed gas in storage tanks or salt caverns
    - Physically stored as a metal hydride compound
    - Chemically converted into ammonia or methanol and stored as a liquid
    - Chemically converted into Synthetic Natural Gas (SNG) and stored in the Natural Gas-grid
    - Dissolved in liquids
- Re-Electrification process: three known methods are:
    - Gas Turbines
    - Engines
    - Fuel Cells

The IRL assessment in this report is particularly focused on hydrogen storage using Alkaline electrolyser technology and fuel cells re-electrification process. Alkaline technology was first utilized in the industry in 1959. The technology consists of two porous carbon electrodes and a catalyst such as platinum (Pt), Silver (Ag), etc. The space between the two electrodes is filled with electrolyte, often a solution of Potassium hydroxide (KOH) or solution of sodium hydroxide (NAOH).

Fuel cells generate power electrochemically from hydrogen delivered to the negative pole (anode) of the cell and oxygen delivered to the positive pole (cathode). Then passing through a fuel cell, hydrogen and oxygen are recombined to produce electricity. Hydrogen can be stored either as a gas, or liquid at temperature below −253°C or as a compressed gas in storage tanks. The use of hydrogen in chemical industry is a mature practice and therefore the transport and containment infrastructure for hydrogen is based on well-established technologies within the supply chain.

The IRL assessment of this technology resulted number of 25.7, and showed advanced developments in three dimensions namely TRL, IPRL and SRL, but limited progresses with MRL and CRL (Figure 14). Below the indicators are reported.

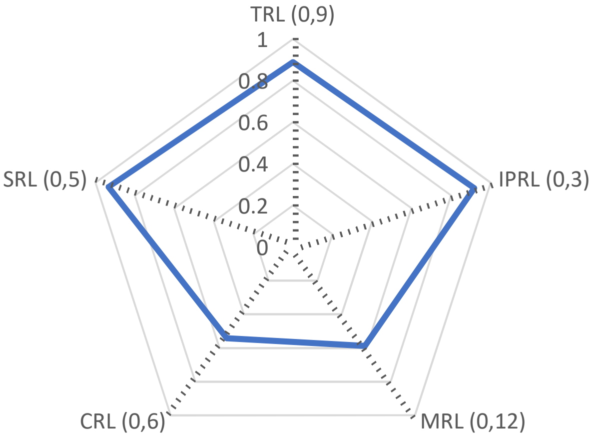

Figure 14- IRL radar chart of hydrogen Alkaline fuel cell technology

Technology readiness level: this dimension recorded numbers of 8-9 out of 9. Experts identify the reliability and maturity of hydrogen fuel cells storage as the main advantages of the technologies. In Europe, chemical storage has had rapid development. Large investments are made in R&D for production, storage and conversion of hydrogen, and its re-electrification via fuel cells. The results of the research have led to the use of new materials and the implementation of new services that enhance the technological opportunities for storage technologies.

The main factors that lower the TRL are the technology high cost, even though the technology's components (e.g., alkaline electrolyser technology) are developed and there are less opportunities for breakthrough. As said by Charles Freese, head of GM's fuel cell business, "*We've clearly left the science project stage and the technology is viable*" [31]. Small production scale and deployment rate are identified as the reasons for high technology cost. Besides, certification processes for installation of hydrogen fuel cell technologies are long and could take up to several years. This is the case for example for the mobility application in vehicles and for charging stations.

Table 5 summarises the SET Plan targets for alkaline technology and Table 6 lists the SET Plan targets for hydrogen technologies. As illustrated in these tables, the main improvements should be directed towards:

- The production capacity of electrolysis units and the technology's cyclability.
- The use of non-Nobel metals which results in reduction of the system cost.
- Designing a bifunctional air electrode which could carry both the oxygen reduction and evolution reactions, leading to the progress of new generation energy conversion and storage devices. This design is in alkaline environment [30].

Table 5 - SET Plan targets for Alkaline technology [4,11]

	Features	Present	Target 2020-2030	Ultimate goal
Alkaline technology	Operating current density (A/cm^2)	0.2–0.5	0.1–1	0–2
	Operating temperature (°C)	ambient – 120	ambient - 150	ambient - >150
	Operating pressure (bar)	1-200	1-350	1-700
	Durability (h)	10^5	> 10^5	> 10^5
	Cyclability	poor	improved	high
	Production capacity of electrolysis units (Unit size 1MW)	1-100 kg/hour (≈ 10-1000 Nm^3/hour)	> 100 kg/hour (≈ 1000 Nm^3/hour)	> 1000 kg/hour (≈ 10 000 Nm^3/hour)
	Non-energy cost (€/kg H_2)	<5	2	1

Table 6 - SET Plan targets for Hydrogen Storage Technologies [4,11]

Storage Technology	Volumetric density (kg H_2/m^3)	Gravimetric density (reversible) (wt %)	Operating pressure (bar)	Operating temperature (K)	Cost* ($ / kg H_2)
Compressed gas (H_2)70	17 - 33	3 - 4.8 (system)	350 & 700	ambient	400-700*
Cryogenic (H_2)71	35 - 40	6.5 – 14 (system)	1	20	200-270*
Cryo-compressed (H_2)	30 - 42	4.7 – 5.5 (system)	350	20	400
High pressure - solid	40	2 (system)	350	243 – 298	
Sorbents (H_2)72	20 - 30	5 – 7 (material)	80	77	
Metal hydrides (H)73	< 150	2 – 6.7 (material)	1 – 30	ambient – 553	>500
Complex hydrides (H)74	< 120	4.5 – 6.7 (material)	1 - 50	423 – 573	300-450*
Chemical hydrides (H)75	30	3 – 5 (system)	1	353 – 473	160-270**

** cost estimates based on 500,000 units production;*
*** regeneration and processing costs not included*

IP Readiness Level: this dimension recorded a level of 2- 3 out of 3. The IPRL suggests that there are established patents in the market. Companies active in the field are knowledgeable about the existing patents, and their activities are not blocked by the existing patents and IP rights. The current problem in the market is financial and that motivates fuel cell companies to work together to grow bigger and facilitate the technology development in the market instead of blocking the market development. Accordingly, the IPRL shows that the existing IPs do not block the technology deployment in the market.

Market readiness level: this dimension recorded a number of 7-8 out of 12. The need for hydrogen storage technology is identified in the market and its potential applications are identified. In a short term, mobility is expected to be the biggest market for hydrogen storage (Figure 15). In mobility applications, hydrogen could be used in cars, tracks, bikes powered by fuel cells. In a longer term, hydrogen storage could be used for balancing the energy system (supply and demand) in grid-scale and off-grid applications, where there is intermittent generation of wind and solar power. It could also be used for grid reinforcement and as grid extension alternative [30]. The technology has reliable supply chain as it does not depend on any rare material and their production could be completely carried out in Europe. The technology production is only dependent on platinum.

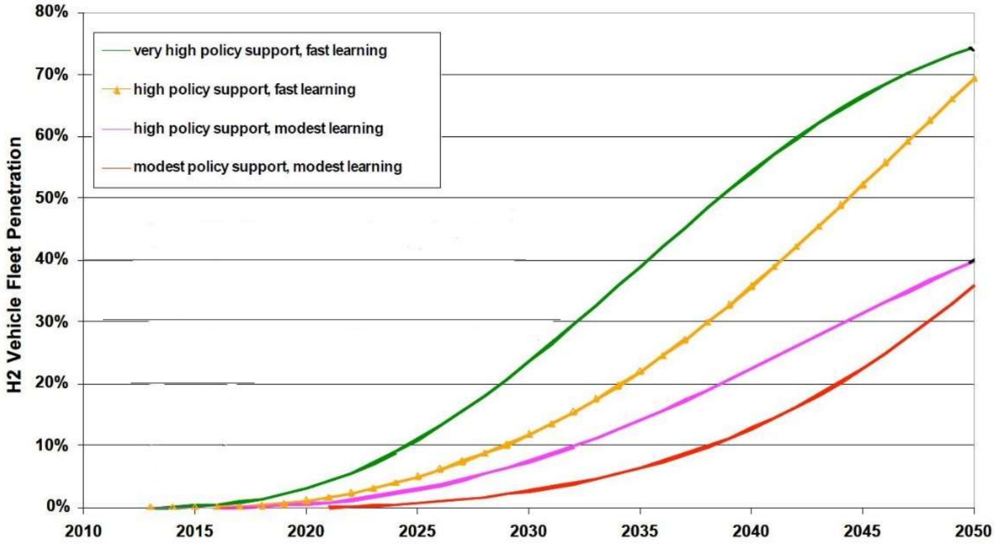

Figure 15- Development of the penetration rate of hydrogen vehicles for passenger transport (Read more on different scenarios in [32, p. 17]*)*

One of the main market issues related to hydrogen storage as identified by experts is the lack of policies and societal support for these technologies. For example, there are less supportive policies for installation of hydrogen refuelling stations in comparison with electric power charging station. An estimation by [31] shows that the cost for construction of a hydrogen charging station is estimated to be close to 2 million Euros in the USA, which is costlier than a power charging station (about 2 thousands Euros). But parameters such as time and charging duration should also be considered when comparing the cost of these two different charging stations. As yet, the limited number of hydrogen charging stations has made car manufacturers hesitant to produce hydrogen fuel cell vehicles, and investments in hydrogen stations are delayed due to limited number of hydrogen vehicles [31].

While there are strategies available for expanding hydrogen technology, especially for mobility applications, high competition between hydrogen and other storage technologies constrain and threaten its market position. For example, in the mobility sectors, fuel cells cars have a hard time to compete with emerging electric vehicles in the market. Lack of customers' awareness about these vehicles further intensifies this situation.

On the other hand, there are limitations associated with the value chain of hydrogen storage. For example, for mobility applications, there is lack of large investment in hydrogen infrastructure. These investments should be made by large companies, e.g., utilities, as small market players cannot alone create the essential infrastructure. Without such investments, the deployment rate of storage technologies remains limited. In Europe, there is currently lack of car manufacturers engaged in production of hydrogen vehicles. While several European car companies are active in electric vehicle business, there are no significant efforts for production of hydrogen vehicles.

Through limited investments in hydrogen technology in Europe, American and Canadian companies may find the chance to grow larger in this sector. This could be seen in the recent investment by Ballard power system which together with its partners invested 6 Million USD in an European company, Dantherm A/S and bought controlling interest in this company [33].

Consumer readiness level: This dimension recorded a level of 3-4 out of 6. This CRL analysis shows that the consumers of hydrogen storage are identified, their needs are explored and their characteristics and routines are acknowledged.

It is remarkable that the consumers of hydrogen storage are varied in different applications. In grid-scale application of hydrogen, consumers are less directly affected, and therefore their influence on the technology deployment is limited. This story is different for consumers in the mobility application, since they can effectively influence the technology deployment. The analysis shows that, currently, a group of consumers is motivated to lower their CO2 emissions and thereby invest in hydrogen fuel cell cars. For the other group, other market parameters such as cost, services and convenience are more decisive parameters. This means that the high cost of hydrogen fuel cell cars and the limited number of charging stations could demotivate their investment decisions. Besides, the consumers are not fully aware of the functionality of hydrogen cars and have concerns about their services. These issues raise consumers’ doubts about investments in the hydrogen storage technology and its emerging market.

Society readiness level: This dimension recorded a value of 4-5 out of 5. Currently in the market the main stakeholders of the technology are identified and positioned along the value chain. The stakeholders have the possibility to actively engage in and contribute to the development of hydrogen storage. Different social factors can influence the technology development. These include political factors both at the EU and country level, and economic factors, as the hydrogen can contribute to the European energy independency. Currently, national policies play a more important role in the deployment of the technology. In the SRL analysis, a factor that was identified as a challenge for the technologies is related to strong lobbying that is happening against larger deployment of hydrogen technology.

III. Conclusion: Comparative analysis of IRL of storage technologies

This report describes the REEEM IRL methodology aiming to inform decisions of investors and policymakers by exploring maturity of technologies, their risk and potential to access markets. Within the REEEM framework, this report is the first attempt to adapt the IRL tool to energy technologies, and was applied in particular to storage technologies. In this process, all the dimensions affecting IRL of energy technologies are identified and explored in a systematic manner. The findings of this report are valuable for continuation of the current and next IRL reports.

This report complements the REEEM Technology and Innovation Roadmap. The REEEM roadmap pursues a market-driven approach, while this report takes a closer look at the technologies, sheds light on innovation processes of storage technologies and explores the potential and risk of the technologies in accessing the energy market. This report explains role and position of a number of storage technologies in transition pathways of European energy industry toward a low carbon EU society.

For this report, data is obtained through questionnaires, several interviews with practitioners and literature review. The report analysed 5 storage technologies, selected from different principle categories and with different maturity levels in order to provide a broader picture of available technologies in the market. The technologies are: li-ion batteries, flow batteries, supercapacitors, CAES, and hydrogen. Table 7 summarizes the results of the IRL assessment on these technologies:

Table 7 - results of IRL dimensions for the studied storage technologies in this report

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

As indicated in Table 7, differences could be seen among the readiness level of technologies in different IRL's dimensions, as well as the total IRL. The parameters blocking the technology access to the market are different for different technologies and are explained for each technology individually in this report. The general lessons that could be learnt from the IRL analysis of this report on energy storage technologies are:

- Energy storage technologies have different technical characteristics and several of those need improvements. Innovation efforts should be harmonised and target the most urgent features that enhance the technology's performance. Several R&D priorities are highlighted in this report. In addition,

the SET Plan targets are presented which could act as a guideline for identification of the crucial technical features for innovation.
- The TRL analysis indicated that there have been significant technological developments of storage technologies. Currently there is a more urgent need for large scale production of technologies to reduce their cost of technologies as the result of economy of scale.
- There is a need for improvement of parameters affecting the technologies' MRL. While the parameters are different for different technologies, the most common parameters are: high competition existing between the emerging storage technologies due to their particular technical limitations, a lack of established and committed value chain due to the existing market barriers (e.g., lack of clear policies) and an uncompetitive European supply chain for storage technologies (e.g., li-ion). In addition, limited number of technology applications in the market delimit possibility of illustrating the actual business cases of storage.
- There is a need for clarification of policies regarding the definition, and actual role of energy storage technologies in the market. The policymakers should clarify the ruled for legal operators of energy storage technologies in order to strengthen the technologies' position in the market and attract potential investors.
- There is a need for improvement of the European supply chain. In many cases, the technologies are partly or completely imported from foreign countries.
- Consumers' lack of knowledge about the benefits of the storage technologies could influence negatively the technology's access to the market. Hence, consumers need to gain better information and awareness about the storage technologies and their specific services. Consumers could facilitate the technologies' access to the market through investment or financial support, and providing feedback.
- While stakeholders of the technologies and their concerns are identified, there is need for action to answer their concerns systematically and effectively in the market. For example, one of the main concerns is the use of land or of rare materials for some of the technologies. Showing the capacity of facilities for recycling of storage technologies could be among the approaches taken to address these concerns.

As mentioned earlier, this report is the first effort to apply the IRL methodology to energy storage technologies. In this process, we faced several challenges. Firstly, we found it difficult to break down the value chain of the studied storage technologies. Secondly, there was not always data and information available to assess and estimate the technologies' market trends. Third, this report did not study all the storage technologies that are available in the market. These challenges, when possible, will be addressed in the next REEEM IRL reports.

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