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Use of Vanadium based redox flow batteries to store electricity from renewable sources: trends and legal framework in southern Europe

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Through my point of view, life makes no sense without having wonderful people around.
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To my mum, sister, grandparents, uncles, cousins and friends.
And to the most remarkable person that I have in memory and that made me approach life through a wonderful and finite way, my father.

Abstract

A low carbon economy is on the world agenda and Europe is at the forefront of this paradigmatic change, therefore an energy transition is becoming one of the main priorities. Renewable energy sources are gaining unprecedented importance in the energy mix creating new challenges. Energy Storage Solutions (ESSs) plays a substantial role in the new energy system requirements and will be extensively analysed, being electrochemical solutions the central point in this work, mainly vanadium redox flow battery technology.

This report is focused, primarily, on gathering Energy Storage Solutions legislation in the European Union, with a more detailed approach to Portugal and Spain national cases. The political effort to achieve an energy transition has been resulting in a continuous publication of energy-related legislation that has its most recent version summarized throughout this work. Considering the differences among country realities, a continuous and meticulous follow up of legislative acts must be done to accomplish the requirements and, at the same time, to take advantage of the opportunities created by the continuously improved legal framework.

Additionally, a comparative approach among the main battery technologies is summarized including an economic overview, focused on LCOS, which is of major importance, considering the continuous deployments of these emerging solutions. The possibility of adopting a circular approach is also approached in the report allowing to create an updated and encompassing overview of the existing electrochemical storage technologies, envisioning its possible trends.

Keywords: Energy storage solutions, batteries legislation, Vanadium redox flow batteries, LCOS.

Resumo

A transição para uma economia de baixo carbono está na agenda mundial e a Europa está na linha da frente desta mudança paradigmática, consequentemente, uma transição energética está a tornar-se uma das suas principais prioridades. Fontes energéticas provenientes de recursos renováveis estão a ganhar uma importância sem precedentes no mix energético provocando o surgimento de novos desafios. As tecnologias de armazenamento de energia são promissoras por responderem de forma substancial às novas necessidades e serão extensivamente analisadas ao longo deste relatório, sendo a bateria redox de escoamento a vanádio o principal foco.

O esforço político para promover uma transição energética tem sido notório e tem resultado numa constante revisão da legislação relacionada com a energia. Como tal, este relatório foca-se essencialmente numa síntese do atual enquadramento legal no que respeita as soluções de armazenamento de energia. Inicialmente é desenvolvida uma análise com especial enfoque no contexto da União Europeia, e posteriormente uma mais direcionada para os casos particulares de Portugal e Espanha. Uma análise contínua e meticulosa tendo em consideração as diferenças entre as realidades dos países deve ser feita para garantir a legalidade da atividade desenvolvida, e, simultaneamente, tirar proveito das oportunidades criadas pelo enquadramento legal.

Adicionalmente, e de forma a contemplar os principais aspetos no que respeita baterias é realizada uma análise geral das principais características destas tecnologias, nomeadamente o *LCOS*. O relatório sintetiza as principais características das baterias e as possíveis tendências das mesmas.

Palavras-chave: armazenamento de energia, legislação de baterias, baterias redox de escoamento a vanádio, LCOS.

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Abbreviations

BTM – behind-the-meter

BTN – “baixa tensão normal”, low normal tension

BTRL – Battery Technology Readiness Level

CEN - European Committee for Standardization

CENELEC - European Committee for Electrotechnical Standardization

CER – “Comunidades de Energia Renovável”, Renewable Energy Communities

DG - Distributed Generation

DGEG - Portuguese General Directorate of Energy and Geology

DL – Decree-Law

DoD – Depth of Discharge

DREN - Azorean Regional Energy Directorate

DSO – distribution system operator

EBRA – European Battery Recycling Association

EC – European Commission

EDA – “Eletricidade dos Açores”, Electricity from Azores

ENTSO - European Network of Transmission System Operators

ERSE – “Entidade Reguladora dos Serviços Energéticos”, Energetic Services Regulatory Entity

ESS – Energy Storage solution

ESVF - The Electricity Storage Valuation Framework

EU DSO – European Union Distribution System Operators

EU- European Union

EU-ETS - EU-Emissions Trading Scheme

GDP – gross domestic product

I&D&I – Investigation, Development and Innovation

IRENA – International Renewable Energy Agency

LCA – Life Cycle Assessment

LCOS – Levelized Cost of Storage

NEMOs - Nominated Electricity Market Operators

NZEB – Nearly Zero Energy Buildings

PEPO – “Plano Estratégico Plurianual e Orçamento” Multi-annual Strategic plan and allocation

PNEC - “Plano Nacional integrado Energia e Clima”, Energy and Climate Integrated National Plan

PNIEC - “Plan Nacional Integrado Energía y Clima”, Energy and Climate Spanish integrated Plan

PV – Photovoltaics

R&D – Research and Development

RDL – Regional Decree-Law

RESP – “Rede Elétrica de Serviço Público”, public service electric grid

RFB – Redox Flow batteries

RNC – “Roteiro para a Neutralidade Carbónica”, Roadmap for Carbon Neutrality 2050

SDG – Sustainable Development Goals

SET-Plan – Strategic Energy Technology Plan

SWOT - Strengths, Weaknesses, Opportunities and Threats

TSO – transmission system operator

UPAC – “Unidade de Produção para Autoconsumo”, Autoconsumption Production Unities

VRES - Variable Energy Sources

VRFB – Vanadium Redox Flow Batteries

1. INTRODUCTION

1.1. ENERGY TRANSITION CONTEXT

The goal of "holding the increase in global average temperature to well below 2ºC above pre-industrial levels and pursuing efforts towards 1.5 ºC" defined by the Paris Agreement is an ambitious settlement and has as main approach the economy decarbonisation (Höhne et al., 2017) (Victoria et al., 2019). This commitment involves a dual challenge: the need to meet global rising energy demand and, simultaneously, a reduction in carbon emissions (BP Outlook, 2019).

The rise of energy demand is motivated mainly by the increasing prosperity in developing countries combined with the correlation between economic growth and energy consumption. Having 2040 as the horizon, the improvements in living standards are supposed to double the gross domestic product (GDP), resulting in an increase of the energy consumption by only a third, due to efficiency gains (BP Outlook, 2019).

The other side of this dual challenge is essentially induced by the established goals in the Paris Agreement which implies shifting to a lower-carbon energy system (BP Outlook, 2019). At a practical level, one of the main strategies to increase energy consumption reducing the CO2 emissions relies on the installation of extensive capacities of Variable Energy Sources (VRES) instead of basing the energy system on fossil fuels (Victoria et al., 2019). As Miller et al. sustain, "the future of energy systems is one of the central policy challenges facing industrial countries" (Miller et al., 2013). In a resumed form this approaches a field that is known as energy transition.

There is not an accepted definition for energy transition concept, although there is a common understanding (Savacool, 2016). By energy transition, it is understood that the energy source or group of energy sources that dominate the market during a certain period are being replaced by another source or sources (Melosi, 2017).

There have been energy transitions throughout the history driven by various scenarios, as the discovery of new energy sources (e.g. natural gas in the North Sea) or the reduction of costs (e.g. coal heating instead of wood), however, they were typically emergent processes, that had no time constraints (Fouquet, 2010).

In contrast, the ongoing transition is critical in terms of duration, with the possibility of occurring in a fast way. Three main aspects differ from the previous transitions. Firstly there is a wide variety of actors attempting to govern a transition through a low carbon energy system, that has been headed by policymakers at international, national, regional and local levels (Hamamoto, 2011). The second different condition is the interconnected world that results in a global influence of national developments (leader-followers pattern) which is a feedback mechanism that is speeding this transition (Kern, 2016). Finally, the climate agreements (as the Paris Agreement) states an engagement with the decarbonisation trends (Kern, 2016).

Regarding the current energy transition concept, it is centred on shifting the energy sources precedence paradigm, based on a logic approach, considering the main source of energy on the Earth: the sun. The energy received from the sun is converted in many different ways through the dynamics of our planet and of its atmosphere (Angelis-Dimakis et al., 2011). There is an eminent need to transform this energy into forms that are suitable for our everyday use, instead of having an energy system based on limited resources that result in releasing pollutants, like CO_2, to the atmosphere. The mechanical energy of wind, water and waves can be converted in electricity, the sunlight itself can be used directly to produce heat in a more usable form or even electricity – Photovoltaics (PV) (Angelis-Dimakis et al., 2011).

Considering the above-described concepts governmental support is crucial to force a shift in the energy system. EU (European Union) commitment to implement VRES across its territory, achieving ambitious targets and lead the decarbonisation progress is shown by the existence of several climate policy instruments. The main ones are expressed through legislative packages (as the Clean Energy for all European Package and EU Green Deal), the creation of an internal energy market (EU energy market) or the establishment of EU-Emissions Trading Scheme (EU-ETS).

The need for developing new technologies to answer this challenge is changing the way energy is produced, transported and consumed. The necessity of a remarkable and without precedent transition is generating a wide range of business possibilities (BP Outlook, 2019).

1.1.1. CURRENT PANORAMA

Renewable energy is continuously growing its share in the energy mix, reaching an addition of 176 GW of installed capacity worldwide in 2019, accounting for a total amount of global renewable generation capacity by the end of 2019 of 2537 GW (IRENA, 2020). In what concerns added capacity, solar kept being the leading technology in 2019 as it can be seen in Figure 1.

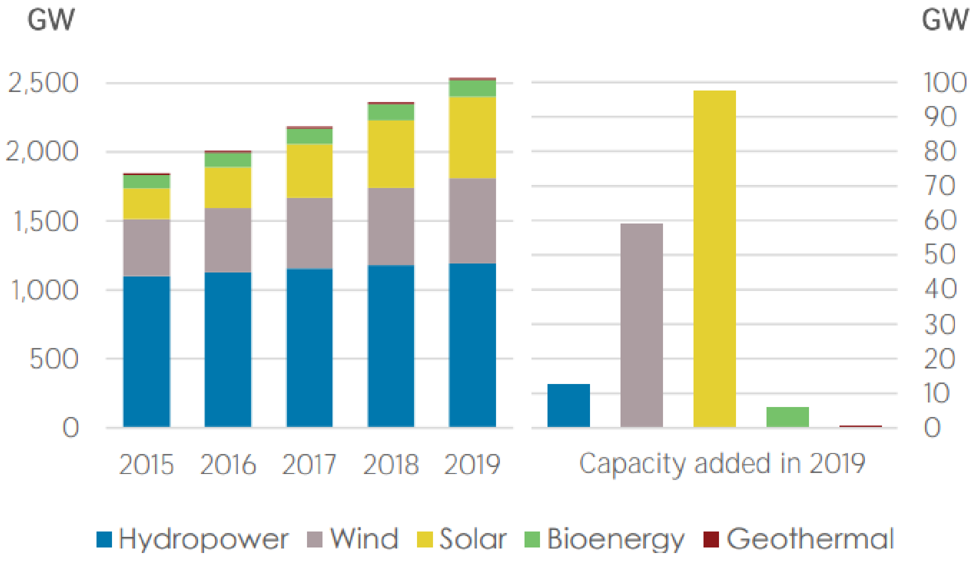

Figure 1. Renewable power capacity growth and added capacity in 2019. From "Renewable capacity highlights", by IRENA, 2020 (https://www.irena.org//media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Highlights_2020.pdf).

In 2019, as it can be seen in Figure 2, hydropower was responsible for the largest share of renewable energy generation (with a capacity of 1190 GW). In second place comes the wind power (that represents 623 GW of the capacity generation), followed by solar that accounts for 586 GW.

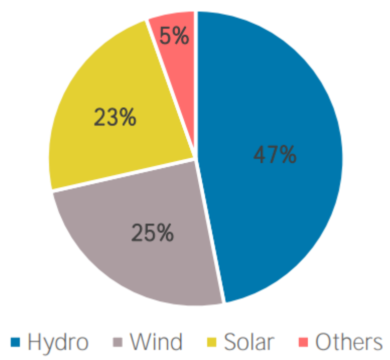

Figure 2. Renewable generation capacity by energy source in 2019. From "Renewable capacity highlights", by IRENA, 2020 (https://www.irena.org//media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Highlights_2020.pdf).

The electricity generated by renewable sources is gaining importance in some countries and regions, but it is facing some challenges in achieving a larger share. This is a result of the growth in total energy production (up 4% in 2018) and persistent investments and subsidies in fossil fuels and nuclear, resulting in CO_2 energy-related emissions global rising (Murdock et al., 2019). Although some regions have reached significant reductions in electricity generation emissions, Europe is an example, that reportedly fell 5% in 2018, mainly, as a result of renewables adoption.

Considering 2019, European renewable generation capacity reached 573 GW (an addition of 35.3 GW when comparing with 2018), that represents 23% in the global energy share (a growth of 6.6%). The 2019 world region leader was Asia with a capacity of 1119 GW, representing 44% of the global share (with a growth of 9.3%) (IRENA, 2020).

When analysing solar energy, Asia continued to dominate the solar capacity expansion, with a 56 GW addition (about 60% of the total added capacity). China, India, Japan and the Republic of Korea were the countries responsible for the leadership. In Europe, Spain and Germany dominated the solar capacity expansion.

1.1.2. ENERGY TRANSITION CHALLENGES

The integration of a large scale of VRES such as solar PV and wind in the power system introduces several new challenges. Among them, one of major importance is the intermittence, that leads to an unpredicted variation of renewable energy inputs, requiring a higher level of flexibility and integrated solutions (Li et al., 2019).

A typical emergent concern is known as the "duck curve" and is related to solar PV technology. The output power of PV generators depends on weather conditions (Lew & Miller, 2016) and, besides that, the power is only generated during the day-time creating an unbalanced demand and supply. In the duck curve shape, gaps between day and night-time load demands are very high (Obi & Bass, 2016) that in cases when the solar PV is grid-connected stress is created on the electrical grid.

For the mentioned issues, it is needed to adopt various actions, among the most significative ones are the development of smart grids and Energy Storage solutions (ESSs) (Obi & Bass, 2016). Currently, Europe considers "Electric storage" an issue with high impact although with some uncertainty associated, being considered "a critical issue for energy leaders, although one that lacks preparedness" (WEC, 2019), as it can be seen in Figure 3.

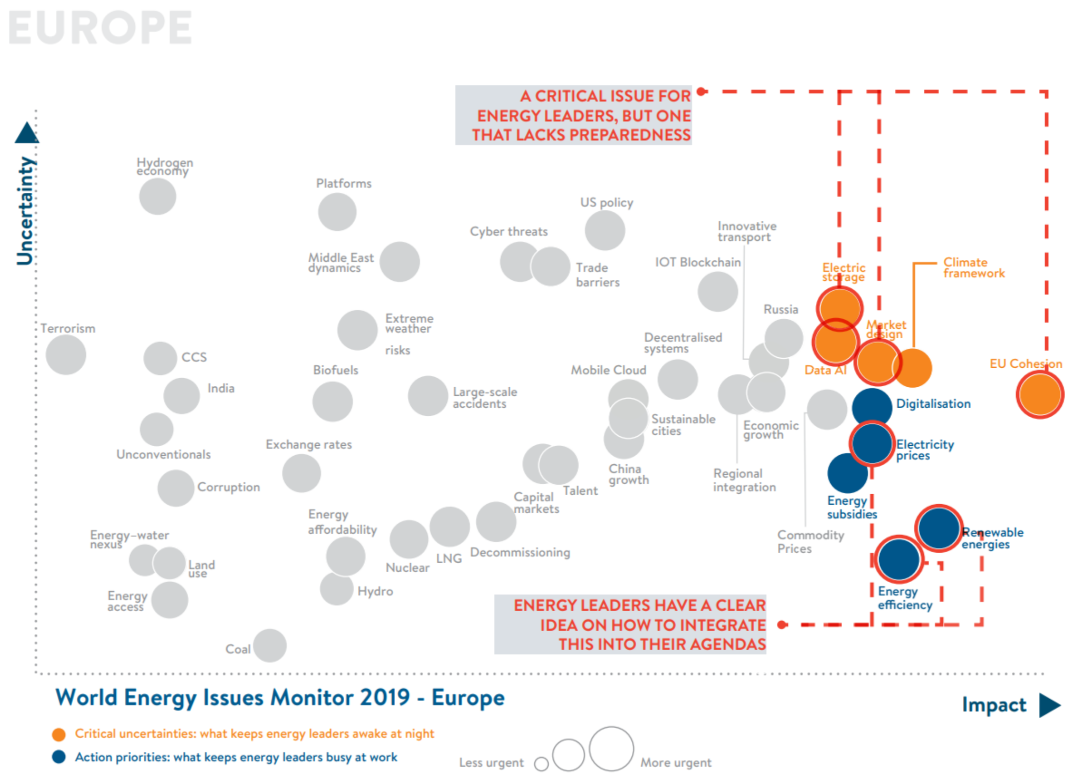

Figure 3. European Energy Issues Monitor, 2019. From "World Energy Issues Monitor 2019", by WEC (World Energy Council), 2019 (https://www.worldenergy.org/assets/downloads/3.-World-Energy-Issues-Monitor-2019-Interactive-Executive-Summary.pdf). "Used by permission of the World Energy Council".

ESSs are also considered an important concern in the "Energy Trilemma Index" 2019 which main results are schematized in Figure 4. A three-dimension performance is evaluated through 32 underlying indicators. To the Index calculation, ESSs are considered, belonging to the Energy Security dimension and is represented in the category of Resilience of Energy Systems (A2, out of 11 categories) that weights 18% of the final value of the mentioned Index. Portugal and Spain are located in the 29 and 18 positions, respectively, of the Energy Trilemma Index with storage as a negative point for both of the countries. It is also sustained in the report that there is a lack of available data concerning energy storage.

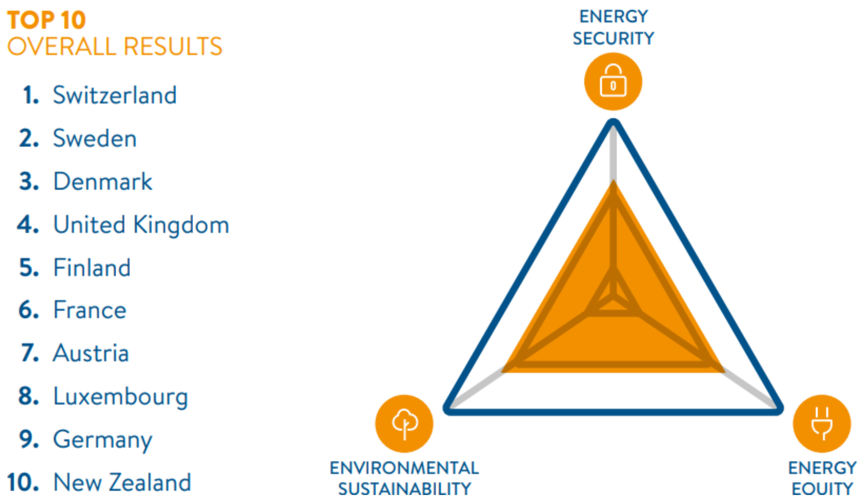

Figure 4. World Energy Trilemma top 10 performers. From "WET Trilemma Index 2019", by World Energy Council, 2019 (https://www.worldenergy.org/assets/downloads/WETrilemma_2019_Full_Report_v4_pages.pdf). "Used by permission of the World Energy Council".

ESSs represent one of the most relevant assets to the new energy system challenges, allowing decarbonization, ensuring power quality, energy management and security, it allows storing the energy surplus generated, being dispatched when it is needed (Lai et al., 2019). This concedes to utilize the surplus generation and to minimize the power curtailment (Locatelli et al., 2015). It also allows the consumers' empowerment becoming prosumers, agents that both consume and produce energy (Parag and Sovacool, 2016).

The ESSs importance as a key factor in the energy transition is no longer questionable. There is an imminent need to find solutions that allow an energy system flexibilization. Portugal and Spain are among the countries that need stronger energy storage solutions implementation. Nevertheless, the adopted solutions should encompass various criteria as environmental impact, reliability and efficiency (Kear et al., 2012).

2. LITERATURE REVIEW

2.1. ENERGY STORAGE SOLUTIONS

ESSs allow “moving energy over time”(Rastler, 2010). Based on the mobility of these solutions, they can be classified in stationary or mobile. Some versatile ESS technologies can be used in both contexts (Wong et al., 2011). Only stationary solutions will be approached in this work. Among the stationary solutions, there are two main assets, when ESS is directly connected to transmission or distribution is named in front-of-meter or grid-scale, contrarily, when, for instance, consumers who generate electricity (prosumers) have an ESS, it is denominated behind-the-meter (BTM) (Kooshknow and Davis, 2018).

To quantify the value of an ESS, the main services should be considered. In what concerns a renewable power integration approach, ESSs services can be divided into five categories: bulk energy, ancillary services, transmission infrastructure, distribution infrastructure and customer energy management (IRENA, 2020). Concerning the first category, bulk energy, it is mainly formed by electric energy time-shift (arbitrage) and electric supply capacity. Examples of ancillary services are fast frequency reserve, reserve (primary, secondary and tertiary), voltage support and black start. For what concerns transmission infrastructure upgrade deferral and congestion relief are the main services. To the distribution infrastructure category, the main services are distribution upgrade deferral and voltage support while to the consumer are power reliability, retail electric energy time-shift, power quality and demand-side management (IRENA, 2020).

The various services provided by ESSs have been leading to an increase in its adoption. Through ESS annual deployment analysis is possible to conclude that it nearly doubled from 2017 to 2018. In 2018, ESS deployment reached over 3 GW, this evolution is strongly dependent on supportive policies and market framework. BTM storage matched for the second consecutive year the grid-scale storage, as it can be seen in Figure 5.

Record levels with significant growth are leaded by Korea, China, Japan and Germany (IEA, 2019).

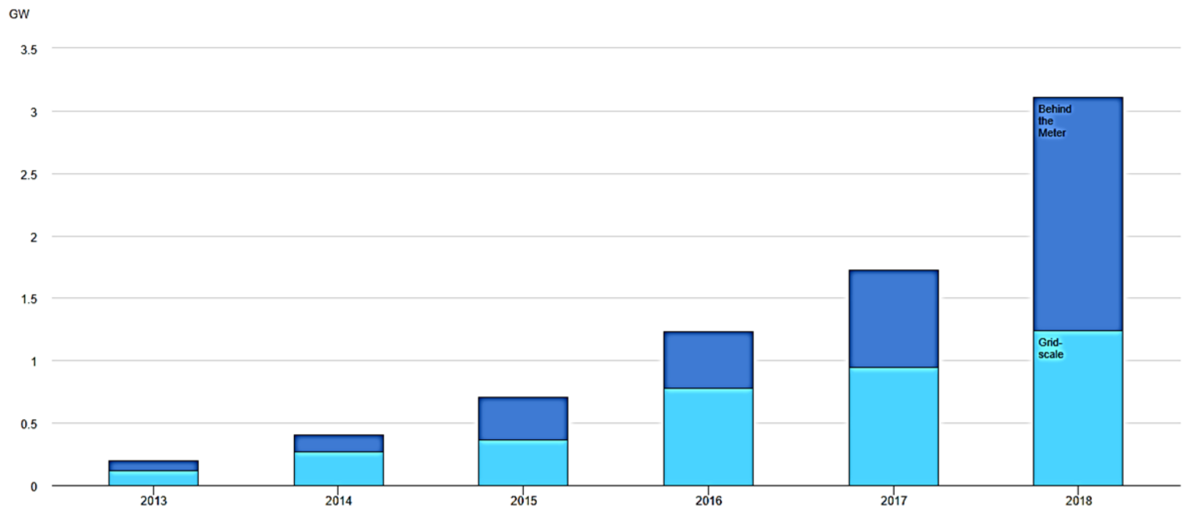

Figure 5. Annual storage deployment, 2013 - 2018. In a darker blue are represented behind-the-meter solutions, in a lighter blue are represented the grid-scale ones. From "Energy Storage", by International Energy Agency, 2019 (https://www.iea.org/reports/tracking-energy-integration/energy-storage).

In 2018, Korea was responsible for over one-third of all global storage capacity installed, as a result of policy measures. In the same year, China became a global market leader, with nearly 0.5 GW of new battery storage installed (12% of the global) and 1 GW in development. Japan is also a strong market for storage due to incentive measures, a wealth of PV projects and a need for resiliency to natural disasters.

In what concerns Europe framework, the leadership is assumed by Germany (followed by the United Kingdom) that has increased BTM storage even beyond the support of subsidy programmes, reaching over 100 000 installed systems (IEA, 2019).

There is a wide variety of ESSs, an oriented analysis should be done to choose the most adequate system for each situation (Kooshknow and Davis, 2018). Depending on the considered scientific literature the storage technologies can have different classifications. As it can be seen in Table 1 a classification according to storage principles is represented, resulting in five energy storage classes. Electrochemical solutions have shown increasing importance in many applications as a result of its flexibility, scalability, efficiency and other attractive features (Alotto et al., 2014). Based on technology rapid improvement, the electricity storage will allow greater system flexibility, a key asset as the share of VRES increases (Ralon et al., 2017).

Table 1
Classification of Energy Storage Systems in five classes based on stored energy and respective technology examples.

	Technology example
Mechanical	Pumped Hydro
	Compressed air
	Flywheel
Electrical	Supercapacitors
	Superconducting magnetic storage
Electrochemical	Classic batteries: - Lead-based acid - Lithium Iron Phosphate - Lithium-ion - Saltwater
	Flow batteries: **- Vanadium redox flow batteries** - Organic flow batteries - Zinc-iron flow batteries - Zinc-bromine flow batteries
	Hybrid Supercapacitors
Chemical	Hydrogen Systems
	Ammonia Dissociation-Recombination
	Methane Dissociation-Recombination
Thermal	Sensible Heat Systems
	Molten Salt Storage
	Latent Heat Systems

Note. Adapted from Kooshknow, S. M. M., & Davis, C. B. (2018). Business models design space for electricity storage systems: Case study of the Netherlands. *Journal of Energy Storage*, 20, 590-604.

Considering electricity storage, three processes are involved in its functioning: converting electricity to a medium (i), storing the intermediate energy (ii) and converting this energy back to electricity (iii) (Rodrigues et al., 2014). The first and third processes are named charging and discharging, respectively.

Stationary power-to-power electrochemical storage solutions are one of the main tools to enable a transport sector dominated by electric vehicles, effective twenty-four-hour off-grid solar homes systems and 100% renewable mini-grids (Ralon et al., 2017).

Regarding batteries utilization, the technology mix remains largely unchanged in the last years, as lithium-ion batteries continue to be the most widely used, making up nearly 85% of all new capacity installed in 2016 (IEA, 2019). Particular relevance has been given to RFBs, in what concerns stationary solutions, mainly due to its scalability, flexibility, high round-trip efficiency, long life, fast response, high depth of discharge and reduced environmental impact (Weber et al., 2011).

2.1.1. ELECTROCHEMICAL TECHNOLOGIES COMPARATIVE OVERVIEW

A comparative overview of the characteristics of the most promising electrochemical technologies is essential when it comes to choosing a technology for a specific application. For instance, the importance of Li-ion technology can be explained through its high specific energy (energy per unit weight) and energy density (energy per unit volume) (Koohi-Fayegh and Rosen, 2020). The mentioned aspects are RFB limitations to mobile applications (as the technology has a low energy density), therefore it is suitable for stationary systems that require high energy storage capacity with no weight or volume limitations.

In Table 2 are represented the current two main battery technologies for stationary purposes (and some of the related quantifiable characteristics). Several parameters allow battery characterization such as efficiency, lifetime, maturity, cost and safety. Due to the high importance of the battery cost when considering the acquisition, this point will be approached in a further and separated point.

To allow a comparison among batteries in what concerns its maturity a Technology Readiness Level (TRL) scale was considered, that goes from a scientific breakthrough (TRL-1) to a material scale-up, cell testing and scale up to pack (TRL 5-6) (Crabtree, 2015).

Table 2
Two main stationary battery technologies and related important characteristics.

	Vanadium RFB	Lithium-ion
Efficiency	85%	84-90%
Specific energy (*Wh/kg*)	25	110 - 170
Lifetime (cycles)	Minimum of 15 000	Approximately 5 000
Maturity (TRL)	6	6
Safety	Improved safety characteristics	Safety issues from overheating
References	Rodby et al., 2020; Lazard, 2018; Debruler et al., 2020	

2.1.2. VANADIUM REDOX FLOW BATTERIES

RFB can be categorised through different types according to the electrochemical redox pairs (iron/chromium, vanadium/bromine, bromine/polysulfide, zinc-cerium, zinc/bromine, and all-vanadium) (Monteiro et al., 2018). RFBs contains two liquid electrolytes where metal ions are dissolved (redox couples as electroactive species) that are stored in external tanks and pumped to the electrochemical cell/stack, where reactions occur.

An important characteristic of RFB is that the number and size of the cells define the power and besides that, the volume of the electrolyte defines the energy of the battery and these two factors are independent (Monteiro et al., 2018).

Among RFB solutions, Vanadium Redox Flow Battery (VRFB) has been considered one of the most promising for stationary purposes (Li et al., 2017) and will be the technology that will be approached during this work, as it is the main technology being developed at Visblue.

The battery system has two tanks where is located the vanadium-based solution (that consists of vanadium pentoxide V2O5, water and sulphuric acid). The stack is constituted, by stack cells (the number depends on the desired power), comprising graphite-polymer based bipolar plate, a polymer membrane that allows the proton exchange and a felt electrolde. Figure 6 is a schematization of a VRFB system.

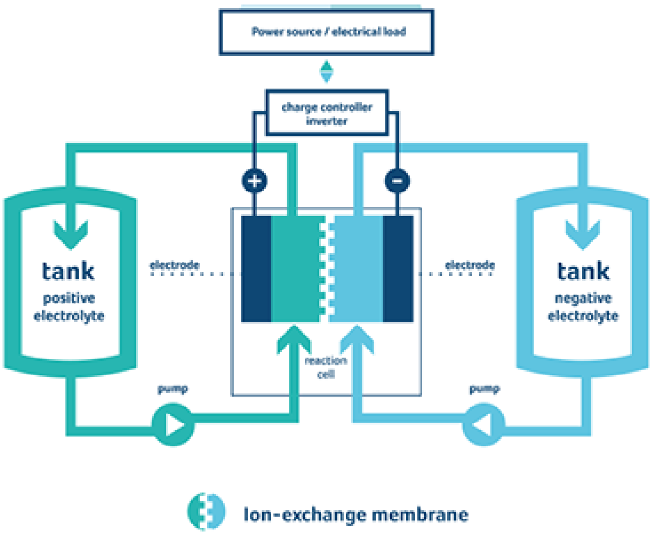

Figure 6. Visblue VRFB schematization.

The process behind this storage system relies on the ability of the chemical element vanadium to be present in four different oxidation states, making it possible to have only one active material in the battery (instead of the most common in RFB technologies: two active species). Using vanadium in an RFB reduces, therefore, the possibility of cross-contamination problems between electrodes (Monteiro et al., 2018). When electrolyte flow through the porous electrodes (separated by a proton permeable membrane), the charging process consists of reduction of V3+ to V2+ (negative electrode, E^0 = -0.26 V_{NHE}) and oxidation of (VO)2+ to (VO2)+ (positive electrode, E^0 = -0.99 V_{NHE}), and the reverse reactions for discharging. Protons, generated at the positive electrode, move through the membrane to maintain the neutrality of the electrolytes

VRFB has gone from being a laboratory curiosity, gaining significant commercial applications over the last decades (Whitehead et al., 2017), having a promising future in storing large amounts of energy (Alotto et al., 2014). This technology is only suitable for stationary purposes due to its low volumetric energy storage capacity. These storage systems can have several applications, among them, are load levelling and peak shaving, uninterruptible power supply, island electrification, emergency backup for hospitals (or air-traffic control) and the integration in wind and PV energy plants (Monteiro et al., 2018).

VRFB's main advantages and disadvantages are represented in Table 3 based on the International Renewable Energy Agency. Its utilization can be done in-front-of-the-meter (for distribution and transport purposes) and BTM (prosumers approach).

Throughout the history, global vanadium demand has been explained, mainly, by two basic variables: global steel production rates and the specific vanadium consumption rate (kilograms of vanadium used per metric ton of steel produced). Changes in these two variables produce an impact in global vanadium demand (Perles, 2012). Vanadium utilization for batteries can impact its demand, although, until now there still isn't registered any pattern.

Figure 7 represents the vanadium price evolution from 2000 until the present, the value from May 22nd, 2020 is US$5.85/lb (11,817 €/kg). The prices of vanadium impact the battery final cost in about one-third of the equipment cost. The increasing demand of the transition metal is offset by the increasing extraction quantity.

Table 3
Fundamental advantages and disadvantages of vanadium redox flow battery electricity storage systems.

Advantages	Disadvantages
Long cycle life (at least 15 000)	Low electrolyte stability and solubility limit energy density and low specific energy limits use in non-stationary applications
Relative high energy efficiency (up to 85%)	Precipitation of V2O5 at electrolyte temperatures above 40°C can reduce battery life and reliability, although this can be managed
One of the most mature flow batteries with multiple demonstrations and deployed at the MW scale	The high cost of vanadium and current membrane designs
Design energy/power (E/P) ratio can be optimised to suit specific application	Unoptimised electrolyte flow rates can increase pumping energy requirements and reduce energy efficiency
Long-duration (1-20 hours) continuous discharge and high discharge rate possible	
Quick response times	
The same element in the active materials on electrolyte tanks limits ion cross-contamination	
The electrolyte can be recovered at the end of project life	
Over 95% of the battery can be reused/recycled at the end of battery lifetime	
Heat extraction due to electrolyte prevents thermal runaway	

Source: Adapted from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

Figure 7. V2O5 Vanadium Pentoxide Flake 98% Price USD / lb. By Vanadium Price, 2020 **(https://www.vanadiumprice.com/).**

3. VISBLUE AT A GLANCE

The internship was conducted under the enlightenment of a Danish/Portuguese spinout company from Aarhus and Porto University: Visblue. Danish Visblue exists since 2014, although, Visblue Portugal was only created in 2017 with a Research and Development (R&D) purpose, having a strong connection with UPorto Faculty of Engineering.

Visblue main purpose emerged from the necessity of developing an ESS that enhances renewable energy consumption through an environmentally friendly technology. As a result of the above-mentioned criteria, VRFB was selected as the best technology that fitted the situation. Visblue invested in the deployment of this electrochemical solution allowing the company to have a tool that can be crucial to the actual energy transition.

VisBlue has its main facilities at Ecopark, Aarhus, Denmark. This includes offices, approximately 200 m2 production and 100 m2 R&D facilities. The R&D includes (i) power electronics lab related to integration of inverters/power electronics and flow-batteries (ii) thermostated flow battery test bench. Here the performance of flow batteries (and stacks) can be tested at elevated temperature (iii) smaller chemistry lab with autotitatator (pH/redox) and conductivity measurement facilities. The Portuguese facilities are located in the Parque da Ciência e da Tecnologia da Universidade do Porto (UPTEC).

Visblue first sale was in 2016 to Realdania (a philantrophic organization that aims to create awareness for society's major problems), the battery was installed in Realdania By & Byg apartment, Denmark first net-zero energy building. In 2017/2018 Visblue has booked 700 000 € in sales for deployment. Remarkably, a battery was installed in Livø, a small Danish island, isolated from the mainland and protected from the Danish Nature Agency. A battery was also installed in Hobro, the headquarters of EuroWind (the wind turbine administrator in Denmark) and in Lille Birkeholm, a housing association in Copenhagen.

An analysis including the technology overall positive and negative aspects is essential to focus on what are the differentiation factors and, on the other hand, in what should be strengthened, taking advantage of the actual energy panorama.

To obtain a simple assessment of the company was used a strategic management tool based on strengths, weaknesses, opportunities and threats, SWOT analysis. This tool was firstly described in 1969 and has grown as a key tool for addressing complex strategic situations, allowing to reduce the quantity of information, improving decision making (Helms and Nixon, 2010). Figure 8 schematizes Visblue SWOT analysis in a summarized form.

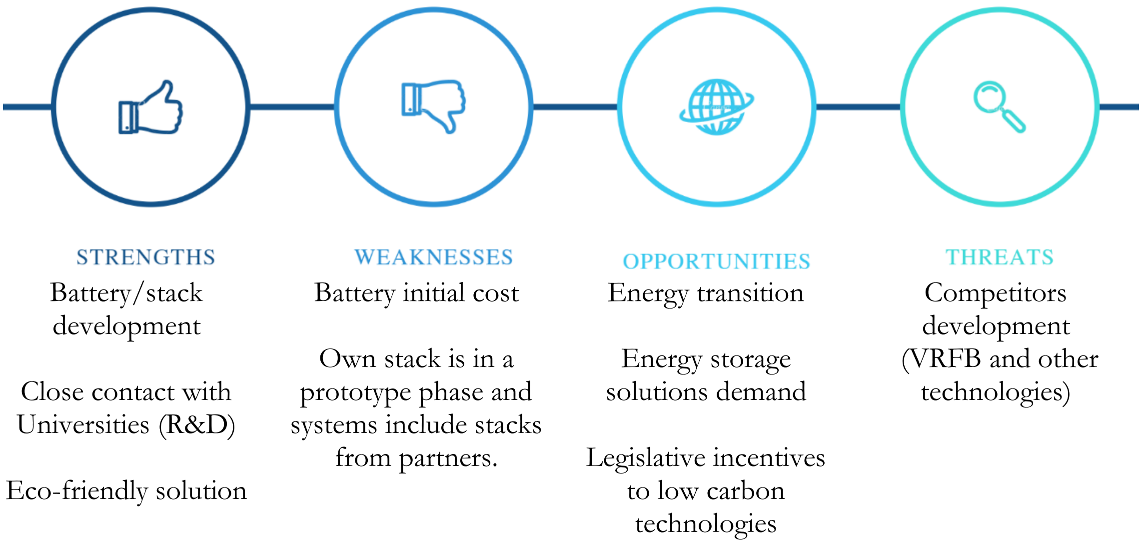

Figure 8. Visblue SWOT analysis schematization.

In what concerns strengths, there are a few, below are enumerated the main ones.

The close contact between Visblue and renown universities from different countries (Portugal and Denmark, Porto University Faculty of Engineering and Aarhus University, respectively) is crucial to ensure continuous and irreproachable development of the technology. This fact results in a final product that is a vanguard solution, having a unique and very well-developed stack. As a second positive point, should be considered that the solution considers environmental aspects, essentially as a result of its recyclability and durability (characteristics that will be approached ahead), unlike lithium batteries. Besides the environmental approach, durability is also a positive facet when considering maintenance aspects and long-term cost competitiveness. Apart from the mentioned qualities, Visblue presents a safe solution, VRFB technology does incorporate an aqueous solution what makes it non-flammable, this is a concerning issue in most of the main competitors' commercial batteries solutions (as lithium-ion batteries).

The considered weaknesses are points that are already being approached. The battery initial cost is the main constraint when considering the adoption of this solution, however, this happens mostly because the costs are not analysed in a long-term perspective. The initial investment cannot be compared with other solutions without being considered the high durability of the battery, having the main component, vanadium, endless durableness, as it will be further approached. Another weakness issue is related to the inexistence of mass production of stacks, being this aspect in prototype phase. Visblue energy storage system can incorporate a variety of stacks.

When considering the global panorama there are lots of opportunities that are an advantage when it comes to Visblue market growth. An energy transition is being enforced, with a strong impact in the European Union. The renewable sources production growth and the demand for solutions to enhance the consumption of energy resulting from renewable sources induces ESS adoption, as it enlarges the energy from renewable sources consumption by storing it until the moment it is needed. This change in the energy model is also being shaped by the legislation, that is getting stricter with targets that also enforces ESS adoption.

The present energy transition is enforcing the search for new solutions consequently new competitors do appear being this fact is the most relevant threat.

When considering competitors, we can approach the analysis through different perspectives. Competitors that do not use VRFB technology, although their solutions answer the same range of power and energy capacity, Visblue is situated in an intermediate power level of ESS, approximately from 3kW to around some hundreds of kW (intending to enlarge its offer to MW solutions). This kind of competitors can belong to any class of ESS, being electrochemical the most direct competitors as lithium-ion. The other group of competitors are companies based on the same type of technology as Visblue, VRFB.

A regular and meticulous follow up of the European, national and regional legislations can have a decisive impact in Visblue accomplishments. A detailed analysis of its battery characteristic complemented with a technology comparative approach is also of major importance. The constant development of the company environmental facet can and should also be a differentiation factor of the company.

3.1. MOTIVATION AND METHODOLOGY

Emerging solutions are essential to answer the challenges created by the vast and rising implementation of VRES, allowing them to have an effective, trustable and sustainable penetration, to accomplish a low carbon economy. ESS intrinsic characteristics can answer a substantial part of energy transition incongruousness, having an important role in the decarbonisation and also in the consumers' empowerment (prosumers).

The work will be focused on batteries for stationary purposes, particularly vanadium redox flow batteries (VRFB). The recent role of ESSs as an integrated part of the energy system is leading to an increase in the legislation amount that should be meticulously analysed.

The European legal framework will be extensively reviewed and the most important aspects resumed along with the report, specifying Portugal and Spain national cases due to the differences among European countries realities.

Furthermore, a comparative overview of the main electrochemical technologies towards the energy transition in Europe will complement the legislative approach culminating in an up to date resumed panorama, highlighting the expected trends based on the gathered information.

4. LEGISLATION ANALYSIS

All the legislation was gathered and synthesised in this document until May of 2020.

4.1 STORAGE SOLUTIONS EUROPEAN APPLICABLE LEGISLATION

EU is on track to meet its greenhouses gas emissions targets, being actively working with other countries and regions to achieve the goals of the Paris Agreement. The increasing incorporation of climate change policies and measures among EU is notable along the years, we can see the evolution between 2015 and 2019 in Figure 9.

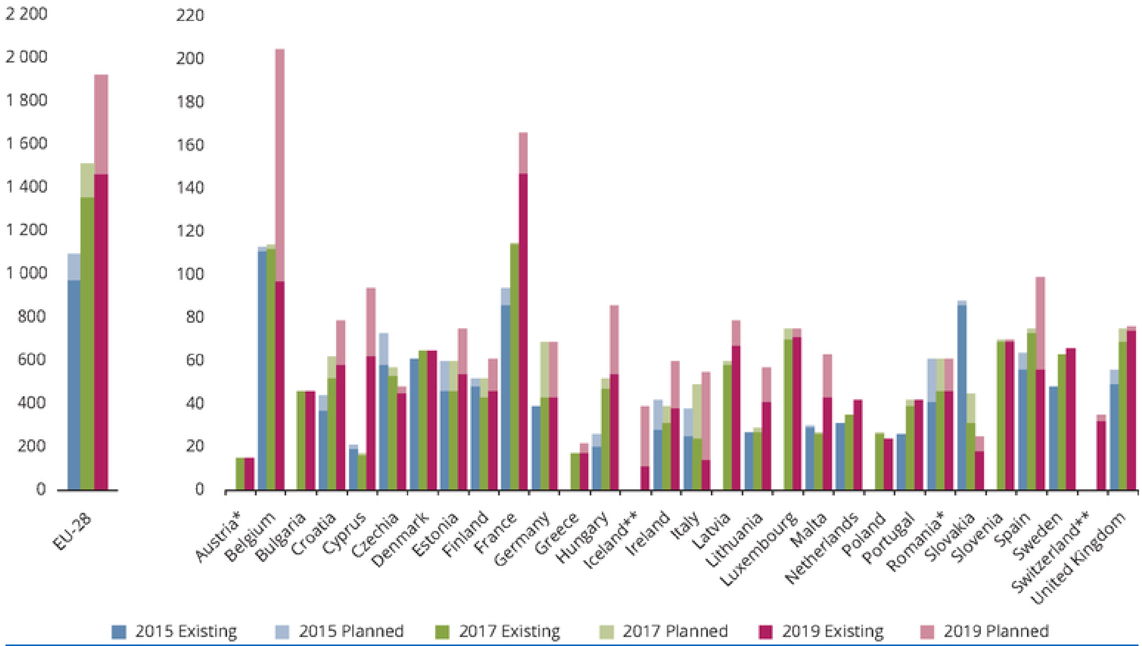

Figure 9. The total number of existing and planned policies in the European Union. EU 28 (left) and by country (right) related to climate change mitigation. From "National policies and measures", by European Environment Agency, 2019 (https://www.eea.europa.eu/data-and-maps/data/external/cdr-uploads-for-obligation-national/view).

Considering Europe energy area, several relevant approaches were developed: energy union strategy (published in February 2015), energy security strategy (published in May 2014), 2050 Long-term strategy (published in November 2018), Clean Energy for all Europeans package (initial proposals published in November 2016, finished in 2019), the declaration of a climate emergency from the Parliament (November 2019) and European Union Green Deal (initial proposals declared in December 2019).

During the next point, Clean Energy for all Europeans package will be fully analysed, focusing on ESS, an analysis decisive to the technology empowerment. The European Union Green Deal will also be approached considering the limited information available.

4.1.1. CLEAN ENERGY FOR ALL EUROPEANS PACKAGE

To promote the energy transition, the European Commission (EC) proposed in 2016, and formally concluded in 2019, a set of new ambitious rules named "Clean Energy for all Europeans package", encouraging a balance between decisions at European Union, national and local levels.

Changing from an energy system that has, essentially, a unidirectional behaviour to a more complex scheme, needs to be preceded and followed-up through a change in the legislative approach.

The creation of this package intended to support and stimulate the energy transition addressing five dimensions (through Directives and Regulations): energy security, internal energy market, energy efficiency, decarbonisation of the economy and research, innovation and competitiveness. The five dimensions are divided into eight legislative acts, as can be seen in Table 4.

Considering the information that is condensed in the table we can analyze if ESSs are referred during the directive/regulation and, besides that, the level of importance of the storage solutions for each legislative act. Based on how much relevance is given to this concept over the legislation, the importance level was divided into low, medium and high (among the legislative acts analysed none was considered to have a low importance approach of ESS, instead, among them, two legislative acts do not approach this subject).

Due to an intrinsic relation between the **Energy Performance in Buildings Directive** 2018/844 and the adoption of energy storage systems BTM, as batteries, this legislative act will be fully approached in a separated point named Nearly zero energy buildings (NZEB) (4.1.1.1).

Table 4
Clean Energy for all Europeans package legislative acts and storage reference.

	Publication date	Legislative act	ESS approach	Importance level
Energy Performance in Buildings Directive	30 May 2018	Directive 2018/844	Yes	Medium
Renewable Energy Directive	11 December 2018	Directive 2018/2001	Yes	High
Energy Efficiency Directive	11 December 2018	Directive 2018/2002	Yes	Medium
Governance of the Energy Union Regulation	11 December 2018	Regulation 2018/1999	Yes	High
Electricity Regulation	5 June 2019	Regulation 2019/943	Yes	High
Electricity Directive	5 June 2019	Directive 2019/944	Yes	High
Risk Preparedness Regulation	5 June 2019	Regulation 2019/941	No	-
Agency for the Cooperation of Energy Regulators Regulation	5 June 2019	Regulation 2019/942	No	-

Note. Adapted from https://ec.europa.eu/info/news/clean-energy-all-europeans-package-completed-good-consumers-good-growth-and-jobs-and-good-planet-2019-may-22_en

In what concerns the **Renewable Energy Directive**, 2018/2001, is established that considering the point (60), storage should be integrated into the transmission and distribution grid and there should not be done any discrimination through the storage systems adoption, also "without hampering the financing of infrastructure investments."(65).

This legislative act further states that storage facilities should be incorporated in grid transmission and infrastructure context, increasing the "technically feasible and economically affordable level of renewable energy in the energy system", using EU funds (article 3º 5c).

Particular emphasis is given to the introduction of appropriated measures (from the Member States) regarding building regulations - to allow the local energy storage (article 15º 4).

This legislative act finalizes with a reference that approaches the avoidance of double charging when these storage systems are adopted "Member States shall ensure that renewables self-consumers, individually or through aggregators" "to install and operate electricity storage systems combined with installations generating renewable electricity for self- consumption without liability for any double charge, including network charges, for stored electricity remaining within their premises"(article 21º 2b).

Through this directive, that should be shaped and embodied in national legislation, the ESSs are also becoming protected of any kind of double charges.

The **Energy efficiency Directive,** 2018/2002, states that should be assessed by 1 January 2021 the "potential for energy efficiency in conversion, transformation, transmission, transportation, and storage of energy" by the European Commission, with the submission of a report to the European Parliament regarding the mentioned parameters, article 1º b) (13). The inclusion of ESS in the report as one of the main assets in the potential achievement of energy efficiency shows its importance.

Governance of the Energy Union Regulation, 2018/1999, in article 4º ("National objectives, targets and contributions for the five dimensions of the Energy Union") states the main objectives, targets and contributions that each Member State shall include in the integrated national energy and climate plan. In the point d) (3) of the mentioned article it approaches the energy storage as a considerable aspect of the "Internal Energy Market" (should be included a timeframe for "when the objectives should be met..."). The article 22 is related to "Integrated reporting on energy security" and mentions in its point d) that the Member States shall include (in the integrated national and climate progress reports) information on the implementation of " national objectives with regard to increasing the flexibility of the national energy system, in particular by means of deploying domestic energy sources, demand response and energy storage". Look upon article 23 ("Integrated reporting on the internal energy market") d) the Member States shall also include, in the national energy and climate progress reports, information concerning the implementation of ESS. Considering the same article (23º), these reports shall include, where it is applicable, (e) "national objectives and measures related to the non-discriminatory participation of renewable energy, demand response and storage…".

During the annexe I of this regulation, the relevance of energy storage systems is evident, in part I 2.3 (related to energy security) is established that "national objectives with regard to increasing the flexibility of the national energy system, in particular by means of deploying domestic energy sources, demand response and energy storage".During the same annexe, I, in the point related to Market integration (2.4.3) storage is also mentioned where is described as a vector to achieve increasing system flexibility.

In what concerns the **Electricity Regulation**, 2019/943, it mainly emphasizes the ESS as an important component in the new paradigm where the customers are no longer just "purely passive" becoming "enabled to fully participate in the market" including the energy storage as one of the drivers (7).In the point 22, it is stated that electricity prices should be determined through demand and supply, and there should be incentives for investments into flexibility sources as the energy storage (interconnection, demand response and flexible generation are the other mentioned flexibility sources). The point 23 refers to decarbonisation, stating that is essential that "the market removes existing barriers to cross-border trade and encourages investments into supporting infrastructure" energy storage is one of the infrastructure examples. The point 39 intend to "level playing field between all market participants", saying specifically that "network tariffs should not discriminate against energy storage".

The establishment of a European Union Distribution System Operators (EU DSO) entity that would cooperate closely with European Network of Transmission System Operators (ENTSO) providing "…guidance on the integration inter alia of distributed generation and energy storage…" is described in the point 60. In article 1 of the present regulation energy storage is mentioned as a subject scope of the document, being identified as a driver to the well-functioning of the integrated electricity markets. In article 3 (g) it is also stated that "…market rules shall deliver appropriate investment incentives for…" "…energy storage", considering point (j): it "shall participate on equal footing in the market…", the (m) states that the "…market rules shall enable the efficient dispatch of energy storage…" and finally on (n) "…market rules shall allow for entry and exit of energy storage…". Article 6 approaches the balancing market, stating that (a) should be ensured "effective non-discrimination between market participants…" and (c) "… individually or through aggregation…" (mentioning the ESS in both points). Article 8 is regarding trade on day-ahead and intraday markets, states that Nominated Electricity Market Operators (NEMOs) shall provide products that are "…sufficiently small in size, with minimum bid sizes of 500 kW or less…" allowing the effective participation of "…energy storage and small-scale renewables including direct participation by customers.".

The redispatching is approached in the entire article 13, that once again states that shall not be adopted discriminatory criteria for ESS. "2. The resources that are redispatched shall be selected from among generating facilities, energy storage or demand response using market-based mechanisms and shall be financially compensated. Balancing energy bids used for redispatching shall not set the balancing energy price." In cases where the ESS available number is "…too low to ensure effective competition..." a" Non-market-based redispatching may be used". In the point 7 of the same article is stated that in cases that non-market base redispatching is done, it shall be subject to financial compensation by the system operator requesting the redispatching to the operator of the dispatched generation. In the article 18 is stated that charges applied by network operators for access to the network shall be non-discriminatory. Network charges shall not discriminate either positive or negative ESS. In the article 55, it is stated that EU DSO should facilitate the integration of renewable sources associated technologies such as energy storage (b).

Another priority is integrating small-size participants into the mix (minimum bid sizes of 500 kW or less – article 8 point 3) allowing the effective participation of demand-side response. EU DSO will be responsible to follow the integration of distributed energy sources (as the one that comes from stored energy). Cooperation between transmission and distribution through the existence of storage devices is also stated in this regulation.

Concerning the 2019/944 **Electricity Directive** that intends to "establish common rules for generation, transmission, distribution, energy storage and supply of electricity" it is shown intention of ESS intensification revealing the importance of facilitating the flexibility of the system (13). Incentives to the distribution system operator (DSO) should be adopted in cases of the utilization of distributed energy sources, avoiding a cost associated with the network expansion (61). In point 62 is stated that system operators should not own, develop, manage or operate ESS. In the new electricity model design ESS should be market-based and competitive, this means that the distribution and transmission cross-subsidisation should be avoided, preventing distortion of the competition (62). Progress towards electricity sector decarbonization asks for progress in seasonal energy storage (64).

Along with the directive, energy storage is appointed as a way to deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier" (article 2 (59)) and energy storage facility a facility where energy storage occurs (60 of the same article). The article 3 states that the Member States shall ensure that "national law does not unduly hamper cross-border trade in electricity" (including energy storage). In cases that active customers own an energy storage facility Member States shall ensure: the right to a grid connection (within a reasonable time after the request) is not subject to double charges, neither subject to disproportionate licensing requirements (article 15, point 5). Incentives for the use of flexibility from DSO networks considering ESS is stated in article 32. Article 36 states the conditions of energy storage facilities ownership by DSO, only when they are fully integrated network components (and the regulatory authority has granted its approval) or where some conditions are fulfilled.

ESSs are not approached along with the **Risk Preparedness Regulation**, 2019/941.

Agency for the Cooperation of Energy Regulators Regulation, 2019/942, likewise in the last analysed legislative act, do not mention ESS directly.

The importance of storage solutions in the legislative acts of Clean Energy for all Europeans package is notorious. Some aspects are of major relevance and are approached in different legislative acts as the avoidance of double charges (that will promote a more adequate price for this solution) and the imposition to make the energy prevenient from storage devices be considered as any other energy source.

Accoupled to these legislative acts there are also **non-legislative initiatives**, that try to avoid any inequity that is not approached by the legislation, covering some sensitive aspects as the next presented projects: "The Coal regions in transition initiative", "Clean Energy for EU Islands initiative" and "Measures to define and better monitor energy poverty in Europe".

4.1.1.1. NEARLY ZERO ENERGY BUILDINGS

The building sector in the EU has a considerable impact on what concerns the energy consumption, being responsible for approximately 40% of the total primary energy consumption and causing nearly 36% of the greenhouse emissions of the EU (D'Agostino & Mazzarella, 2019). Currently, about 75% of the EU's building stock is energy inefficient and about 35% of buildings are over 50 years old, while only 0.4-1.2% is renovated each year (depending on the considered country). The renovation of existing buildings has the potential to reduce the EU's total energy consumption by 5-6%, lowering the CO_2 emissions by about 5%. Besides that, the investments in energy efficiency would also stimulate the economy, particularly the construction industry (creating directly 18 million jobs). Moreover, it creates a positive impact on levels of comfort and wellbeing, reducing energy poverty throughout the EU.

Considering this scenario a remarkable turning point should be reached. On 19 July 2018, as part of the Clean Energy for All Europeans package, new rules for energy performance in buildings came into force, the Directive 2018/844/EU, amending the existing Directive 2010/31/EU, with more restricted rules, intending to create a more effective impact, and that includes storage as a tool, as it is possible to see summarized in Table 5.

Table 5
Energy performance in buildings legislative evolution and relationship with storage.

Directive	Publication Date	Main action area	Storage mention
2010/31/EU	19 May 2010	Energy performance of buildings	None
2018/844/EU	19 June 2018		Three direct references

NZEBs is defined as a building with very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources produced on-site or nearby. The Directive in force does not define numeric ranges or thresholds, what allows the member states to delineate flexibly their targets, considering each country-specific conditions (climate conditions, primary energy factors, building traditions and ambition level).

Besides that, member states and investors are required to establish clear indicative national actions for energy efficiency to achieve in the short-term (2030), mid-term (2040) and long-term (2050), monitoring developments (by setting domestic indicators).

In article 14º 5 b) is stated that Member states should set out requirements to warranty that residential buildings are equipped with effective control functionalities to ensure optimum storage (other aspects that should be considered in this control: generation, distribution and use of energy).

Along with the directive it is given importance to the promotion of a smart readiness indicator that consists of adapting the operation of a building (or building units) to the needs of the occupants, optimizing the energy efficiency and performance, matching the system reaction with the signals from the grid. In the described methodology shall be taken into account several features, as the energy storage (other aspects that should be considered: reaching points for electric vehicles, built-in home appliances, regulation of indoor air temperature). The interoperability of the mentioned features should be analysed through performance levels and enabled flexibility as it is mentioned in the Annex IA point 1 of the directive.

This legislative act was still not transposed to Portuguese or Spanish legislation.

4.1.2. EUROPEAN GREEN DEAL

The EU Green Deal, presented in December of 2019, is the European Union new growth strategy, that shows a commitment to ensure an inclusive and fair transition, that can be of further importance for batteries empowerment. Changes encompass all economic sectors, from energy (through the sector decarbonisation), building renovation, industry (innovation and green industry empowerment) to mobility. The EU Green Deal is constituted mainly by ten key actions, the one that directly impacts batteries is the "Industrial strategy for a clean and circular economy", that beyond other strategies plans that by october of the current year should be published "Legislation on batteries in support of the Strategic Action Plan on Batteries and the circular economy". Considering the EU Industrial Strategy, it outlines three drivers for industrial transformation: global competition, climate neutrality, and a digital future, batteries solutions can impact three out of three of the mentioned drivers. Although, currently there are no clear recommendations on how the strategies will be delivered at the regional level. It will be of major importance to follow up closely the publications regarding the New Deal.

Although the EU Green Deal is previous to the pandemic, Europe is focusing on a strategy for the post-crisis period. The European Commission emanated a communication document on May 27th of the current year named "Europe's moment: Repair and Prepare for the Next Generation" that mainly expresses the intention to focus on a green and digital recovery. Along with the document was stated the commitment to keep the Green Deal as the main growth strategy, creating through the various actions 700,000 new jobs by 2030 and help the EU to reduce its dependency on external suppliers and increase its resilience to global supply issues.

4.2. IBERIAN LEGISLATION FRAMEWORK

4.2.1. PORTUGUESE APPLICABLE LEGISLATION

Portuguese energy legislation is mainly derived by European, therefore is important to analyse it accordingly. Highlighted by an energy storage approach, in Table 6 is possible to analyse the up-to-date relation between the "Clean Energy for all Europeans Package" legislation and the related Portuguese transposition, which is in the form of Decree-Law (DL) or Plan (only the transposed documents are represented in the table).

Table 6
Clean Energy for all Europeans package legislative acts (only represented the ones that approach the storage concept) and related Portuguese legislative transpositions.

European Legislative act	Portuguese transposition date	Portuguese legislation	ESS approach	Storage importance level in the document
Renewable Energy Directive (2018/2001)	25th October 2019	DL 162/2019	Yes	High
Governance of the Energy Union Regulation (2018/1999)	3rd January 2020	PNEC 2030	Yes	High

Comparing Tables 4 and 6, that represent a European and Portuguese approach, respectively, is predictable that in the upcoming months will be published national legislation that will enforce the ESS adoption.

The European Directives and Regulations that are still being transposed do emphasize the ESS adoption (classified in Table 4 with a medium and high relevance). Therefore, is expected that the upcoming Portuguese Decree-laws do incentivize the ESS adoption.

In what concerns the **Energy Performance of Buildings** is important to note that the Directive 2018/844/EU was still not transposed to Portuguese legislation, being in force the transposition of the Directive 2010/31/EU, the (DL) 118/2013.

Both the Directive 2010/31/EU and the transposed Portuguese DL do not mention the adoption of energy storage solutions. Contrarily, the latest Directive, from 19th June of 2018 approaches ESS, therefore the promotion of these technologies in buildings context should be soon incorporated in the national legislation related to Energy Performance in Buildings.

In what concerns the **Renewable Energy** directive it was transposed to DL 162/2019 and states the achievement of 47% of renewable energy in the gross final consumption until 2030, which implies that at least 80% of the electricity production will be provided from renewable sources (values that are in accordance with PNEC 2030). This DL is relevant in what concerns renewable energy adoption, its main intention is to promote an active energy transition without public subsidies, enabling the aggregation among producers – collective self-consumption.

Regarding the UPAC (auto consumption production unities) exercising conditions are summarized in Table 7.

Table 7
UPAC mandatory exercising conditions, article 3 (DL 162/2019).

UPAC power	Mandatory exercising conditions (described article 3)
UPAC <350 W	No need of any register
350W<UPAC<30kW	Communication through the DGEG portal
30kW<UPAC< 1MW	Registration and exploration certificate
1MW< UPAC	Production and exploration licences

The activity types are enumerated in article 5 and explained along with the Decre-Law. Three possibilities are stated and can be consulted in Table 8.

Table 8
Auto consumer types, description and article reference (DL 162/2019).

Auto consumer types	Description	Article
Individual	A final consumer that produces renewable energy for its own consumption (can store and sell electricity) In non-domestic situations, it cannot be its main activity	2º
Collective	At least two auto consumers in a condominium, in the same building or close neighbourhood (being the proximity subject to DGEG approval) Internal procedures should be created (regarding entering and exit of participants, among other factors) These consumers category answers collectively to the compliance of the present decree-law	6º
Renewable Energy Community (CER)	Legal person, with or without profit motives Possibility of production, consumption, storage and selling aggregation to the final consumer (including the domestic one) Non-discriminatory procedures must be followed	19º

Considering Visblue technology, a collective consumer approach is of most importance due to the energy capacity and power characteristics of the mentioned technology. This consumer type is detailed in the article 6. It states that the registration to installation or utilization of the UPAC is preceded of authorization from the tenants, that there should be an intern regulation that defines the requirements to the access of new members and the exit of existing participants, deliberatives majorities, the rules of electricity sharing to antoconsumption and the related coefficients, the final destination of the surplus. It also should be designated a responsible technician and a collective autoconsumption management entity that is entrusted to manage the activity and the intern network in articulation with the RESP.

In the article 7 point 2 d) (e) is stated that the auto consumer who possesses a storage system should not be double charged (an issue that previously was considered a barrier regarding this technology adoption). In article 14 is stated the certification control, that obligates the manufacturing companies to evidence in the DGEG portal the equipments certification (accomplishing the requirements stated by European Committee for Standardization (CEN) and, simultaneously, European Committee for Electrotechnical Standardization (CENELEC)). In case there have not been published European norms regarding the considered technology, International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) norms should be the ones considered.

Is further mentioned, in the article 16, the requirement of the energy storage equipment to count the energy that flows into and out of the system in cases where the system is connected to the Public Service Electricity System and, simultaneously, integrate an electrical installation that is separated from the production unit.

The **Governance of the Energy Union** Regulation is now in force through the 2030 Energy and Climate Integrated National Plan "Plano Nacional Integrado de Energia e Clima" (PNEC). The considered plan stipulates the achievement of 80% of renewable energy in the final consumption of electricity by 2030. The energy storage is mentioned intending to guarantee the flexibility and stability of the national electric system, the investments BTM in buildings and industries are also emphasized.

Is possible to verify in Table 9, in a summarized form, the relation between the acting lines of PNEC and its ESS related measures, that includes BTM and grid-scale ESS.

Table 9
PNEC summarized acting lines analysis considering an energy storage approach.

Acting line number and summarized name		Action measures	Expected acting time
7.1.	Promoting industry decarbonization	Storage is mentioned in the acting line description as a technology that should be adopted in an industrial context (not associated with any particular measure)	2020-2030
3.1.	Accelerate electricity production from renewable sources	3.1.7. Promote projects that involve solar panels with storage – mentioned as pilot projects scarcely disseminated	2020-2030
3.5.	Transport and distribution networks	3.5.1. Adapt the distribution and transport planning criteria considering the inclusion of storage systems	2020-2025
4.1.	Storage system promoting	**4.1.1. Create the legal framework that allows a strong energy storage implementation**	2020-2021
		4.1.2. Creation of Portugal Storage Roadmap (emphasizing security of supply approach)	2020-2025
		4.1.3. Promote and support storage projects in renewable electroproduction sites	2020-2025
		4.1.4. Promote the storage in islands (increase the stability of isolated electric systems)	2020-2030
4.5.	Adequate planning of the national energetic system towards the energy transition	4.5.3. Stimulate a continuous improvement in grid planning tools 4.5.4. Low voltage grids pass from being passive, integrating new concepts as the storage	2020-2030
4.2.	Promote interconnection development	4.2.5. Promote the isolated insular interconnection with associated ESS	2020-2030
4.3.	Introduction of new management tools	4.3.3. Study and promote the introduction of the "Demand Aggregator" figure	2020-2025
2.6.	Stimulate I&D&I in energy efficiency	2.6.1. Stimulate energy efficiency projects in new residential buildings and energy/thermic rehabilitation, integrating storage solutions	2020-2030
3.8.	Stimulate I&D&I in renewable energy, storage, hydrogen, biofuels and other fuels 100% renewables	3.8.2. Promote I&D&I national programs to support technological development (storage solutions are one of the mentioned technologies)	2020-2030
		3.8.4. Promote the qualification of specialized technicians (development of professional activities related to storage solutions – among other technologies)	2020-2025

Over the PNEC there are several important measures to promote the ESS adoption. Among them, the 4.1.1., "create the legal framework that allows a strong energy storage implementation", show the increasing importance of these technologies and the government intention plan regarding this issue.

Another document with high importance, although whose practical operation is not immediate, is the **Roadmap for Carbon Neutrality 2050**, in Portuguese, "Roteiro para a Neutralidade Carbónica" (RNC 2050). By the Council of Ministers Resolution, is stated the objective of achieving 100% of renewable sources in the electricity production (with defined intermediate targets of 90% and 97% for 2030 and 2040, respectively, nevertheless, in the PNEC 2030, approved more recently, the target value for 2030 is 80%).

The transition is explained, among other aspects, considering a reduction in ESS costs, allowing an increase in the flexibility and intelligence in what concerns the grid management and also ensures the backup production. The Roadmap for Carbon Neutrality also states that combined, ESSs technologies will represent in 2050, 7.5 GW, 14% of the total installed capacity, allowing and assisting the efficient management of the demand and supply.

More specifically, regarding batteries, and considering PNEC predictions, is expected that will become cost-effective, achieving a storage capacity of 187 MW in 2025 associated with a renewable capacity of sun and wind of 16GW. Although is from 2030 that the weight of ESSs is expected to have a higher impact, achieving values between 0.6 and 1.0 GW in 2030 and growing to 4GW in 2050, representing between 7 and 8% of the total installed capacity of the 100% renewable system. Is also stated that more than half of the ESSs are expected to be batteries by 2050.

There is another relevant DL that do not have a relation with the Clean Energy for all Europeans Package, although, approaches ESS, the **DL 76/2019**, from June 3rd of 2019 mentioning it as a security main aspect. This legislative act also states that in cases where there is electricity production, the production licence should incorporate the conditions that storage should be subjected to, otherwise, when the storage activity is exercised autonomously it is subject to a proper storage licence (article 5º point 10 and 11, respectively).

4.2.1.1. PORTUGUESE REGIONAL LEGISLATION

To conclude the Portuguese analysis is also important to analyse the Regional most relevant legislation regarding this subject. Portugal has two ultraperipheral regions, Azores and Madeira Autonomous Regions, these two archipelagos are endowed of politic and administrative autonomy. In issues as energy, climate or mobility, the regions develop their strategies and plans considering their reality but aligning it with the national main targets as the national targets for renewables and emissions reduction. The legislative acts created by the Regional Government are named as Regional Decree-Law (RDL). Table 10 schematizes the main legislative acts of both archipelagos that approach ESS.

Table 10
Portuguese regional legislative tools that approach ESS technologies adoption.

	Legislative act	ESS importance level
Azores	RDL nº 14/2019/A	High (grid-scale and behind-the-meter)
	Multi-annual Strategic Plan and allocation – PEPO 2019	High (grid-scale)
Madeira	Paesi-Madeira	Low (under actualization)
	Paesi-Porto Santo	

Analysing both insular scenarios is possible to conclude that a more detailed approach concerning ESS is already in force in the Azores Island. Regarding Madeira Island, the legislation approaching this issue is still under actualization, and the previous document mention ESS briefly only as a component of the storage security.

The 14/2019/A RDL from Azorean Autonomous Region, designated as PROENERGIA, establishes the incentive system to energy production and storage from renewable sources (stated in the article 1º).

This document stimulates the increasing development of projects that are dedicated to renewable energy in UNESCO Biosphere Reserve areas, namely, Corvo, Flores, Graciosa and São Jorge islands. This regional decree-law is conceived to support investments in electric energy storage, among other renewable sources technologies (article 2º 1 a) ii)). A percentual monetary incentive is given depending on the considered conditions of the proponent.

Every year Electricity from Azores, in Portuguese, "Eletricidade dos Açores" (EDA) develop a document named as Multi-annual Strategic plan and allocation – "Plano Estratégico Plurianual e Orçamento" (PEPO). The last report is from 2019 and includes the investments program from 2019 to 2032. An investment in storage systems (22% of the allocation) is expected, mainly for the construction of storage systems in Santa Maria, São Miguel and Terceira Islands (grid-scale).

Several documents are being developed from the Azorean Regional Energy Directorate (DREN) that are currently in a phase of public discussion. One example is the 2030 Azorean Strategy for Energy, this document emphasizes the ESS adoption as a demand management tool and an instigator to the utilization optimization of resources.

Regarding the Madeira Island, there are two Action Plans to Sustainable Energy "Plano de Ação para a Energia Sustentável da Ilha" (Paesi) that are now under reformulation/actualization for the Porto Santo and Madeira. The previous publication of these documents mentioned the storage solutions adoption, relating it with the security of the energy system.

4.2.2. SPANISH APPLICABLE LEGISLATION

In what concerns Spanish legislation, most of the documents from Clean Energy for all Europeans package are currently being transposed to the national legislation. Considering a storage approach, a schematization analysis of the existing legislation is summarized in Table 11.

Table 11
Clean Energy for all Europeans package legislative acts and related Spanish legislative transpositions, storage references associated with the DL and concerned importance level.

European Legislative act	Spanish transposition date	Spanish Legislation	ESS approach	Storage importance level in the document
Renewable Energy Directive (2018/2001)	5th April 2019 (Partially transposed)	244/2019 Royal Decree	Yes	Low
Governance of the Energy Union Regulation (2018/1999)	Public consultation (suspended)	Provisional PNIEC 2021-2030	Yes	High

Through the analysis of Table 11 is possible to conclude that ESS adoption through legislative incentives is still not a solid reality in Spain, though, the European legislation should be transposed in the upcoming months.

In what concerns the **Renewable Energy** directive it was partially transposed to the Royal Decree 244/2019. Article 5, point 7 mentions that the installation of storage devices is allowed when an auto consumption equipment exists, and the ESS should measure the stored energy.

The **Governance of the Energy Union**, 2018/1999 is still under the transposition process to the Energy and Climate Spanish integrated Plan "Plan Nacional Integrado Energía y Clima" (PNIEC) 2021-2030. Through this plan, that still isn't in its final form, is stated an engagement to reach 74% of renewable sources in the electric generation until 2030 in Spain (Lanza, 2020). In Table 12 is possible to analyse through a summarized form the ESS measures accordingly with the PNIEC.

Table 12
PNIEC 2030 summarized acting lines analysis considering an energy storage approach.

Acting line number and summarized name		Action measures
1.2.	Renewables integration in electric grids	The flexibility of the electric system is mainly based on ESS. Until 2030 batteries integration is supposed to achieve 2.5 GW (with a 0.5 GW target for 2025)
1.8.	Technology renovation plan in electric renewable generation existing projects	Through administrative simplification and coordination with Autonomous Communities is supposed the incorporation of storage solutions to already existing projects
4.4.	Electric market integration	Renewable energy as service and adjustment tools, considering the ESS
5.2.	SET-plan implementation	Technology development, including battery solutions
5.9.	International cooperation	I&D&I Strategic projects with Latin America in ESS area

Storage solutions, mostly grid-scale solutions, are highly associated with flexibility and security issues along with the Plan. Also is mentioned the importance of the Innovation Fund to promote the development of new ESS.

5. ESS FINAL CONSIDERATIONS

5.1. COST

ESS future role is not questionable. When considering batteries, its diversity, regarding characteristics as cost and performances, requires an appropriate energy storage cost assessment to allow a correct comparison among technologies. Most of the studies that have been done are limited to the investment costs analysis (Schmidt et al., 2017); a fair comparison among the different technologies is essential to allow choosing the most adequated storage technology. The Levelized Cost of Storage (LCOS) allows comparing different technologies. The calculation incorporates the investment costs per kWh (€/kWh), the lifetime of the storage system (cycles), its efficiency and utilization rates. Through consulting Table 13 is possible to compare the Visblue values with the ones from the main technologies' literature and its evolution in the considered years.

Table 13
Batteries LCOS evolution, considering 2018 and 2020, comparison of Visblue and literature data of RFB, Lithium-ion and Lead-Acid.

	Efficiency	LCOS €/*kWh* 2018	LCOS €/*kWh* 2020
Visblue (40 *kWh* 5*kW*)	0.8	August **0.15***	
Visblue (40 *kW* 3.5*kW*)	0.8		January **0.11***
Redox flow batteries (From Energy Storage Technology Cost Characterization Report)		From **0.19** to **0.37** (July 2019, page viii)	
Lithium-ion batteries (40 *kWh* 10*kW*) Residential applications (From Lazard Levelized cost of storage analysis)		From **0.43** to **0.66** (v 4.0 for November 2018, page 11)	
Lead Acid batteries (40 *kWh* 10 *kW*) Residential applications (From Lazard Levelized cost of storage analysis)		From **0.46** to **0.64** (v 4.0 for November 2018, page 11)	

*considers 20 years lifetime and 95% discharge

When comparing Visblue LCOS with literature values, the lowest LCOS among the considered electrochemical technologies is the one from Visblue in January of 2020 (0.11 *€/kWh*). Is also of major importance to have in consideration that at the end of life of the battery there is a residual value associated with the recyclability/reusability of the battery components. The most relevant one is associated with the vanadium (that could be used to restore the battery, build another one or to use as a vanadium alloy) if considered, this would lower the LCOS.

Table 14 represents the main information regarding the battery main competitors companies, were considered 10 batteries, values were collected in the first trimester of the current year, through direct contact with companies or resellers. These values differ from the ones presented in Table 13 as they represent a more recent approach that is only available through the direct contact with the companies, therefore these values are lower than the ones from literature.

Table 14
Comparative overview of the main technologies LCOS

	Lowest LCOS (*€/kWh*)	Average LCOS (*€/kWh*)	Considered batteries
Vanadium RFB	0.11	0.12	2
Lithium-ion	0.09	0.11	4
Lithium iron phosphate	0.11	0.15	4
Salt-water	No exact values provided		
Zinc-bromine RFB	No cost information provided		
Organic RFB	Inexistence of comparable power and capacity		
Lead Acid	-	-	-
Zinc-Iron flow battery	Inexistence of comparable power and capacity		

Note. Values were obtained through direct contact with a total of 41 companies, only 25 provided the capital costs. Only batteries with capacity values between 6.8 and 40 kWh and power ranged from 3 to 10.9 kW were considered to obtain the most reliable comparison, although the batteries have some different characteristics due to the differences among the existing solutions currently in the market. The LCOS was calculated through the same way except for one of the VRFB which the value of LCOS was directly provided from the company.

Through the analysis of the table above it is possible to conclude that Visblue has a competitive LCOS.

After considering the ESS LCOS is relevant to compare the obtained results with the market-based price of electricity, when it comes to considering battery adoption, beyond environmental aspects.

Table 15 addresses the minimum, maximum and average electricity prices for industrial and domestic users considering the time interval from 2000 until 2019 in Portugal and Spain.

Table 15
Lowest, Highest and average electricity prices for domestic and industrial consumers considering the time interval from 2000 until 2019 (inclusively) for Portugal and Spain national cases

	Domestic price (2000-2019) €/*kWh*			Industrial price (2000-2019) €/*kWh*		
	Lowest	Highest	Average	Lowest	Highest	Average
Portugal	0.126 (2000)	0.235 (2016)	0.173	0.068 (2000)	0.143 (2014)	0.101
Spain	0.105 (2002)	0.240 (2019)	0.168	0.063 (2002)	0.151 (2014)	0.110

Note. Values consulted and calculated based on Eurostat information.

If we compare Portugal domestic electricity price annual values (for the considered period) with the 2020 Visblue LCOS (0.11€/*kWh*) is relevant to mention that the ESS LCOS is lower than the electricity price in the twenty consecutive years. In what concerns domestic Spanish electricity consumption values, it is higher only from 2006 (0,1147 €/*kWh*) until 2019, which accounts for fourteen consecutive years.

Regarding the industrial segment in Spain, it surpassed the LCOS (from Visblue) during twelve consecutive years (from 2008). In what concerns Portuguese industrial scenario, the value of ESS was surpassed from 2012, for a total of eight years.

When considering a diary dual tariff plan the prices during the off-peak period are considerably reduced but is important to contemplate that the off-peak hours are from 10 pm until 8 am. Therefore, a substantial part of the day where the conditions are not ideal for electricity production, from PVs for instance, are covered by peak tariffs.

Through this analysis is possible to conclude that even not considering ethic or climate change issues, battery adoption in a long-term perspective does create a positive impact when a comparative analysis based on LCOS is done.

When analysing electricity future trends, is important to consider the growing influence of grid access tariff in the total amount of tariffs. Considering 2020 values from Energetic Services Regulatory Entity (ERSE) is possible to conclude that 56% account for grid access tariff, 39% energy tariff and 5% for commercialization tariff as it can be seen in Figure 10, considering low normal tension (BTN).

	Electricity BTN comparison 2019 - 2020
Final clients Selling tariff	-0.4%
Grid access tariff	+1.3%
Energy tariff	-4.1%
Commercialization tariff	+11.7%

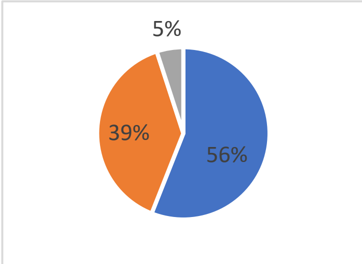

Figure 10. 2020 Portuguese Energy tariffs, comparison with 2019 values and 2020 percentages per tariff. Adapted from ERSE https://www.erse.pt/media/yt0l1efg/tarifas-e-pre%C3%A7os-2020.pdf.

Beyond storage, when considering prosumers surplus production, selling the electricity to the grid is the most diffused action. An analysis of the Portuguese administrative costs is summarized in Table 16, separated in mainly two assets: with and without Public Service Electric Grid (RESP) injection, based on the 16/2020 Decree from 23 January 2020.

Table 16
Portuguese administrative procedures costs, considering the power of the systems and if there is RESP injection (based on the 16/2020 Decree). These values are actualized and published annually (as it is described in article 3 of the mentioned Decree).

Administrative procedure	Power (*kW*)	UPAC without RESP injection	UPAC with RESP injection
Registration request appreciation	≤30 *kW*	exempt	
	>30 *kW* and ≤100 *kW*	140€	200€
	>100 *kW* and ≤250 *kW*	240€	400€
	>250 *kW* and ≤1000 *kW*	400€	600€

When considering a maximum 30 *kW* power system an integrated approach can be done without impact the administrative procedure costs, combining production, storage and RESP injection, that can be achieved with an ideal dimension of the system.

UPAC RESP injection electricity price in Portugal is based in an auction model that has been implemented since 2016, with a maximum value of 0.095€/kWh (for solar source).

In Spain, the price paid to renewables producers is based on a pool price, with no source distinction. Taking the month of May of 2020 as an example, the highest value was registered in 31st of May and accounts for 0.035 €/kWh and the lowest was registered in 1st of May accounting for 0.001 €/kWh.

5.2. CIRCULARITY APPROACH

Previous studies regarding the VRFB Life Cycle Assessment (LCA) show the importance of considering a cradle-to-cradle life cycle perspective when comparing different batteries, mainly because VRFB recyclability is significantly higher than lithium-ion batteries (Weber et al., 2018).

Recyclability is a characteristic of the material that states if it maintains useful physical or chemical properties that allow it to be reused, after serving the main purpose for what it was done (Kubba, 2012). The nature of VRFB allows the majority of its components to be reused/recycled at the end of the life cycle, allowing the battery to be considered recyclable.

The element of major importance in what concerns the recyclability of the battery is vanadium. Significant impacts are associated with the vanadium pentoxide production which is why the origin and processing of the vanadium bearing ores are a key for further reducing the environmental impacts associated with the VRFB manufacturing (Weber et al., 2018). Vanadium recycling impacts positively the circularity of the equipment and also creates a residual value when the life cycle of the equipment comes to an end. The vanadium needs to be removed and cleaned from the electrolyte. The remaining part of the battery is composed of plastics, being the membrane the only part that up to date is still not recyclable.

In Portugal there are five managing entities of batteries and accumulators with different action areas (Ecopilhas, Valorcar, Electrão, ERP Portugal, GVB) all of them were contacted and none of these companies recycles lithium or vanadium batteries.

In what concerns European general scenario, European Battery Recycling Association (EBRA) was contacted and exposed that there are some recyclers of lithium batteries in Europe. Due to the similarities of portable and stationary lithium batteries the recycling process adopted is the same, although, for both of them, there is a need for dismantling the batteries and follow various processes. Regarding the vanadium batteries and considering the actual inexistence of end-of-life batteries the Association exposed that there isn't still an implemented recycling process in Europe.

Actually, and because of the battery directive requirements, 2006/66/EC, that states that recyclers have to reach a recycling rate above 50% of the weight of vanadium or lithium batteries, processes will have to emerge. However, the EU is currently revising the battery directive and most likely the recycling requirements towards a higher rate. It is expected a huge investment in recycling capacities in the upcoming years. Besides that, the residual value of vanadium batteries fosters battery companies and the customers to guarantee its recycling/reuse, giving place to a circularity approach.

Visblue itself, as a producer in the future can re-use components at end of life of the battery, not being dependent on an external entity to be responsible for that process.

Furthermore, it will be possible, and perhaps mandatory, to achieve a total circular approach that will allow batteries simultaneously to be recycled/reused and recyclable. By now, the impossibility of manufacturing total reused/recycled vanadium batteries was confirmed through contacting diverse recycling agencies that up to date do not have vanadium quantities that allow a battery construction.

5.3. ESS TRENDS AND SUGGESTIONS

Along the years there have been some barriers in the ESS adoption, firstly caused by laws and regulations and also market-based limitations (Kooshknow and Davis, 2018). The majority of regulatory barriers was surpassed in the recent, and above-examined, legislation. These obstacles, as the lack of legal classification for ESS that conducted to double taxation or ESSs being not defined as a renewable energy resource (Kooshknow and Davis, 2018), were associated with a high limitation in ESS entrance in the market, although, these issues are being solved in the EU and transposed to national legislation.

Batteries adoption is no longer a concern. Regarding its cost, it is important to consider that battery prices are already down 84% since 2010 and that by 2050, 40% of all battery deployment will be BTM. This will result in a five-time fold growth in small-scale batteries market (New Energy Outlook, 2019).

Currently, considering The Electricity Storage Valuation Framework (ESVF) 2020 IRENA report, beyond battery cost one of the major concerns regarding these technologies is the difficulty for storage owners to monetise value (fair allocation of benefits of storage among stakeholders) (IRENA, 2020). When considering BTM (that is supposed to have a relevant market growth) it significates a value of "dual participation" providing both grid services (provide flexibility, defer investment in the network and peaking plants) and individual services (IRENA, 2020).

The legislation is also leading to the ESS implementation. The above analysed Directive 2018/2001 fosters the production and storage aggregation, allowing the establishment of a sharing economy in the energy area. The main economic motivation of the sharing principle in battery storage operation is to increase the profitability, by generating higher revenues for different users, while "sharing" the costs of the investment. This directive is already embodied in the Portuguese national legislation (DL 162/2019) and is decisive in what concerns the trends of this technology in Portugal, creating the possibility of a higher willingness to adopt Visblue batteries due to its capacity and power characteristics.

This concept applies to VRFB technology as it may increase the profitability of a system when compared with one owner scenario. Before the acquisition, a simulation is done considering the client production of energy and daily demand, evaluating the optimum size of the battery to arrive at the best return on investment, when considering VRFB technology this value is better considering a bigger system.

Previous LCA of VRFB point the mining as the most critical part of the assessment, a meticulous follow up of this phase is of major importance, being the recycling process a decisive in the future technology empowerment.

An application to verify and control the battery remotely is of major importance allowing to take more advantage of the equipment. This is already provided by the main lithium-ion battery companies and also Visblue.

The exceptional conditions of Portugal and Spain in what concerns VRES production (mainly solar and eolic) is notable, the Iberia does have a huge potential in what concerns becoming energy independent. The poor grid connection with remaining Europe leads to a waste of produced energy when ESSs are not considered. The inclusion of ESSs must be done in both countries through grid-scale and BTM solutions.

6. CONCLUSION

Batteries are gaining importance due to the current energy transition context. Among the existing electrochemical stationary solutions, VRFB is one of the most promising technologies.

The initial cost of batteries coupled with the difficulty for storage owners to monetise its value is the main driver concerning the inhibition of these technologies acquisition.

The European Union legislation, that once also limited these technologies empowerment, is now enforcing batteries adoption (PNEC 2030 shows it very well) and this trend is expected to keep significant, due to the actual European Commission presidency efforts, that through the EU Green Deal intends to create new legislation for batteries. To take advantage of the present and future conjuncture, a meticulous follow up of all the legislative material should be done.

Considering the analysed legislation, there are a few relevant documents, like the Renewable Energy Directive (2018/2001) that is already embodied in the Portuguese national legislation (DL 162/2019) that changes the way ESSs can be organized allowing a more profitable utilization in case of VRFB through the collective auto consumer approach.

When it concerns to choose among ESS, one of the main differentiation factors of VRFB when comparing with other electrochemical technologies is its recyclability and the possibility of being created a circularity approach in the upcoming future that will also empower the technology. Regarding the cost analysis, a cradle-to-cradle approach must be done to allow a fair and encompassing comparison, being one of the most appropriated tools the LCOS, that is beginning to be competitive even when it is compared with the electricity cost (Portugal and Spain national cases).

Due to the high VRES production capacity of Portugal and Spain batteries will be of major importance to maximize its penetration in both of the countries.

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