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Decentralized electricity storage evaluation in the Portuguese context

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\textbf{ABSTRACT}

Portugal has made great progress in implementing renewable energy systems (RES) to use its endogenous renewable resources. As the cost of renewable energy generation is decreasing, mainly for photovoltaic energy, a significant increase in its production is expected, in particular at the local and domestic levels. Yet, much investment and development is still needed to fulfil the goals for renewable energy generation defined by the Portuguese government and the European Union, in order to decarbonize energy generation and reduce energy dependence. Besides limitations in the installed capacity, the full potential of existing and future RES is not fulfilled, mainly due to imbalances in supply and demand, resulting from the varying climatic conditions and limited energy storage capacity. Although some investment was made in large scale Energy Storage Systems (ESS), especially pumped hydro, distributed energy storage (DES), in particular for stationary domestic storage appliances, have received little attention from decision makers. When properly defined, designed and implemented, they can contribute to increase the efficiency of existing and future RES and the capacity factor. Thus, in this work the questions regarding the implementation of DES are analysed. The main criteria that have to be considered when selecting the proper storage technology for DES are defined, taking into account information and data from current legislation and/or strategic plans and goals, and the technical and scientific literature, in order to support decision making and policy definition at different levels. The proposed application of the various criteria leads to the conclusion that for DES, electrochemical based ESS are the most adequate, among which Li ion batteries and redox flow batteries, particularly suited for local and/or household applications. The current policies sought out for Portugal are also examined in order to identify which aspects should be improved to promote and increase the relevance of DES in the Portuguese energy mix, and it is concluded that specific policies and support are needed to increase the relevance of decentralized electricity storage systems.

1. Introduction

Modern societies require abundant quantities of energy to perform normal daily activities, such as cooking or transportation, to ensure human comfort and wellness, and to provide the products and services used by people and companies. As the standards of living are improving, in particular in the developing world, the energy consumption is increasing and will continue to rise in the near future (BP, 2019). Currently, most of the energy needs is generated from fossil sources, in particular oil, coal, and natural gas, a state of affairs that is clearly unsustainable and has resulted in significant environmental problems, in particular climate change due to increasing emissions of greenhouse gases, and in economic and even social impacts due to price variability and supply security.

Therefore, it is consensual that it is necessary to develop and implement other energy sources, intrinsically renewable, and with lower environmental impacts (Dincer, 2000). Hence, governments and international organizations are developing and implementing policies and/or strategies to promote the generation of more renewable energy, contributing to reduce the dependence on fossil fuels and to decarbonize the economy, thus also contributing to fulfil the goals of the Paris Agreement (UNCC, 2016).

In particular, the United Nations (UN) Sustainable Development Goals (UN, 2014) explicitly consider energy in its goal 7 - Affordable and clean energy, which states that people should have access to affordable, reliable, sustainable and modern energy. This implies not only access to energy for common daily activities, but also to produce all the goods and services needed for modern societies. Also, any policy and
strategy aimed at promoting RES must also consider explicitly all other UN goals, in particular goal 9 - Industry, innovation and infrastructure; goal 10 - Reduces inequalities; goal 11 - Sustainable cities and communities; goal 12 – Responsible consumption and production; and goal 13 - Climate action; as these UN goals are the most related to energy generation and consumption.

The European Union (EU) defined specific strategies, in particular the recent directive on renewable energy (EC, 2018a), that determines a goal of a least 32 % on the overall energy mix until 2030, with the possibility of upwards revision in 2023. To address the specific questions of different activities, several directives and regulations were approved, currently under implementation, each one defining particular goals and activities, that collectively are combined in the “Clean Energy for all Europeans” (EC, 2019c), a key part of the “European Green Deal” recently proposed to tackle the sustainability issues affecting all members of EU (EC, 2019a, b). An important part is the “Energy Performance of Buildings” directive that deals with the reduction and a more efficient utilization of energy in buildings, either households or commercial/industrial (EC, 2018b). This sector accounts for around a third of the primary energy consumption in the EU, and includes specific measures and goals to be achieved, as for example the objective of all new buildings to be Net Zero Energy Buildings (NZEB) from 2021 onwards.

In 2019 the Portuguese government has launched several documents and strategic plans, especially the “National Roadmap for Carbon Neutrality” (RCM, 2019) and the “2030 National Energy and Climate Plan” (PNEC, 2019). The main goal is to make Portugal a carbon neutral country in 2050 in terms of energy generation and consumption, taking into consideration the goals and main development strategies/policies defined by the EU strategic plans, as described above. To accomplish those goals, 80 % and 100 % of renewable energy generation are devised for 2030 and 2050 respectively. This naturally implies a significant investment in the renewable energy capacity, and most of the increase will come from photovoltaic (PV) electricity, in particular a 10 fold increase in installed capacity between 2020 and 2030, with more modest increases planned for hydro and wind.

Although energy generation from renewable sources is increasing rapidly (BP, 2019), and various renewable energy systems (RES) are being developed and implemented for different settings, the impact of RES on the energy mix is still small. Some reasons behind this situation include limitations on their scope, type of energy generated, production strongly depends on factors outside the producer’s control, in particular climatic factors, imbalances in supply and demand, availability of key raw materials, high production costs, among others (IEA, 2013). Demand and supply imbalances are important in RES that provide electricity, in particular wind and PV systems, that represents today most of the renewable energy produced (IEA, 2011).

Energy storage is currently seen as an adequate form to mitigate those issues. The incorporation of energy storage systems (ESS) can also increase existing or future RES efficiency, resilience, and ultimately their competitiveness, as it allows a reduction of the energy production costs (IRENA, 2015; Frankel and Wagner, 2017). Various energy storage technologies based on various physical or chemical phenomena were proposed in literature, each one with its specific range of applications, scale, advantages and weaknesses (Huggins, 2016; IRENA, 2017). Moreover, the most adequate options may depend on the local and regional conditions, in particular climatic conditions, and/or already existing infrastructures (IRENA, 2015, 2017). Whereas large scale ESS are valuable to balance the supply and demand imbalances in a regional and national scale, distributed energy storage (DES) may be valuable in smaller scales. In particular, DES could be used in small communities, sparsely populated regions or in islands, in which investment in the electricity distribution network may be too expensive considering the benefits. Also, for a household or building to be a NZEB it is necessary to generate renewable energy locally, and the inclusion of energy storage can help achieve this goal.

The EU has recognized the importance of combining ESS in existing and future RES, and has published several strategic and guidance documents on the subject, as well as supporting various research and development programs and stakeholders (companies, researchers, end user, among others) consortia in specific ESS, such as batteries, hydrogen, and others energy storage technologies (https://ec.europa.eu/energy/topics/technology-and-innovation/energy-storage_en). Two relevant examples include the Batteries Europe initiative (https://ec.europa.eu/energy/topics/technology-and-innovation/energy-storage/batteries-europe_en), and the EERA - European Energy Research Alliance (https://eera-es.eu/), in which the various scientific, technological, practical/implementation and commercial aspects of ESS are taken into account, with the goals of contributing to fulfill the EU goals concerning the increase in the generation and consumption of renewable energy. In a Portuguese context, the two strategic plans referred above (RCM, 2019; PNEC, 2019) also consider large scale energy storage, focusing in two forms: batteries and hydrogen. Similar capacities are planned for both forms, and the main focus will be in the storage of excess electricity produced in large scale PV solar farms. It is planned that hydrogen will be used by industry, either as raw material or as energy carrier, or by households and other consumers, after mixing it with biogas and injecting it in the existing gas distribution network.

Despite the ongoing strong investment in research and development of ESS coupled to RES, many key issues still need to be adequately analysed. One of the most relevant involves the definition of objective criteria to define what are the most adequate technology options for ESS depending on the specific application conditions. Thus, in this work we look to the current Portuguese situation and expected evolution, in particular fostered by the development strategies referred above (RCM, 2019; PNEC, 2019), in order to identify which are the best energy storage options in a Portuguese context, considering the already existing technologies. The main criteria for technology selection will be identified, taking into account key aspects such as regional geographic and climate conditions, main sources of renewable energy, infrastructure, population distribution, economic and social aspects, energy storage characteristics, among others; and analysed to identify the currently more viable technology for DES in a Portuguese context. Also, the strategies and plans defined at the national scale (RCM, 2019; PNEC, 2019) will be critically analysed, especially how they consider energy storage and DES.

2. Electricity generation in Portugal

Portugal does not possess significant fossil energy resources to fulfil the needs of citizens and companies. This state of affairs has resulted in significant dependence on imported energy (Pordata, 2017), especially in the transportation sector, where the dependence on fossil fuels is almost complete. Thus, it is imperative to counteract this dependence that has significant economic and supply security impacts. To generate the energy needed to support the economic development and the expansion of electrical network to supply the electricity necessary to increase the standards of living, there is an ongoing strategy to develop the internal energy resources, focusing in electricity generation since the second half of the twentieth century (Martins et al., 2018). Due to its climate conditions and topography, there is significant potential in hydroelectricity and wind power in the Northern Portugal, and PV power nationwide (DGEG, 2019).

On an initial phase, a focus was given to explore hydro power resources (Nunes, 2018). But, by the beginning of the 21st century most of the hydro resources were exploited, as almost all the sites and rivers adequate to construct and implement large hydro are already used. Although retrofitting existing hydroelectric power plants is being implemented and considered to increase the generation of hydroelectricity, the overall increase in the renewable energy capacity is limited and not enough to fulfill the increasing energy needs.

In the last two decades most business investments were directed to
wind power farms, with a 10 fold increase in the first decade of 21st century (IRENA, 2013), as shown in Fig. 1 (APREN, 2020). Only recently there was a significant increase in the large-scale generation from PV and biomass based power plants (Nunes, 2018). Currently most investments in RES are forecasted to be done in PV capacity (RCM, 2019; PNEC, 2019), even though solar is still not very significant in the overall electricity mix (Fig. 1).

Currently, the electricity mix consists of roughly 50 % renewables, with large variations between the years, as shown in Fig. 1 (APREN, 2020). The variations are due to different dominant climatic conditions, especially the occurrence or not of droughts, as the availability of water and proper wind conditions are interrelated and depend on the passage of weather systems from the Atlantic Ocean. Depending on the particular conditions, in some periods the existing RES can generate enough electricity to supply the needs for several days (The Guardian, 2016), excluding the Azores and Madeira archipelagos that have independent electricity generation and supply networks. This situation also explains why in Fig. 1 for some years the total energy generated is larger than consumption, as the periods when electricity is exported cover the periods when imports are required. Yet, as fossil is still very relevant, currently between 20 to 30 %, this means that in practice Portugal is a net energy importer.

Although Portugal has made impressive investments in large-scale renewable energy technologies during the last 20 years, the participation of small-scale decentralized generation systems has assumed a growing role in electricity generation, as shown in Table 1.

The weight of decentralized generation on total electricity produced from renewable sources has steadily increased since 2012, especially after the publication of the national diploma (DL 153, 2014) that establishes the legal regime for self-consumption and small production units. This piece of legislation has brought greater certainty for private and small-scale investors, and it boosted the UPAC/UPP generation. On the other hand, national and local regulations are mandatory for the installation of RES in new buildings, public buildings, infrastructures and on existing buildings subject to deep rehabilitation, following also the goals defined by the Energy Performance of Buildings Directive (EC, 2018b). All the previous factors are pressing and creating room for an increasing presence of decentralized generation on national energy scenario. However, to increase its efficiency and relevance to the electricity mix proper ESS must be employed.

Concerning the current status of energy storage in Portugal, there is still a renewable energy surplus in the range of 800–1200 GW h (Miguel et al., 2018) that is lost, mainly in Winter and Spring. Pumped hydro, based on reverse pumping systems installed in the large hydro plants is currently the dominant form of energy storage. However, given the variability of the rainfall and the tendency for more frequent drought periods, as well as the sharing of major international rivers with neighbouring Spain with the consequent pressure on the various uses of the water, this solution may not fill the country future needs. Thus, it is important to consider other options. Paradoxically, the plans that embody the strategies defined for Portugal, place a great emphasis on large scale ESS (RCM, 2019; PNEC, 2019), while DES are not considered.

### Table 1

Evolution of decentralized generation and decentralized installed capacity in Portugal (DGEG, 2019).

| Decentralized generation (MWh) | Decentralized installed capacity (kW) |
|--------------------------------|-------------------------------------|
| **Year** | **2012** | **2016** | **2019** | **2012** | **2016** | **2019** |
| Total generation (MWh) | 145 088 | 321 788 | 496 114 | 105 709 | 226 216 | 335 502 |
| UPAC/UPP* generation | 0 | 48 308 | 222 162 | 0 | 51 850 | 165 245 |
| Wind | 0 | 64 | 88 | 0 | 34 | 41 |
| PV | 0 | 48 154 | 220 701 | 0 | 51 644 | 164 160 |
| Biogas | 0 | 90 | 1 373 | 0 | 172 | 1 044 |
| Mini/micro generation | 145 088 | 273 480 | 273 952 | 105 709 | 174 366 | 170 258 |
| Small hydro | 40 | 643 | 643 | 24 | 237 | 237 |
| Wind | 379 | 325 | 329 | 361 | 480 | 461 |
| PV | 144 669 | 270 665 | 270 525 | 105 054 | 173 649 | 169 603 |
| Biogas | 0 | 1 847 | 2 455 | 0 | 0.7 | 0.7 |

* UPAC - self-consumption production unit. UPP - small production unit.
4. Criteria identification and evaluation

A literature review is essential to identify the available technologies for decentralized energy storage and to systematize their main features. After that, a comparative analysis among the identified technologies must be performed, considering the various possibilities identified and taking into account several factors, such as: costs, storage capacity, safety of operation, sustainability, among other issues. Hence, a full multidimensional analysis is necessary, involving the environmental, technical, economic and social aspects, in order to select the most adequate technology option. However, in many cases the economic aspects take precedence over others. Specific indicators are then proposed, as for example the levelized cost of energy (LCOE) and levelized cost of storage (LCOS), available in the literature for the various technologies, that will support the decision making process according to the particular application conditions. At this stage, it is important to identify the Portuguese specific context and conditions that frame domestic electricity storage. Market and regulatory barriers to electricity storage have been widely studied, but we intend to identify those that apply to a specific region within a restricted set of technologies. From the previous constraints, criteria and guidelines will be defined to identify the most adequate energy storage technologies for the specific case of Portugal.

Fig. 2 presents the main types of criteria involved in the selection of an ESS, including economic, technical and environmental/sustainability aspects. They cover all the main aspects/criteria that should be taken into account, and may be classified according to the main dimension of sustainability to which they are more related.

The aspects presented in Fig. 2 are also applicable to the selection of energy storage technologies for DES, taking into account the local or regional specificities. Although a general analysis can be done, valid in a qualitative way regardless of the geographic conditions, in this work each criteria/aspect will be analysed considering the Portuguese specific conditions.

From a technical point of view, DES should be robust, easy to operate, control and maintain, as most distributed RES are operated by non-specialists or people with limited knowledge of the inner workings of the RES and/or DES under their responsibility. It is also desirable that the DES will be implemented and operated as a turn-key project. Thus, ESS that involve the combination of various processes, in particular chemical-based, such as Power-to-Gas or biofuels that require specific raw materials and complex, are not suitable for DES. Likewise, ESS that require very specific conditions, in particular pumped hydroelectric that requires buildings dams and water reservoirs, or very specialized equipment such as cryogenic storage or CAES, are not adequate for DES. Also, as space to install the DES is normally an issue, compact technologies that do not have moving or separated parts are more suitable, among which batteries are currently seen as a good option.

A key issue is the integration or the coupling of ESS with existing or future RES. While it may be reasonable in some cases to use non-renewable resources to generate the energy supplied to a ESS, for example when the ESS will operate off-grid in an emergency situation, the ESS should be used only with renewable electricity or integrated directly with a RES. The same arguments also apply naturally to DES, and as the
storage capacities of DES are limited, the most adequate RES in which they will be integrated are PV systems in particular households, small hydroelectric power plants or wind turbines. This also impacts the distribution network that should allow the two-way movement of electricity, and be smart to account for the various fluxes within the network.

The flexibility and adjustment to the final user’s needs are other key issues to consider. In particular, the DES should be flexible enough to account for the variability of the user’s needs and intended uses of the energy. Thus, DES based on thermal energy storage, such as PCM storage, have limited use, as they are not easy to control and the energy uses are very limited. Moreover, as in most cases DES will be used in households, buildings and small to medium size companies, that consume mostly electricity, the most viable options for DES will be technologies that store and generate directly electricity, among which the various batteries technologies are good options. Also relevant is the ability to change the storage capacity according to the users need or the characteristics of the RES in which the DES change. Once again, electrochemical storage is the most adequate option, in particular those in which energy storage and power generation are separated, as for example flow batteries (Soloveichik, 2015).

Health and safety issues are also important aspects to be taken into account. As DES will be mostly operated by non-specialists and in environments where the vigilance and ability to mitigate will be limited, the technologies used for DES should be intrinsically secure, in particular with minimal or non-existent fire and toxic risks. Based on this criterion, DES based on chemical compounds, such as hydrogen, are not desirable options, as they are highly flammable and require special containment equipment.

Environmental and sustainability issues are increasingly more relevant, as recent decades have witnessed an increased attention to environmental and sustainability issues, to the point that currently any decision making process should consider them explicitly within a life cycle thinking approach. A DES installation should have a minimal impact on the surrounding environment, if possible not involving potential irreversible changes in ecosystems and other natural systems. Also, the DES construction should not involve as much as possible non-renewable resources, especially of materials with limited supply, as for example lithium. Also, their operation should be smooth, without any noise or emissions. After decommission, the materials should be easily recyclable and/or reusable.

Legislative and policy issues should also be considered. Currently, the Portuguese national strategy focuses mainly in large scale storage and hydrogen to store the excess electricity generated by the existing and future RES, for the later mainly based on PV power (RCM, 2019; PNEC, 2019). Also, no specific support for DES is available, in particular in form of fixed prices for electricity injection in the supply network or subsidies/fiscal support. Yet, some current policies and strategic goals implicitly promote the deployment of DES. Key examples are the imposition of all new buildings to be NZEB (EC, 2018b), and the efficiency measures imposed in industry, that will be much easier to reach if DES are implemented, in particular combined with RES such as PV (Gouveia et al., 2019).

Energy density and duration of storage are also important issues. Similar to the distributed RES in which they are incorporated, DES will also have variable operating conditions, depending on the availability of renewable energy for storage, and the users energy needs. Thus, it is imperative that the energy is not lost during periods of non-operation, as it will represent an economic loss and lower the DES overall efficiency. Energy density, normally defined as quantity of energy per unit volume, is also relevant, as the higher its value the smaller and lower deployment impacts are expected.

The local resources should also be taken into account. Although under Portuguese conditions PV is valuable nationwide, in certain regions other forms of renewable energy may be significant, as for example wind power in the north, and geothermal energy in the Azores archipelago. Also, the local or regional capabilities of the electricity distribution network may limit the ability of DES to interchange electricity with it, reducing their overall efficiency.

Several aspects have to be considered in the economic issues. First, the initial investment costs and the cost of the capital are important issues, and a suitable indicator for these is the Energy Investment Costs (IRENA, 2017). As DES will be mostly implemented by individuals and small-medium companies, ESS that involve large initial investments are not adequate, as they normally do not have the necessary funds or access to credit. This sub criterion limits the potential technologies for DES to those that do not require large initial investments, as for example batteries. Second, a comparison between different ESS should also consider the operation and investment costs and the capital deprecation. Although a normal project evaluation analysis is suitable, an indicator that is becoming increasingly more consensual to assess the viability of a given ESS or to compare different ESS is the Levelized Cost of Storage, LCOS (Lazard, 2018; Schmidt et al., 2019; Julch, 2016; Zakeri and Syri, 2015). This indicator represents the sell price of the energy stored to ensure that levelized costs are equal do the levelized revenues during the ESS shelf life. For both indicators, several ranges of values are available in the literature (IRENA, 2017; Lazard, 2018; Schmidt et al., 2019; Julch, 2016; Zakeri and Syri, 2015) and they could be used to compare different technologies. LCOS can be calculated from data obtained from suppliers and/or the literature. LCOS estimation depends on the assumptions made for the investment, technology and operation and on the specificities of the installation conditions. The indicator may present large differences between ranges (Lazard, 2018).

For example, considering residential PV and storage, LCOS (US$/MWh) varies between 476 and 735 for lithium batteries, between 512 and 707 for lead batteries, and between 498 and 675 for advanced lead. The reported value shows that presently, from an economic point of view, it is unclear which is the most suitable battery technology without considering other factors (IRENA, 2015, 2017; Lazard, 2018). It is expected that estimated LCOS values for batteries would reduce largely over the next few years as a result of technology development and reduction of production costs (Lazard, 2018). This is also agrees with the goals defined by the EU in its SET – Strategic Energy Technology – plan (EC, 2016). Moreover, the support policies may play a role in terms of subsidies or fiscal abatements, reducing the investment and operational costs of DES. This is important in poor and sparsely populated regions, as it is the case of some Portuguese regions, where households and companies may lack the capital needed to invest in ESS or DES.

Taking into account the various criteria and the current state of the art, electrochemical-based storage, in particular batteries, are seen as the best option for DES. Some of the key reasons are the robustness of existing technologies, easiness of operation and natural integration in the currently dominant RES that are currently dominant. There are various available technologies that are able to fulfil the needs of different users. Thus, while the solutions already available in the market are adequate for many situations, the present strong investments in R&D, focusing for example in reducing costs and increasing the energy storage density, ensures that batteries will be increasingly seen as the most adequate choice for DES. Hence, policies to stimulate energy storage should promote as much as possible electrochemical energy storage, especially batteries.

5. Conclusions and policy implications

Better ESS can improve the overall efficiency of existing RES, providing energy/electricity when it is not possible to generate energy, mainly due to climatic conditions. ESS contribute to stabilize the energy distribution network, and to reduce the uncertainty in grid management, helping flatten the electricity price and providing energy storage in lower demand hours. Storage systems may allow that the renewable energy generation fixed costs are distributed for a larger marketed production, inducing the price per kWh to fall. As a result, electricity
from renewable sources may become more competitive and cheaper. Thus, there is a strategic interest in promoting ESS, as their development and implementation contributes to accelerate the transition to a fully renewable and decarbonized energy generation system.

Despite the advantages, the selection of the proper ESS for a given system is a complex process that depends on many factors, not only the economic issues, but also technical, safety and environmental ones. This work identified the criteria and guidelines that are most suitable to select an adequate energy storage technology for DES, with a focus in the Portuguese context. The analysis performed showed that for DES electrochemical based ESS, in particular batteries, are the most adequate options. Batteries are expected to have an increasing presence in the near future, as the costs are falling and the energy density is increasing due to the strong investment in R&D. Although, it is still not clear which is the most adequate battery technology, as many technologies have similar performance and costs. The results support the idea that policies that promote DES should be put in place.

Although decentralized generation presently represents a low weight in national generation, storage systems can contribute to limit the fluctuating availability to solar and wind energy, promoting the development of local grids, and increasing the resilience and flexibility of the energy system. The European Union regulatory framework encourages the use of small-scale decentralized electricity storage systems; however support for its local implementation is still vague or nonexistent, as it is the case of Portugal that supports large scale storage in its strategic plans (RCM, 2019; PNEC, 2019). There is room to improve recent national strategic plans relating to decentralized small-scale storage, to capture the opportunities and advantages that can arise from the ongoing technical developments. Yet, the incentives for promoting storage technologies in Portugal, mainly those at decentralized level, are unclear. Our research also indicated that mechanisms for payment of flexibility services inherent to the use of energy storage devices are still missing. The capacity market is lacking further studies in the economic and social perspectives that ground the institutional support for its promotion and development. Our results integrate a preliminary study of the use of batteries on decentralized generation. The next steps for the present research are a quantitative and a hierarchical analysis that could treat and structure the data collected in the literature and in the market place, so it can be used to help support decision making.

Declaration of Competing Interest

None.

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photosynthetic micro-organisms in a biorefinery perspective, or incorporating energy storage systems such as batteries or related to Power to Gas or Power to X.

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