# *LDES* DEPLOYMENT FOR THE PROVISION OF FLEXIBILITY AND RESILIENCE TO THE GRID

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# ABSTRACT

The response of many nations to address climate change, focuses on the decarbonization of the electricity generation and on the electrification of the industrial, transport and buildings sectors. The combination of these electrification strategies, together with the growth of population and global economies results into a very remarkable increase in electricity demand, which occurs simultaneously with a very important transformation of the electricity generation resources mix. This electricity generation resources mix transformation requires the retirement of the conventional polluting generation plants, which are replaced by the rapid addition of large amounts of *RERs*, especially, of the highly variable, uncontrollable and intermittent wind and solar *PV* resources. Therefore, as countries move closer to meet their decarbonization targets, the increased variability in electricity generation outputs, entails major challenges on the provision of the required grid operational flexibility in all time scales. In addition, the increased number of extreme weather events resulting from climate change, rather than just reducing the resilience of electricity grids, also pose additional sources of variability in *RER* electricity generation outputs over longer multi-day, multi-week and seasonal periods.

*LDES* deployment is driven by their large power capacity, large energy capability, long discharge durations, their modularity and scalability. *LDES* technologies can become totally reliant on charging their units from *RERs* electricity supply and so, contribute to decarbonization. The main objectives of this work focus on the investigation of the drivers for *LDES* deployment and how they can be accommodated with the ability to enhance grids resilience, eliminate *RER* curtailments, reduce grid congestion and overall provide electricity grids with the increasing long duration grid operational flexibility required. To explain the contribution of *LDES* in a concrete electricity grid, we develop a case study, in which we demonstrate the needs of resilience and mainly of long duration flexibility that arise as the Spanish electricity system evolves according to the decarbonization objectives set by the *EU*.

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# CHAPTER 1. INTRODUCTION

The generation of electricity contributes close to one-third of total global emissions [1], what makes its decarbonization key to achieve global climate change reduction targets by 2050. Most decarbonization strategies rely on the rapid addition of large amounts of *RERs*, especially of the highly variable and intermittent wind and solar *PV* resources, as they have become the cheapest technologies in at least two-thirds of the world [2]. Thus, due to their low cost and the need to reduce emissions, the share of variable energy resources (*VERs*) has increased in recent years, while the share of generation of controllable but pollutant resources has decreased. At the same time, as reflected in the increased number of extreme weather events, the impacts of climate change have become increasingly noticeable in last decades. Consequently, if electricity grids evolve as forecasted, as decarbonization targets are realized, among all the increasing difficulties that electricity grids will have to face, *LDES* technologies emerge primarily to contribute to the reduction of two major problems, which can be even further aggravated if the impacts of climate change are not reduced: the lack of flexibility and the lack of resilience.

Long duration energy storage (*LDES)* is a term used to define any zero emissions technology with the capability to store energy in various forms for long periods of time, and then discharge electricity in an economically efficient manner during hours, weeks or even months. *LDES* technologies have long discharge durations, the energy capability is decoupled from the power capacity so the charging or discharging rate is independent of each other, they are modular, scalable, widely deployable and have short lead times compared to grid expansion projects. In this report, *LDES* are defined as any technology with the capacity to store and supply electricity for more than 8 hours.

This first chapter presents the motivators for the deployment of *LDES* technologies, as well as an outline of the main contributions of the thesis.

## 1.1 Motivators for *LDES* deployment

The two main motivators for the deployment of *LDES* technologies are its contribution to the provision of resilience and long duration flexibility in electricity systems.

Flexibility is the ability of an electricity grid to reliably and cost-effectively manage the variability and uncertainty of demand and supply over all time scales [3], while resiliency is the ability of an electricity grid to withstand, adapt to and recover from a disruptive event, usually an extreme weather event.

Controllable but pollutant generation resources, such as nuclear, natural gas or coal, provide most of the flexibility today, so as these controllable but pollutant generation resources are retired and grids move towards deeper penetrations of *RERs,* the main sources of flexibility disappear. In decarbonized grids, where the vast majority of electricity is generated by *RERs*, the added supply side variability poses a major challenge to balance supply and demand and so it can result in two different types of supply and demand imbalances. First, there can be periods when the maximum potential supply of electricity is greater than the demand for electricity, in these cases, as the matching of demand and supply has to be done instantaneously, the generation has to be limited and, consequently, not all the electricity that *VERs* can generate is injected into the grid. This renewable electricity that can be generated but cannot be injected is known as curtailed electricity. Secondly, there can also be periods when generation is not sufficient to meet demand, what increases the difficulty to ensure the security of electricity supply. Both types of periods result in different duration flexibility needs [1],[3],[4]:

Firstly, the intraday flexibility is the need for flexibility during 8 or less consecutive hours and generally involves the provision of grid stability services and peak shifting, such as electricity demand peaks at night.

Secondly, multi-day and multi-week flexibility extends over periods ranging from 8 hours to days and weeks. It usually occurs due to the presence of long periods of time with unusually high or low *RER* generation, unusually high or low demand, or electricity curtailment due to grid congestion.

Finally, seasonal flexibility is caused by the natural variability of wind, sun and rain throughout seasons, as well as by the potential exposure to extreme weather events. For example, wind and rain tend to be more abundant during the winter, so countries with deep penetration of wind or hydro resources and summer peak demand have a greater need for this type of flexibility. On the contrary, in most countries sun tends to be more abundant during summer, so countries with deep solar *PV* penetration and peak demand in winter are also in need of this flexibility. Also, both the duration of extreme weather events and the time to get equipment back to their operational state, can last for very long periods of time, what increases the need for flexibility over periods of time on the order of months.

On the other hand, the increasingly frequency and severity of extreme weather events resulting from climate change are the main threat to the resiliency of electricity grids. Extreme weather events affect to a greater extent those assets, that such as *T&D* lines and *RERs*, are directly exposed to nature. Some of these extreme weather events can last for very long periods of time, such as years, while others, even if they last only two or three days, can cause equipment repairs to take even weeks or months, mainly due to the difficulty to access the damaged equipment. We have defined resilience as the ability of an electricity grid to withstand, adapt to and recover from a disruptive event, usually an extreme weather event, therefore, techniques to enhance resilience must focus on the improvement of the following capabilities: robustness and recovery.

Robustness is the ability of an electricity grid to withstand impacts and continue to operate properly. Both *RERs* and *T&D* lines are directly exposed to nature, so, their resistance to extreme weather events is much lower than that of other non – exposed assets, such as controllable but pollutant conventional generation plants. Conventional generation plants can operate during most extreme weather events because they are usually protected from them. However, *RERs* are much more vulnerable, for example, onshore and offshore wind resources must be shut down before and during the occurrence of an extreme weather event, that such as a hurricane, can cause serious damage to turbines if they continue their operation.

Recovery is the ability to quickly restore the operation of an electricity grid after an interruption caused by climatic hazards impacts. In most cases, the rapid recovery of electricity grids is marked by the difficulty to access the damaged equipment. Because *RERs*, are very decentralized resources, which tend to be located in remote sites, the recovery time of a grid with a deep *RERs* penetration can be very long, since a large number of crew members have to be sent to the many remote and difficult to access facilities that make up such electricity grid. These remote sites are for example mountains, in the case of wind onshore, or oceans, in the case of wind offshore. In contrast, conventional plants are usually easily accessible, so then the dispatch of crew members to repair damaged equipment, is in general much easier. Also, conventional plants are more resilient than *RERs*, as we have discussed above, so the failure of many of them at the same time is very unlikely.

This transformation of electricity grids occurs at the same time as electrification increases the demand for electricity and the impacts of climate change are greater, so rather than just to maintain, it is necessary to increase flexibility and resilience capabilities of electricity grids. To this end, it is required to develop and integrate zero emissions technologies, which in addition to being easily accessible and resilient, have the capability to satisfy the long and short duration flexibility needs that arise due to the transformation of electricity grids.

## 1.2 Outline and summary of contributions of the report

The main objective of the report is to explain those drivers that allow us to propose *LDES* technologies as an important contributor to the provision of the increasing needs for long duration flexibility and resilience that arise as decarbonization goals are realized. The content of this report is divided into two parts, a first part explaining the drivers for the emergence of greater flexibility and resilience needs, and a second part explaining why *LDES* emerge as an important contributor to flexibility and resilience provision.

In Chapter 2, we analyze the main causes of the increasing need for the provision of long duration flexibility. To this end we explain the main drivers for the increase in electricity demand. Then, we describe the evolving nature of the electricity generation resources mix required to cope with the increase of electricity demand, as well as, to meet decarbonization goals. Consequently, given that *RERs* will be the main source of generation in future electricity grids, we analyze the variability in electricity generation of *RERs* and the impact of this variability on the flexibility needs. Also, we explain the evolution of electricity networks to integrate vast amounts of RERs, as well as to integrate new distributed energy resources and to cope with new electricity loads.

In Chapter 3, we analyze those factors that allow us to explain the increasing need for resilience. To this end, we analyze the impact of climate change on the number of extreme weather events, as well as the effects of extreme weather events on electricity grids.

Then, in Chapter 4, we explain the role of *LDES* technologies to reduce *RER*´s curtailment, reduce grid congestion, enhance resilience capabilities, and above all, to ensure the security of supply via the provision of the required long duration grid operational flexibility.

In Chapter 5, we explain the increasing need for *LDES* deployment that arises in Spain, as the country gets closer to achieve its decarbonization goals. In this case study, we first provide a description of the evolution of the Spanish electricity resource mix, and of the impacts on the grid of more frequent extreme weather events in Spain. Then, to show how *VERs* variability can be extended over longer periods of time, we perform an analysis of the electricity generation outputs of solar *PV* and wind resources. Finally, we have estimated the supply and demand imbalances according to a possible scenario we have developed for Spain in the year 2050.

# CHAPTER 2. INCREASING NEED FOR LONG DURATION GRID OPERATIONAL FLEXIBILITY

The increase in world's population, together with the development of global economies, results in an increase in electricity demand that becomes more acute as decarbonization goals are realized. At the Paris Agreement, 180 countries adopted the first global climate deal, which aims to limit the temperature increase to between $2\ ^{\circ}C$ and $1.5\ ^{\circ}C$ above preindustrial levels. To this end, the response of many nations to reduce global warming, focuses on the reduction of emissions of energy end use sectors, especially, of the industrial, transportation and buildings sectors. As electricity has the potential to be the cleanest source of energy [5], most decarbonization strategies involve the electrification of the industrial, transportation and buildings sectors, and the decarbonization of the generation of electricity.

In this Chapter we analyze the main drivers for the increasing need for long duration flexibility that arises as countries move closer to meet decarbonization targets. To this end, in the first section we describe the drivers for the increase in electricity demand and the magnitude of this increase. Then, we describe the transformation that the electricity generation resources mix needs to undergo to cope with this increase in demand, which occurs at the same time as countries focus on the reduction of emissions in the generation of electricity. In the third section we evaluate how the variability of *RERs* electricity outputs impacts in the flexibility requirements of electricity grids. In section 4, we provide with an explanation of the additional flexibility required due to the grid congestion events in extended grids.

## 2.1 Electricity demand growth

Global population and *GDP* increase are the main drivers for the increasing energy demand [6]. World´s population has increased by 29 $\%$ in the last 20 years and is projected to increase a 6.25 $\%$ by 2030 and 25 $\%$ by 2050 [6], [7]. With regards to *GDP* increase, although it slowed during the pandemic, it increased at an average annual rate of 2.88 $\%$ between 2017 and 2019 [8], and consequently as global economies recover, it is forecasted to increase on average a 3 $\%$ per year until 2050 [6]. In addition, the increasing urbanization, also results in an important increase of energy demand. In cities, the demand for energy is much larger, as it is supported by historical data, which shows that, although in 2020 only 56 % of the population lived in cities, energy consumption in them accounted for two-thirds of total global energy consumption [6]. By 2050 the percentage of people living in cities is expected to reach 75 %, what derives in an even more marked increase in energy demand [6].

Simultaneously, due to the electrification of energy end use sectors, mainly the industrial, buildings and transport sectors, this increase in energy demand leads to marked increase in electricity demand. The industrial, transport and building sectors together account for 94 % of total global final energy consumption, and are still highly dependent on fossil fuels, which account for 80 % of the energy consumption of these sectors [6]. Thus, the electrification of such important sectors together with the increase of global population and *GDP*, increases the demand for electricity, which although it is already considerably large, it is forecasted to be even larger in the future. Such as it is reinforced by the three latest *IEA*´s representative scenarios, which forecast an increase in the demand for electricity between 30 % and 42 % by 2030 [6].

## 2.2 Evolving nature of electricity generation resources mix

In recent years there has been an increase in the installed capacity of renewable energies, caused mainly by the growing push for clean energy, which stems from the global objective to reduce climate change. More than 80 % of all new electricity generation capacity added in 2020 was renewable, with solar *PV* and wind resources accounting for 91 % of all renewables added [9]. Moreover, this increase has not only occurred in terms of installed capacity, but there has also been a marked increase in the electricity generated by renewables, which is expected become more acute as decarbonization targets are realized [6]. To achieve climate change reduction, most countries rely primarily on deepening the penetration of renewable energy resources (*RERs*) and on aggressive fossil fuel plants retirements. These actions lead to an important transformation of the electricity generation resources mix, which is supported by the three representative scenarios used by the *IEA* in the "World Energy Outlook 2021" [6]. In this report, the *IEA* reserves a chapter for electricity, which forecasts the evolution of the global electricity generation resources mix, according to the following three representative scenarios:

- the net-zero emissions scenario for 2050 (*NZS*): this *IEA*´s scenario shows a path for the global energy sector to achieve net $CO_2$ emissions by 2050;

- the announced pledges scenario (*APS*): under which countries fully implement their national climate targets for 2030 and 2050;
- the stated policies scenario (*SPS*): does not assume that governments achieve all the announced targets. Instead, it looks in more detail, sector by sector, at what has been put in place to achieve these and other energy-related targets, taking into account not only existing policies and measures but also those that are being developed.

The growing push for renewables, coupled with the fact that solar and wind resources are expected to become the cheapest resources in at least two-thirds of the world in the next decade [6], leads to a very significant increase in renewable´s share of electricity generation, mainly of the variable and intermittent solar and wind resources. Figure 1 shows the differences between the shares of electricity generated by primary energy sources in 2020 and that forecasted for 2030 by *IEA*'s three representative possible scenarios.

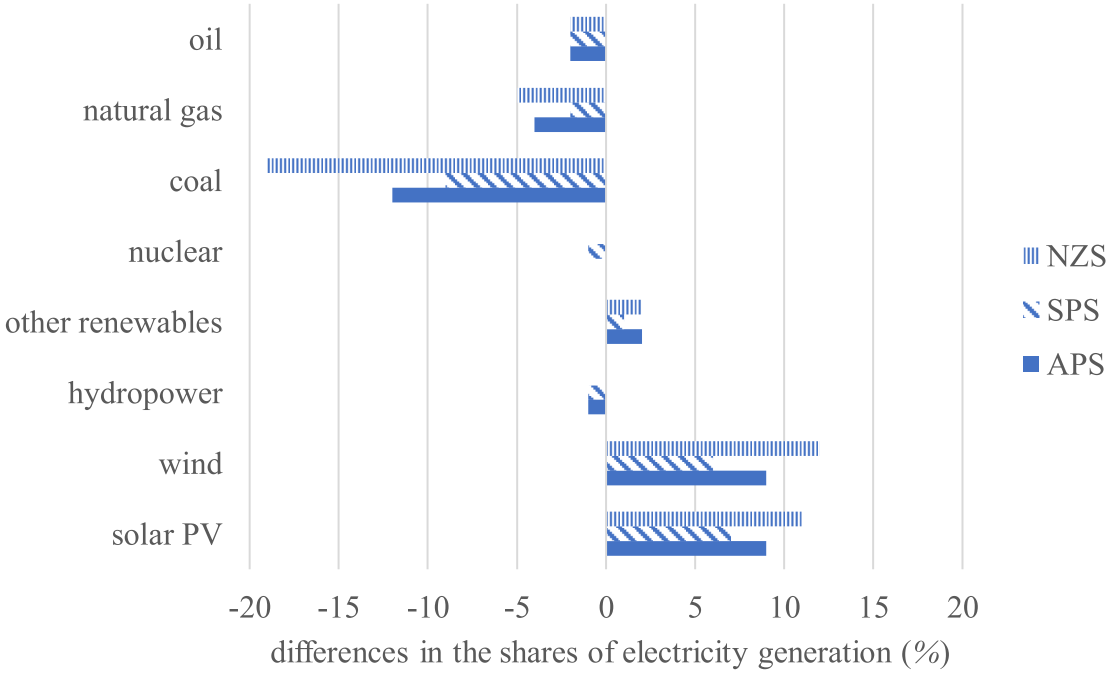

Figure 1: Forecasted differences in global shares of electricity generated by primary energy sources under 3 selected scenarios:2020-2030 [6]

The generation share of solar *PV* resources increases from 3 % in 2020 to between 12 % and 14 % by 2030, while the share of wind resources increases from 6 % in 2020 to between 15 % and 18 % by 2030. The remaining renewable technologies, hydropower, geothermal and concentrated solar power (*CSP*), have a much slower capacity increase, although together they keep providing around 20 % of the electricity generation in these three scenarios. Respect to nuclear, the three scenarios reflect that its generation share remains around 10 % since 2020 to 2030. In contrast, the decarbonization of the electricity sector entails a significant reduction in the generation share of conventional controllable but pollutant resources, as its share of generation reduces from 61 % in 2020 to between 35 % and 48 % by 2030.

Moreover, the deeper renewable penetration and the reduction in the share of electricity generation of controllable but pollutant generation resources are even more acute by 2050, as it is illustrated by the differences in the shares of electricity generated by primary energy sources that result from the three *IEA* representative scenarios shown in figure 2.

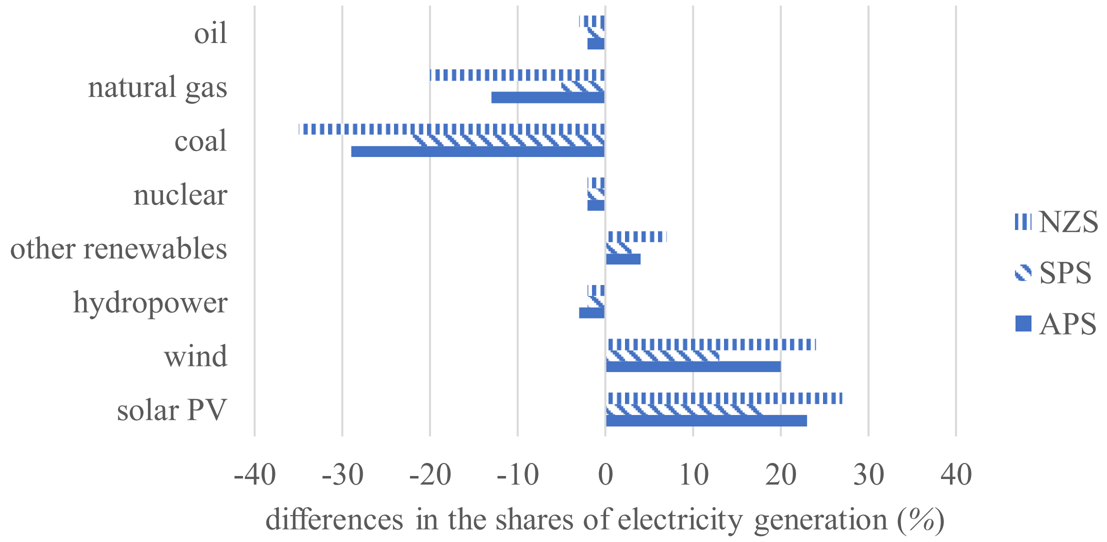

Figure 2: Forecasted differences in global shares of electricity generated by primary energy sources under 3 selected scenarios:2020-2030 [6]

While the share of electricity generation of wind and solar *PV* resources increases between 31 % and 61 % by 2050, the share of fossil fuel power plants decreases between 29 % and 58 % by 2050. The nuclear and hydropower primary energy sources for generation maintain a share close to 8 % and 14 %, respectively, which is similar to the 2020 data.

## 2.3 Impacts of *RER* output variability

One of the fundamental tasks of every electricity grid is to balance electricity supply and demand. Conventional electricity grids have been designed to mainly manage load variability, but as electricity grids evolve towards a deeper penetration of *VERs*, the added supply side variability poses a major new challenge. Nowadays, most of the flexibility electricity grids is provided by controllable generation resources, such as nuclear, coal or natural gas plants. Thereofre, as controllable but pollutant energy resources are retired, and replaced by the uncontrollable *RERs*, the main sources of flexibility disappear.

*VERs* only produce electricity when the sun shines or when the wind blows, in contrast, conventional and controllable power plants are available whenever the grid needs them and so, they are able to fulfill flexibility needs in all timescales. In the near term, while controllable but polluting electricity generation resources still account for an important share of electricity generation, most of the flexibility required is forecasted to be in the form of intraday flexibility needs, which can be covered by short duration storage technologies [4].

However, the variability of *VERs* electricity generation outputs can also be extended over longer periods of time, what derives in longer multi-day, multi-week and seasonal flexibility needs that short duration storage systems cannot fulfill. In many cases, when a particular weather regime sets in, it lasts for several consecutive days or weeks, regardless of whether it is a low or a high wind speeds regime, which increases or decreases wind electricity generation, or whether it is a squall or anticyclone, which increases or decreases solar electricity generation. In addition, electricity generation can also change from one season to another. In most countries, throughout the year, electricity generation from every wind turbine increases during the winter and decreases during the summer, whereas, solar *PV* generation peaks during the summer and declines during the winter. At the same time, the load often peaks during the summer, due to air conditioning and refrigeration systems, and during the winter, due to heating systems. Therefore, this longer duration variability of *RERs* electricity generation outputs, gives rise to a dire need for the deployment of technologies with the capability to shift electricity generation from days to days, weeks to weeks, and seasons to seasons, which becomes evens more acute as decarbonization goals become realized and the main sources of flexibility are retired.

Furthermore, these needs for flexibility in all timescales can increase even more in isolated grids, such as islands or military bases, where because generation is highly concentrated, low generation in one area cannot be covered by the generation from another area with a different climate.

## 2.4 Electricity networks expansion

Decarbonization implies a very important transformation of electricity grids, mainly because they will have to be able to manage a very large increase in electricity demand, which leads to a very large and rapid integration of large amounts of *RERs* into the grid. Conventional electricity grids used to have large capacity generation plants, however, as electricity grids evolve and these plants are retired, the average capacity of generation resources decreases, while the number of facilities and their geographical diversification increases, resulting in a much more decentralized portfolio [10]. At the same time, the integration of distributed energy resources and the connection of new loads to distribution networks, pose additional challenges for networks operators [11]. To overcome these challenges, countries will have to make a very notable investment in electricity networks, both in the transmission and distribution levels [6]. In the last five years, investment in grids averaged *USD* 300 billion per year, while in the next decade, future scenarios indicate that it increases to an average of *USD* 370 billion per year, according to the *SPS*, and up to *USD* 630 billion in the *NZS* [6]. These figures, will mean that at least, network investment will be 23 *%* higher in 2030 than it is today. The failure to undertake this investment in time hinders the deployment of *RERs*, as in this case, grids will be prevented from having the necessary transfer capability to transmit all the electricity that *RERs* can generate, without exceeding thermal, voltage and stability limits. This lack of transfer capability results in a remarkable increase in the number and duration of grid congestion events, which seriously increase the amount of electricity curtailment. In addition, the fact that the grid does not expand as fast as new *RER* plants are built [10], also increases both the number and the duration of grid congestion events, and consequently increase the amounts of electricity curtailment.

## 2.5 Concluding remarks

Decarbonization strategies lead to an accelerated transformation of electricity grids. The electrification of end use sectors and the increasing *GDP* and global population derive in an increase in electricity demand which occurs at the same time as the decarbonization of the generation of electricity leads to the retirement of controllable but pollutant generation resources together with a deeper penetration of *RERs*. Whereas todays electricity grids depend on controllable and pollutant generation resources, as electricity resources mix evolve, the retirement of the latter, coupled with the limited dispatchability/controllability associated with the rapidly varying, highly uncertain and, intermittent solar and wind resources, entail major challenges in the provision of the required grid operational flexibility in all time scales. Also, the new decentralized portfolio resulting from the deep penetration of *RERs*, together with the grid modernization required to cope with the bidirectionality of electricity flows and with change in the shape of the electricity load curve, derives in a dire need for longer duration flexibility provision in order to reduce the number and duration of grid congestion events in both the transmission and distribution levels.

# CHAPTER 3. CLIMATE CHANGE IMPACTS ON GRIDS RESILIENCE

An extreme weather event is defined as a time and place where weather, climate or environmental conditions are above a threshold value near the upper or lower extremes of the range of historical data [12]. Extreme weather events have very significant impacts on electricity generation resources, *T&D* lines and electricity demand, and so, can seriously hamper the security of electricity supply. Indeed, extreme weather events are the major cause of electricity power outages [13]. In addition, electricity grids have long operational lifetimes, and so, due to climate change, in many cases they are forced to operate under conditions very different from those for which they were designed [13].

In the first section of the chapter, we analyze the impact of climate change on the number of extreme weather events. Then, in section 2, we explain the impacts of extreme weather events on electricity grids. For this purpose, we have selected the following extreme weather events: floods, which we define as an overflow of water on normally dry land; heatwaves which we define as a period of consecutive days with extremely unusual high temperatures; droughts, which we define as a period of unusually dry weather long enough for the lack of water to cause a notorious hydrological imbalance in a given area; storms/cyclones, which we use to encompass disturbances in the atmosphere which involve huge amounts of rain, and high wind speeds, including hurricanes; and wildfires, defined as an uncontrollable fire that burns a natural area.

## 3.1 Increasing number of extreme weather events

Today's electricity grids have to cope with a growing number of problems caused by climate change, for which they are not prepared. Global warming is mainly driven by a larger concentration of greenhouse gases in the atmosphere, especially $CO_2$ [14]. The last decade (2010-2019) was the warmest since temperature records began and in 2019, the global average temperature was 1.1 $°C$ higher than preindustrial levels. As a result of this increase in temperatures, extreme weather events have considerably increased in number, as figure 3 illustrates.

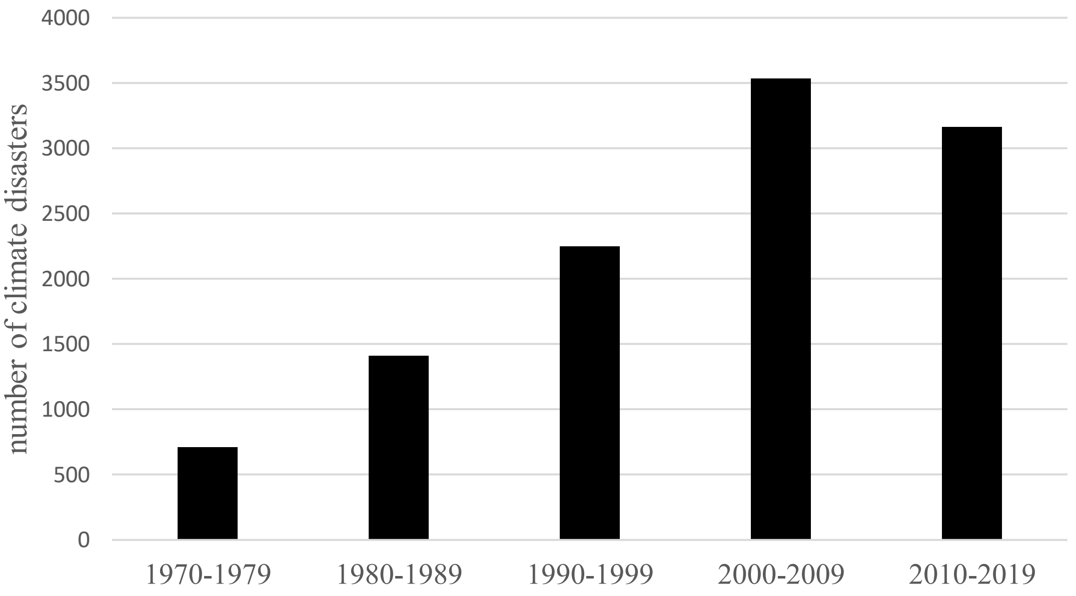

Figure 3: Number of global reported climate disasters: 1970-2019 [15]

Furthermore, the increased number of extreme weather events, is further aggravated by their increase in the economic losses they cause, which according to the historical data presented in figure 4, were approximately 8 times larger in the last decade than they were 4 decades ago.

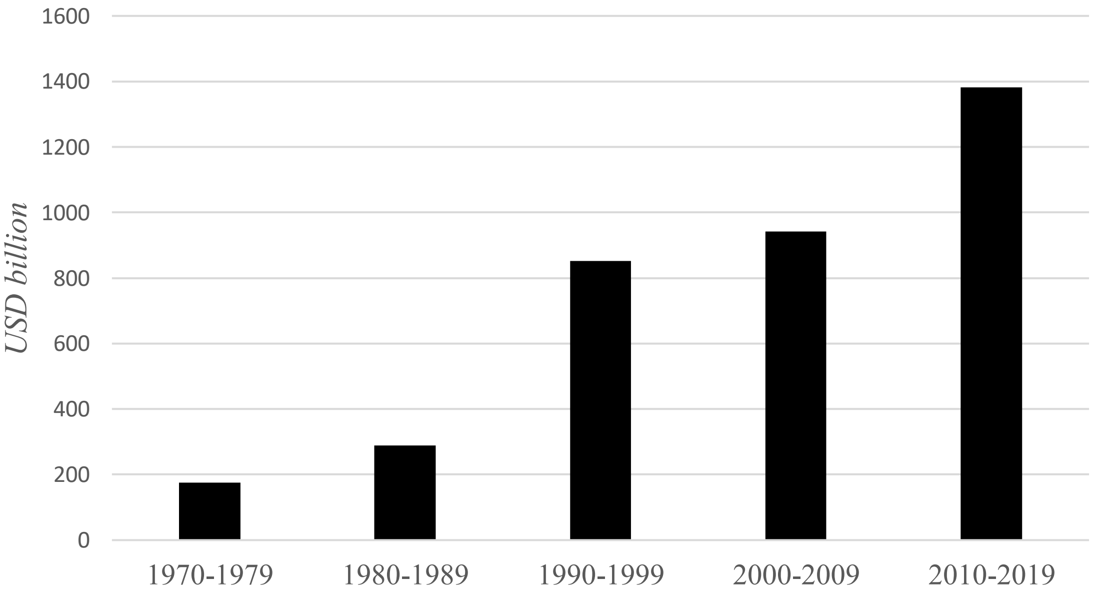

Figure 4: Global reported economic losses provoked by climate disasters in *USD* billion: 1970-2019 [15]

## 3.2 Impacts of extreme weather events on electricity grids

The growing impact of climate change on electricity grids is becoming an increasingly serious problem, which together with the evolving nature of electricity grids, entails major complications in resilience provision.

Floods accounted for 44 % of all extreme weather events recorded in 1970-2019 [15]. In addition, their forecasted increase in number adds further complications for the provision of resilience [16]. Inland floods become more frequent due to the increase of the number of storms and cyclones while coastal flooding increases mainly due to sea level rise [16]. Floods impacts on electricity assets varies depending on the length of time the equipment is submerged, however, since water is a very good conductor of electricity, the exposure of the equipment to water for seconds can cause an irreparable damage. In addition, in many cases flooding can cause landslides, which can damage transmission and distribution lines. When floods occur, recovery time ranges lasted from less than 24 hours to more than 3 weeks, and even up to 5 weeks, when floods occur together with storms and high speed winds [17].

The number, intensity and length of heatwaves has increased in many large areas of mainly Europe, Asia and Australia [16]. A heatwave typically affects really large areas and can last for as long as a few weeks [16]. High temperatures have important effects on the efficiency of electricity generation resources, on the efficiency of *T&D* lines and on electricity demand. Electricity demand increases to meet the loads of air conditioning and refrigeration systems, while the efficiency of generation resources and *T&D* lines decreases. The efficiency of solar *PV* plants can be reduced by up to 0.5 % per 1 °*C* [18], and the efficiency of thermal plants can be reduced by 0.1 % to 0.5 % per 1 °*C* [18]. Also, due to heat dissipation limitations, extreme temperatures can lead as well to a substantial reduction in the transfer capability of electricity networks, which can increase the number and length of grid congestion events [18].

Climate change increases the variation in geographical precipitation patterns, what makes wet regions wetter and dry regions dryer. Usually, drought periods last for many years, resulting mainly in large changes in the electricity generation outputs of certain resources during long periods of time [19]. Droughts, because of the reduction in the amount of rainfall together with an accelerated water evaporation caused by high temperatures, can lead to a very significant reduction of hydropower electricity generation. However, water scarcity does not only affect hydropower plants, but also has an impact on thermal power plants that use water to generate steam and as a coolant. In many cases, water shortages can cause water cooled thermal power plants to reduce their production capacity or even shut down completely.

Rising global temperatures and more frequent droughts in certain areas exacerbate the intensity and number of wildfires. Wildfires can affect the entire electricity infrastructure, but typically *T&D* lines are the most damaged asset. However, the problem with wildfires is not only the direct damage they cause to electrical equipment, but also sometimes damage prevention tools also cause a considerable decrease in electricity supply. When there is a high risk of wildfire in a given area, which in many cases, this risk can last for several days, it is necessary to cut electricity supply during long periods of time, since *T&D* lines can initiate fires [16]. When fire damages transformers, switchgear, telecommunications and other ancillary equipment, substations must be taken completely out of service. To return the equipment to normal operating conditions, crews need to be physically present to inspect and repair equipment if necessary and as these assets are sometimes quite inaccessible, not only because of their location, but also because of fire, these repairs can take several days.

Cyclones and violent storms, due to the large amounts of rain per square meter and the very high wind speeds involved, besides being common, are one of the phenomena with the worst consequences in electricity grids, especially in coastal areas [6]. Electricity grids are not prepared for the increasing number of these phenomena, and therefore 25 *%* of the world's electricity grids are currently at high risk from cyclones, with this share being even as large as 40 *%* in places such as North America and Australia [6]. In these storms, *T&D* lines are in many cases the most damaged equipment. Also, as was the case with wildfires, workers have to wait for the storm to cease before they can repair damaged assets, what results in recovery times lasting for several days. For example, just the replacement of an accessible transmission pole typically takes 10 days, so then, when the storms have damaged the access to *RER* plants and *T&D* lines, these times can substantially increase [16]. Moreover, the problem with these storms is not only the reduction of electricity caused by direct damage to equipment, but in many cases, it is necessary to shut down wind turbines before and during the storm to avoid further damage.

As electricity grids evolve and *RERs* penetration deepens, as renewable generation resources are more exposed to nature than conventional pollutant generation plants, the disruptions in grids caused by extreme weather events are larger, and so it is the need for resilience. In addition, *RERs*, unlike conventional controllable power plants, are usually not easily accessible, as they tend to be located in remote areas where their electricity generation is larger. Also, the greater number of electricity generation plants and their wider geographical distribution, resulting from deeper penetrations of *RERs*, makes recovery times longer, since their repair involves the mobilization of a large number of crew members to more numerous and more distant locations. Thus, the lower resilience of electricity grids derives in a significant reduction in electricity supply over long periods of time, caused either by more common and prolonged damage to grid assets, or by the long duration of the extreme weather events themselves.

## 3.3 Concluding remarks

The number of extreme weather events – floods, wildfires, droughts, heat waves and storms/cyclones has increased worldwide in recent decades and, furthermore, if climate change is not reduced, this will also be the case in the future. The impacts of these events on the electricity grids can be very varied, but all of them, either because of the increases in electricity demand, the reduction in electricity generation they cause, or due to the reduction of the transfer capability of electricity networks, all result in remarkable difficulties to ensure the security of supply. Also, given the duration of extreme weather events themselves or of the problems they cause, there is a need not only for methods and technologies with the ability to increase the resilience of electricity grids, but also for technologies with the capability to provide flexibility during the time extreme weather events last or during the time their consequences are suffered, which in both cases can be very long.

# CHAPTER 4. *LDES* ROLES IN FLEXIBILITY AND RESILIENCE PROVISION

The variability of electricity generation in a grid marked by the deep penetrations of *RERs*, the increase in electricity demand, and the numerous and long grid congestion events, increases the need for flexibility on all time scales. In addition, the resilience of future electricity grids is considerably reduced by the increasing number of extreme weather events as well as by the increased vulnerability intrinsic to the nature of *RERs*. Therefore, as decarbonization goals are realized, it becomes increasingly necessary to deploy technologies, such as *LDES*, with the capabilities to meet these dire needs for long duration flexibility and resilience.

From all the factors that characterize *LDES*, power capacity, energy capability and discharge duration, are three of the most significant among all them. Power capacity is the largest amount of energy that a storage system can discharge in a particular moment, while energy capability is the maximum amount of energy that a storage system can store. Then, by the combination of these two metrics we obtain the discharge duration, which is the longest period of time in which a storage system can be discharged at its maximum power. In *LDES* technologies, power capacity and energy capability are decoupled, so, unlike other forms of energy storage, energy capability can be increased without increasing power capacity, what results in a reduction of the cost of increasing the amount of energy stored, and consequently, in a reduction of the cost of increasing the discharge duration [1], [20]. Also, many of the new *LDES* technologies have other additional characteristics that also favor their deployment, such as being modular, which makes them scalable, their few allocation constraints and their low risk to population.

In this Chapter we associate the salient characteristics of *LDES* to their ability to reduce *RERs* electricity curtailment, to reduce grid congestion and overall to contribute to resilience enhancement and long duration grid operational flexibility provision.

## 4.1 Long duration flexibility provision

The ability of the *LDES* to provide flexibility services relies primarily on energy time shift to balance supply and demand. *LDES* technologies can become totally reliant on charging their units from otherwise curtailed renewable electricity and then discharging it for long periods of time when generation is less than the required. The variability of electricity generation by wind and solar resources, which indeed, can be increased by extreme weather events, can increase the duration of periods of curtailment or shortage of electricity. Furthermore, it is not only the duration of these periods that favors the deployment of *LDES* technologies, but also the large amount of electricity that can be needed to store or release, what also requires technologies such as *LDES*, with very large energy capability and power capacity. In the near term, while controllable but pollutant generation resources still have a considerable share of electricity generation and the penetration of *RERs* is not as deep as the achievement of decarbonization goals require, most of the flexibility needs that arise involve the provision of flexibility for short periods of time. Most of this flexibility can be provided by short duration energy storage systems, nevertheless, there are already some cases where the time in which the flexibility provision is required over longer time scales, such as, during or after the occurrence of an extreme weather event or in grids in which they plan a much rapid evolution towards future electricity grids, as for example, the city of Los Angeles, which plans to become net-zero by 2035 [21]. In addition, as electricity grids evolve and more controllable but polluting generation sources are retired and *RER´*s share of electricity generation increases, the need for long duration flexibility becomes more acute.

Also, *LDES* technologies can have other functions related to energy time shifting that favor their deployment, such as, their ability to maximize the electricity production of *RER* plants in situations of grid congestion. When *LDES* technologies are combined with one or more *RER* power plants, *LDES* store the electricity produced by the power plants whenever this electricity is larger than the interconnexion bus transfer capacity, and then release it when the constraint is not binding. Throughout history, the solution to integrate new power plants has been the electricity networks expansion. The development of grid expansion projects requires a huge capital investment and long-term planning and so, the pace of grid expansion is slower than that of the construction of new *RER* plants [6],[10]. Therefore, due to the rapid integration of *RERs* that must take place to achieve the decarbonization targets by 2050, this strategy can lead to numerous and lengthy episodes of grid congestion. *LDES* technologies, due to their shorter lead times, which last on average one year, and their low investment needed compared to grid expansion projects [1], emerge as a cost -effective and rapid to integrate alternative to reduce the number and duration of grid congestion events without expanding electricity networks. To this end, the main idea is to combine *RERs* with *LDES* technologies when transfer capability constraints reduce *RERs* electricity injection into the grid. These network transfer capability constraints are usually observed during the integration of new plants, but are also notably common in other situations such as when repowering existing plants. This last situation is very frequent in wind power plants, because existing plants are already located in most of the best locations, and in many cases it is more cost – effective to upgrade a plant than to build a new one. As technology improves, modern wind turbines have more power capacity, what can result in certain electricity lines no longer being able to transmit all the electricity that the repowered wind power plant can inject into the grid. In addition, the energy time shifting capability of *LDES* also plays a key role in the provision of flexibility in isolated grids, where the limited interconnection capability poses a significant challenge in their decarbonization.

## 4.2 *LDES* deployment for resilience enhancement

*LDES* technologies can also play an important role in the provision of flexibility and resilience in an era of more frequent extreme weather events. Extreme weather events, either through the direct damage they cause, the preventive actions they force into place or the reduction in efficiency they cause to *T&D* lines and electricity generation resources, always result in a reduction of the electricity supply, which, combined with the increased demand that these events cause, can result in long power outages. To reduce the number and duration of these electricity supply shortages, *LDES* technologies can contribute in the same way as they did to provide flexibility, and so discharge the previously stored electricity until the effects of these extreme weather events cease. Additionally, they can also contribute to increase the resilience of the grid. The resilience of future electricity grids can be reduced mainly for two reasons, the increasing number of extreme weather events, and the lower resilience of grids with deep *RER* penetration. On the one hand, the increasing number and severity of extreme weather events is caused by climate change, which mainly derives from greenhouse gases emissions. *LDES* technologies emerge as a zero emissions contributor to facilitate the decarbonization of the electricity sector, and consequently, *LDES* deployment can lead to a reduction of the frequency and intensity of extreme weather events. On the other hand, an important part of the reduction in the resilience of future electricity grids is caused by the low resistance to extreme weather events of *RERs* and *T&D* lines driven by their direct exposure to nature and by the long repair times caused by the decentralization and difficult access to *RERs*. Some *LDES* technologies have few allocation constraints and pose a low risk to the population, so they can be even be built underground or in close proximity to populated areas what reduces the dependence on *T&D* lines. Also, because of these same reasons, *LDES* technologies, can also be located in accessible and protected locations from extreme weather events, to in this way improve the robustness and recovery times of the grid.

## 4.3 Concluding remarks

Large power and large energy capability, as well as their ability to discharge or store electricity during long periods of time, are some of the characteristics that make *LDES* technologies emerge as a great contributor to the provision of the long duration grid operational flexibility needed as electricity grids retire more controllable but pollutant generation resources and *RER*´s penetration deepens. In addition, these characteristics, together with their modular architecture, short lead times and low risk to the population, favor as well the deployment of these technologies to reduce grid congestion and increase the resiliency of the grid.

# CHAPTER 5. CASE STUDY: SPAIN

Spain as a member of the *EU* adopts all its decarbonization objectives. To achieve these objectives, the *EU* requires to each country to develop an “Integrated Plan of Energy and Climate 2021-2030” (*PNIEC* for Spain [22]), which is reviewed every two years to include any possible updates on the *EU* objectives. On July, 2021, the *EU* emitted the package "Fit for 55", in which stipulates that greenhouse gas emissions must be reduced to 55 % by 2030 [23]. For this reason, the strong and rapid transformation of the electricity grid indicated in today´s *PNIEC* will become more acute when the new objectives are included in the next revision.

In this Chapter we demonstrate the growing needs for resilience and long duration flexibility that arise in Spain as a result of climate change, the increase in electricity demand and the change in the electricity resource mix derived from decarbonization. To this end, we begin this chapter with a description of the evolution of the electricity generation resource mix that the Spanish government plans for 2030. In the second section we provide an explanation of the effects of the most common extreme weather events in Spain. In section 3, we provide an analysis of the variability of the electricity generation outputs of solar *PV* and wind resources in Spain, which, based on 2019 data, shows how the electricity generation of these resources tends to settle into long regimes of either small or large electricity generation outputs. Finally, as the effects of variability in electricity generation from the *RERs* are more noticeable as their penetrations deepen, in the last section of this chapter, we present the results of the simulation, explained in detail in the Appendix B, which based on a possible scenario we have developed, extracts as output, the magnitude and duration of curtailment and lack of supply events in Spain in the year 2050.

## 5.1 Electricity generation resource mix evolution

The Spanish electricity generation resource mix is planned to evolve in accordance with the objectives set in the *PNIEC*, which are:

- 23 % reduction in greenhouse gas emissions compared to 1990.
- 42 % of renewables over total gross final energy consumption.
- 39.5 % improvement in energy efficiency.
- 15 % electricity interconnection ratio between member states

The achievement of these objectives, entails the addition of vast amounts of renewables, mainly of wind and solar *PV*, and the retirement of controllable generation resources. As shown in figure 5, the transformation of the Spanish electricity generation resource mix results in a 30.6 % reduction in the capacity of controllable non-renewable generation resources by 2030 compared to 2020 data, driven by the retirement of coal generation plants by 2022, nuclear resources retirement around 50 % by 2030, and their full retirement by 2035. In contrast, to replace these retired conventional generation plants and to cope with the increase in electricity demand, which is forecasted to be 4 % higher in 2030 than in 2020 [22], the Spanish government, states that *VER´*s capacity in 2030 has to be 145 % larger than in 2020.

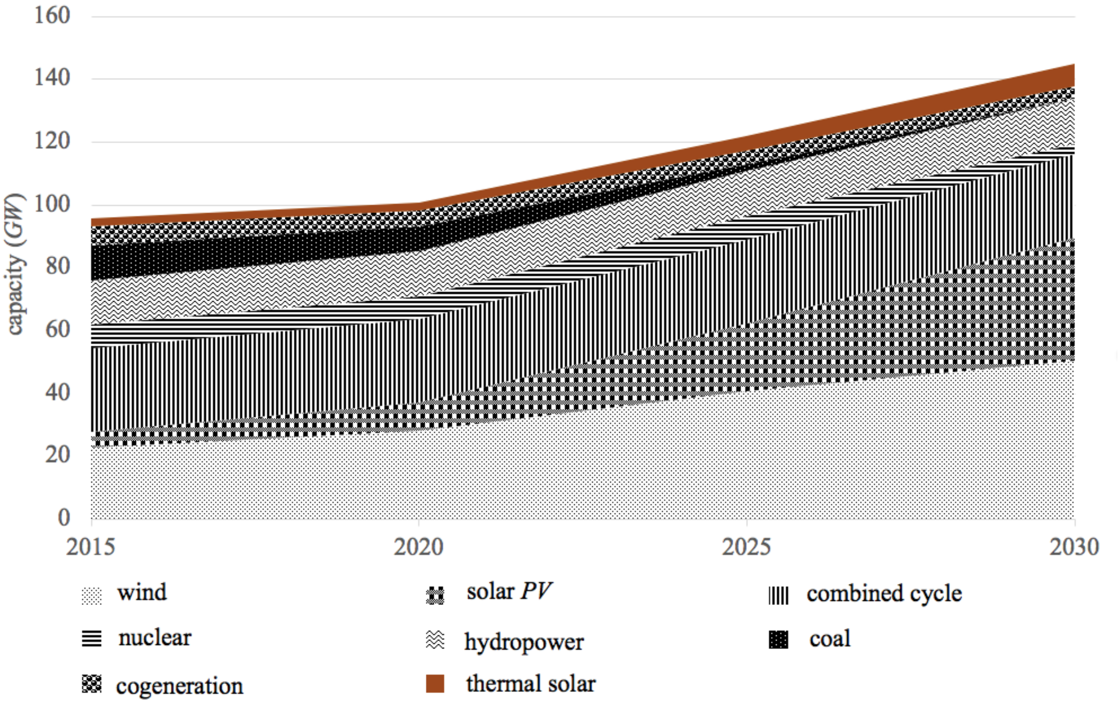

Figure 5: Historical and planned capacity of primary electricity generation resources: 2015-2030 [22]

The increase in the installed capacity of *VERs*, together with the decrease in controllable generation resources capacity, occurs equally in terms of the planned share of electricity generation by both types of technology, as indicated in table 1. From 2020 to 2030, the planned share of electricity generation of controllable generation resources decreases from 67 % in 2020 to 33 % in 2030 and that of *VERs* increases from 29.6 % to 63.3 %. In addition, the Spanish government's goal is to complete the decarbonization of the electricity grid by 2050, so by this year all electricity generated must come from renewable energies.

Table 1: Planned and historical electricity generated by primary generation resources: 2020, 2025 and 2030 [22]

| technology | electricity generated 2030 (%) | electricity generated 2025 (%) | electricity generated 2020 (%) |
|---|---|---|---|
| nuclear | 7.2 | 18.5 | 22.2 |
| coal | 0 | 3.7 | 2 |
| combined cycle | 9 | 4.2 | 17.5 |
| hydropower | 10.5 | 11.9 | 12.2 |
| wind | 35.7 | 32.1 | 21.8 |
| solar *PV* | 21.2 | 13.4 | 6 |
| thermal solar | 6.4 | 5 | 1.8 |
| other renewables | 3.9 | 2.7 | 2.1 |
| cogeneration and other resources | 6 | 8.5 | 13.2 |

With regards to energy storage, it is stated in the *PNIEC* that it has to increase by 6 *GW* between 2020-2030, where 2.5 *GW* must correspond to batteries and 3.5 *GW* to *PHS* [22].

## 5.2 Climate change impacts

In Spain, as in the rest of the world, in recent decades there has been an increase in the number of extreme weather events, which due to climate change, far from decreasing, is forecasted to increase in the future. The vast majority of extreme weather events that Spain faces, stem from global warming and from the reduction in the average amount of rainfall [24].

As a consequence of global warming, in the last 50 years, the average annual temperature in Spain has increased by 1.5 *°C*, what has doubled the number of heat waves compared to 1984 and has caused summers to be 5 weeks longer than in 1980. Also, the comparison between the month of June in recent years with that of the years 1980 and 1990, indicates that there are currently 10 more days of heat waves, which far from reducing, are forecasted to keep increasing in number [25]. Rising temperatures and heat waves, among many other consequences, lead to a loss of efficiency in electricity generation and in electricity transmission, as well as to an increase in electricity demand derived from the greater use of cooling systems.

Respect to precipitation patterns, in recent years there has been a decrease in the average amount of precipitation, which is even forecasted to increase even more in the coming decades. This reduction in the amount of rainfall makes droughts more frequent, what reduces hydropower electricity generation, as happened in 2016-2017 when hydropower generation of electricity was reduced by 50 *%* [24]. Also, drought affected areas are more prone to flooding after a torrential rain event, so, as these torrential rains are foreseen to become more frequent, the number of floods in certain areas increases.

However, it is the combination of the decrease in the average amount of rainfall with the increase in temperatures that really hampers the operation of the electricity grid. High temperatures together with heat waves accelerate the evaporation of water reserves, what added to the decrease in the amount of rainfall, leads to a remarkable increase in water scarcity. This, not only increases the pressure on hydropower generation, but it also has negative consequences on the output of water – cooled thermal power plants. Also, this reduced amount of rainfall that leads to more frequent and severe droughts, together with high temperatures and more frequent and longer heat waves also greatly increases the number of wildfires.

## 5.3 Variability of solar *PV* and wind electricity generation outputs

In order to demonstrate that the variability of *RER* electricity outputs can be extended over long periods of time (more than 8 hours, days or weeks), and therefore, long duration flexibility needs increase as *RERs* penetration deepens, we analyze the onshore wind and solar *PV* electricity generation outputs in Spain during the year 2019.

To analyze wind´s variability, we obtain the capacity factor for each hour of the year 2019 in Spain [26]. Capacity factors for each hour are calculated as the maximum electricity that could be generated in each hour of the year 2019 by all the wind plants in Spain over the wind resources installed capacity in Spain in the year 2019.

Wind speed can change drastically from one hour to another, but normally, when a low or high wind speed regime sets in, it usually lasts for several days. To prove this statement, since wind speed is strongly related to wind resources electricity generation, we analyze the duration of large or small wind electricity generation events in Spain in 2019. To do so, we grouped the hourly capacity factors into three different time scales: hours, days and weeks and then, we quantify the consecutive periods for each different time scale in which generation was considered small or large. We define a small generation event as period of consecutive hours, days or weeks when the capacity factor is less than 0.1457, which represents the first quartile of the hourly capacity factors in Spain in 2019. On the contrary, we define a large generation event as a period of consecutive hours, days or weeks when the capacity factor is higher than 0.3503, which represents the third quartile of the hourly capacity factors in Spain in 2019.

To link the results with the need for *LDES*, we compute the number and duration of small and large generation events above 8 consecutive hours. The number of small or large wind generation events above 8 consecutive hours results in 1,892 hours of small generation and 1,950 hours of large generation, distributed as in figure 6. The longest multi-hour event of small generation was 91 hours, while the event with longest number of consecutive hours of large generation was 118 hours, what demonstrates the long durations of the events in which a Spanish electricity grid very dependent on wind resources would need to either store or generate electricity in order to reduce possible supply and demand imbalances.

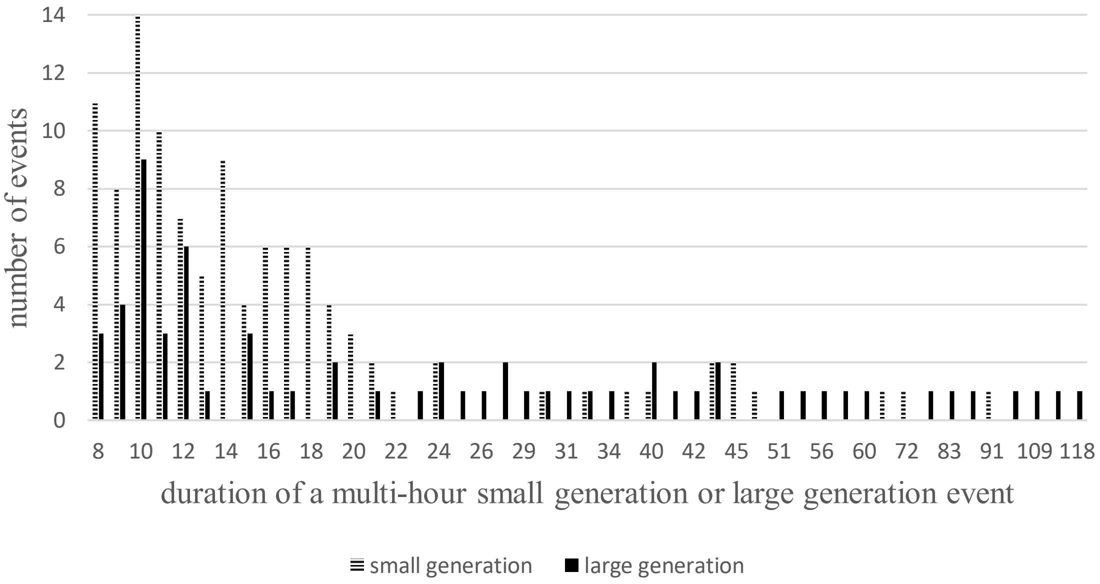

Figure 6: Number and duration of multi-hour events with small and large wind electricity output in 2019.

The results we obtain under daily time scale, presented in figure 7, highlight even more the long duration variability of wind resources, as in the year 2019, there was a number of 73 small generation days and 81 large generation days.

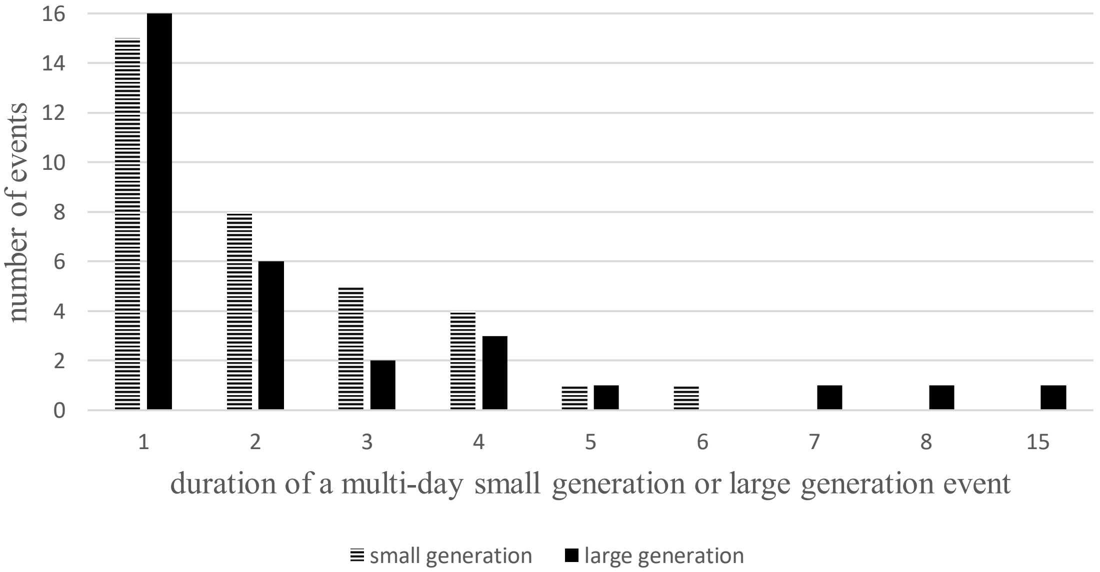

Figure 7: Number and duration of multi-day events with small and large wind electricity output in 2019

The longest small generation event had a duration of 6 consecutive days, while 1 day is the most repeated small generation event. Respect to large generation events, results show that the longest duration of a large generation event was of 15 consecutive days, while 1 consecutive day the most repeated event.

Under the week time scale, as illustrated in figure 8, the longest large generation event had a duration of 5 consecutive weeks, while there was only 1 consecutive week of small generation.

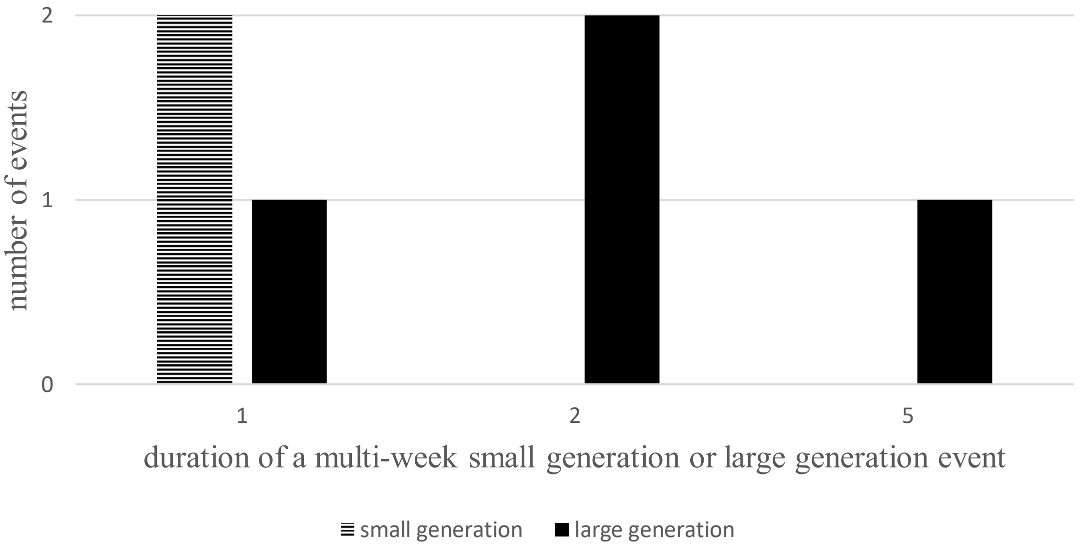

Figure 8: Number and duration of multi-week events with small and large wind electricity output in 2019

This analysis has been performed taking into account all wind facilities in Spain, so then, low generation in some locations can be offset by high generation in other locations. In contrast, in small and little interconnected grids, such as the Canary or Balearic islands, this does not occur and thus, this long duration variability of wind resources can produced more acute supply and demand imbalances

To demonstrate the extended duration of the variability of solar *PV*, we obtain the solar capacity factors in Spain for each hour of the year 2019 [26]. Sun is also a very variable resource, that does not produce at night, what leads to about 10 consecutive hours of non-generation each day. Then, due to the large number of periods of zero generation, in order to select the values that determine whether we have an event of small generation or an event of large generation we apply a slightly different criterion than for wind electricity generation. We calculate the first and third quartile, as we did for wind power generation, but without considering nights. We define a small generation event as period of consecutive hours, days or weeks when the capacity factor is less than 0.131, which represents the first quartile of the hourly capacity factors in Spain in 2019. On the contrary, we define a large generation event as a period of consecutive hours, days or weeks when the capacity factor is higher than 0.525, which represents the third quartile of the hourly capacity factors in Spain in 2019.

Although Spain is a very sunny country and solar *PV* resources are very geographically distributed, long events without sun affecting to the whole country are not as rare as expected. On the contrary, since every night there are approximately 10 hours of zero electricity generation, the number of large generation events is zero for all selected time scales. Therefore, in the following figures, we only represent the duration and the number of small generation events. Our results in figure 9 show that the duration of the small generation events, is concentrated between 12 and 14 hours, in addition, there are also isolated events of many consecutive hours of small generation, being the maximum of 21 hours.

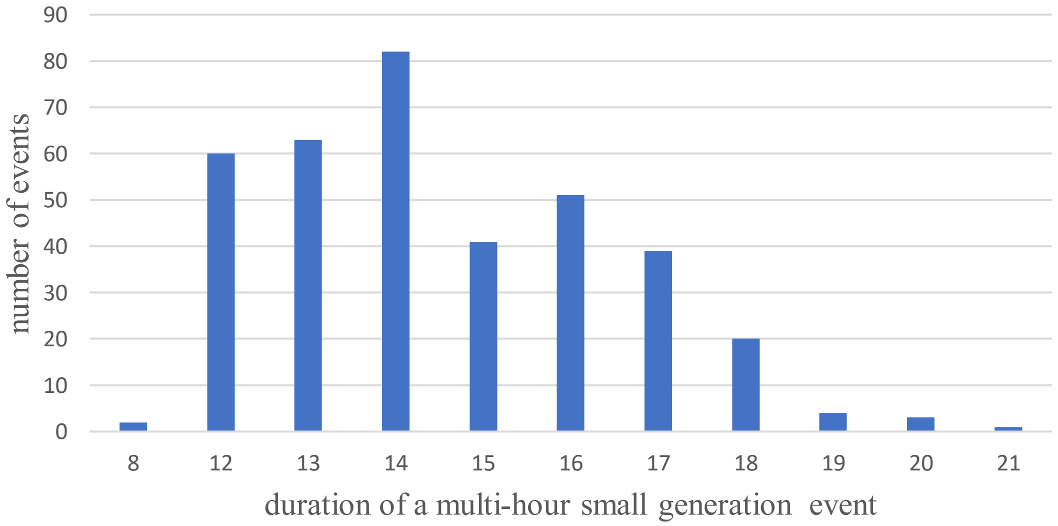

Figure 9: Number and duration of multi-hour events with small solar *PV* electricity output in 2019

Under the daily perspective, as figure 10 shows, the number of days of low generation is 92, being 2 consecutive days the most repeated event. In Spain, as in many other places with very different climates between seasons, the number of sunshine hours during winters is considerably low compared to summer. In this case, this has resulted in the longest duration of an event to be of 54 consecutive days of low generation, which took place during January and February, in 2019.

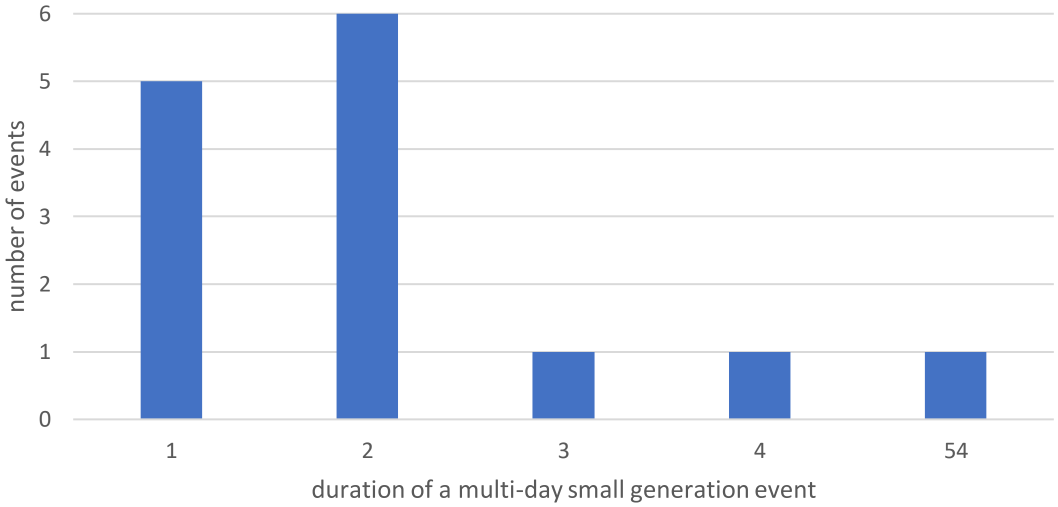

Figure 10: Number and duration of multi-day events with small solar PV electricity output in 2019

Figure 11, illustrates the number and duration of small or large solar *PV* generation under the weekly timescale, which due to the much more reduced amount of sun in winter months, resulted in an event with three consecutive small generation weeks on January and a maximum event of 10 consecutive small generation weeks, which took place since the end of November until December of 2019.

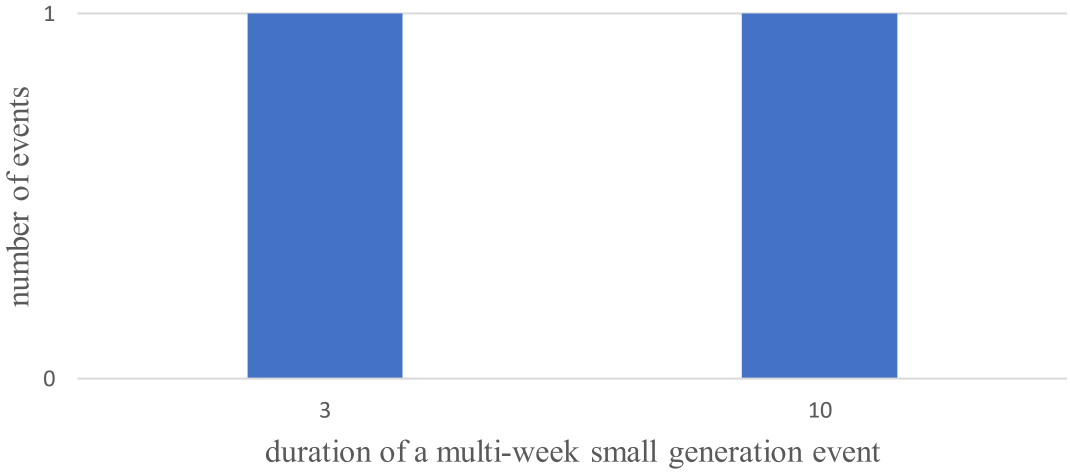

Figure 11: Number and duration of multi-week events with small solar *PV* electricity output in 2019

## 5.4 Electricity supply and demand imbalances in 2050 possible scenario

The long duration variability of electricity generation from wind and solar *PV* resources can cause the presence of long periods of time in which their generation is either very large or very small. Consequently, in those grids totally dependent on *RERs* electricity generation, just as it is forecasted for Spain by 2050, the long duration of these periods coupled with an increasing electricity demand can lead to more frequent and larger periods of curtailment or of lack of supply and as result to a greater need for long duration flexibility. Therefore, to prove this statement, in this section we present the magnitude and duration of the electricity supply and demand imbalances resulting for the 2050 possible scenario we have developed.

First, it is important to note the large amount of electricity curtailment that our results reflect. According to our estimates, the sum of the electricity curtailed in all the hours of 2050, results in 22.17 *TWh*. When our forecast results in a curtailment event, the average electricity curtailed in one hour is 9.89 *GWh*, while the maximum is 40.66 *GWh*. In addition, curtailment events are not only large, but they are also common and long, as shown in figure 12. The most common long duration of a curtailment event is 8 and 9 hours, as each period accounts for 33 events, while the longest duration of a curtailment event reaches a maximum of 65 consecutive hours.

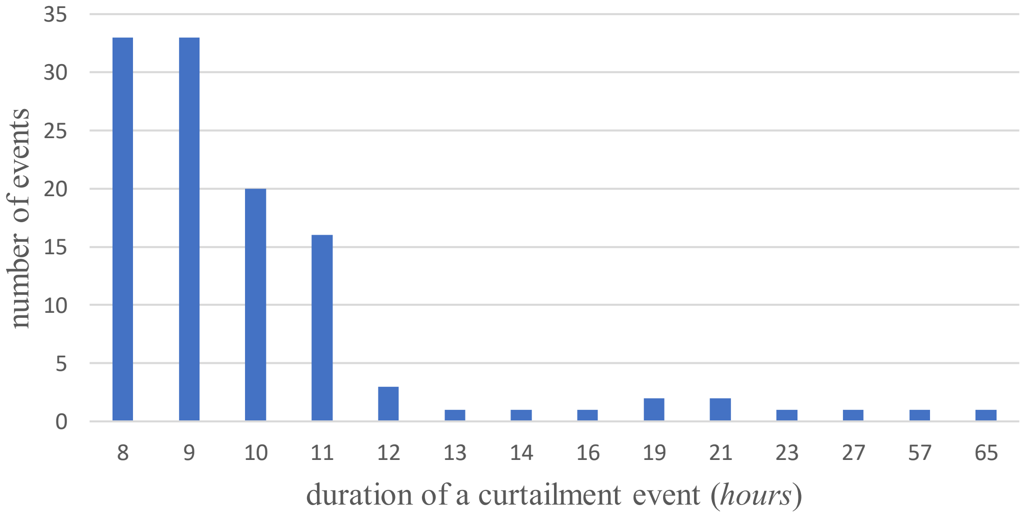

Figure 12: Possible 2050 scenario: duration and number of long curtailment events

In table 2, we summarize the results we obtain for electricity curtailment events in our 2050 possible scenario.

Table 2: Possible 2050 scenario: results of long electricity curtailment events

| average electricity curtailed per hour (*GWh*) | maximum electricity curtailed per hour (*GWh*) | average duration (*hours*) | maximum duration (*hours*) |
|---|---|---|---|
| 9.89 | 40.66 | 10.92 | 65 |

With respect to the events in which there is a lack of supply to meet electricity demand, the magnitude of these figures is also very remarkable, since in our 2050 possible scenario we forecast a lack of 19.17 *TWh*, distributed as in figure 13.

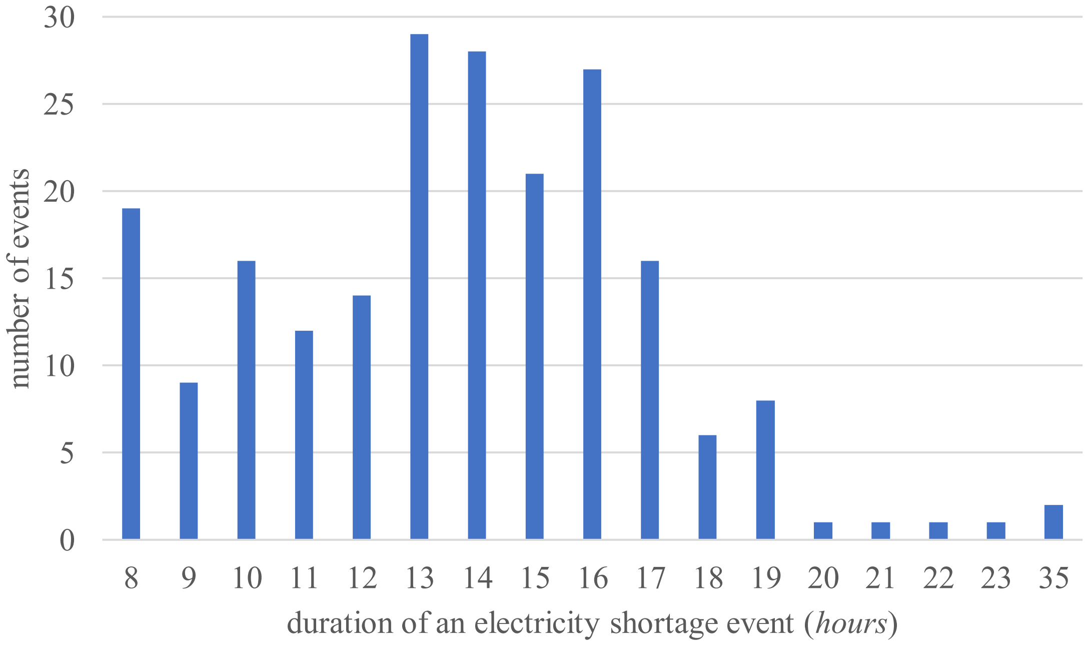

Figure 13: Possible 2050 scenario: duration and number of long electricity inadequacy events

The amount of electricity shortage in one hour reaches a maximum of 22.76 *GWh*, and the average electricity shortage per hour results in 5.6 *GWh*. Regarding the number of long duration electricity shortage events, our 2050 possible scenario, results in 2,897 hours of supply shortages grouped into 211 different events. Respect to the duration of these periods, we notice that most of these events are in a range between 13 and 16 hours. At the same time, as in the case of curtailment periods, there are also isolated events with very long durations, with a maximum of 35 consecutive hours of lack of supply.

In table 3, we summarize the results we obtain for electricity shortage events in out 2050 possible scenario.

Table 3: Possible 2050 scenario: results of long electricity inadequacy events

| average electricity shortage per hour ($GWh$) | maximum electricity shortage per hour ($GWh$) | average duration ($hours$) | maximum duration ($hours$) |
|---|---|---|---|
| 5.6 | 22.76 | 13.72 | 35 |

## 5.5 Concluding remarks

Spain, in order to meet *EU* targets, must carry out a major transformation of its electricity generation resource mix, at the same time as rising temperatures, droughts, and wildfires resulting from climate change add further complications to this already difficult mission. The analysis of the electricity generation outputs of solar *PV* and wind resources in 2019, points out the existence of long and frequent periods of time in which the generation is either very small or very large, what can undoubtedly pose a great risk to the proper functioning of the 100 % renewable electricity grid planned by the Spanish government for the year 2050. Indeed, the danger of such variability in the electricity generation outputs of an electricity grid, is demonstrated by the large and long supply and demand imbalances resulting from our 2050 possible scenario, which reinforces the importance of *LDES* deployment in Spain.

# CHAPTER 6. CONCLUSIONS AND FUTURE CONTRIBUTIONS

In this chapter, we summarize the contributions of the work presented in the report and discuss some possible directions for future work.

## 6.1 Summary of contributions

The electrification of end-use sectors, rising global *GDP* and the increasing world´s population are the main drivers of the increase in electricity demand. At the same time, the achievement of decarbonization goals requires a major transformation of the electricity generation resources mix, which focuses on the retirement of controllable but polluting generation resources and their replacement by vast amounts of the uncontrollable, highly variable and intermittent wind and solar *PV* resources. Wind and solar resources, in addition to their rapidly changing nature, can settle into certain stable regimes, and therefore, as decarbonization targets are realized and the main sources of flexibility are retired, the provision of grid operational flexibility on all time scales becomes an increasingly difficult challenge. Furthermore, the rapid integration of such vast amounts of *RERs*, the integration of new distributed resources and the integration into the grid of new loads, leads to a need for a rapid and capital intensive network expansion, which while being realized, leads to a large increase in the number and duration of grid congestion events at both the transmission and distribution level.

Also, the increasing number of extreme weather events, coupled with the lower resilience inherent in the nature of electricity grids with deep *RER* penetration, leads to a reduction of grid resilience, which also derives in an added need for the provision of long duration grid operational flexibility. The impacts and duration of extreme weather events vary widely, but all of them, either because of their duration or because of the long periods of time required to repair damaged assets, cause a reduction in electricity supply which, together with the increase in electricity demand they cause, leads to important difficulties in the supply of electricity.

Thus, as electricity grids deepen the penetration of *RERs*, flexibility needs in all timescales increase mainly due to the variability of *RERs*, which is further aggravated by the impact of extreme weather events, which given their increased number, also reduce the resilience of the already vulnerable electricity grids forecasted for the future. *LDES* technologies emerge as an important zero emissions contributor to the provision of resilience and especially long duration flexibility. *LDES* technologies emerge as an important zero-emission contributor to the provision of resilience and especially long-duration flexibility. The main contribution of *LDES* is based on the storage of electricity and its subsequent discharge during long periods of time when electricity supply is lower than needed. In addition, their modularity, scalability and shorter lead times, propose them as very good alternatives to reduce the amount of curtailed electricity derived from grid congestion events. Also, the few allocation constraints of many of these technologies, and their low risk to the population, allow the strategic selection of their locations to improve the robustness and recovery capabilities of the electricity grid. Indeed, in the case study we demonstrate the need for the deployment of *LDES* technologies in Spain, which mainly derives from the long duration variability in solar and wind resources electricity generation outputs and from the 100 % renewable grid planned for the year 2050.

## 6.2 Directions for future contributions

In this report, we have explained how *LDES* technologies can contribute to the provision of resilience and flexibility, based on their salient characteristics. However, there are many *LDES* technologies with different characteristics, and therefore it is convenient to study the contribution of each one of them. I believe it is also convenient to make an economic study of these technologies that allows the comparison of the cost of *LDES* energies, with the cost of those technologies they seek to replace, such as generation sources or grid expansion projects. With respect to resilience improvement, the geographic distribution of *LDES* technologies is a very important factor in determining the extent to which these technologies improve the resilience of grids, so it is necessary to develop models, based on probabilistic studies of extreme weather impacts, to analyze the best places to place these technologies.

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# APPENDIX A: LIST OF ACRONYMS

| | |
|---|---|
| *APS* | announced pledges scenario |
| *CCGT* | combined cycle gas turbines |
| *CCUS* | carbon capture utilization and storage |
| *CSP* | concentrated solar power |
| *CRS* | Congressional Research Service |
| *EU* | European Union |
| *EPA* | Environmental Protection Agency |
| *GDP* | gross domestic product |
| *IDEA* | Instituto para la Diversificación y Ahorro de Energía |
| *IEA* | International Energy Agency |
| *IRENA* | International Renewable Energy Agency |
| *ISO* | independent system operator |
| *LCOE* | levelized cost of energy |
| *LCOS* | levelized cost of storage |
| *LDES* | long duration energy storage |
| *MITECO* | Ministerio para la Transicion Ecológica y el Reto Demográfico |
| *NREL* | National Renewable Energy Laboratory |
| *NOAA* | National Oceanic and Atmospheric Administration |
| *NZS* | net zero emissions scenario |
| *PHS* | pumped hydro storage |
| *PNIEC* | Plan Nacional Integrado de Energía y Clima |
| *PV* | photovoltaic |
| *RD&I* | research, development and innovation |
| *REE* | Red Eléctrica Española |
| *RER* | renewable energy resource |
| *RFF* | Resources for the Future |
| *SPS* | stated policies scenario |
| *T&D* | transmission and distribution |
| *US* | United States |
| *VER* | variable energy resource |
| *WMO* | World Meteorological Organization |

# APPENDIX B: MODEL FOR SPAIN ELECTRICITY GRID 2050, METHOLODOGY AND DATA

In this appendix we explain the procedure, the assumptions and estimates that have allow us to develop the 2050 possible scenario, used as input for the model from which we obtain the results on the duration and magnitude of the supply and demand imbalances presented section 5.4.

The model takes as inputs the estimated installed capacity by technology in 2050, the capacity factors by technology in 2019, as well as the estimated demand for 2050 and the estimated interconnection capacity of the country for 2050. Then, after a series of calculations, we obtain as outputs the electricity generated by technology on an hourly basis, the estimates for the year 2050 of the curtailed electricity by technology and the electricity shortage in each hour of the year 2050.

To explain in a clear and didactic way how we obtain our results we have developed the following diagram:

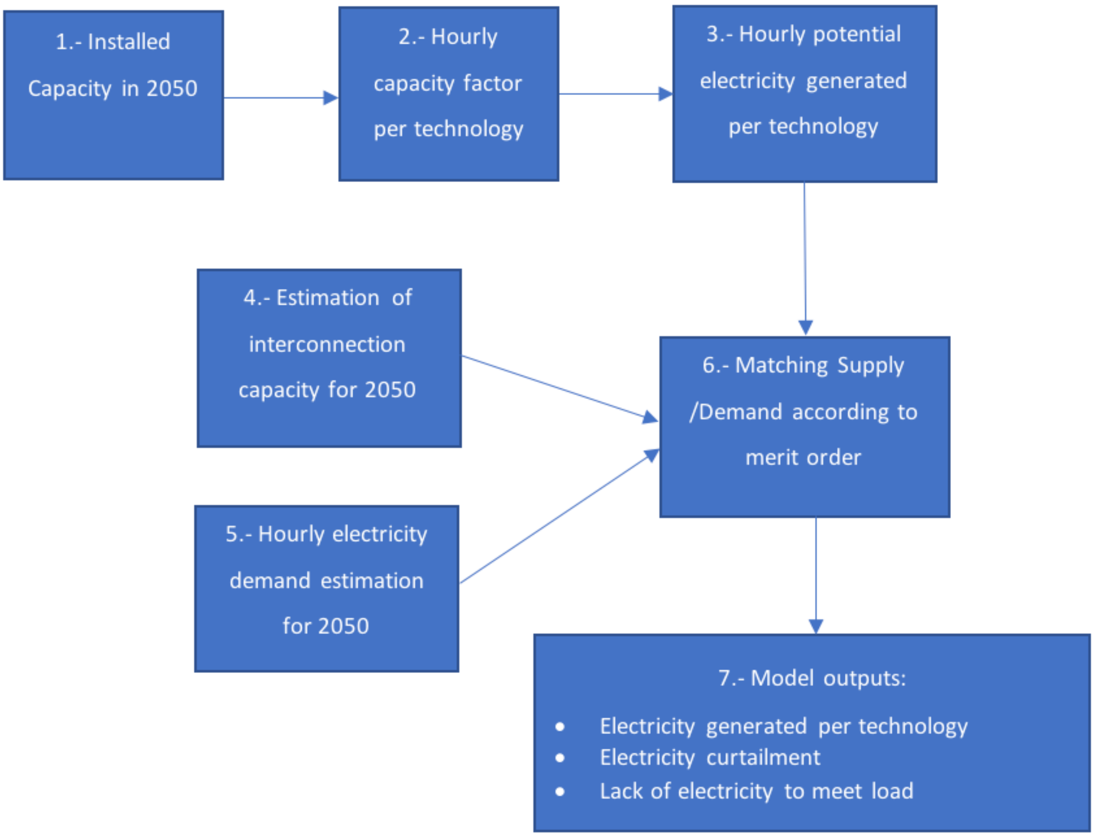

Figure 14: Model´s methodology graphical description

Firstly, to forecast the electricity that each technology can generate in each hour of 2050, we estimate the installed capacity of each technology in 2050. Next, we estimate the capacity factor of each technology in each hour of the year. And finally, we multiply hour by hour the installed power of each technology by its respective capacity factor, what gives us the maximum electricity that each technology will be able to produce in each hour of the year 2050, according to our forecast.

Secondly, in order to quantify the amount of electricity generated in each hour by each technology, we have to estimate the demand in each hour of the year 2050, as well as create a merit order for matching the supply with the demand. The term merit order is used to explain the mechanism that establish the order in which generation technologies enter the market to try to meet demand. This idea is very complex, but the basis of its operation is to reduce the cost of electricity, so in this report, we simulate this mechanism in the following way. The cheapest resource is the first to try to provide all the electricity needed to meet demand, if it fails to do so, then, the next cheapest energy source comes in, and so on. Moreover, since in this merit order, it is necessary to take into account the interconnection between countries, it is also necessary to estimate the interconnection ratio.

At this point we have already made all the necessary estimates to be able to make the balance between supply and demand, which allow us to obtain the outputs of the model. Also, it is important to understand the following additional assumptions. This model does not consider the curtailed electricity due to grid congestion, therefore, the resulting flexibility needs can be even higher than the ones obtained. In addition, both demand and generation are referenced to power plant busbars, so it is not necessary to account for *T&D* line losses.

Next, once we understand the functioning of the model, we explain how we have obtained or made the different estimates used in the case study developed in the thesis.

1.- Installed capacity by technology in 2050.

To make this first estimate, we base ourselves on the 2030 targets set in the *PNIEC* [22], as well as on the estimates made for 2050 in the document "Flexibility Solutions for High-Renewable Energy Systems " [27]. In table 4 we show the data given by both sources.

Table 4: Forecasted installed capacity of primary electricity generation resources in Spain: 2030 and 2050 [22],[27]

| technology | installed capacity 2050 (*GW*) | installed capacity 2030 (*GW*) |
|---|---|---|
| wind onshore + offshore | 54 | 50.33 |
| solar *PV* | 49 | 39.18 |
| solar thermal | 7.31 | 7.31 |
| hydropower | 16 | 14.61 |
| biomass and waste | 2.55 | 1.75 |
| biogas | - | 0.24 |
| natural gas | 27 | 32.14 |

However, the document [27], makes its estimates for a grid in which 88 % of the electricity generated comes from renewable resources, while in our analysis the totality of the electricity generated has to come from renewable resources, as it is established in the *PNIEC*. For this reason, we extend the installed capacity estimated in [27] to a 100 % renewable grid. According to the projections of [27], *CCGTs* account for all the nonrenewable electricity generation, with 27 *GW* of installed capacity. The study divides the use of this capacity into 2 types: 2 *GW* of base load capacity and the remainder for peak load use. In our case study, we assume that the 2 *GW* of base load capacity is replaced by the same installed biogas capacity, as we assume the same capacity factor for both technologies. For the peak load electricity generation mix, we assume that the gas fired power plants used for this purpose are replaced by solar *PV* and wind, which are likely to be the two most important generation resources in 2050 according to [27]. To calculate the additional installed capacity of each technology that has to be installed in addition to that indicated in [27], we assume that solar *PV* and wind energy will each contribute to 50 % of the electricity previously generated by the gas peaking technologies.

Next, we assume that the average annual capacity factor of each technology in 2050 is the same as in 2019, and thus, we calculate the additional installed capacity that has to be installed for each technology. We have now extended the installed capacity estimate of [27], to a 100 *%* renewable grid. However, this estimate does not take into account the promising development of offshore wind energy in Spain. In Europe, it is forecasted 60 *GW* of installed offshore wind capacity for 2030 and 300 *GW* for 2050 [28], while for Spain it is forecasted 3 *GW* of installed offshore wind capacity for 2030 [29]. Thus, the use of the same growth rate as predicted for Europe, indicates 15 *GW* of installed capacity in Spain by 2050. However, given that Spain has an insular geography, a great experience in wind technologies, a very developed port-maritime sector and a strong investment in *RD&I*, which places it among the 3 European countries with the highest investment in the sector, we prefer to make a more aggressive estimate. In our model, as it was forecasted this year at the "Wind Europe 2022" event, we assume 17 *GW* of installed offshore wind capacity in Spain [30]. Now, we have to divide the installed wind capacity obtained into onshore wind and offshore wind according to the above estimate. Finally, after the corresponding calculations, we obtain the following estimate of the installed capacity in Spain in 2050, shown in table 5.

Table 5: 2050 possible scenario forecasted installed capacity of primary electricity generation resources in Spain

| technology | installed capacity in 2050 (*GW*) |
|---|---|
| wind onshore | 37.49 |
| wind offshore | 17 |
| solar *PV* | 49.74 |
| solar thermal | 7.31 |
| hydropower | 16 |
| biomass and waste | 2.55 |
| biogas | 2 |

2.- Hourly capacity factor by technology

For the calculation of hourly capacity factors in 2050, we assume that they are the same as in 2019 due to the following reasons:

- we assume that wind, sun and rain generation electricity outputs remain the same, which is a conservative assumption because although the amount of sun and wind are forecasted to remain the same, the amount of rain is forecasted to be less;
- we assume that technological improvements will not be large enough to produce major changes in the efficiency of technologies, and if they were, their contribution will not make much of a difference.

According to publicly available data, we follow different approaches to calculate the capacity factor of each technology:

- solar *PV* and wind onshore: data is obtained from [26];
- biomass-waste and biogas: since they are controllable generation sources that work in a very similar way as combined cycles gas turbines, we assume that their capacity factors are the same. To calculate the capacity factor of a *CCGT*, we take from, the available power in each hour of 2019, and then we divide these data by the installed capacity in that same year [31];
- solar thermal: we obtain the hour by hour power available in 2019 from [31], then we divide these data by the installed capacity of this technology in that year, what results in the hour by hour capacity factor;
- hydropower: in the case of hydropower, given its operation, unlike other technologies, when we divide the available power by its installed capacity, we do not obtain its real capacity factor. This is because hydropower bases its operation on water storage, so if all the available power is used in one hour, all the water reserves will be exhausted, what means that no electricity can be generated until these reserves are filled again. Therefore, to calculate the hourly capacity factor in this case, we have divided the hour per hour average of hydropower generation in 2017, 2018 and 2019

by the installed capacity in 2019, since this was the same as in 2017 and 2018 [31];

- coal and nuclear as they will not exist in Spain in 2050 according to our scenario, their calculation is not necessary;
- wind offshore: at present, there is no offshore wind installation in Spain, so it is not possible to obtain the hourly generation output of this technology. Also, since there is no study that predicts these data, we have had to make the following estimate. The best areas to install offshore wind power plants in Spain, which are located on the Galician coast, on the Catalan coast and on the coast of Cadiz. Then, to obtain the hourly capacity factors in 2019, we used the software of [26], to simulate the hourly generation of three fictitious plants located in these locations. Finally, we do the hour to hour average between these three plants to obtain the hourly offshore generation output used in our model. In this way we have obtained an average annual capacity factor of 48 *%,* which is very close to the number certain predictions give for 2050 [32].

3.- Potential electricity generated by technology

We multiply the hourly capacity factor by the installed capacity in 2050 of each generation technology.

4.- Estimation of interconnection capacity in 2050

A country's interconnection is measured by the interconnection ratio, which is a percentage measure obtained by the comparison of the country's interconnection capacity with its installed capacity. In 2002, the *EU* recommended to all member countries to achieve an interconnection ratio of 10 *%* by 2020. However, by 2020, Spain had not only failed to reach this target, but was well below it, with less than 6 *%* interconnection ratio. Furthermore, the *EU* continues to increase the required interconnection ratio, and establishes that all member states have to reach an interconnection ratio of 15 *%* by 2030.

Currently, among the projects existing in Spain, 4 of them stand out due to their magnitude and importance. These projects are expected to be completed by 2030-2035 and will increase the interconnection capacity from the current 6.7 *GW* to 12.6 *GW* [33], which stills very far from the *EU* targets.

In our model, based on historical trends, the current situation, the planned projects, the European targets and the political and procedural difficulties that usually arise in this type of projects, we prefer to assume a conservative estimate for the development of the interconnection capacity, therefore we assume that the interconnection ratio in 2050 will be 10 *%* of the installed capacity of that year, which results in 15.5 *GW* of interconnection capacity.

However, it is unrealistic to assume that this interconnection capacity is available at every moment, since the fact that Spain has too much or too little electricity does not mean that neighboring countries need it or have too much of it to be able to export or import it. We assume that in the coming years the generation mix of neighboring countries evolves according to the trends observed today, so we assume that the relationship between Spain and its neighboring countries in terms of electricity interconnection remains similar to the current one. Portugal has both a climate and a generation mix very similar to Spain, so it is logical to think that this continues to be the case in the future. France plans to maintain a generation mix very similar to the current one, relying mainly on nuclear and renewables. And finally for Morocco, which has only 0.8 *GW* of interconnection with Spain, we assume they maintain a very similar electricity generation mix to that existing today. Therefore, to calculate the power available for import and export we have obtained from [31], the electricity imported and exported in the year 2021. Then, the division of these results by all the hours of a year, results in the annual average import and export capacity of the year 2021. Finally, we first divide these results by the interconnexion capacity in 2021, and then we multiply it by the estimated interconnection capacity in 2050, what results in the hourly average of import and export capacity available during the year 2050.

- Import capacity: 4650 *MW*
- Export capacity: 2604 *MW*

### 5.- Electricity demand estimation for 2050

First, it is necessary to estimate the electricity demand in 2050 and then distribute it by hours. The study [27] forecasts a 19 *%* higher demand in 2050 than in 2019 (249,010.775 *TWh*) [34], what results in a projected electricity consumption in 2050 of 296,322.82 *TWh*. To distribute this demand on an hourly basis, we assume that its distribution in 2050 is the same as in 2019, since demand is conditioned by factors that vary very little from one year to another, such as population habits or climate. Notice that we have not taken into account the change in consumption patterns that generation at behind-the-meter installations can cause in demand at busbar power plants.

6.- Supply and demand matching

Once we have obtained the maximum hourly generation estimates for each technology, the hourly demand and the interconnection ratio that will exist according to our predictions in 2050, we move on to establish the matching of supply and demand. Following the sequence marked by the concept of merit order explained previously in this chapter, 3 types of situations can occur:

On the one hand, we can have situations in which generation does not meet demand. If this occurs, electricity will be imported, up to the limit set by the interconnection ratio. On the other hand, it can happen that generation is greater than demand in a given hour. In that case, electricity will be exported up to the limit set by the interconnection ratio. And in the last case, it can happen that generation is exactly equal to demand, in which case neither electricity will be exported or imported.

Based on the *LCOE* of the different resources [35], the merit order is as follows:

I. Hydropower
II. Wind onshore
III. Biomass-waste
IV. Solar *PV*
V. Wind offshore
VI. Thermal solar
VII. Imports / exports

After running the model as indicated and with the previous merit order, we obtain as a result, for each hour of the year 2050: the electricity that each technology generates, the electricity curtailed for solar *PV*, thermal solar, wind offshore and wind onshore, as well as the shortage of electricity to meet demand.