Renewable and Sustainable Energy Reviews 174 (2023) 113094

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review article

The 2030 power sector transition in Spain: Too little storage for so many planned solar photovoltaics?

Roberto Gómez-Calvet [a,*], José M. Martínez-Duart [b], Ana Rosa Gómez-Calvet [c]

[a] Universidad Europea de Valencia, Faculty of Social Sciences, Paseo Alameda, 7, 46,010, Valencia, Spain
[b] Universidad Autónoma de Madrid, Spain
[c] Universidad de Valencia, Spain

ARTICLE INFO

JEL classification:
Q4
Q47
Q58

Keywords:
Electricity
Spain
Variable renewable energies
Energy storage
NIECP

ABSTRACT

This work deals with the 2030 power transition in Spain following the pledges with the European Union targets of reaching climate neutrality, or net zero emissions, by 2050. Within this context, we analyze in this work the plan established by the Spanish government under the umbrella of the National Integrated Energy and Climate Plan which fixes very specific objectives for the evolution of the electricity power mix for the period 2020–2050. In the case of photovoltaics, it would imply to multiply by almost a factor of four its 2020 value, reaching near 40 GW in 2030. Being photovoltaics a variable, non-dispatchable renewable energy, to take full advantage of it, it would be needed a large amount of storage capacity and backup power with very fast ramping responses. Otherwise, we would have to curtail part of the incoming solar photovoltaic energy. Based on historical data and making use of duck curves, we have also shown that the large growth of PV (2020–2030) will require needs of storage capacity and/or backup reaching values of 5 GW per hour during 4 h during the afternoon–evening. According to the National Integrated Energy and Climate Plan, our results show that this plan has not yet properly foreseen these requirements and some curtailment may be needed.

1. Introduction

The aim of this study is to evaluate the impact of high penetration of renewable energies, mainly solar photovoltaics (PV), into the national power grid of Spain. We will mainly focus on PV since, according to the National Integrated Energy and Climate Plan (NIECP) for the 2030 Power Transition, it will increase by close to 4-fold up to 39.2 GW in 2030 [1]. Added difficulties of integration of large percentages of PV, as well as wind, come from the fact that they are variable or non-dispatchable renewables sources.

In this work, after a short description in Section 2 of the power system in Spain during the 2019–2021 triennium, we report in Section 3 the targets of the power system mix to be reached in 2030, and already approved by our Government and the European Union [2]. Later, in Section 4 we analyze the consequences on the national distribution grid of implementing large amounts of solar PV, using the concept of the "duck curve". As we will see, the introduction of this concept will be of great help for the calculation of the large amounts of needed power (around 20 GW) during several hours before sunset and evening when the PV energy rapidly goes down. Finally, in Section 5 we reach the conclusion that in 2030, the available back-up systems, like natural gas turbines, as well as the projected storage (hydro-pumping, batteries, hydrogen), are mostly not enough to provide all the power needed during periods of several hours in parts of the afternoon and evening.

2. The power system in Spain during the 2019–2021 triennium

In Table 1 it is represented the power capacity and electricity generated by each source during the period 2019–2021 in Spain. Focusing on 2021 it can be deduced that the percentage of renewable electricity is 48% and, by adding nuclear, the percentage of electricity free of CO_2 emissions is 70%.

It will very convenient for the further analysis of the system to have a representation of the average hourly demand for all days of the year as in Fig. 1. Observe that during the 5–8 a.m. interval, the relative high slope of the demand is provided mainly by hydro power and combined cycle gas turbines.

By making some plots from the data of Table 1, we can show in this work some important advances towards the 2030 Energy Transition. First, it can be observed that coal generating plants decreased their contribution to the whole system from 14.5% in 2018 to just 4.5% in

* Corresponding author.
E-mail addresses: roberto.gomezcalvet@universidadeuropea.es (R. Gómez-Calvet), martinez.duart2@gmail.com (J.M. Martínez-Duart), ana.rosa.gomez@uv.es (A.R. Gómez-Calvet).

https://doi.org/10.1016/j.rser.2022.113094
Received 8 June 2022; Received in revised form 16 November 2022; Accepted 24 November 2022
Available online 23 December 2022

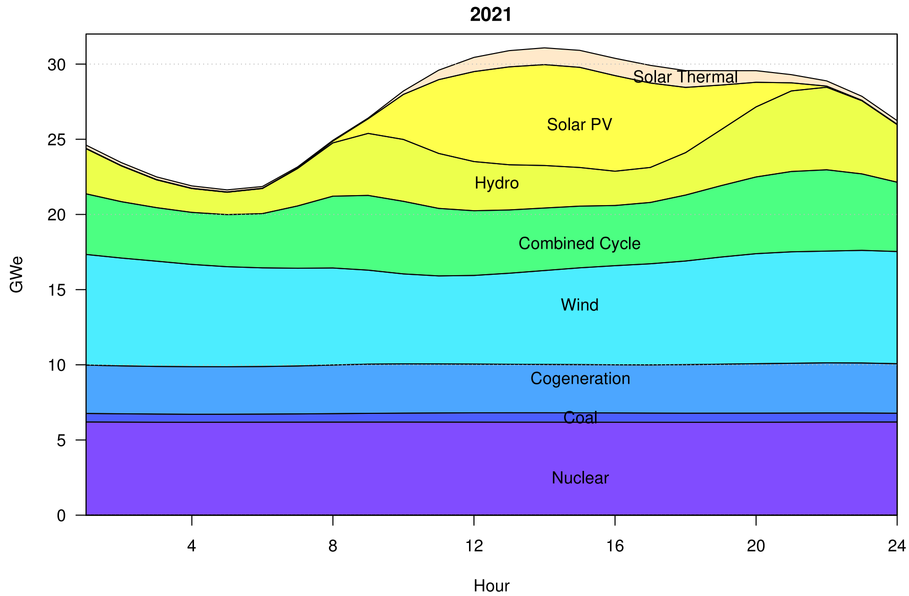

Fig. 1. Average of hourly demand-generation for all days of 2021.
Source: Authors using data from [3].

Table 1
Power generated and installed capacity during the triennium 2019–2021. Units: Power generated in GWh. Installed Capacity in MW, all sources in AC.
Source: Authors using data from [3].

	Electricity generated (GWh)			Installed power (MW)		
	2019	2020	2021	2019	2020	2021
Nuclear	55 962	55 813	54 199	7 117	7 117	7 117
Coal	11 092	5 133	5 138	9 741	8 482	4 832
Hydro	23 356	28 694	28 084	17 092	17 098	17 093
Combined cycle	51 575	38 793	38 177	26 250	26 250	26 250
Wind	52 382	53 149	59 012	24 140	26 544	27 853
Solar photovoltaic	9 215	15 477	20 650	6 265	10 119	13 211
Solar thermal	5 199	4 556	4 698	2 304	2 304	2 304
Cogeneration	32 353	29 862	28 337	5 745	5 721	5 677
Total	244 784	236 081	243 090	98 654	103 636	104 338

2019. This fact can be observed in Fig. 2 in which we can notice for the year 2019 (8760 h) that a large part of the coal production was substituted by other sources. This could be done in a short period of time since our power system had a very large network (26.2 GW) of idle combined cycle plants (see Table 1). In addition, this transition was also favored by the high prices of carbon in the European Emissions Trading System [4].

The other point we would like to remark is the very large increase of solar photovoltaics (PV) which has multiplied its power capacity by more than double, since it evolved from 6.3 GW in 2019 to 13.2 GW in 2021 as shown in Table 1 and Fig. 3. In later sections we will come back to this point when we discuss the so-called “duck curves”.

3. The Spanish National Plan for Energy and Climate

Based on the directives of the 2030 European Energy Transition, the Spanish Government elaborated a 10-year program, named National Integrated Energy and Climate Plan 2021–2030 (NIECP), and also known by its Spanish acronym of PNIEC.[1] The Plan, approved by the Parliament, was published on March 25, 2021 [1]. The NIECP has as one of its main objectives that the Spanish power system should become carbon-neutral by 2050 and for this purpose, a calendar was elaborated with objectives of all energy sources every five years and ending in 2030 (see Table 2).

Table 2
Summary of the NIECP *Objective Scenario* of the installed capacity (MW in AC) for 2030 Energy Transition.
Source: Ministerio Transición Ecológica y el Reto Demográfico [1].

	2015	2020	2025	2030
Wind(On/Off shore)	22 925	28 033	40 633	50 333
Solar PV	4 854	9 071	21 713	39 181
Solar thermal	2 303	2 303	4 803	7 303
Hydro	14 104	14 109	14 359	14 609
Open-loop pumped-hydro storage	2 687	2 687	2 687	2 687
Close-loop pumped-hydro storage	3 337	3 337	4 212	6 837
Biogas	223	211	241	241
Other renewables	0	0	40	80
Biomass	677	613	815	1 408
Coal	11 311	7 897	2 165	0
Combined cycle	26 612	26 612	26 612	26 612
Cogeneration	6 143	5 239	4 373	3 670
Fuel/Gas (Non peninsular areas)	3 708	3 708	2 781	1 854
Waste and others	893	610	470	341
Nuclear	7 399	7 399	7 399	3 181
Storage	0	0	500	2 500
Total	107 176	111 829	133 803	160 837

With respect to the 2030 values of Table 2, it can be deduced that around 73% of the power capacity would be renewable. Furthermore, 56% of total power capacity will be constituted by non-dispatchable sources (PV plus wind).

Regarding to nuclear energy, it can be observed from Table 1 that in the period 2019–2021 it has been the first source of power generation, around 55 TWh per year. However, before 2030, four out of the seven reactors now in operation, each one with a power of a little over 1 GW, are scheduled to be put out of service. Therefore, a relevant part of base-load power will be substituted by power from non-dispatchable renewable sources.

[1] PNIEC stands for the *Plan Nacional Integrado de Energía y Clima* in Spanish.

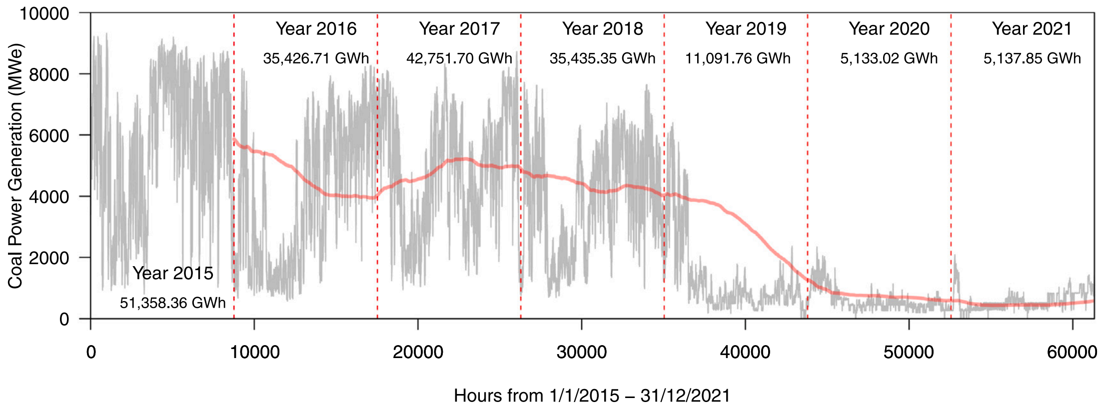

Fig. 2. Evolution of coal power generation in the yearly period 2015–2021. Red line: moving average using 365 days interval.
Source: Authors using data from [3].

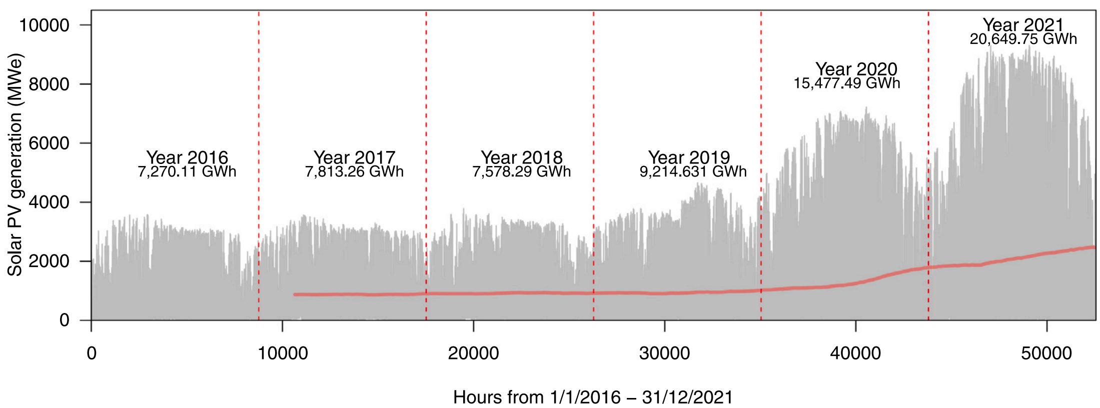

Fig. 3. Evolution of the solar PV in the yearly period 2015–2021. Unit in vertical axis: MWe in AC. Red line: moving average using 365 days interval.
Source: Authors using data from [3].

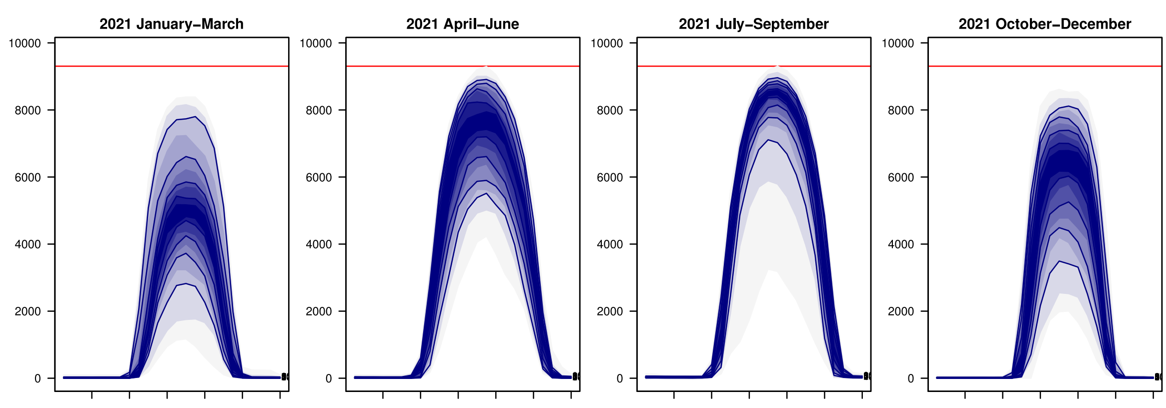

Fig. 4. Fan chart of Solar PV seasonal generation. Units: Horizontal axis in hours, Vertical axis: MW in AC.
Source: Authors using data from [3].

It will be instructive for further discussions to remark that among all generation sources displayed in Table 2, the one with the highest relative power increase in the period 2020–2030 is solar PV. In effect, it is supposed to increase by a factor of about 4, reaching a value of some 39 GW in 2030. As it will be discussed later this amount of displayed PV might be too large to be handled by the planned storage facilities and regulation. From Fig. 3 it can be deduced the evolution of PV from 2018 to 2021, which if it continues at this rate it will reach the forecasted 2030 value for generation.

Though solar PV is considered a variable renewable source, its degree of uncertainty is lower than other non-dispatchable sources like wind. However, this source is highly influenced by seasonality. In Fig. 4, we depict a set of fan-charts[2] of hourly solar PV generation plotting ten deciles with a color grade scale. The percentile 50th has

[2] Based on time series, these representations illustrate prediction intervals according to how likely is each value, running from the darkest shade of the figures for the 50th prediction interval (50th percentile) to the lightest ones

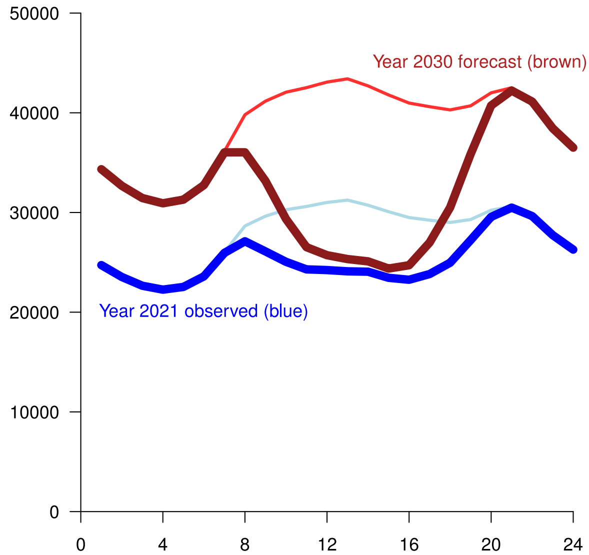

Fig. 5. Duck curves for present situation (blue curves) and 2030 NIECP *Objective Scenario* (brown curves). Thin line: demand, thick line: residual load. Units: horizontal axis: hour, vertical axis: MW.
Source: Authors using data from [1,10].

been shown with the highest intensity and those percentiles less likely with less intense color. From these pictures it is clear that for some parts of the day, like the sunset, the variance of PV generation is very low.

4. Consequences of large amounts of PV (2030). The duck curve

As remarked above, the integration of Variable Renewable Energy Sources (VRES) in the grid presents clear benefits, but might also lead to some problems. As shown by Gómez-Calvet et al. [7], wind generation in Spain is greatly contributing to generation along day and night, but it shows a large degree of hourly uncertainty and seasonal dependence. However, as shown in Fig. 4, solar PV it is more predictable for each location but only provides energy during the daylight fraction of the day.

Therefore, in order to evaluate the effects of the PV on the grid we will follow the method of the *duck curve* as used by Denholm [8], and Denholm et al. [9], since it allows to better evaluate "ramping rates", or rates at which the load-following sources must supply power. According to this technique, the PV variable generation is considered that provides a reduction in the load. The new lower load, called the "residual load", is therefore equal to the normal demand minus the electricity produced by the PV sources as it shown in Fig. 5 and explained below.

Under the current pattern of the demand, with a maximum in the afternoon (see Fig. 1), solar generation helps to lessen the generation requirements. For a better understanding of this interaction in Fig. 5 we show two situations, one corresponding to the present year (2021), and the other, a forecast to the 2030 NIECP. In the situation corresponding to 2021, we depict the hourly median demand (thin blue line) jointly with this demand minus the observed solar PV for this year (thick blue line). Secondly, we present similar curves for the 2030 Spanish NIECP *Objective Scenario* (brown lines). The graph corresponding to 2021 shows that when solar PV is implemented at a moderated scale, the residual load is flatter in comparison to 2030, which is a positive contribution to the stability of the system. However, when the penetration of solar PV reaches higher stages, which will be the situation under the 2030 scenario proposed in the Spanish NIECP, the residual loads are curves with higher slopes than those of the 2021 analysis. This figure is known as the *duck curve*, due to its similarity to the shape of a duck of the area between the demand and the residual load.

In the line of Hou et al. [11], and in order to improve the lack of statistical significance of the deterministic duck curve (Fig. 5), we propose the use of a simulation of the hourly data to build a set of fan-charts based on the percentiles of the residual load curves for 2030. In Fig. 6 we present four seasonal fan-charts of duck curves. In these figures we can observe that the ramping power needs in Spring and Summer will present a median value of about 20 GW growth during 5 h, that is a gradient of 4 GW per hour during the afternoon–evening. This issue is not new and has been evidenced in some areas with large integration of solar PV in the grid. Regions of the globe with high solar irradiation such us California [9] or some areas in Australia have brought up this issue and entitled these figures as *duck* curves.

ENTSO-E [12] provides plenty of information about collection and publication of electricity generation, transportation and consumption data and information for the pan-European market. Among this information, there are two recently released documents [13,14] that address this issue. Both documents evaluate the flexibility requirements of power system in terms of: ramping flexibility needs and scarcity periods flexibility needs. Also, the European Electricity Regulatory Forum (also known as Florence Forum), in their last meetings, have raised awareness about the importance of market design and price signals to enhance system flexibility and balancing responsibility for all VRES generators.

Based on the analysis shown in [13] of three large economies (Germany, France and Belgium) they conclude that for 1-, 3- and 8-hour steepest ramps in the 2025 and 2030 residual load, the German system will require 25, 80 and 120%/MW which is consistent with the ramping need of 20 GW calculated for Spain in 5 h period. However, the most critical issue for Spain is the serious lack of both: flexibility as dispatchable capacity, and flexibility of imported from neighboring countries which is very limited. Otherwise, VRES would need to be curtailed in a well-coordinated and properly anticipated so as to cover such ramps.

Cross-border exchange can provide reciprocal flexibility between countries. However, ramping needs should be addressed and agreed. Transmission System Operators (TSOs) have established methodologies and regulated the maximum gradient for change in flow of energy. To do so, they have created Load–Frequency Blocks (LFB) for monitoring the network stability within defined areas (more detailed information can be found in [15]). In this line, the Nordic TSOs, ENTSO-E [16,17] have agreed on some actions necessary to maintain an acceptable frequency quality and network security in High Voltage Direct Current (HVDC) connections, and the incorporation of these restrictions in the day-ahead spot electricity market.

As previously stated, the most critical point is the high upwards ramping response shown by the duck curves, which is needed during part of the afternoon–evening. This issue has been scarcely evaluated in the academic literature [11,18]. The mentioned ramping requirement can only be met by a limited set of flexible power sources like: gas turbines (first stage of combined cycles), hydroelectric power, large batteries or pumped-hydro generation. All of these alternatives are not free of constraints and require massive investments which seems to be underestimated in the 2030 Spanish NIECP scenario as we will discuss in next section.

for the 10th (at the bottom) and 90th (at the top) intervals. This type of plots are a particular case of cluster modeled using statistical distributions based on the observed hourly percentiles. This type of plots have been used to display uncertainty/volatility in economic indicators, but barely applied in the context of energy. These plots have been built thanks to the package fan plot [5] of R Core Team [6].

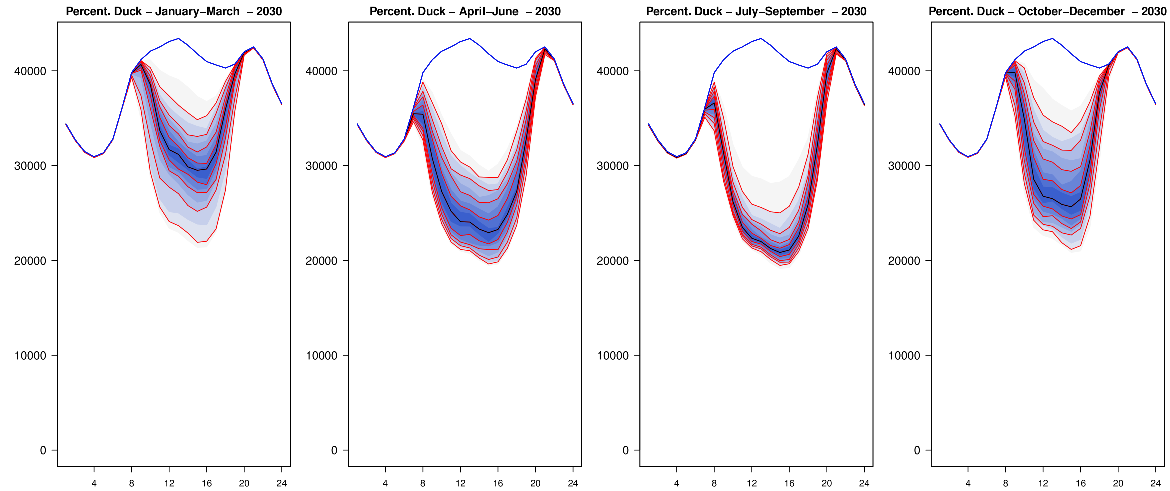

Fig. 6. Seasonal fan charts of duck curves for the 2030 NIECP objective scenario. Units: Horizontal axis in hour, Vertical axis: MW.
Source: Authors using data from [3].

5. Storage limitations in the Spanish NIECP

Detailed analysis of the ramping requirements depicted in previous Section, shows that in 2030 the ramping response needed will depend on the season of the year. More precisely, Spring and Summer will require about 20 GW of median value during about 5 h interval, with similar figures for nearly 70% of the days (see the percentiles of Fig. 6 corresponding to Summer). These high response sources need to be ready to supply this power in the afternoon–evening hours. This means that the system requires idle power stations, or stored energy, ready to supply massive amounts of power during a few hours interval. In other words, we need additional *flexible resources* and/or storage techniques in order to incorporate large amounts of variable renewables into the grid.

Regarding to the scheduled storage power foreseen in the Spanish National Integrated Energy and Climate Plan (NIECP), which is presented in Table 2, it accounts for doubling the current hydro-pumped storage power capacity up to 6.837 GW, and also is programmed an additional storage capacity about 2.5 GW. Later reports from a governmental institutions [19] recognize that it will be necessary to increase these figures up to 20 GW. However, about 10 GW out of the mentioned 20 GW is categorized as *seasonal storage* with an ambiguous definition of this type of storage [19, p. 84]. In addition, no information is given about the total energy storage capacity which is required to be known.

Another promising storage alternative is the use of hydrogen as energy vector. In the particular case of Spain, the report from "[20]" states a target of 4 GW of installed capacity of hydrolizers by 2030, but this increase is mostly focused towards industrial applications and mobility. This document only mentions the power sector in the last position and does not give further information. In this line, the study of Price Waterhouse Coopers [21] presents a comprehensive summary of the storage alternatives for Spain and shows that hydrogen is still an immature technology for energy storage. Also, batteries are currently presented as reasonable alternatives to maintain frequency stability, In addition, battery storage will play a prominent role in the nearly future providing not only flexibility but also storage. Battery storage costs are sharply falling and the Levelized Cost of Energy of utility-scale batteries in the United States has fallen by 71% from USD 2 152/kWh to USD 635/kWh in just three years [22] and the total worldwide installed battery storage in the Net Zero Scenario (2015–2030) is expected to grow from 17GW in 2020 until 585 GW in 2030 [23]. In Spain, the only mature and sustainable storage technology is pumped-hydro storage thanks to its orography and hydro resources [24,25], but its promotion is not free of constrains and controversy.

It is clear that examining the availabilities of flexible resources during scarcity periods is critical, especially when demand response and sector coupling resources such as vehicle-to-grid, or seasonal thermal or hydrogen storage may play a key role. For the particular case of Spain, the orography provides certain locations where pumped-hydro storage can be further developed. It is also crucial to continue with the phase-out of coal in Spain and Europe, but also with the reduction of fossil gas due to the problematic dependences after the Ukraine war.

If the supply from storage systems and high response sources cannot meet the demand, and to avoid the risk of blackout, the unique alternative is to reduce the demand in the evening interval of those days with high PV generation. In the nearly future, the demand will not be an exogenous variable and the demand response will play a key role in the shape of the generation pattern.

6. Summary and conclusions

In this article we evaluate the 2030 power transition in Spain as it has been described in the National Plan for Energy and Climate and already approved by the EU Commission. This plan has established a *roadmap* and targets for 2030 in order to reach climate neutrality by 2050.

For the particular case of Spain, and bearing in mind that half of nuclear power will be put out of service about 2030, the promotion of variable renewable sources play a key role in the NIECP. For the solar PV generation it has been scheduled a massive growth from 5 GW in 2015 up to nearly 40 GW by 2030. This large increase of solar PV will surely have a positive impact in the generation of electricity from renewable sources, but it will also imply a higher dependence on backup power plants with very high ramping response as well as massive storage capacity. None of these resources have been sufficiently programmed in the Spanish NIECP and a further analysis would be convenient. In line with this issue, making use of the *duck curves*, we have evidenced the large need of daily flexible backups of about 20 GW during several hours, as well as ample storage.

It is clear that curtailment should be the last alternative. In this regard, we have emphasized in this study about the need of promoting flexible technologies jointly with appropriate regulation to send the right market signals for investing to build a flexible network in line with the rest of European countries. Also, demand side response will play a key role. It is also fundamental that the market design enhance system flexibility by balancing responsibility for all VRES generators designing cost-reflective imbalance prices that stimulate flexibility in a cost-effective manner.

Consequently, in the nearly future, the need of large storage capabilities and the use of hydrogen as energy vector may play a key role in countries with scheduled large deployment of solar PV. Jointly with these challenges, the development of distributed generation and demand response will surely influence future energy policies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We would like to give thanks to the members of the Spanish Association for Energy Economics (AEEE) for their fruitful comments during the last Conference held in Alcalá de Henares (May, 2022).

Also to acknowledge the research support from *Proyectos I+D+i - Retos de Investigación- del Programa Estatal de I+D+i orientada a los retos de la sociedad*. Ministry of Science, Innovation and Universities, Spain. Ref: RTI2018-100983-B-I00.

References

[1] Ministerio Transición Ecológica y el Reto Demográfico. Plan nacional integrado de energía y clima (PNIEC). Spain. Resolucion de 25 de marzo de 2021 publicado en BOE de 31 de marzo de 2021. Technical report, 2021b.
[2] European Commission. Assessment of the final national energy and climate plan of Spain. SWD(2020) 908 final. Commission Staff Working Document; 2020.
[3] Red Eléctrica Española (REE). 2021 Hourly generation dataset in Spain [data file]. 2021.
[4] Perino G, Pahle M, Pause F, Quemin S, Scheuing H, Willner M. EU ETS stability mechanism needs new design. Chaire Écon Clim Policy Brief 2021;1:2021.
[5] Abel GJ. fanplot: An R package for visualising sequential distributions. R J 2015;7(2):15–23, URL: http://journal.r-project.org/archive/2015-1/abel.pdf.
[6] R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2022, URL: https://www.R-project.org/.
[7] Gómez-Calvet R, Martínez-Duart JM, Serrano-Calle S. Current state and optimal development of the renewable electricity generation mix in Spain. Renew Energy 2019;135:1108–20.
[8] Denholm P. Consequences of high penetration renewables, chapter 43 in fundamentals of materials for energy and environmental sustainability. Cambridge University Press; 2012.
[9] Denholm P, O'Connell M, Brinkman G, Jorgenson J. Overgeneration from solar energy in California. A field guide to the duck chart. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States); 2015.
[10] Red Eléctrica Española. Sistema de información del operador del sistema eléctrico en España. 2020, https://esios.ree.es/en. Accessed: 2020-01-11. URL: https://www.esios.ree.es/en.
[11] Hou Q, Zhang N, Du E, Miao M, Peng F, Kang C. Probabilistic duck curve in high PV penetration power system: Concept, modeling, and empirical analysis in China. Appl Energy 2019;242:205–15.
[12] ENTSO-E. European network for transmission system operators, transparency platform. 2022.
[13] ENTSO-E. The assessment for the future flexibility neesds in practice. Technical report, European association for the cooperation of Transmission System Operators (TSOs) for electricity; 2021.
[14] ENTSO-EAISBL. Position paper assessment of future flexibility needs. Technical report, European association for the cooperation of Transmission System Operators (TSOs) for electricity; 2021.
[15] ENTSO-E. All TSOs' proposal for the determination of LFC blocks for the synchronous area continental europe in accordance with article 141(2) of the commission regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation. Technical report, European Association for the Cooperation of Transmission System Operators for Electricity; 2018.
[16] ENTSO-E. Evaluation of the ramping restriction in the energy market. Technical report, Nordic Operations Development group (NOD); 2010.
[17] ENTSO-E. Amended nordic LFC block methodology for ramping restrictions for active power output in accordance with article 137(3) and (4) of the commission regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation. Released date: 2 December 2021. Technical report, Nordic Development Group; 2021.
[18] Li M, Song Y, Zheng Y, Hu B, Chu P, Gadh R. Game-based strategy for load service entity to level duck chart as well as gain EV consumers. Int Trans Electr Energy Syst 2016;26(10):2204–15.
[19] Secretaría de Estado de Energía. Estrategia de almacenamiento energético. Technical report, Ministerio para la Transición Ecológica y el Reto Demográfico; 2021.
[20] Ministerio Transición Ecológica y el Reto Demográfico. Hoja de ruta del hidrógeno: Una apuesta por el hidrógeno renovable. Technical report, Ministerio para la Transición Ecológica y el Reto Demográfico; 2021a.
[21] Price Waterhouse Coopers. El papel del almacenamiento en la transición energética. Technical report, Ciemat y Fundación Naturgy; 2021.
[22] IEA. Total installed battery storage capacity in the net zero scenario, 2015–2030. 2022, URL: https://www.iea.org/data-and-statistics/charts/total-installed-battery-storage-capacity-in-the-net-zero-scenario-2015-2030.
[23] IEA. Renewable power generation cost in 2021. 2022, URL: https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021.
[24] Huclin S, Chaves JP, Ramos A, Rivier M, Freire-Barceló T, Martín-Martínez F, Román TGS, Sánchez Miralles A. Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy. Energy Rep 2022;8:4041–57. http://dx.doi.org/10.1016/j.egyr.2022.03.032, URL: https://www.sciencedirect.com/science/article/pii/S2352484722005881.
[25] Oyler AF, Parsons JE. The value of pumped hydro storage for deep decarbonization of the spanish grid. Technical report, MIT Working Papers; 2020, URL: https://ceepr.mit.edu/wp-content/uploads/2021/09/2020-007.pdf.