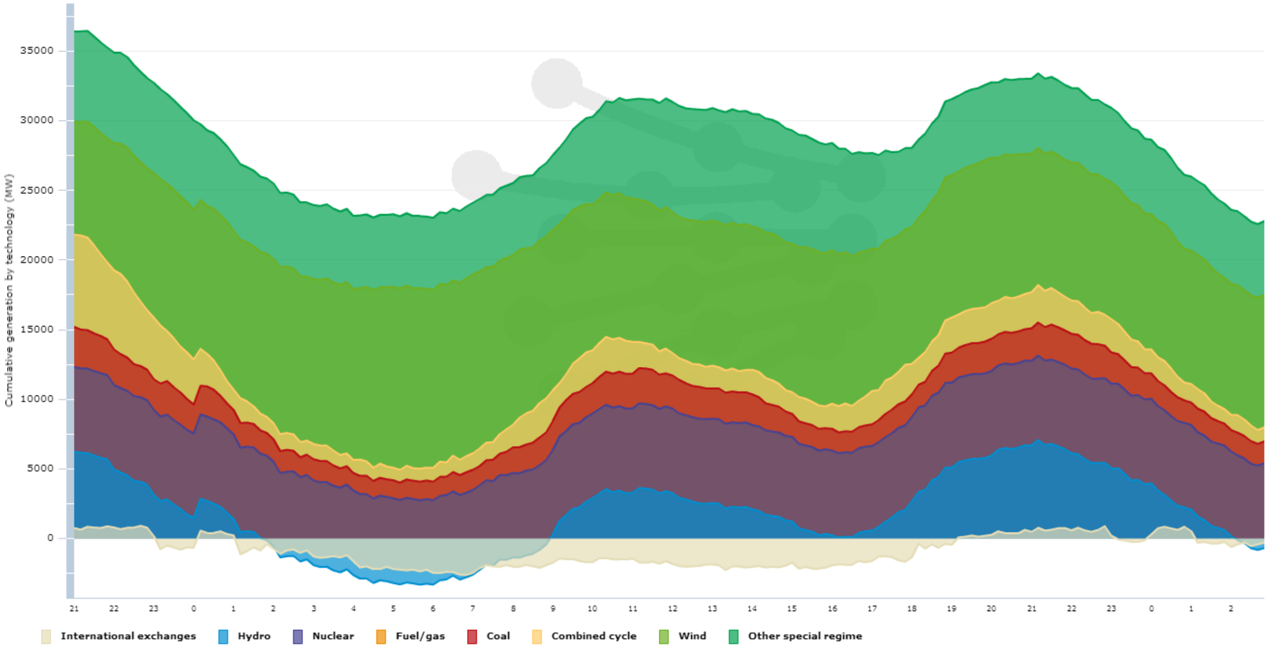
stoRE
www.store-project.eu

Facilitating energy storage to allow high penetration of intermittent renewable energy

D5.2 - SPAIN

Overview of current status and future development scenarios of the electricity system, and assessment of the energy storage needs



Supported by
INTELLIGENT ENERGY
EUROPE

Acknowledgements

This report has been produced as part of the project “Facilitating energy storage to allow high penetration of intermittent renewable energy”, stoRE. The logos of the partners cooperating in this project are shown below and more information about them and the project is available on www.store-project.eu

The work for this report has been coordinated by HSU and NTUA

Table of Contents

Supported by INTELLIGENT ENERGY EUROPE

List of Abbreviations

AA-CAES	…	(Advanced-) Adiabatic Compressed Air Energy Storage
CAES	…	Compressed Air Energy Storage
CF	…	Capacity Factor
CPL	…	Controllable Plants Load
CSP	…	Concentrated Solar thermal Power
EC	…	European Commission
ENTSO-E	…	European Network of Transmission System Operators for Electricity
ES	…	Energy Storage
EST	…	Electricity Storage Technology
EU	…	European Union
GW	…	Giga Watt
GWh	…	Giga Watt hour
HES	…	Hydro Energy Storage (dam- or barrage-hydro power plant)
kW	…	kilo Watt
kWh	…	kilo Watt hour
min	…	Minute
MW	…	Mega Watt
MWh	…	Mega Watt Hour
NREAP	…	National Renewable Energy Plan
O&M	…	Operation and Maintenance
PHES	…	Pumped Hydro Energy Storage
P_N	…	Nominal rated power
PV	…	Photovoltaics
RE	…	Renewable Energy
RES-E	…	Renewable Energy Sources for Electricity generation
RL	…	Residual Load
TSO	…	Transmission System Operator

EXECUTIVE SUMMARY

This report aims to provide a clear overview of the energy storage infrastructure needs in order to achieve high penetration of renewable energy in the electricity system of Spain. The existing power generation mix and transmission system, and the planned development and reinforcements are considered, along with the national plans for renewable energy development in the next decades up to 2050. The necessity of new Pumped Hydro Energy Storage (PHES) units and their feasibility from the energy and economic point of view is investigated with the aid of simulations of mainland electricity system operation characteristics, using specially developed software. The produced qualitative and quantitative results highlight the added value of energy storage in the electricity grid and consumers, and allow for a better estimation of such needs for the future.

The electricity production and transmission system of Spain

The peninsular electric demand in 2011 in Spain was 254.8 TWh, suffering a decrease of 2.2% compared to 2010. The highest peak load of the peninsular system reached 43.9 GW in 2011, far from the record of 45.5 GW in 2007. The share of renewable energies in electricity generation was at 31.5% for the reference year 2011. The set of wind farm generating facilities finished 2011 with an installed capacity of 21,091 MW, accounting for 21.1% of the total capacity on the Spanish peninsula, while solar technologies exceeded 5,000 MW of installed capacity.

Currently, the Spanish electricity system is suffering an overcapacity in installed power, due to the simultaneous growth during the last decade of wind farms and CCGT plants. Besides, the reduction of the industrial activity has been limiting the electricity demand since 2008. Consequently, during the last years the capacity factor of CCGT plants has been below 50%. Now, after the Royal Decree supporting national coal consumption the situation is even worse for these plants. Given this situation, there is no expectation of investments in new capacity in the short-term, except for renewable technologies and for fuel power plants substitution in the islands.

In relation to international exchanges, Spain is a net exporter of electricity to Portugal and Morocco. Regarding France, while historically Spain has been importer of electricity from France, this exchange has been gradually reduced during the last years due to the wind power penetration and now the net exchange is mainly balanced.

However, the Spanish electricity system does not reach the minimum level recommended in Europe, as their commercial exchange capacity with the European system only represents 3% of the installed generation capacity in Spain. Furthermore, due to the geographical position of Spain, the possibilities of interconnection with the rest of Europe are very limited. The fact that only the interconnection with France allows the exchange of energy with the rest of the European Union, together with a low exchange capacity, makes the Iberian Peninsula an «electrical island».

System development plans (2020-2050)

The National Renewable Energy Action Plan (PANER) responds to the requirements and methodology of the Renewable Energy Directive, and follows the model of NREAPs adopted by the European Commission.

Meanwhile, the Royal Decree 661/2007, which deals with the activity of electricity production under special regime, foresees the development of a Renewable Energy Plan (PER) for its application in the period 2011-2020. The application of this plan is temporary stopped after the change in Spanish Government and given the current economic situation.

Supported by INTELLIGENT ENERGY EUROPE

The PER 2011-2020, developed in parallel with the PANER, includes the essential elements of the latter as well as additional analysis not included in PANER. These plans present two different scenarios: the reference scenario or BAU, and the additional energy efficiency scenario which is the target of the plan. The PER also includes a target for new pumped hydroelectric plants installation, increasing the power capacity by 65% from 2010 to 2020.

Additional energy efficiency scenario: National electricity balance. PER 2011-2020

TWh	2005	2010	2015	2020
Coal	81.5	25.5	33.2	31.6
Nuclear	57.5	61.8	55.6	55.6
Natural gas	82.8	96.2	120.6	133.3
Oil products	24.3	16.5	9.1	8.6
Renewables	42.4	97.1	112.8	146.1
Pumped hydro	4.5	3.1	6.6	8.5
Gross production	**293.0**	**300.2**	**338.0**	**383.6**
Consumption in generation	11.9	10.0	8.9	9.0
Net production	**281.0**	**290.3**	**329.1**	**374.7**
Pumped storage consumption	6.4	4.4	9.4	12.1
International exchanges (net exports)	1.3	8.3	11.2	12.0
Demand (at power station busbars)	**273.3**	**277.5**	**308.5**	**350.6**
Consumption in transformer sections	5.8	4.1	5.8	5.8
Transport and distribution losses	26.0	24.5	26.9	29.8
Final demand	**241.6**	**249**	**275.8**	**314.9**
Annual increase	4.3%	2.1%	2.5%	2.7%
% renewables vs gross production	**14.5%**	**32.3%**	**33.4%**	**38.1%**

The examined future RES development scenarios

Four RES development scenarios are studied within the report. Each of them presents different possible scenarios according to conditions such as the following:

- BAU vs efficient growth of the demand
- Possible life extension of the existing nuclear power plants, even new installations
- Development of a cost-effective CO_2 capture and sequestration coal plants
- Scenario of maximum penetration of renewable energy

The scenarios for 2020/2030/2050 show the uncertainty concerning the possible economic growth and the success of the energy efficiency measures. However, the demand is expected to increase over these periods. The current installed capacity is expected to be enough to meet the demand at least until 2020, especially if renewable technologies continue their development according to 2020 targets. After that period, a different focus is needed taking into account the necessity of installing new capacity by 2030/2050, attending to different political and technical considerations. Ultimately, a decision will have to be made about nuclear capacity favoring or avoiding this technology, given that the whole installed nuclear capacity reaches the 40 year milestone by the 2020-2030 period. On the other hand, due to the high renewable penetration, flexible technologies will need to be competitive operating less than 2,000 hours per year. Certainly, PHES will have to be one of these technologies.

Supported by INTELLIGENT ENERGY EUROPE

Electricity demand according to different future scenarios for Spain (TWh)

Organism	**Year**	**2020**	**2030**
Eurelectric [1]	2010	349.8	411.2
REE [2]	2010	303.0 - 345.5	
MITyC [3]	2010	366.0	
MITyC [4]	2010	350.1	
MITyC [5]	2010	354.9 - 393.1	
European Commission [6]	2009	297.3 - 309.0	344.3 - 361.5
PWC [7]	2010		461.6

Scenarios for simulation

Two future scenarios for RES development are examined. The first concerns the year 2020, when, according to the reference BAU scenario of PANER-2020 and the PER 2011-20 reports, the RES share in electricity will approach 40%. The latest estimations for wind and solar technology development are adopted for the present study. Consequently, only two alternative cases are studied in the 2020 scenario, regarding the new PHES system installations: 3 GW in Case 1 and 6 GW in Case 2.

The second scenario is for a much higher RES share of 80%, which is the objective for the next decades. For this scenario, the relative development of the two most important RES technologies, wind and solar, is also tested, because there are market drivers that can influence the development of one technology against the other. Consequently, 3 alternative configurations are tested for the 80% RES share scenario, from Case A favoring wind development, to Case C that represents a favored solar systems development. The present modeling will also examine a nuclear-system development scenario, assuming power extension of the existing nuclear power plants (and corresponding reduction of CCGT needs). Although this has no effect on the RES installed power, it affects the RES feed-in limit of the system.

Residual load

The Residual Load (RL) curve for a future electricity system of Spain is calculated by subtracting the uncontrollable hourly wind, solar and hydro production from the corresponding system load. This way, the cumulative hourly penetration of uncontrollable RES (wind and solar) production can then be calculated from the RL curve and the technical minimum of the inflexible production units that are dispatched. The latter include nuclear, coal fired and CCGT units, as well as the rest of the special regime uncontrollable production. The technical limits considered in the simulations are 15 GW and 18 GW for the 2020 scenario, and 0 GW and 10 GW for the 80% renewable scenario.

The results reveal that the configuration of Case A (wind favored development) is the most effective for the Spanish electricity system, achieving the highest penetration of intermittent RES production and the least rejections, as well as causing the smallest increase of system load variations, and hence the least impact on system stability. Moreover, life extension of the existing nuclear power plants will constitute a potential obstruction to the high RES penetration in the future electricity system of Spain.

Supported by INTELLIGENT ENERGY EUROPE

Comparative results for the 3 cases of the 80% RES development scenario

Case	Max. power below limit (MW)	Rejected production % Wind – PV – cumulative			Total rejected energy (GWh)
A	35,300	4.3	3.9	4.2	11,800
B	34,200	4.0	6.0	4.7	13,100
C	36,800	4.8	9.5	7.3	20,750
Results for nuclear scenario (system feed-in limit 10 GW)					
A-n	45,300	12.0	10.7	11.7	32,800
B-n	44,200	10.6	15.5	12.4	34,600
C-n	46,800	10.5	22.4	16.0	45,300

Energy storage needs

In this section the system configuration cases listed above are investigated with regard to the scheduled storage capacity and the maximum storage needs for the integration of rejected energy from RES. The overall efficiency of the charging/discharging cycle is fixed at 75% for the simulations.

In the 2020 scenario, the implementation of PHES for storing the rejected RES production does not cause any changes in the system stability characteristics, due to its negligible utilization in both cases 1 and 2. In the 80% renewable scenario, the corresponding installed pumped storage power is at first estimated at 12 GW, while the storage capacity is 144 GW, namely 12 hours of continuous pumping operation. Here, the contribution of these units to the reduction of remaining load peaks is more pronounced than in 2020 scenario, due to the greater storage power and capacity. Maximum power needs after PHES incorporation are about the same for all three cases of this scenario (45 – 44 GW). However, variations of the CPL curve are not similar; Case C shows much stronger fluctuations of the CPL in order to absorb the more significant solar production during a short period of the day.

The peak shaving operation of the PHES units is about the same also in the nuclear scenario, in which the technical feed-in limit for RES is set to 10 GW instead of zero. However, in this case the RES rejections are greater and more frequent, and hence the utilization of storage system is higher.

The wind-solar blending of Case A is the best in respect of RES production penetration for the non-nuclear scenario, whereas the blending of Case C is the worst, with almost 21 TWh of rejected energy. On the other hand however, the latter case seems to achieve the highest effectiveness of the PHES system, i.e. over 70% of rejections are stored compared to 49% in Case A.

The simulations show that full exploitation of PHES units for smoothing the system load curve can increase significantly their capacity factor, and hence their economic results. Moreover, this indicates that the economic results of the PHES units installed by the year 2020 will be continuously improved during the subsequent decades.

Comparative results for the cases of 80% RES development scenario.

Case	Rejected RES (GWh)	Stored RES (GWh)	Recovered portion after losses	Stored System (GWh)	Total PHES discharge (GWh)	Pumping station Capacity Factor (%)		
						RES	System	Total
A	11800	5740	36.5 %	21900	20730	5.4	20.8	26.2
B	13100	8915	51.0 %	25910	26120	8.5	24.6	33.1
C	20750	14620	52.9 %	23900	28890	13.9	22.7	36.6
Results for nuclear scenario (system feed-in limit 10 GW)								
A-n	32810	9665	22.3 %	14390	18040	9.2	13.6	22.8
B-n	34600	14975	32.7 %	15950	23190	14.2	15.1	29.3
C-n	45300	22470	37.4 %	12550	26265	21.3	11.9	33.2

Parametric studies

The last simulations presented, illustrate in hill charts the combined effect of the two critical design parameters of the PHES system, pumping power and storage capacity, on the two most important performance characteristics, exploitation degree of the RES rejected energy, and annual utilization degree (Capacity Factor) of the pumping units. The latter can be directly associated with the economic results and viability of the PHES investments.

The exploitation degree for Case A shows a continuous increase with the storage capacity, whereas it is not substantially affected by the pumping power. The corresponding hill chart for Case C exhibits a different pattern. That is to say, wind power demands a bigger storage capacity, while PV power demands a higher storage power, used on a day-night basis.

One way to use the hill charts in order to select the optimum PHES system is to start from the estimated storage capacity that will be available in the 80% RES share scenario. For example, if it will be of the order of 100 GWh, then the optimum pumping power should not exceed 8-9 GW for all cases, because for higher values the exploitation degree does not increase, while the pumping CF decreases. On the contrary, if the available storage capacity will be of the order of 200 GWh, then the exploitation degree of RES rejections increases in all cases with the pumping power. Hence, the latter can be sized up to the viable CF limit (e.g. 30%), corresponding here to 10, 14 and 20 GW for cases A, B, and C, respectively.

Finally, considering the specific pattern of the contours in these hill charts, the optimum PHES installed power for the nuclear scenario assuming available capacity of 100 GWh will be less than 8 GW in Case A-n, and around 10 GW in Cases B-n and C-n. The corresponding power for 200 GWh storage capacity remains small, around 8 GW, in Case A-n, but it may exceed 12 and 16 GW for Cases B-n and C-n, respectively.

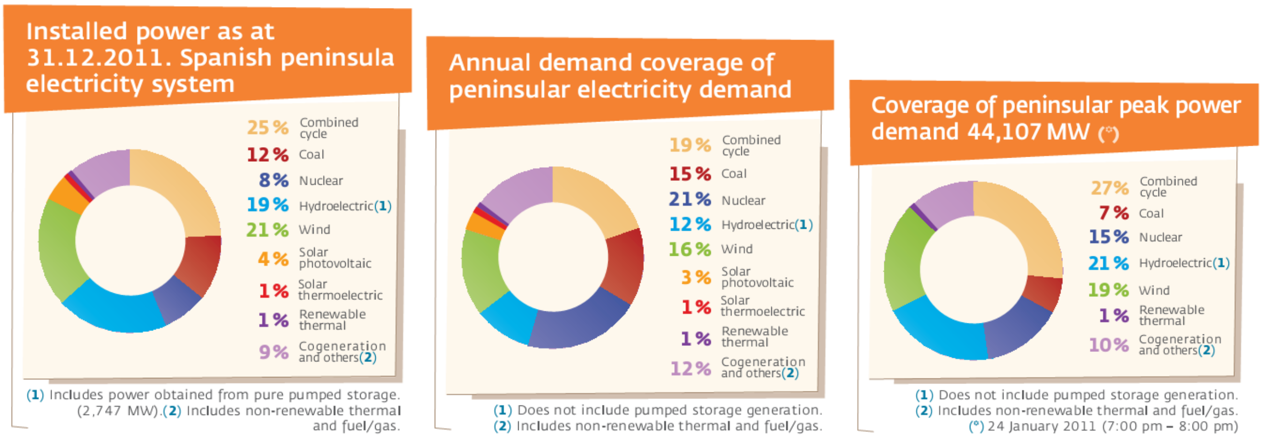
Supported by INTELLIGENT ENERGY EUROPE

1. System data and future scenarios

In this chapter the current configuration of the Spanish power system and the future development plans and scenarios are presented and discussed.

1.1. Power plant mix and energy production

Peninsular electric demand in 2011 in Spain was 254.8 TWh, suffering a decrease of 2.2% compared to 2010. Taking the islands into account, the total demand amounted to 269.8 TWh, a 2.1% below 2010. The highest peak load of the peninsular system reached 43.9 GW, far from the record of 45.5 GW in 2007. The share of renewable energies in electricity generation was at 31.5% in 2011.



(1) Includes power obtained from pure pumped storage. (2,747 MW).(2) Includes non-renewable thermal and fuel/gas.

(1) Does not include pumped storage generation.
(2) Includes non-renewable thermal and fuel/gas.

(1) Does not include pumped storage generation.
(2) Includes non-renewable thermal and fuel/gas.
(°) 24 January 2011 (7:00 pm – 8:00 pm)

Figure 1.1. Main features of the Spanish electricity system in 2011. Source [8]

Table 1.1. Power capacity installed in Spain (End of 2011). Source [8]

	Peninsular system		**Extrapeninsular system**		**National total**	
	MW	**%11/10**	**MW**	**%11/10**	**MW**	**%11/10**
Hydroelectric	17,563	0.0	1	0.0	17,564	0.0
Nuclear	7,777	0.0	-	0.0	7,777	0.0
Coal	11,700	2.8	510	0.0	12,210	2.7
Fuel/gas	1,492	-34.6	2,884	0.7	4,376	-15.0
CCGT	25,269	0.1	1,854	-0.5	27,123	0.1
Total ordinary regime	**63,801**	**-0.7**	**5,249**	**0.2**	**69,050**	**-0.6**
Hydroelectric	2,041	0.3	1	0.0	2,041	0.3
Wind	21,091	7.0	149	1.7	21,239	7.0
Solar photovoltaic	4,047	10.7	202	8.8	4,249	10.6
Solar thermoelectric	1,049	97.1	-	0.0	1,049	97.1
Renewable thermal	858	14.0	1	-96.8	859	8.5
Non-renewable thermal	7,282	1.3	119	0.9	7,401	1.3
Total special regime	**36,367**	**7.4**	**471**	**-3.8**	**36,838**	**7.2**
Total	**100,168**	**2.1**	**5,720**	**-0.1**	**105,888**	**2.0**

Supported by INTELLIGENT ENERGY EUROPE

In 2011, the installed power in the generating facilities of the Spanish peninsular electricity system registered a net increase of 2.1 GW, a figure that at the end of the year establishes the total capacity of the system at 100.2 GW. This increase corresponds primarily to new renewable energy installations that have experienced a growth in power of 2.4 GW.

The set of wind farm generating facilities finished 2011 with an installed capacity of 21,091 MW (1,380 MW more than in 2010), accounting for 21.1% of the total capacity on the Spanish peninsula. Meanwhile, solar technologies have continued to increase their production capacity with respect to the previous year (a new 390 MW of photovoltaic and a new 517 MW of thermoelectric) together exceeding 5,000 MW of installed capacity in late 2011. [8]

Table 1.2. Power generation balance in Spain (2011). Source [8]

	Peninsular system		**Extrapeninsular system**		**National total**	
	GWh	**%11/10**	**GWh**	**%11/10**	**GWh**	**%11/10**
Hydroelectric	27,571	-28.7	-	0.0	27,571	-28.7
Nuclear	57,731	-6.9	-	0.0	57,731	-6.9
Coal	43,488	96.8	3,031	-10.4	46,519	82.6
Fuel/gas	-	0.0	7,479	-3.2	7,479	-21.7
CCGT	50,734	-21.5	4,406	10.4	55,140	-19.6
Ordinary regime	**179,525**	**-5.1**	**14,915**	**-1.2**	**194,440**	**-4.8**
Consumption in generation	- 7,247	8.6	- 882	-1.9	- 8,129	7.4
Special regime	**91,815**	**1.1**	**996**	**3.2**	**92,811**	**1.1**
Hydroelectric	5,283	-22.6	1	0.0	5,284	-22.6
Wind	41,799	-3.3	361	7.1	42,160	-3.2
Solar photovoltaic	7,081	15.3	333	17.7	7,414	15.4
Solar thermoelectric	1,823	163.6	-	0.0	1,823	163.6
Renewable thermal	3,792	19.5	33	-79.4	3,825	14.8
Non-renewable thermal	32,037	4.1	268	45.3	32,305	4.3
Net generation	**264,092**	**-3.4**	**15,030**	**-0.9**	**279,121**	**-3.2**
Pumped storage consumption	- 3,215	-27.9	-	0.0	- 3,215	-27.9
International exchanges	- 6,090	-26.9	-	0.0	- 6,090	-26.9
Demand (at power station busbars)	**254,786**	**-2.2**	**15,030**	**-0.9**	**269,816**	**-2.1**

The Spanish electricity system is suffering an overcapacity in installed power, due to the simultaneous growth during the last decade of wind farms and CCGT plants. Besides, it is also worth noting that the reduction of the industrial activity has been limiting the electricity demand since 2008. Consequently, during the last years the capacity factor of CCGT plants has been below 50%. Now, after the Royal Decree supporting national coal consumption the situation is even worse for these plants.

Given this situation, there is no expectation of investments in new capacity in the short-term, except for renewable technologies and for fuel power plants substitution in the islands.

In relation to international exchanges, Spain is a net exporter of electricity to Portugal and Morocco. Regarding France, while historically Spain has been importer of electricity from France, this exchange has been gradually reduced during the last years due to the wind power penetration and now the net exchange is mainly balanced. Namely, the net exchange with France was 1,531 GWh exported in 2010, and 1,524 GWh imported in 2011.

Supported by INTELLIGENT ENERGY EUROPE

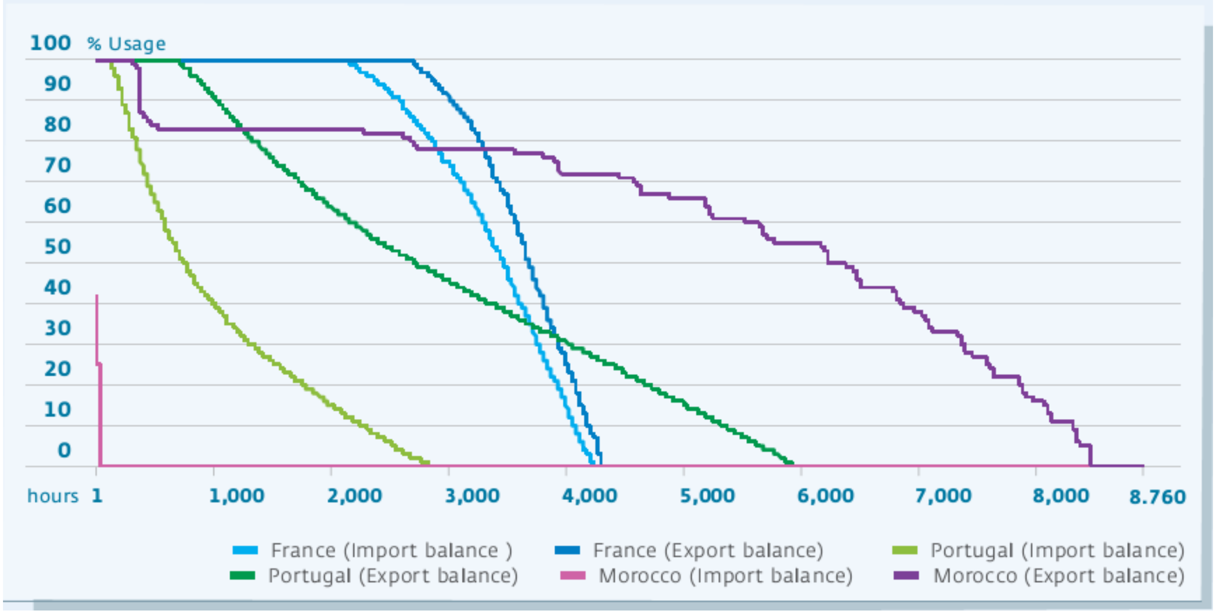


Figure 1.2. Commercial exchange capacity usage sorted in decreasing order (monotone curves) Source [9]

1.2. Transmission system and planned reinforcements

REE is responsible for the transmission of high voltage power in Spain. REE is the manager of the transmission grid and, as such, acts as the sole transmission agent under a regime of exclusivity as set out in Law 17/2007 of 4 July. REE's transmission grid is composed of more than 40,100 kilometres of high voltage electricity lines and more than 4,800 substation bays, and has more than 74,000 MVA of transformer capacity [9].

REE continues to make significant investments aimed at reinforcing grid meshing with the objective of facilitating primarily the evacuation of the new generation of installed renewables, providing support for the high-speed train power feed, supporting the distribution networks and above all, strengthening international interconnection projects as well as other projects such as the interconnection of the peninsula with the Balearic Islands. During 2010, with these activities, which have signified an investment of 819 million euro, a total of 1,738 km of new circuit line, 247 new substation bays and 2,700 MVA of additional transformer capacity have been installed.

Table 1.3. Characteristics of the Spanish electricity network. Source [10]

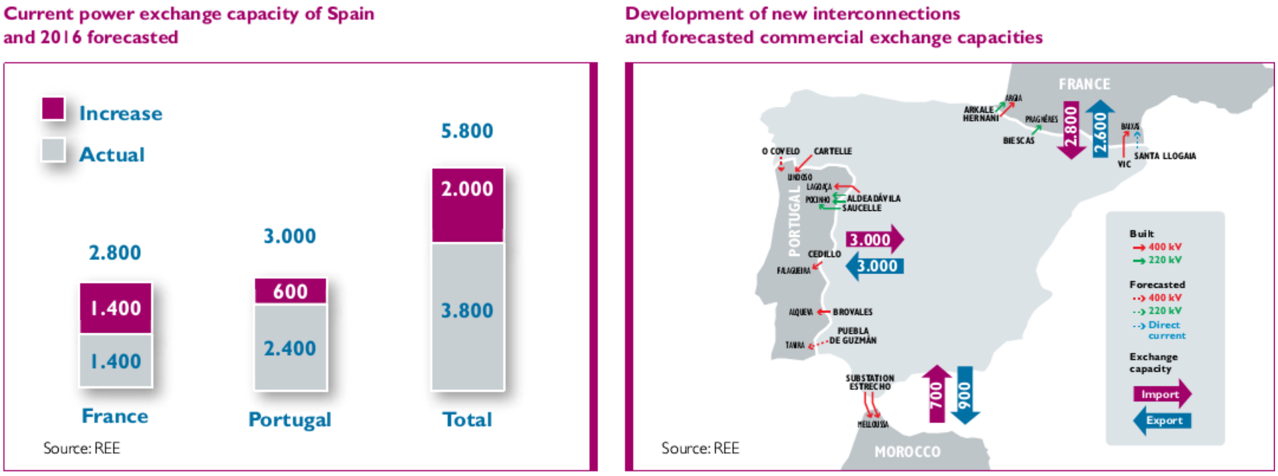
Transmission grid (peninsular and extrapeninsular)					
Km of circuits	**2007**	**2008**	**2009**	**2010**	**2011**
400 kV	17,134	17,686	17,977	18,765	19,622
220 kV	16,457	16,558	16,698	17,352	18,218
150-132-110 kV	75	75	75	280	295
150-132 kV	-	-	-	1,998	1,998
Total	33,665	34,319	38,750	38,395	40,133
Transformer capacity (peninsular and extrapeninsular)					
Power (MVA)	**2007**	**2008**	**2009**	**2010**	**2011**
Total	58,372	62,772	65,797	72,220	74,920

Supported by INTELLIGENT ENERGY EUROPE

Among other activities, in 2011 the interconnection with the Balearic Islands has been carried out. Meanwhile, the progress on the interconnection with France continues. The future interconnection between Santa Llogaia and Baixas, that will be commissioned in 2014, will be a direct current interconnection with the highest capacity in Europe (2x1,000 MW) and the longest underground link (64.5 km).

Today, the Spanish electricity system does not reach the minimum level recommended in Europe, as their commercial exchange capacity with the European system only represents 3% of the installed generation capacity in Spain.

Furthermore, due to the geographical position of Spain, the possibilities of interconnection with the rest of Europe are very limited. The fact that only the interconnection with France allows us to exchange energy with the rest of the European Union, together with the low exchange capacity, makes the Iberian Peninsula an «electrical island».


Current power exchange capacity of Spain and 2016 forecasted

Source: REE

Development of new interconnections and forecasted commercial exchange capacities

Source: REE

Figure 1.3. Power exchange capacity in Spain. Source [11]

Spain and France are connected by means of four high voltage lines: there are two in the Basque Country (one 400 kV line connecting Hernani with Argia and one 220 kV connecting Arkale with Argia), one in Aragon (220 kV line between Biescas and Pragnères) and one in Catalonia (400 kV line connecting Vic with Baixas). This set of lines allows a maximum exchange capacity of around 1,400 MW. Since 1982 no new interconnection lines have been built, despite the growth of the electricity demand in both countries.[11]

Meanwhile, the projects included in the 2008-2016 plan of the Ministry of Industry amount 7,488 km of new 400 kV lines and 4,782 km of 220 kV lines, added to the repowering of 3,850 km of 400 kV lines and 4,458 km of 220 kV lines.[10]

The estimation of the total cost of the investment in electric infrastructures planned for the 2016 horizon is that of 3,533 M€ corresponding to lines and 5,687 M€ corresponding to substations. In total, 9,220 M€ representing an average annual investment of 1,024.5 M€.

The distribution of the total cost is the following: 68% corresponds to the meshing of the transmission network, international interconnections and support to distribution; 25% corresponds to the evacuation of new generation, either from special or ordinary regime; and 7% corresponds to the supply to the high-speed train.

The new developments of the transmission network in the 2008-2016 plan are aimed at the following needs.

Peninsular system

- Structural reinforcement in the 400 kV network
- Development of the 220 kV network, increasing security and guarantee of supply
- Reinforcement of the international connection with Portugal through two new 400 kV lines, and with France through a new 400 kV line via the central Pyrenees
- Supply to new high-speed train axis through the 220 kV and 400 kV networks
- Development of 220 kV and 400 kV networks enabling the integration of renewable energies
- Increase in the number of 400/220 kV and 400/132-100 kV transformer units, throughout the peninsula, improving the support between transmission and distribution networks
- Supply to the desalination plants in the Mediterranean coast
- Development of international interconnections

Extrapeninsular system

- Reinforcement of the planned network to connect the different island systems through additional submarine connections
- Reinforcement of the 220 kV networks

Fuente: Red Eléctrica de España.

Figure 1.4. New developments in the Spanish transmission network. Source: REE

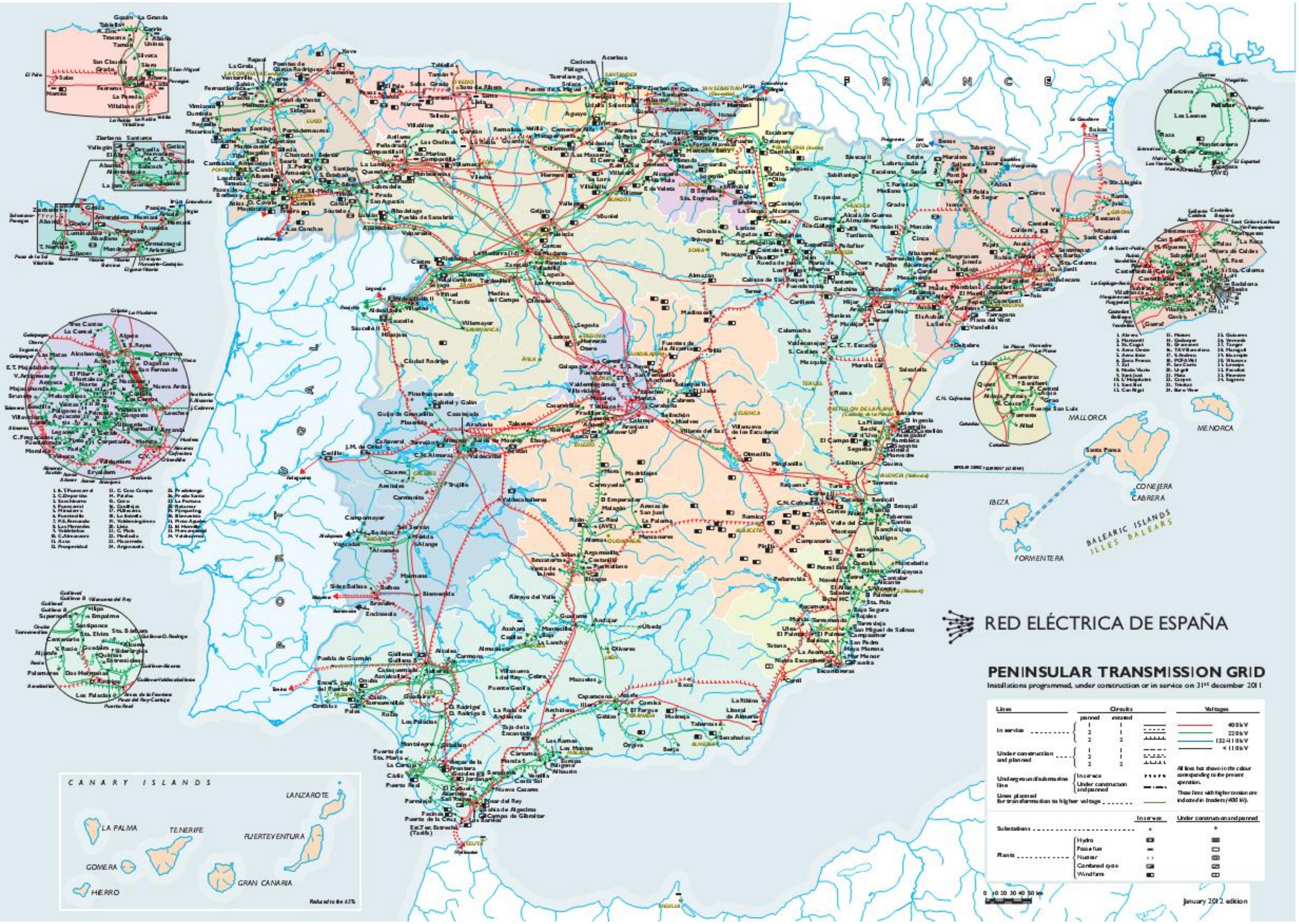


Figure 1.5. Peninsular transmission grid. Source: REE

1.3. National energy plans for the future

1.3.1. PANER/PER 2011-2020

The National Renewable Energy Action Plan (PANER) responds to the requirements and methodology of the Renewable Energy Directive, and follows the model of NREAPs adopted by the European Commission.

Meanwhile, the Royal Decree 661/2007, which deals with the activity of electricity production under special regime, foresees the development of a Renewable Energy Plan (PER) for its application in the period 2011-2020. The application of this plan is temporary stopped after the change in Spanish Government and given the current economic situation.

The PER 2011-2020, developed in parallel with the PANER, includes the essential elements of the latter as well as additional analysis not included in PANER. These plans present two different scenarios: the reference scenario or BAU, and the additional energy efficiency scenario which is the target of the plan (see the table).

Table 1.4. Additional energy efficiency scenario: National electricity balance. Source [12]

TWh	**2005**	**2010**	**2015**	**2020**
Coal	81.5	25.5	33.2	31.6
Nuclear	57.5	61.8	55.6	55.6
Natural gas	82.8	96.2	120.6	133.3
Oil products	24.3	16.5	9.1	8.6
Renewables	42.4	97.1	112.8	146.1
Pumped hydro	4.5	3.1	6.6	8.5
Gross production	**293.0**	**300.2**	**338.0**	**383.6**
Consumption in generation	11.9	10.0	8.9	9.0
Net production	**281.0**	**290.3**	**329.1**	**374.7**
Pumped storage consumption	6.4	4.4	9.4	12.1
International exchanges (net exports)	1.3	8.3	11.2	12.0
Demand (at power station busbars)	**273.3**	**277.5**	**308.5**	**350.6**
Consumption in transformer sections	5.8	4.1	5.8	5.8
Transport and distribution losses	26.0	24.5	26.9	29.8
Final demand	**241.6**	**249**	**275.8**	**314.9**
Annual increase	4.3%	2.1%	2.5%	2.7%
% renewables vs gross production	**14.5%**	**32.3%**	**33.4%**	**38.1%**

Supported by INTELLIGENT ENERGY EUROPE

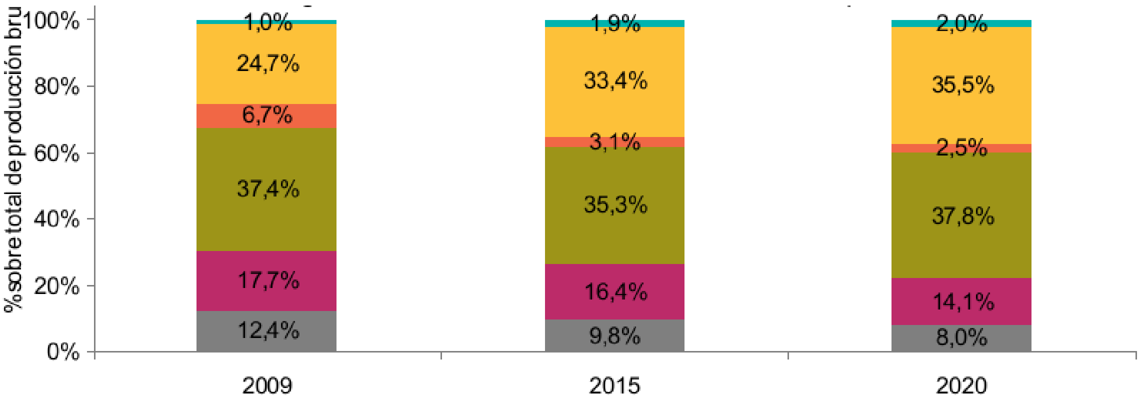


Figure 1.6. Additional energy efficiency scenario: Share over gross production

Technologies (top-down): Pumped hydro; Renewable energies; Oil products; Natural gas; Nuclear; Coal. Source: Mityc/IDAE

Regarding renewable energies, we can see in the figure that wind power maintains a share around 50% in 2020. Hydroelectricity shows little margin for new generation while the rest of renewable technologies increase gradually along the decade, diversifying the electricity production.

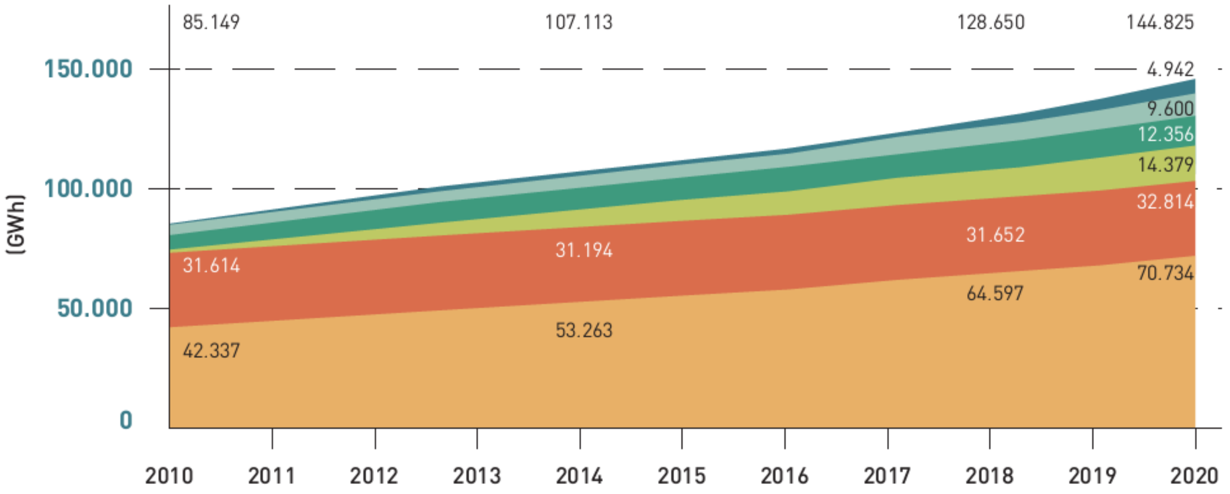


Figure 1.7. Final gross consumption of renewable electricity. Source [5]

Technologies (top-down): Off-shore wind; Solid biomass; Solar photovoltaic; Solar thermoelectric; Hydroelectric; On-shore wind

Last, PER also includes a target for new pumped hydroelectricity installation, increasing the capacity by 65% from 2010 to 2020.

Table 1.5. Targets of PER for installed capacity in pumped hydro

MW	2010	2015	2020
Pumped hydro	5,347	6,312	8,811

Supported by INTELLIGENT ENERGY EUROPE

1.4. Other power system development forecasts

The Spanish power system experienced a continuous increase in capacity installed during the last decade, due to the strong development of renewable energies and due to a growing CCGT capacity. Now, the situation of the economy has changed the increasing trend of the demand and the Spanish power system has reached a situation of overcapacity. In the incoming years the demand is expected to grow slowly, so little new capacity should be installed until 2020. Additionally, the annual installed capacity of renewable energy technologies have been dramatically reduced since the cancellation of the feed-in-tariffs for new installations in January 2012.

That is to say, scenarios for 2020 in Spain do not show a very different panorama from the current one, except for the growth of renewable energies determined by the European targets. On the contrary, the end of lifetime of some plants and the growing demand will change the figure for 2035 and 2050.

Table 1.6. Compilation of future scenarios for Spain.

Organism	**Year**	**2020**	**2030**
Eurelectric [1]	2010	349.8	411.2
REE [2]	2010	303.0 - 345.5	
MITyC [3]	2010	366.0	
MITyC [4]	2010	350.1	
MITyC [5]	2010	354.9 - 393.1	
European Commission [6]	2009	297.3 - 309.0	344.3 - 361.5
PWC [7]	2010		461.6

1.4.1. “Analysis of the Spanish energy strategy for the next 25 years” report from the sub-commission

The Spanish parliament decided in May 2009 the creation of a sub-commission within the Industry, Tourism and Commerce Commission for the analysis of the Spanish energy strategy for the next 25 years. Parameters like energy intensity or the evolution of prices were analysed in the different scenarios. Moreover, the impact of the possible measures taken to stabilize the concentration of greenhouse gases was also taken into account.

The scenarios proposed follow the ones presented in the last report of the IEA

a) BAU (business as usual) scenario. In this case, the GHG emissions worldwide would increase from 29 Gt in 2007 to 40 Gt in 2030, almost three times over the sustainable level of emissions

b) Efficiency scenario. It is the result of a sustained active energy policy, committed with climatic change, with a continuous effort on energy efficiency measures and with an ambitious renewable energy support.

In the proposed Efficiency scenario, renewable energies reach 35.5% of the gross electricity production in 2020, after an increase of 10% in the next decade. Renewable energies practically double their production, up to 196.6 TWh in 2020.

Finally, the report presents some conclusions about the "vectors of evolution" for the period 2020-2035 but no quantitative results are presented.

Table 1.7. Electricity balance for 2020. Source [4]

	2009	**2020**	**2020**
	GW	**GW**	**TWh**
Hydroelectric	16.09	16.66	33.14
Nuclear	7.72	7.26	55.60
Coal	12.00	8.13	31.58
Natural gas	31.25	37.97	148.50
Oil products	7.61	2.31	9.92
Onshore wind	19.14	35.00	71.61
Offshore wind	0.00	0.50	1.31
Solar PV	3.44	6.74	11.52
Solar thermoelectric	0.23	3.81	11.51
Biomass/biogas	0.75	1.74	10.54
PHES	2.55	5.70	8.02
Gross production			**393.26**
Consumption in generation			8.97
Net production			**384.38**
Demand (at busbars)	**100.78**	**126.07**	**350.09**

1.4.2. UNESA study for 2030

UNESA (Spanish Association of the Electrical Industry) presented in 2007 a study on the power system for 2030. It is based on data of installed capacity, programmed commissioning and decommissioning of plants and assuming an annual increase of demand at 2.4% for the 2005-2020 period and at 1.7% for the 2020-2030 period, two scenarios were defined giving priority to coal or gas respectively.

Different cases are analysed within each scenario, focused on the following assumptions:

- maximum use of the capacity installed in 2011
- expansion of the nuclear capacity
- maximum penetration of renewable energies
- availability of installed capacity of coal plants with sequestration and absorption of CO2

together with a slightly increased nuclear capacity

The results for each case include the capacity mix, the required investments, the CO2 emissions and the dependence on foreign energy.

Table 1.8. Evolution of installed power (GW). Common installed capacities in both scenarios: coal priority and natural gas priority. Source [13]

Cases:	**Maximum use of 2011 capacity**	**Nuclear expansion**	**Maximum renewable penetration**	**Clean coal with capture**
2020	**GW**	**GW**	**GW**	**GW**
Nuclear	7.5	7.5	7.5	7.5
Coal	7.8	7.8	7.8	7.8
CCGT	28.4	28.4	28.4	28.4
Hydroelectric	18.1	18.1	18.5	18.1
Special regime	45.0	45.0	52.2	45.0
Peak power	7.3	7.0	5.9	7.3
Total capacity (at busbars)	**114.0**	**113.8**	**120.3**	**114.0**
2025	**GW**	**GW**	**GW**	**GW**
Nuclear	7.5	12.5	7.5	7.5
Coal	1.6	1.6	1.6	6.7
CCGT	28.4	28.4	28.4	28.4
Hydroelectric	18.1	18.1	21.4	18.1
Special regime	49.0	49.0	64.0	49.0
Peak power	18.6	13.1	13.7	13.3
Total capacity (at busbars)	**123.2**	**122.7**	**136.5**	**123.0**
2030	**GW**	**GW**	**GW**	**GW**
Nuclear	7.5	13.8	7.5	7.5
Coal	0.6	0.6	0.6	6.8
CCGT	28.4	28.4	28.4	28.4
Hydroelectric	18.1	18.1	21.4	18.1
Special regime	52.0	52.0	75.7	52.0
Peak power	25.2	18.4	19.2	18.7
Total capacity (at busbars)	**131.7**	**131.2**	**152.7**	**131.4**

Supported by INTELLIGENT ENERGY EUROPE

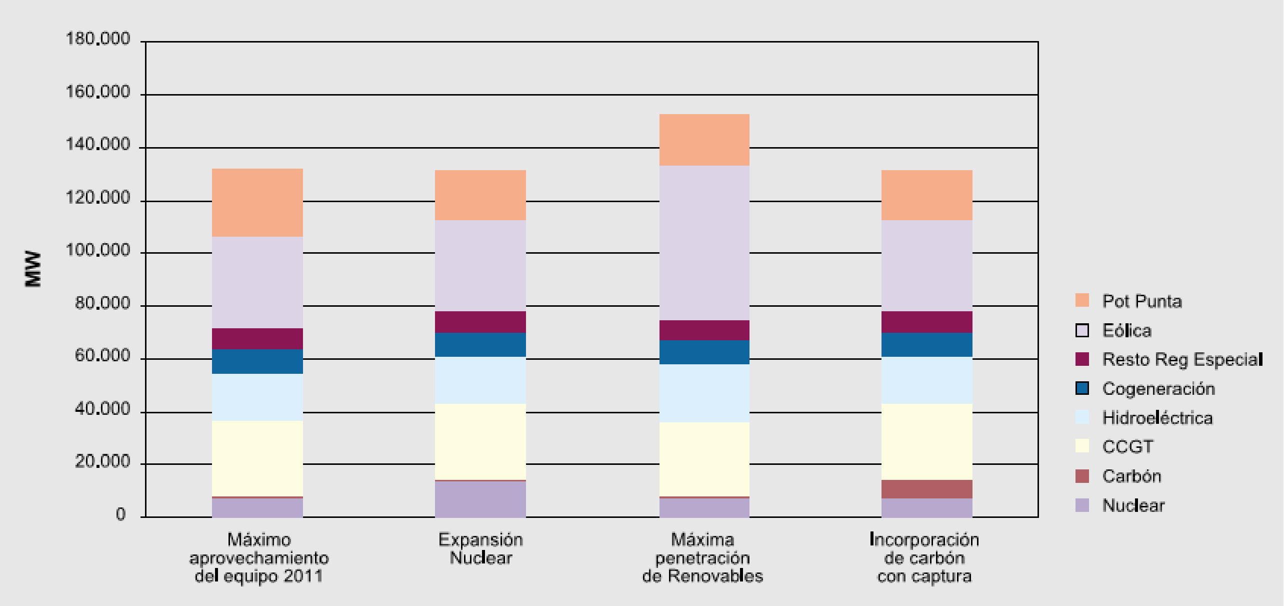


Figure 1.8. Capacity installed at power station busbars, 2030. Source: [13]

1.4.3. PriceWaterhouseCoopers study for 2030

The consultant company PWC presented in 2010 a study of the electricity capacity mix for 2030. In this document, different alternatives of the 2030 scenario were presented, with different economic, environmental and security related conditions. Each scenario could be considered as a possible planning proposal, and the numerical results obtained enabled the comparison under the referred assumptions.

Basic assumptions of the scenarios

Scenario 1

- Power supply of 50% from renewable energy technologies
- Progressive closing of the existing nuclear capacity

Scenario 2

- Power supply of 50% from renewable energy technologies
- Life extension of the existing nuclear plants until 60 years

Scenario 3

- Power supply of 30% from renewable energy technologies
- Life extension of the existing nuclear plants until 60 years

Scenario 4

- Power supply of 30% from renewable energy technologies
- Life extension of the existing nuclear plants until 60 years; New construction of 3 nuclear plants of 1,500 MW each

Table 1.9. Energy balance of the scenarios of power generation mix for 2030 (Scenarios 1-2)

	Starting capacity installed	**Scenario 1**		**Scenario 2**	
	Capacity installed (GW)	**Capacity installed (GW)**	**Electricity generation (TWh)**	**Capacity installed (GW)**	**Electricity generation (TWh)**
Thermal	25.5	48.7	165.5	41.6	110.1
Nuclear	-	-	-	7.3	57.1
Peak plants	-	12.9	-	12.9	-
Conventional hydro	16.5	20.9	29.1	20.8	28.1
Renewables	25.4	96.2	208.4	96.2	207.6
Cogeneration	6.8	12.0	58.6	12.0	58.6
Total	**74.1**	**190.7**	**461.6**	**190.7**	**461.6**

Table 1.10 Energy balance of the scenarios of power generation mix for 2030 (Scenarios 3-4)

	Scenario 3		**Scenario 4**	
	Capacity installed (GW)	**Electricity generation (TWh)**	**Capacity installed (GW)**	**Electricity generation (TWh)**
Thermal	53.3	202.2	48.6	164.3
Nuclear	7.2	57.7	11.7	93.5
Peak plants	6.9	-	6.9	-
Conventional hydro	20.9	27.1	20.8	29.3
Renewables	51.5	116.0	51.5	115.9
Cogeneration	12.0	58.6	12.0	58.6
Total	**151.8**	**461.6**	**151.5**	**461.6**

1.4.4. Study of Club Español de la Energía

This study presents a diagnostic of the Spanish Energy system, focusing on the electricity system. The “Alternative scenario” presented in the document, assumes 330 TWh of demand in 2020 as a base, which is compatible with PANER. Regarding renewable energies, it is assumed that PER 2020 is fulfilled reaching 41% of renewable penetration in the gross production of electricity in 2020.

Table 1.11. Electricity balance for 2020 (Alternative scenario)

	2009	**2020**	**2020**
	GW	**GW**	**TWh**
Ordinary regime	**61.16**	**60.55**	**206.38**
Hydroelectric	16.09	20.00	34.00
Nuclear	7.72	7.26	55.60
Coal	12.00	7.49	31.58
CCGT	25.35	25.80	85.20
Special regime	**32.00**	**62.08**	**156.67**
Cogeneration	5.90	8.37	30.55
Onshore wind	19.14	35.00	71.64
Offshore wind	0.00	0.75	1.85
Solar PV	3.44	7.25	12.36
Solar thermoelectric	0.23	4.80	14.38
Small hydro	2.55	2.50	6.29
Biomass/biogas	0.75	1.75	10.70
Solid waste	0.75	0.91	4.49
Solid waste treatment	0.75	0.60	3.90
Sea energies	0.00	0.10	0.22
Geothermal	0.00	0.05	0.30
Gross production			**363.05**
Consumption in generation			8.97
Net production			**354.08**
International exchange			-12.00
Consumption in pumping			12.08
Demand (at busbars)		**122.63**	**330.00**

The scenarios for 2035/2050 show the uncertainty concerning the possible economic growth and the success of the energy efficiency measures. However, the demand is expected to increase over these periods. After that period, a different focus is needed taking into account the necessity of installing new capacity by 2030/2050, attending to different political and technical considerations. In this new model, the installation of carbon free technologies will be inevitably taken into account. Thus, all the base generation will need to be carbon free. On the other hand, due to the high renewable penetration, flexible technologies will need to be competitive by operating less than 2000 hours per year. Certainly, PHES will have to be one of these technologies. Ultimately, a decision will have to be made upon nuclear capacity favoring or avoiding this technology.

Supported by INTELLIGENT ENERGY EUROPE

1.5 Reference and future development scenarios

The installed power capacity and the power generation balance in Spain electricity system for the year 2011 are given in section 1.1 above. They are considered as reference system data and summarized in Table 1.12.

Two future scenarios for RES development are examined. The first concerns year 2020, when, according to the reference BAU scenario of PANER-2020 and the PER 2011-20 reports, the RES share in electricity will approach 40%. The latest estimations for wind and solar technology development are adopted for the present study, as shown in Table 1.12. Consequently, only two alternative cases are studied in the 2020 scenario, regarding the new PHES system installations: 3 GW in Case 1 and 6 GW in Case 2 (Table 1.12). In both cases, the existing pumped storage units of 2.75 GW is assumed not participating in RES rejections storage, because their operation is already programmed to support the system operation (i.e. night time storage of surplus thermal production, and day-time peak-shaving). In Case 1 it is assumed that 3 GW of conventional hydroelectric plants will be conversed to PHES units, whereas Case 2 assumes an additional construction of 3 GW new PHES units.

The second scenario is for a much higher RES share of 80%, which is the objective for the next decades. The electricity demand for this scenario is computed based on the growth rates reported in Deliverable 2.3 (EEG, Table 1). Calculations start from 2020 and the corresponding given values in the PANER-20 report. Due to the forecasted high RES development for the next decades, it was assumed to achieve the 80% target by the year 2040. The growth rate of demand for the BAU scenario is taken 1.6% for 2020-30 and 1.3% for 2030-40, whereas for GREEN scenario it is taken 0.6% for the whole period. The corresponding net annual electricity generation will be 420 TWh and 500 TWh, as shown in Table 1.12.

Calculations for 80% RES share are performed only for the GREEN scenario, which is associated with high RES development. For this scenario, the relative development of the two most important RES technologies, wind and solar, is also tested, because there are market drivers that can influence the development of one technology against the other. Consequently, 3 alternative configurations are tested for the 80% RES share scenario, from Case A favoring wind development, to Case C that represents a favored solar systems development (Table 1.12). In all cases, the cumulative production of both wind and solar power plants is kept the same, so as the total RES share in all cases be about 80%.

Decarbonization of the electricity production system of Spain is considered for the 80% RES share scenario at about 2040, in accordance with the age structure of thermal plant-portfolio in the Iberian Peninsula, as given in Deliverable 2.3 (Appendix 4). In the same results nuclear power plants are estimated to phase-out by that year. However, the present modeling will also examine a nuclear-system development scenario, assuming power extension of the existing nuclear power plants (and corresponding reduction of CCGT needs). This has no effect on the RES installed power, and hence the nuclear scenario is not included in Table 1. However, it affects the RES feed-in limit of the system, as explained in the next section.

Concerning the PHES potential for the 80% scenario, it is assumed that 5 GW of conventional hydroelectric plants will be converted to PHES and 5 GW of new PHES units will be constructed by then. Also, most of the 2.75 GW existing today PHES will also participate in the RES energy storage. The above give a sum of 12 GW of PHES installed (pumping) power, namely double than that of Case 2 in 2020. It was also assumed that the available PHES storage capacity will correspond in all cases to 12 hours of continuous pumping operation at nominal power. This gives a PHES capacity of 144 GWh for the 80% scenario and of 36 and 72 GWh for the corresponding

Cases 1 and 2 of 2020. A sensitivity study of the system performance on the values of the above critical parameters (storage power and capacity) is also carried out, and the results are presented in the last section of this report.

Finally, the installed power of other RES is estimated by projection from the updated PER 2011-20. Table 1.12 summarizes the input system data for all the above examined cases. The total gross electricity production from all renewable sources does not include the portion of PHES generation that comes from the stored RES rejections. Also, the total RES production should be lowered by the surplus amount that cannot be stored in the PHES systems, as well as by the pumped-storage cycle losses of the stored energy.

Table 1.12. Overview of main factors of the energy system for various scenarios examined.

	Ref.	**2020 Scenario (GW)**		**80% Scenario (in GW)**		
	2011	**1**	**2**	**A**	**B**	**C**
Thermal plants						
Coal	11.7	11.7		-		
CCGT	25.3	28.4		30 - 40[5]		
Fuel/gas	1.5	1.5		-		
Nuclear	7.8	7.5		-		
Oil & other thermal	7.3	3.0		2.0		
RE power plants						
Wind	21.1	(35.0)[1] 35.0		100[2]	85[2]	72[2]
Wind (offshore)	-	(3.0)[1] 0.75				
Solar PV	4.05	(8.4)[1] 7.25		35[3]	50[3]	65[3]
Solar Thermal (semi-controllable)	1.05	(5.1)[1] 4.8				
Hydropower	14.8	14.8 (11.7 net hydro)		15.5 (10.5 net hydro)		
Pumped storage	2.75	5.75	8.8	12.75		
Small hydro	2.04	2.2		2.5		
Geothermal	-	0.05		~ 1.5		
Other RES	0.9	(1.7) 2.2		~ 4.5		
Yearly peak (GW)	43.9	~ 62		~ 70		
Electr. Net Generation (TWh/a)	264.1	374.7		420.0 (~500.0 BAU)		
PHES (TWh/a)	3.2	8.5		27 - 38[4]		
Intern. Exch. (TWh/a)	6.1	12		-		
Electr. Consumption (bc) (TWh/a)	254.8	~ 354				
RE production, TWh	87	(150) 146		336		
RE share	33%	~ 39%		~ 80%		

[1] According to the first NREAP (2010)

[2] Equivalent for both onshore and offshore wind farms

[3] Equivalent for both PV and Solar thermal

[4] Computed from system simulation (Table 3.2)

[5] Estimated from the computed data

2 Development of the residual load

Most updated and detailed hourly production data of all conventional thermal and RES power systems are extracted from the web site of the Red Eléctrica de España (http://www.esios.ree.es/web-publica) for the last year 2012, and they will be used in the present study.

The Residual Load (RL) curve for a future electricity system of Spain is calculated by the following method: At first, the load demand time-series is constructed by multiplying the data of reference year 2012, so as the total electricity consumption become equal to the one given in Table 1.12 (for the corresponding scenarios 2020 and 80%). The hourly production data of wind farms, solar systems and hydropower plants for the reference year are also properly projected to represent the increased installed power of these sources in each of the cases of Table 1.12.

The RL is then obtained by subtracting the uncontrollable hourly wind, solar and hydro production from the corresponding system load. For the wind farms production, an equivalent power of onshore installations is adopted, which is 36 GW for 2020 (NREAP forecasted: 35 onshore + 0.75 offshore), and three different assumed values for the corresponding cases of 80% scenario. Analogous is the treatment of PV and solar thermal technologies, and an equivalent PV installed power of 10 GW is adopted for 2020 (7.25 PV + part of solar thermal), whereas three different equivalent PV installations are examined for the 80% scenario (Table 1.12).

Concerning hydropower, although large reservoir plants may be able to provide some flexibility to the system in order to support and manage high RES penetration, in this study it was assumed that these specific needs are served only by the new PHES installations. Hence, the production of the installed hydropower plants (including existing pumped storage and small hydropower plants) is considered as uncontrollable, assuming that the large hydro plants are already used for peak-shaving and water management purposes. The rejected RES energy stored in the hydroelectric plants that are conversed to PHES is added to their initial production. Hence, the total hydro production is computed using the initial installed hydro power and not the remaining net hydropower plants. This corresponds to almost 17 GW in 2020 (11.7 + 3 conversed + 2.2 small) and to 18 GW in the 80% scenario (10.5 + 5 conversed + 2.5 small).

For the 80% scenario and additional amount of 1 GW constant power is also abstracted to account for the estimated minimum power of the geothermal production (~2/3 of installed). Finally, as a first approximation, the import/export energy is set to zero in the simulations, although it can be seen as an additional storage system, because it is strongly dependent on the load situations of the neighboring countries and on their needs for RES storage, as well as on the correlation level. Also, the import/export capabilities of the Iberian Peninsula are limited, due to its location at the edge of the European electricity system.

The cumulative hourly penetration of uncontrollable RES (wind and solar) production can then be calculated from the RL curve and the technical minimum of the inflexible production units that are dispatched. The latter include nuclear, coal fired and CCGT units, as well as the rest of the special regime uncontrollable production. At present, the minimum power of nuclear units during the night is usually about 6 GW, whereas coal fired and CCGT production can be reduced to a minimum of the order of 1 GW each. The rest special regime uncontrollable production has a minimum of about 5 GW (Fig. 2.1). The above values are not expected to change considerably by 2020, therefore the feed-in limit for intermittent RES production is estimated to be about 15 GW. A maximum possible feed-in limit of 18 GW is also considered in the simulations of 2020 scenario.

Supported by INTELLIGENT ENERGY EUROPE

Concerning the 80% scenario, the model is applied for two different penetration limits: The first has zero value, representing a very flexible and optimally managed system, without any units with significant technical minimum, which could be achieved until 2040. On the other hand, a second feed-in limit of 10 GW is tested in order to examine the case of a less flexible system, containing also the nuclear power plants. Hence, the actual behavior of the system in the 80% scenario should be between the above two simulated cases.

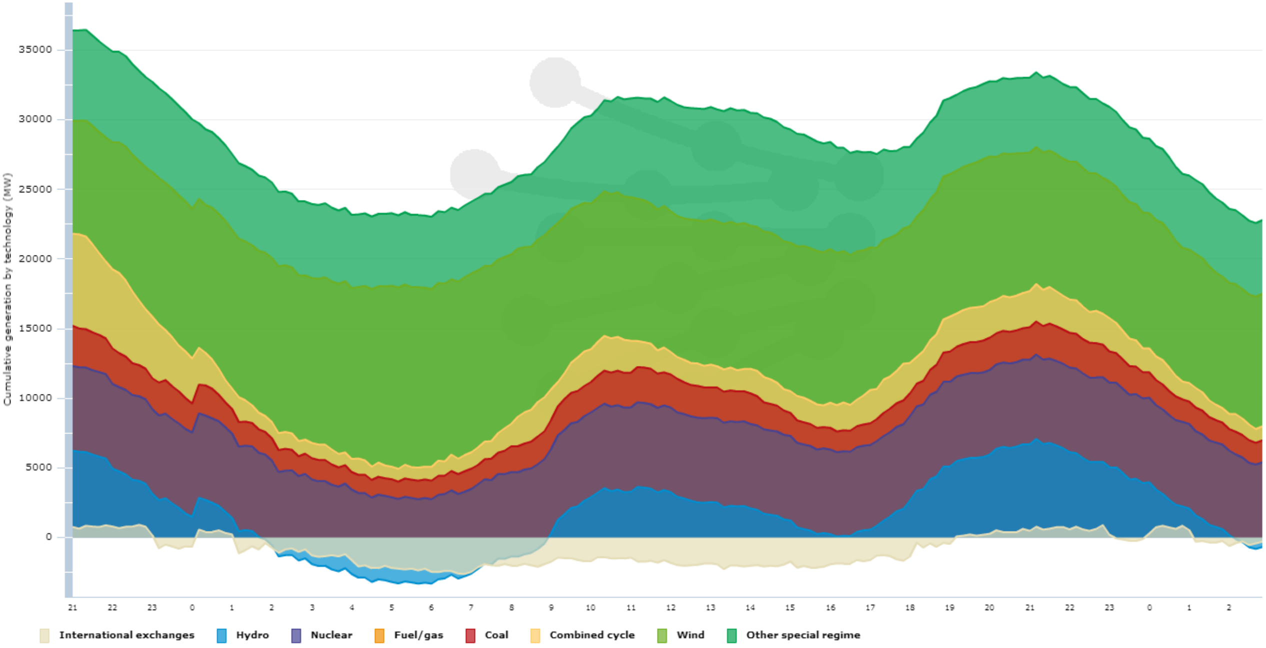


Figure 2.1. Indicative electricity production mixture of Spanish system during a high wind production day (Jan 26, 2013). Source: REE

2.1 Results for 2020 scenario

The annual load and residual load variation for the 40% RES share scenario expected by the year 2020 is plotted in Fig. 2.2. Rejection of inflexible RES production happens for RL values below the technical feed-in limit. Fig. 2.2 shows that the first considered limit of 15 GW is clearly less than the RL curve during the entire year. Therefore, almost all uncontrollable RES production can be absorbed. Hence, the simulation results will be presented only for the highest possible technical minimum of 18 GW.

The quantitative results are tabulated in Table 2.1. It must be noticed that the relative penetration of wind and solar production in the system is not known, and it will be decided each time by the TSO, depending on grid stability and generation costs characteristics. Here, an indicative but reasonable penetration strategy was adopted, assuming that in case of surplus RES production, the rejections are analogous to the instant production of each of these two technologies.

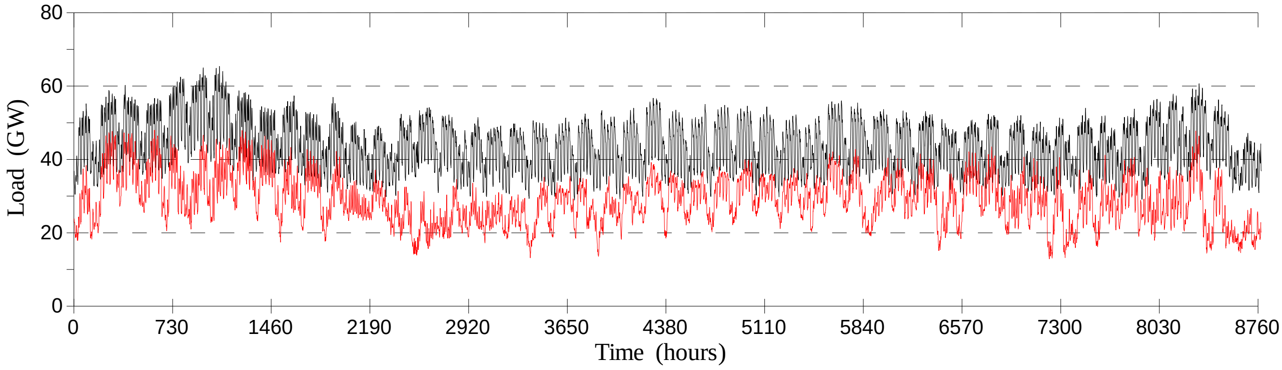


Figure 2.2. Load (black) and residual load (red) for the 40% RES share (2020)

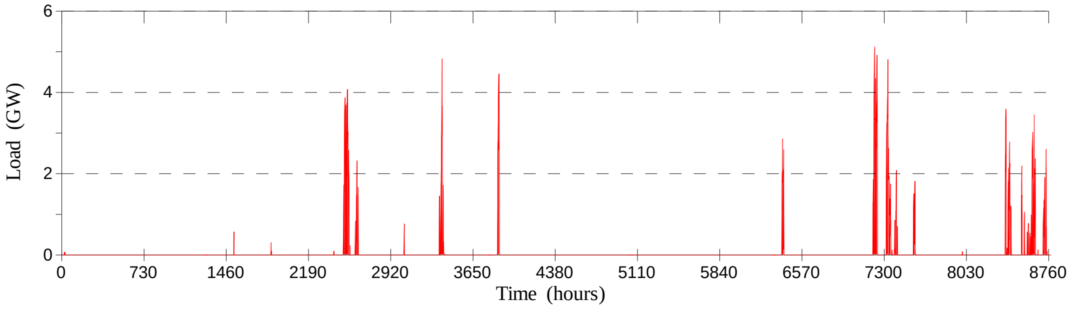


Figure 2.3. Rejected energy for storage from intermittent RES for 40% scenario (2020)

Figure 2.4 shows that the variation of the load that has to be covered by the left over power plants does not change much in this scenario. Stability is even slightly improved, due to the peak-shaving action of the RES production during the high load demand hours that compensates for the increased variation caused when there is considerable wind production during the night. This is more clearly demonstrated in the detailed view of Fig. 2.5.

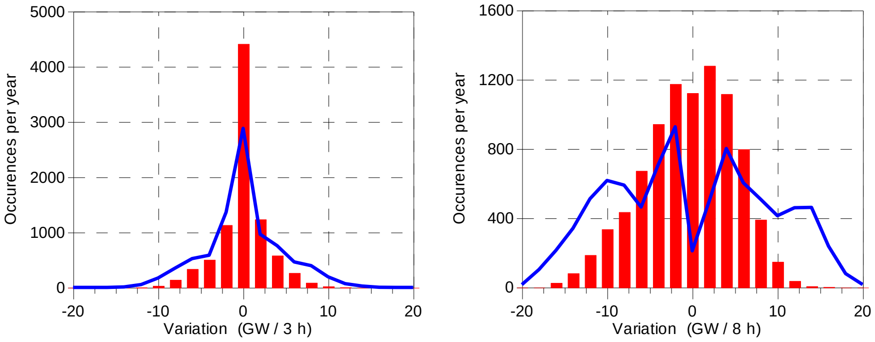


Figure 2.4. Total load variation (cont. lines) and residual load (bars) for the 40% scenario.

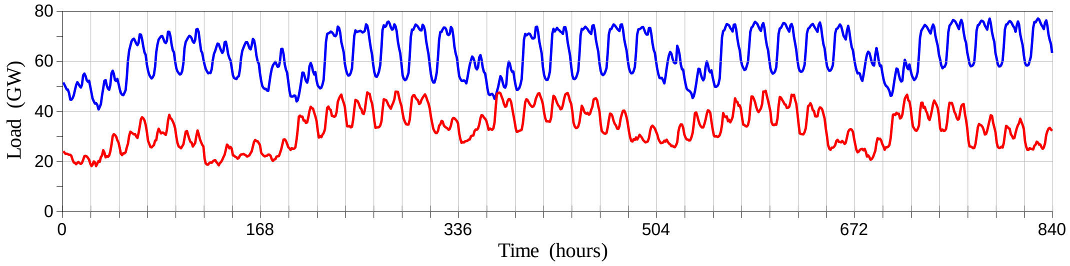


Figure 2.5. Detailed view of Load (blue) and Residual Load (red) variation for the 40% scenario.

Supported by INTELLIGENT ENERGY EUROPE

Table 2.1. Results for different technical minima for 40% RES scenario.

Tech. min. (MW)	Max. power below limit (GW)	Rejected production % Wind – PV – cumulative			Total rejected energy (GWh)
18000	5.1	0.67	0.33	0.6	575
15000	2.1	0.04	0.04	0.04	40

2.2 Results for the 80% scenario

The annual load and residual load variation for the 80% RES share scenario are plotted in Fig. 2.6 for the three cases examined (A, B and C, Table 1.12). For all three cases the variation rate of the RL is high, and the minimum-maximum power varies between +55 and -35 GW, before applying energy storage.

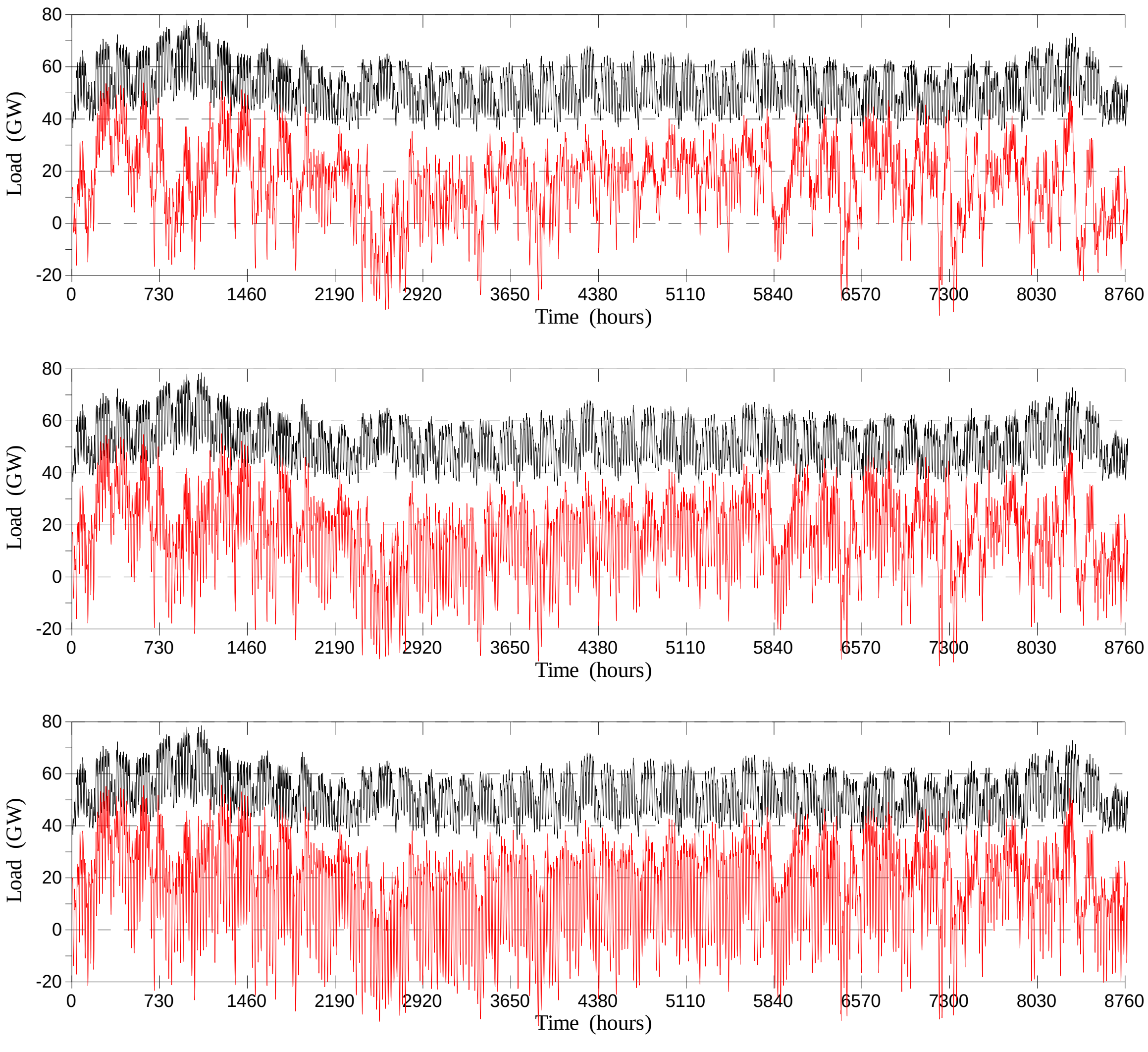


Figure 2.5. Load (black) and residual load (red) for the 80% RES share and cases A, B and C (from top to bottom).

Even for zero technical feed-in limit (assuming that the system will be very flexible and optimally managed, as discussed previously), the RES energy rejections are much higher and more frequent than in 2020 scenario (Fig. 2.6). Also, rejections are more frequent and higher in Case C, when the installed solar power is highest. The total rejected energy amount varies from about 12 TWh for Case A to almost 21 TWh for Case C, whereas the corresponding maximum negative power is about the same for all cases (34-37 GW). The fraction of the intermittent production (wind-solar) that cannot penetrate to the system becomes now substantial, between 4 and 7%.

The rejections for the nuclear scenario and the higher technical minimum of 10 GW are as expected quite higher and more frequent during the year, as shown in Fig. 2.7. The total rejected energy becomes around 2.5 times than for the corresponding zero limit rejections, and the negative power varies between 44 and 47 GW, depending on the wind-solar mix. The fraction of the intermittent production (wind-solar) that cannot penetrate to the system becomes now substantial, between 4 and 7%. Table 2.2 summarizes the numerical results for both the above limits and for all three cases A, B and C.

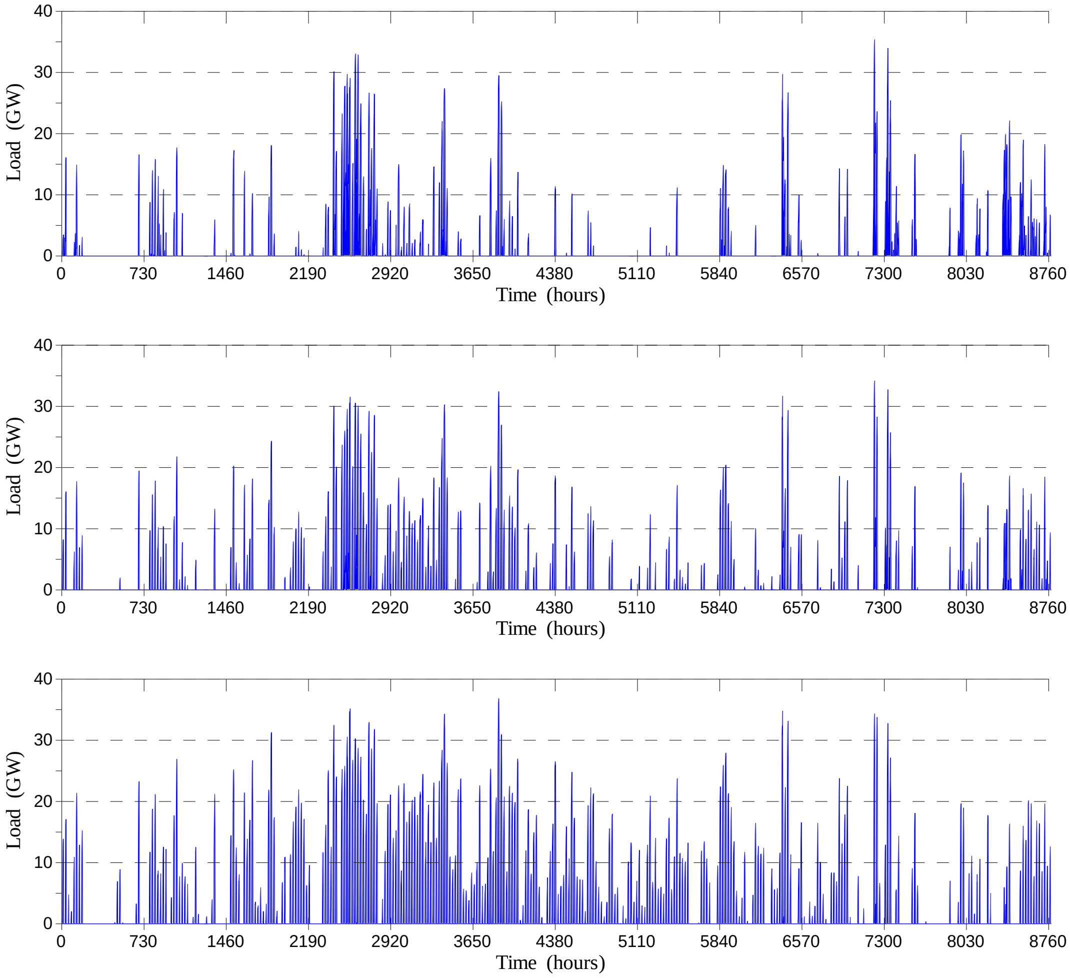


Figure 2.6. Rejected energy from intermittent RES for 80% scenario and cases A, B and C (from top to bottom).

Supported by INTELLIGENT ENERGY EUROPE

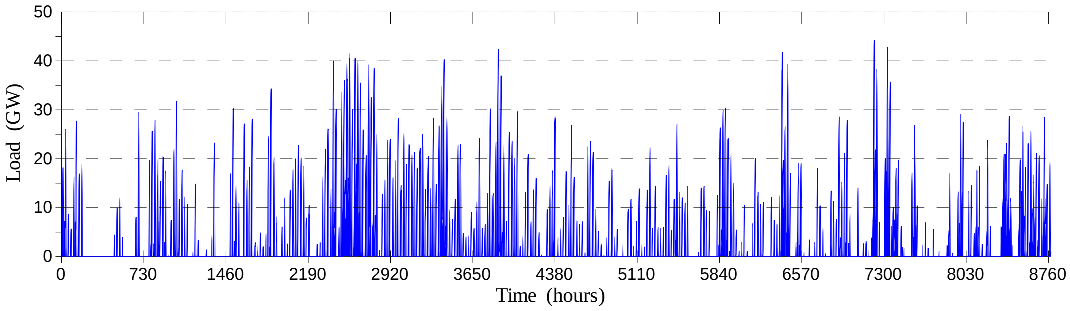


Figure 2.7. Rejected energy from intermittent RES for 80% scenario and case B, for technical minimum 10 GW (case B-nuclear)

Due to the higher share of fluctuating energy and the larger spread of the residual load (about 90 GW compared to only 35 GW in the 2020 scenario), the system load variations will increase. Considering that the left-over power production system cannot operate below its technical minimum, the load variations of the controllable plants are computed and presented in Figs. 2.8 and 2.9. The influence of intermittent RES production on the system variations during 1 hour are small in all cases, increasing the maximum values from about 7 GW of the initial system to 8 GW. The influence on system load variations in longer periods (3 and 8 hours) is also small for Case A (Fig. 2.8). However, system stability is significantly affected in Case C, where the above variations are remarkably increased, reaching up to 30 GW/3h and becoming much higher for 8-hours periods (Fig. 2.9). This is because solar installations produce only during the day, and hence the total RES production is more concentrated during shorter periods when the solar power becomes higher.

As can be seen in the detailed view of Fig. 2.10, the excessive production of solar units in Case C creates large troughs in RL curve during the day-time, much higher than the night-time lows. The situation is slightly improved for the nuclear case, where the higher feed-in limit reduces the RL curve variations above the limit, which are taken into account for these graphs (Fig. 2.9 right). Energy storage systems can reduce these fluctuations and enable the left over power plant mix to adapt to the load accordingly.

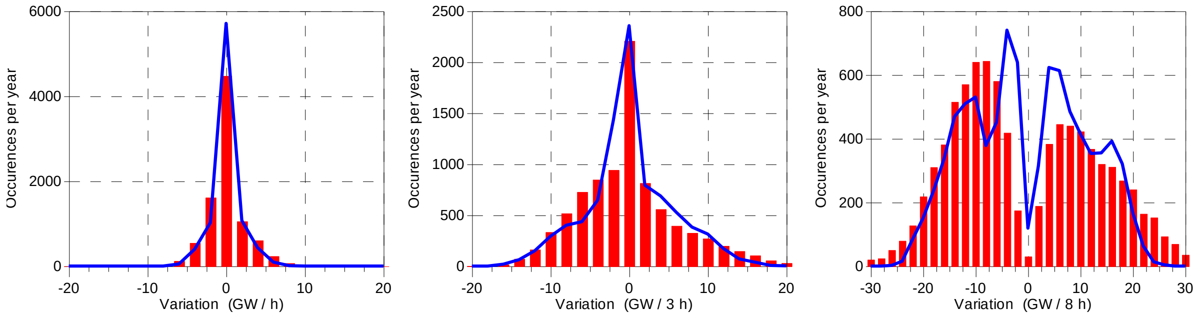


Figure 2.8. Variation of the system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – case A.

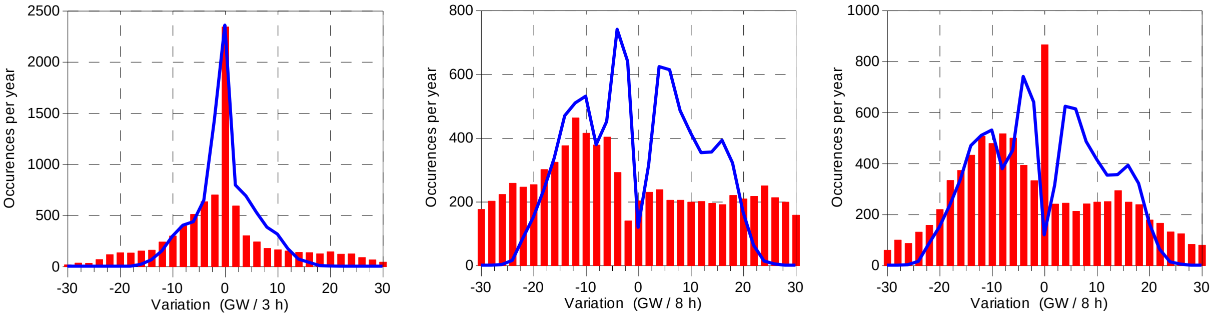


Figure 2.9. Variation of the system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – case C (left-center) and C-nuclear (right).

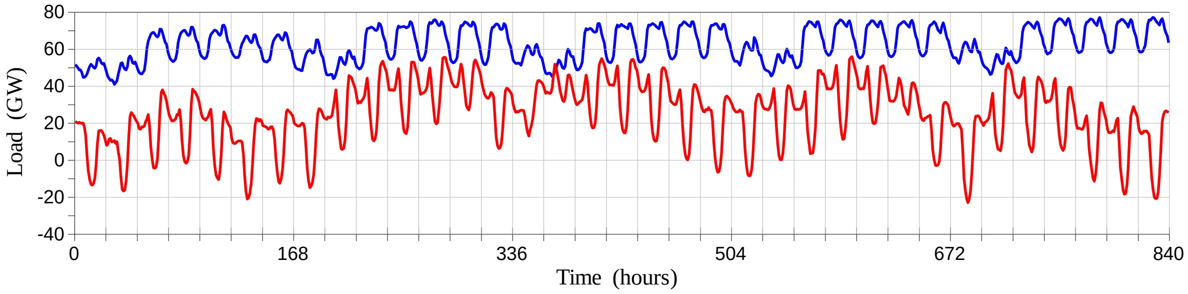


Figure 2.10. Detailed view of Load (blue) and Residual Load (red) variation for the 80% – case C.

The above results reveal that the configuration of Case A (wind favored development) is the most effective for the Spanish electricity system, achieving the highest penetration of intermittent RES production and the least rejections, as well as causing the smallest increase of system load variations, and hence the least impact on system stability.

The corresponding results for the nuclear scenario, which are included in Table 2.2, reveal that the RES feed-in limit has a major effect on the intermittent RES penetration. If the flexibility of the left over units in the system is low then the rejected wind and solar production may be significant for any combination of their installed power. Hence, life extension of the existing nuclear power plants will constitute a potential obstruction to the high RES penetration in the future electricity system of Spain.

Table 2.2. Comparative results for the 3 cases of the 80% RES development scenario.

Case	Max. power below limit (MW)	Rejected production % Wind – PV – cumulative			Total rejected energy (GWh)
A	35,300	4.3	3.9	4.2	11,800
B	34,200	4.0	6.0	4.7	13,100
C	36,800	4.8	9.5	7.3	20,750
Results for nuclear scenario (system feed-in limit 10 GW)					
A-n	45,300	12.0	10.7	11.7	32,800
B-n	44,200	10.6	15.5	12.4	34,600
C-n	46,800	10.5	22.4	16.0	45,300

Supported by INTELLIGENT ENERGY EUROPE

3. Energy storage needs for future RE development scenarios

In this section the system configuration cases listed in Table 1.12 are investigated with regard to the scheduled storage capacity and the maximum storage needs for the integration of rejected energy from RES. The effects of the development and operation of PHES units on the future electricity system of Spain are also examined and presented.

In the framework of the present project specific computer algorithms were developed to simulate the yearly operation of PHES system in the electricity grid of Spain, and to assess its performance in respect of both desired roles: Recovering of RES rejected production and smoothing of residual load fluctuations. A brief description of the computer algorithms is given in Annex A.

In order to determine the storage needs an additional storage technology is introduced with unlimited power and unlimited storage capacity. Thus the algorithm can compute how much storage installations would be needed to fully accommodate all rejected energy from renewable sources, as well as the possibility of returning this amount of energy back to the system during the simulated period of one year.

The modeling algorithm is also applied for parametric studies of the effect of available storage power and capacity of the PHES system on the storage efficiency of the rejected RES energy, as well as on the capacity factor of the pumping machinery. The latter is then used as criterion for the optimum sizing of the PHES system, in order to correspond to the future storage needs of the grid in a cost effective and economically viable way.

3.1 2020 Scenario

As discussed previously in section 2, a fixed RES feed-in limit of 18 GW is adopted for the 2020 grid system. This implies that the lower boundary of the residual load curve is set to 18 GW, and the so formed curve represents the load that should be covered by the left over controllable plants (Controllable Plants Load, CPL). Fig. 3.1 illustrates this load variation during the year 2020 for Case 2 of Table 1.12, before and after incorporating PHES units of total storage power 6 GW and capacity 72 GWh. The RES rejections are small in this scenario, and hence the major contribution of PHES system is to smooth-out the CPL curve and to reduce its peaks, as shown also in the detailed view of Fig. 3.2. The attainable reduction of maximum power needs from left over units is about 5 GW (from 48 to 42.7 GW), almost equal to the production power of the PHES system (assumed equal to the pumping power, namely 6 GW).

Supported by INTELLIGENT ENERGY EUROPE

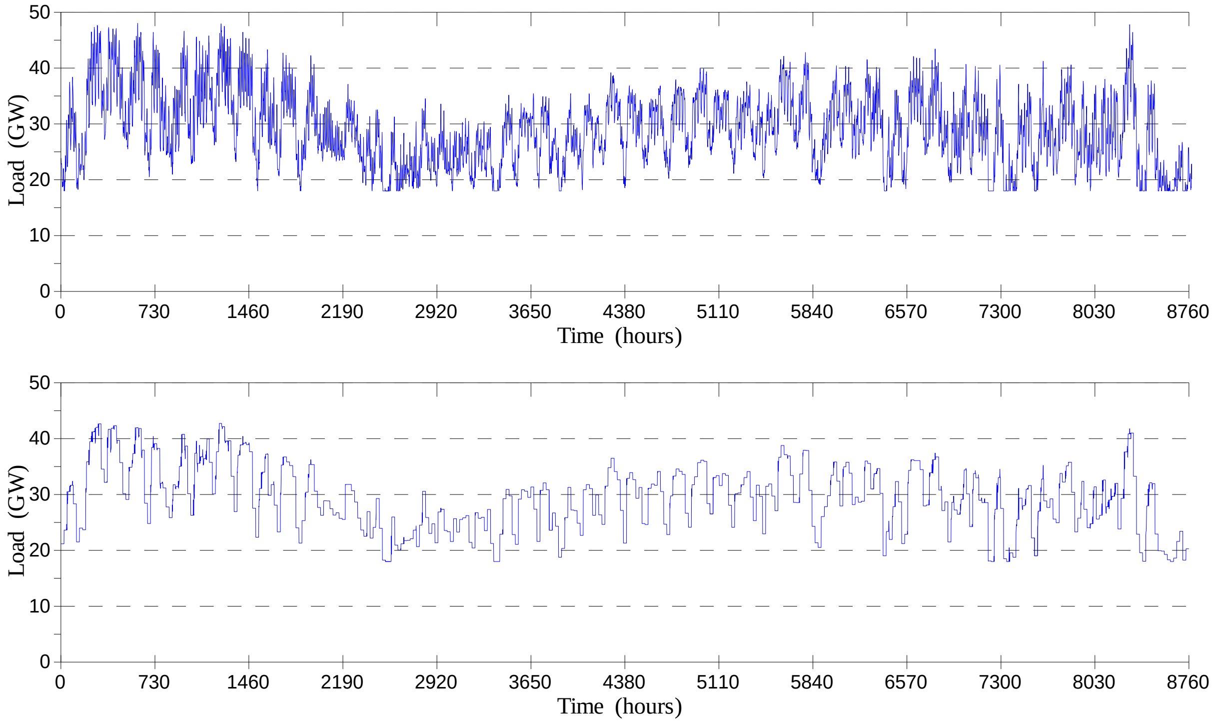


Figure 3.1. Controllable Plants Load without storage (upper), and after fully exploited PHES (lower), for 40% scenario – case 2.

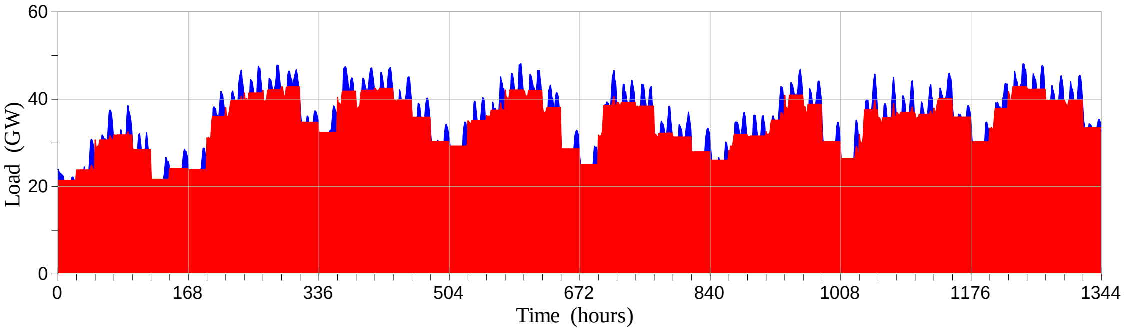


Figure 3.2. Detailed view of CPL curve without and with PHES for 40% scenario – case 2.

The duration curves of the rejected RES production are computed and plotted in Fig. 3.3, and are similar for both Cases 1 and 2. Rejections occur only for about 360 hours or 4% of the year. They are above 2 GW only for about 100 hours, while only for few hours the rejected power exceeds 4 GW. The implemented PHES system of Case 1 (3 GW) is able to exploit only part of this energy, whereas the storage capacity of 6 GW in Case 2 can store almost the entire rejected energy (Fig. 3.3). The finally recovered energy at the PHES units (hydroturbines production) is further reduced due to various losses in the PHES cycle (estimated here about 25%). In both cases, the remaining unstorable energy is small and its duration curve is too short to be exploitable by any other energy storage system.

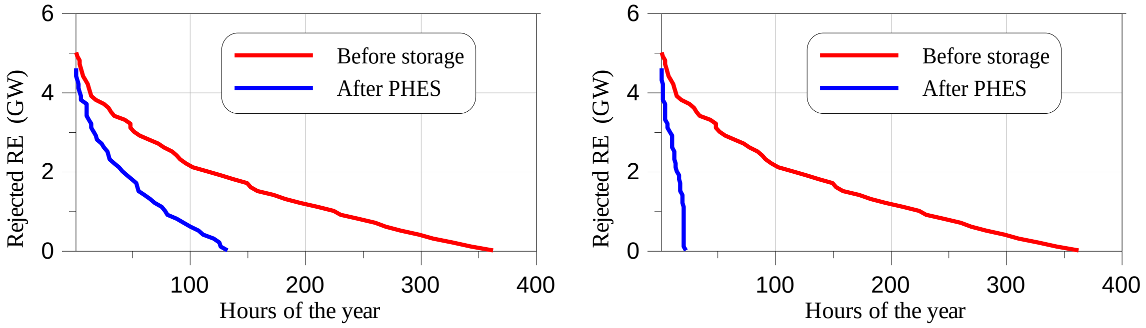


Figure 3.3 Duration curves of RES rejected production for 40% RES share, and cases 1 (left), and 2 (right).

The accumulation of total and remaining after storage rejections during the year 2020 are plotted in Fig. 3.4. Due to the increased demand in the winter, the entire RES production can be absorbed without any rejections. The latter are observed mainly during the spring and autumn, when there are some periods of high RES production. The much higher storage efficiency of PHES system in Case 2 is evident in Fig. 3.4.

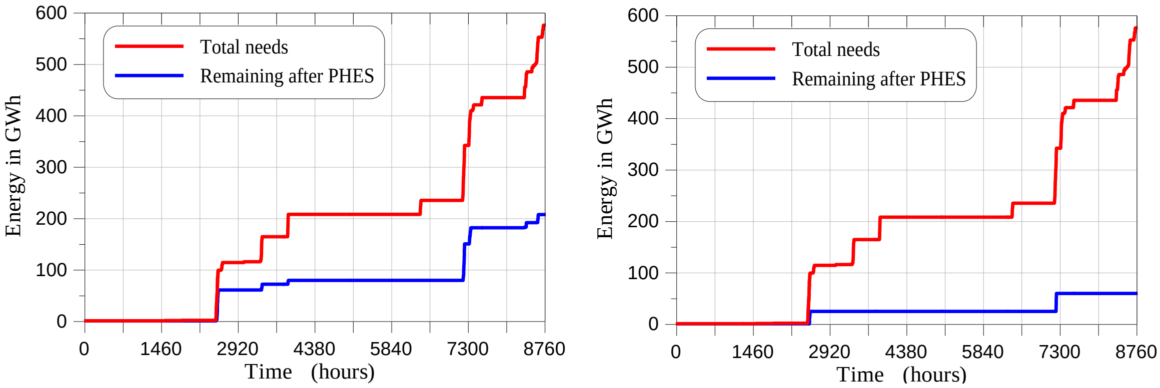


Figure 3.4 Cumulative RES energy rejections /storage needs during one year, for 40% share – cases 1 (left), and 2 (right).

The plots in Figure 3.5 illustrate the operation history of the PHES system in Case 1 during the year 2020, if it is used only for storage of RES energy rejections. The results show again that the PHES system is activated only few times a year, exhibiting a very low capacity factor of the machinery (pumps and hydroturbines), which is of the order of 1-2%. The corresponding diagrams for Case 2 are quite similar and they are not plotted.

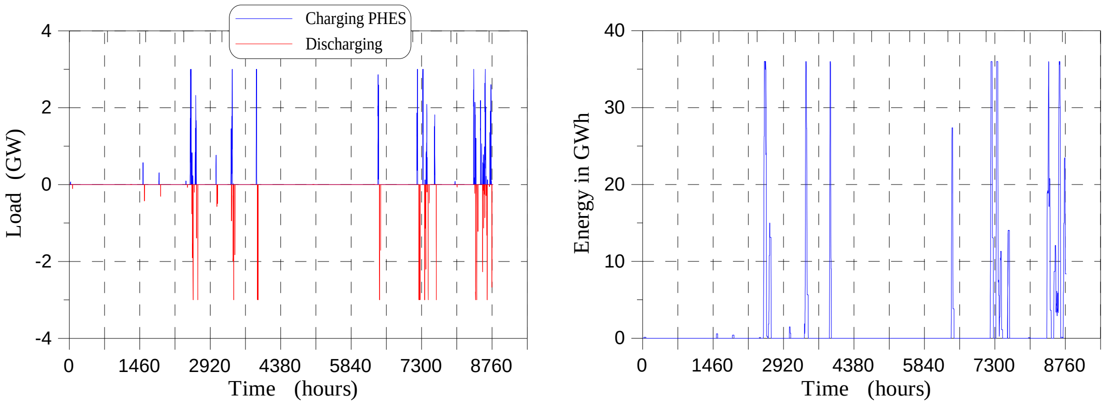


Figure 3.5. Power and charging level of PHES system only for RES storage, for the 2020 scenario – case 1.

Supported by INTELLIGENT ENERGY EUROPE

Further exploitation of the PHES units for peak shaving of the RL curve by storing night-time production of thermal plants results in remarkable increase of their capacity factor, by about 21% to 24%. Hence, the overall CF of the pumping units reaches 25% for Case 1 and almost 22% for Case 2. This can be observed in the dense diagrams of Fig. 3.6, while all the above quantitative results are concentrated in Table 3.1.

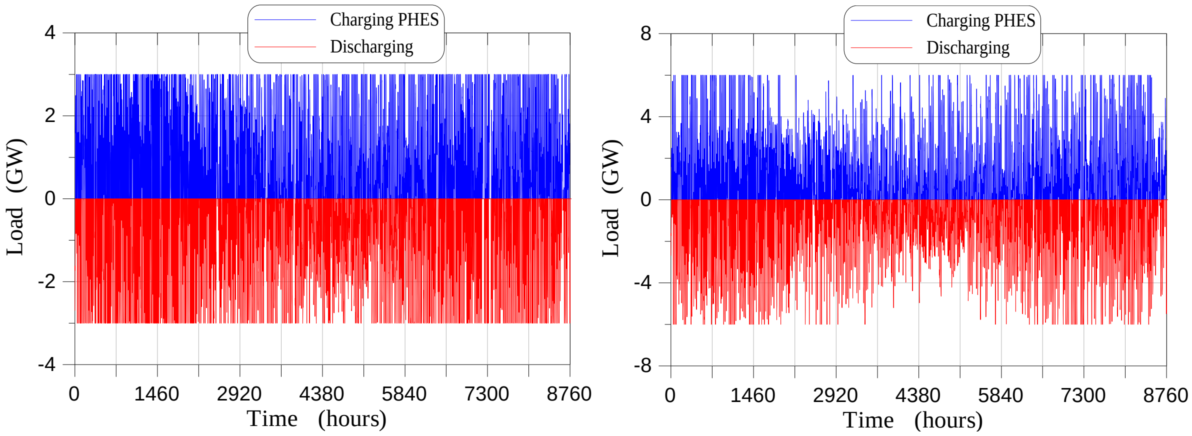


Figure 3.6. Final power level of the PHES system for 2020 scenario – cases 1 (left), and 2 (right).

Table 3.1. Comparative results for the cases of the 2020 scenario.

Case	Rejected RES (GWh)	Stored RES (GWh)	Recovered portion after losses	Stored System (GWh)	Total PHES discharge (GWh)	Pumping station Capacity Factor (%)		
						RES	System	Total
1	575	360	47.0 %	8253	6458	1.4	23.5	24.9
2	575	508	66.3 %	10980	8615	1.0	20.8	21.8

The implementation of PHES for storing the rejected RES production does not cause any changes in the system stability characteristics, due to its negligible utilization in both cases 1 and 2 of 2020 scenario. However, after full exploitation of the PHES system the variations of the load for the left-over plants can be significantly reduced, especially in Case 2 that has the higher storage capacity, and the system becomes more stable than the initial one (Fig. 3.7, compared to Fig. 2.4).

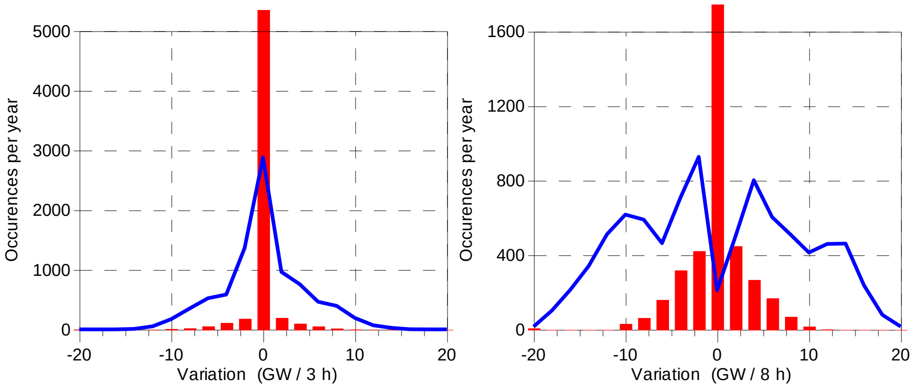


Figure 3.7. Total load variation (cont. lines) and Controllable Plants Load variation with fully exploited PHES (bars) of the 40% scenario – case 2.

3.2 80% RES share scenario

Three cases of different wind-solar development are examined for the 80% RES share scenario, the ‘wind favored’ Case A, the ‘equal development’ Case B and the ‘solar favored’ Case C, as defined in Table 1.12. As discussed in section 1.5, the corresponding installed pumped storage power for the 80% RES share scenario is at first estimated to 12 GW, while the storage capacity is 144 GW, namely 12 hours of continuous pumping operation.

Fig. 3.8 presents the annual CPL curve variation for Case A, before and after incorporating the PHES units. Here, the contribution of these units to the reduction of remaining load peaks shown in Fig. 3.8 is more pronounced than in 2020 scenario, due to the greater storage power and capacity. The attainable reduction of maximum power needs from the left over units is about 10 GW (from 55 to 45 GW), while the periods of needs above 40 GW are restricted.

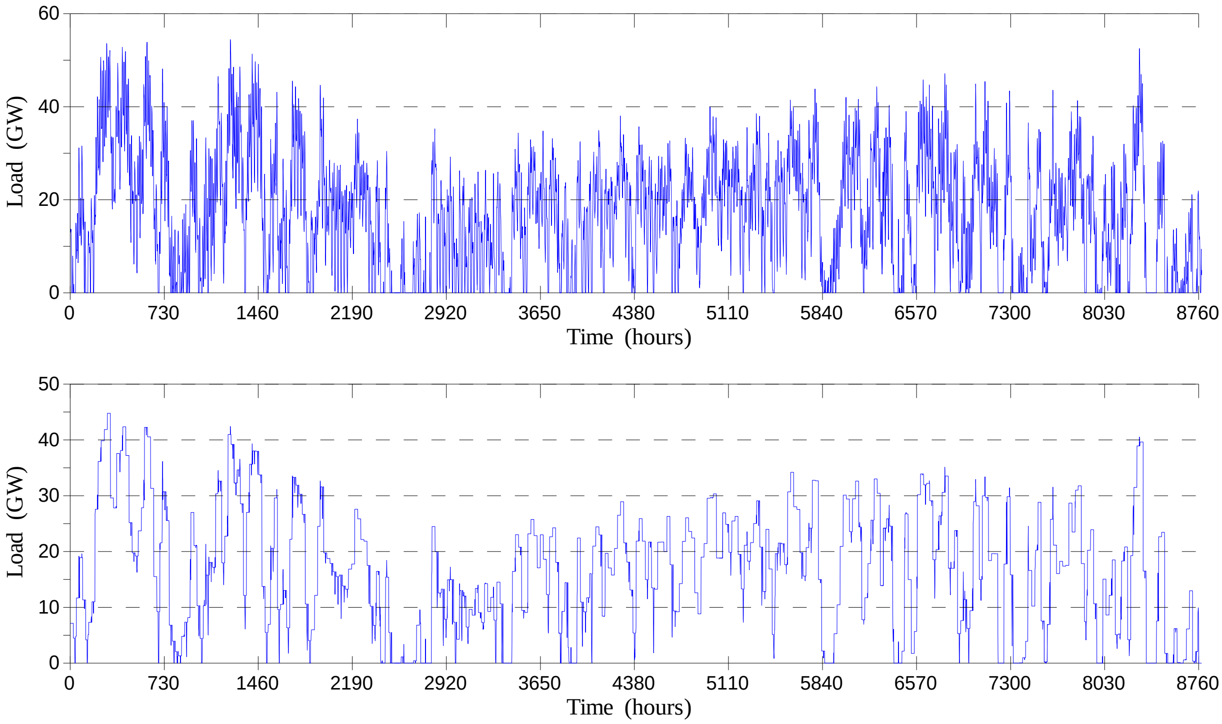


Figure 3.8. Controllable Plants Load without storage (upper), and after full PHES exploitation (lower), for 80% scenario – case A.

Maximum power needs after PHES incorporation are about the same for all three cases of this scenario (45 – 44 GW). However, variations of the CPL curve are not similar. Case C shows much stronger fluctuations in order to absorb the more significant solar production during a short period of the day (Fig. 3.9).

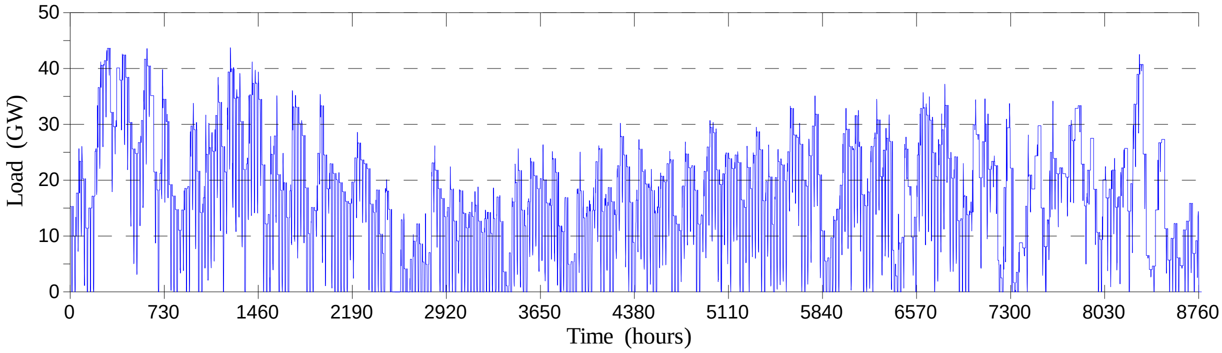


Figure 3.9. Controllable Plants Load after full PHES exploitation for 80% scenario – case C.

The next Figures 3.10, 3.11 and 3.12 demonstrate the operation of the PHES system during the year for cases A, B and C, respectively, as well the loading of the left-over controllable plants. The peak shaving achieved by the PHES units, as well as their capability to store the rejected RES production can be more clearly observed in the detailed views of Fig. 3.11 and 3.13. The utilization of PHES units for RES storage (the additional storage of thermal plants is not shown), is restricted and occasional for Case A (Fig. 3.10), and becomes more frequent as the installed solar power increases, towards Case C (Figs. 3.11, 3.12). The increased solar production causes also stronger fluctuations of the CPL curve, with large troughs during the midday, throughout the whole year.

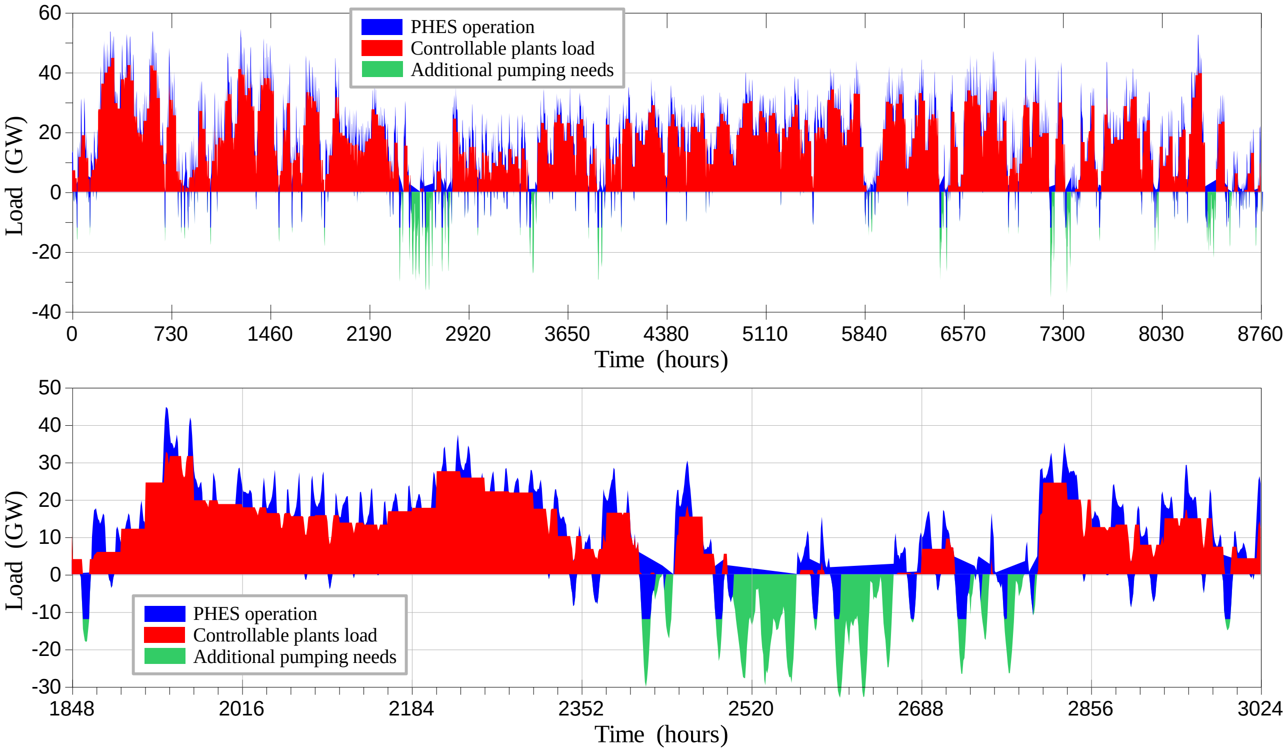


Figure 3.10. PHES and Controllable plants load variation for 80% scenario – case A.

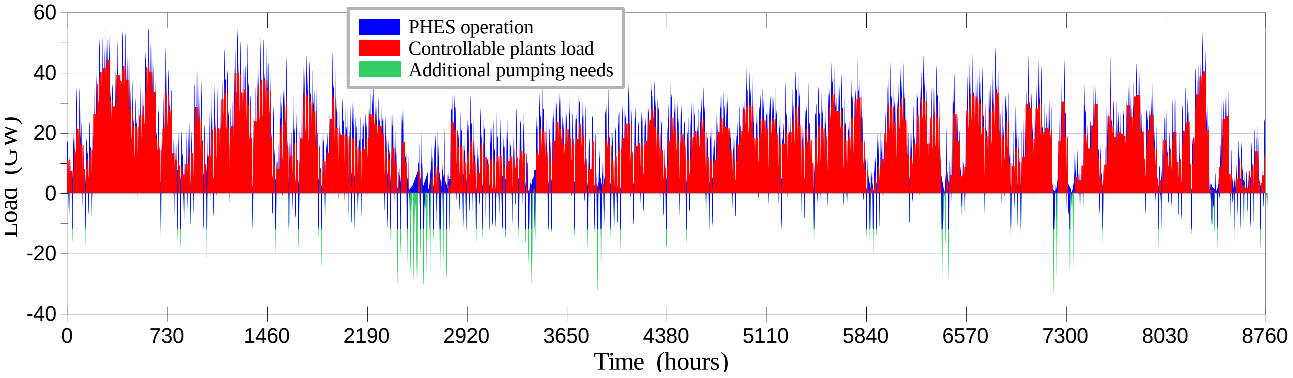


Figure 3.11. PHES and Controllable plants load variation for 80% scenario – case B.

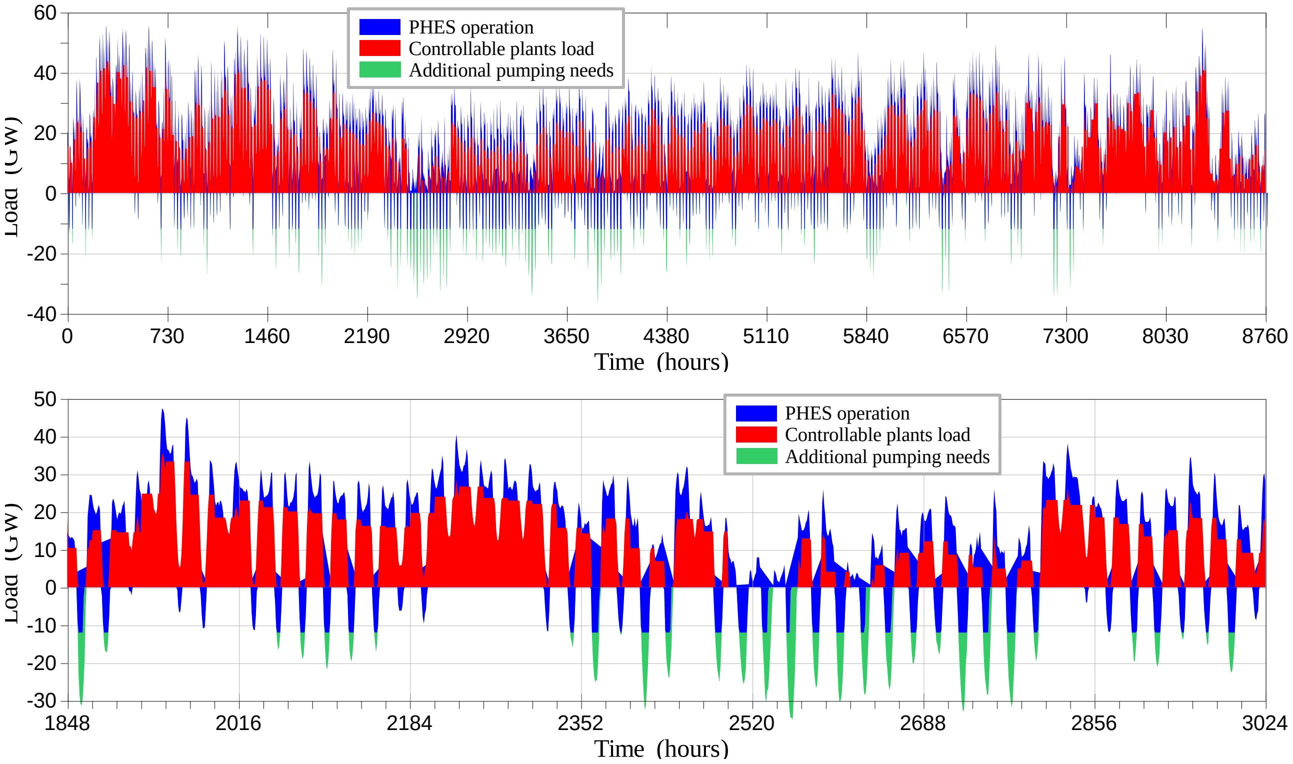


Figure 3.12. PHES and Controllable plants load variation for 80% scenario – case C.

The peak shaving operation of the PHES units is about the same also in the nuclear scenario, in which the technical feed-in limit for RES is set to 10 GW instead of zero (Fig. 3.13, compared to Fig. 3.10). However, in this case the RES rejections are greater and more frequent, and hence the utilization of storage system is higher.

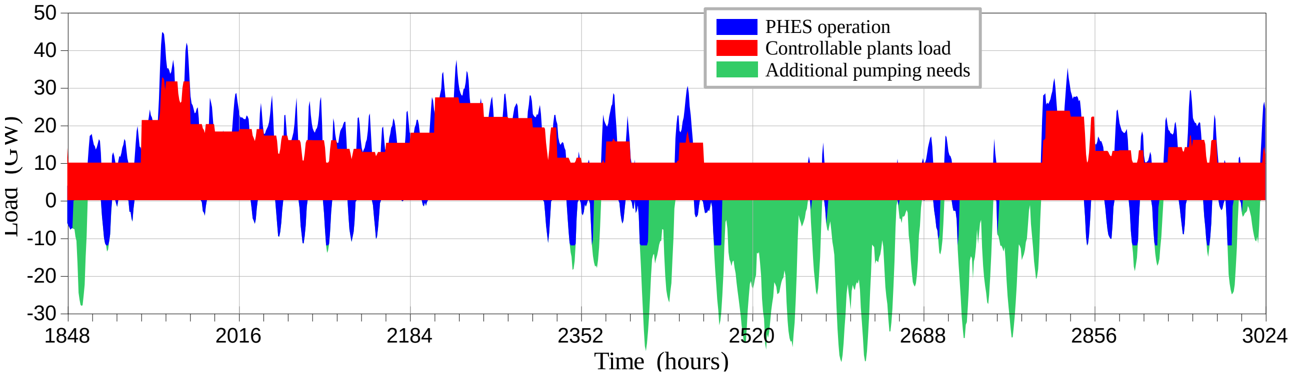


Figure 3.13. Indicative view of PHES and Controllable plants load variation for 80% scenario – case A-nuclear.

The duration curves of the rejected RES production are plotted in Fig. 3.14 for all examined cases of 80% RES share scenario. Here again it can be observed that the frequency of RES rejections increases from Case A to C and maximizes for the higher technical minimum of nuclear scenario.

In all cases, the PHES system of 12 GW storage power is capable to store a substantial part of rejections (area below dotted line and red curve). But it is clearly more effective in Case C, where the duration curve of the remaining unstorable energy exhibit the least slope and power almost always below 20 GW. Consequently, this energy is more likely to be cost-efficiently recovered by another storage technology. The same is also valid in all cases with the nuclear scenario.

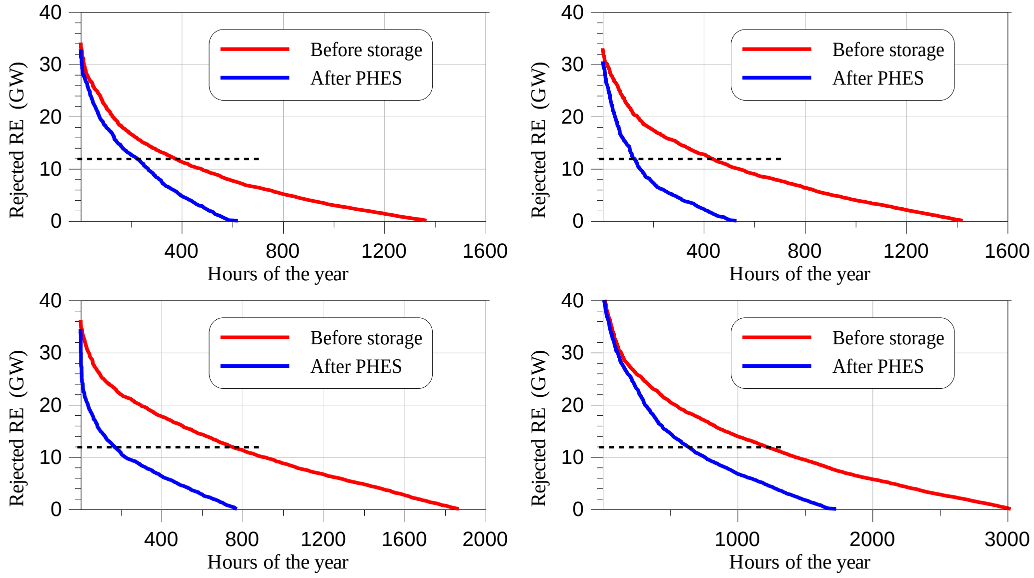


Figure 3.14. Duration curves of RES rejected production for 80% RES share, and cases A, B (upper), C and B-nuclear (lower).

The accumulation rate of RES rejections is higher during the spring and autumn for Case A (Fig. 3.15), like in the 2020 scenario. But this pattern changes as more solar power in injected to the system, and the rate becomes considerable throughout the whole year in Case C, as also in the nuclear scenario. In all cases the rejections are smaller during the first 3 months of the year, and their major portion can be recovered by the PHES system.

Fig. 3.15 depicts that for the non-nuclear scenario the wind-solar blending of Case A is the best in respect of RES production penetration, whereas the blending of Case C is the worst, with almost 21 TWh of rejected energy. On the other hand however, the latter case seems to achieve the highest effectiveness of the PHES system (stored rejections above 70% compared to 49% in Case A), that stores the largest amount of energy, about 15 GWh (Fig. 3.15). Maximum accumulated rejections about 45 GWh are observed in Case C of the nuclear scenario, and about half of that energy is storable by the considered PHES system.

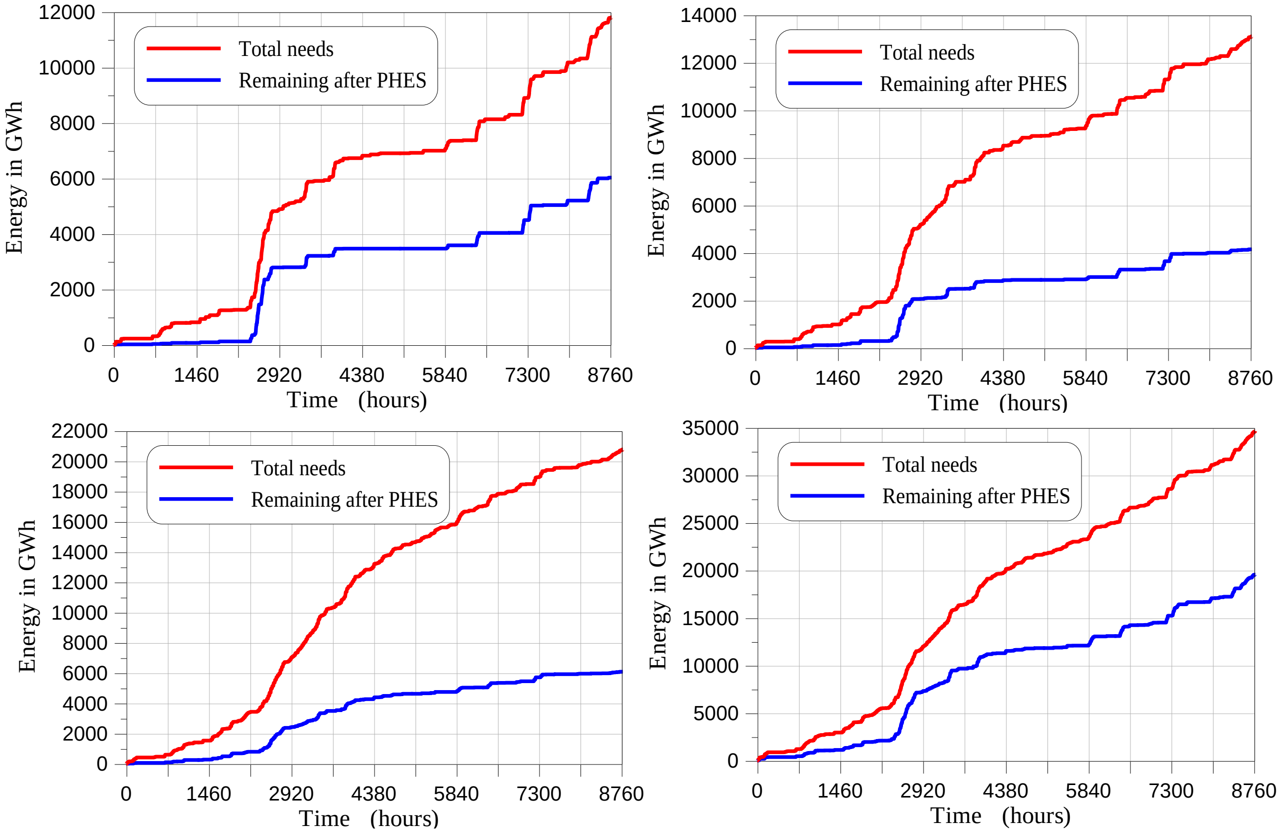


Figure 3.15. Cumulative RES energy rejections/storage needs during one year, for 80% share – cases A, B (upper), C and B-nuclear (lower).

The operation history of the PHES system (12 GW, 144 GWh) when it is used only for RES rejections storage is plotted in Fig. 3.16. The maximum storage capacity and production power are more frequently needed as the solar share increases in the wind-solar production mix. The capacity factor of the PHES units becomes even higher in the corresponding cases of the nuclear scenario.

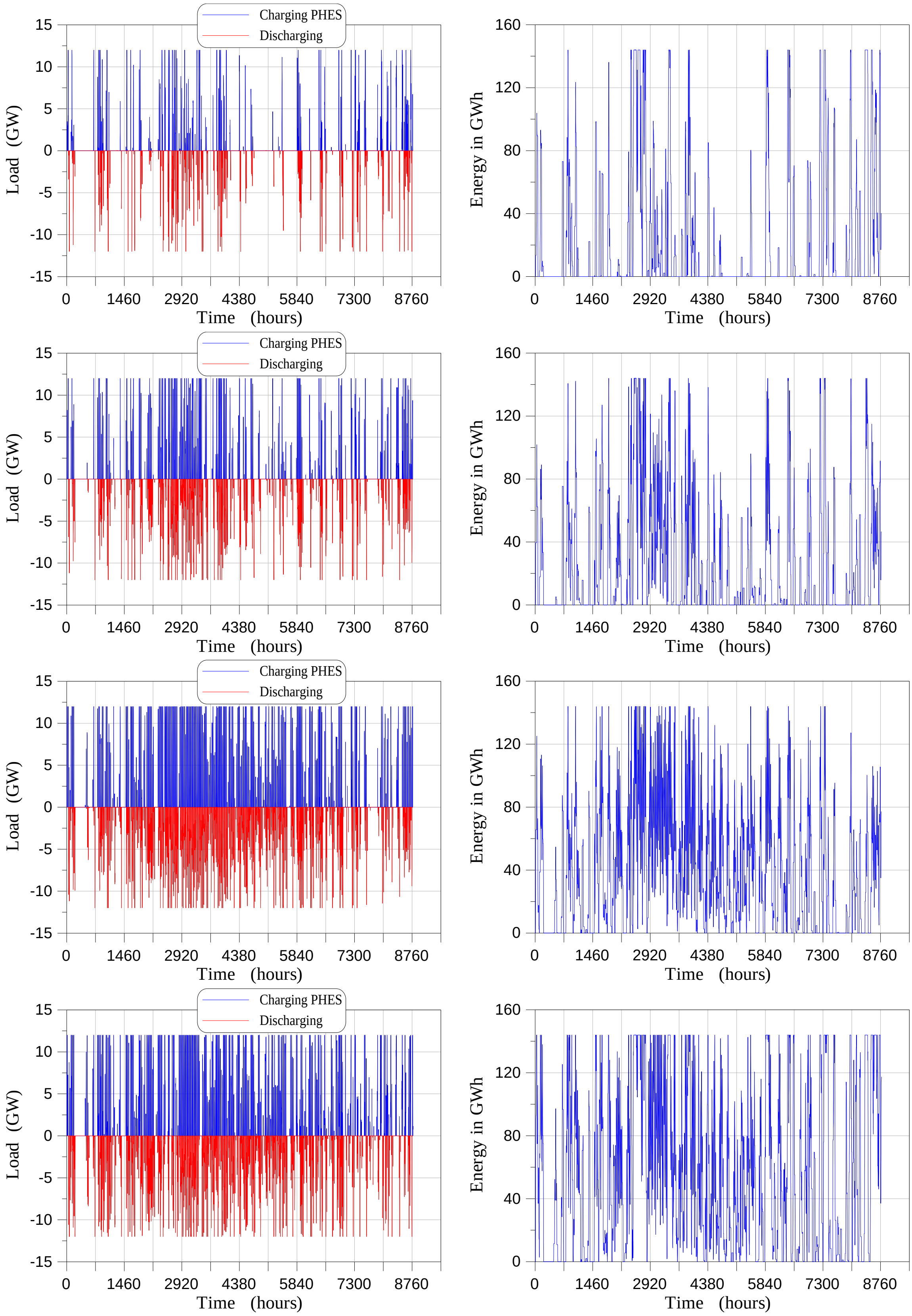


Figure 3.16. Power and charging level of the PHES system only for RES storage, for 80% share – cases A, B, C, and B-nuclear (from top to bottom).

Figures 3.17 and 3.18 show that full exploitation of PHES units for smoothing the system load curve can increase significantly their capacity factor, and hence their economic results. The gain in CF gain is about 20-25 percentage units in the reference scenario and at a smaller degree in the nuclear scenario. Hence, the overall CF of the pumping units exceeds 26% for Case A and 36% for Case C. Such utilization degrees are quite higher than the corresponding of 6 GW PHES units in the 2020 scenario, and can be considered economically viable. Moreover, this indicates that the economic results of the PHES units installed by the year 2020 will be continuously improved during the subsequent decades.

Most of the above results are also quantitatively given in Table 3.2. As expected, the higher RES power and energy rejections in the nuclear, high technical minimum scenario, result in reduced storage effectiveness of that energy, which drops below 50% for all cases. Moreover, although the utilization of PHES units for RES rejections storage is remarkably increased, their total capacity factor is 3.5 – 4 percentage units lower than the corresponding in the zero feed-in limit scenario.

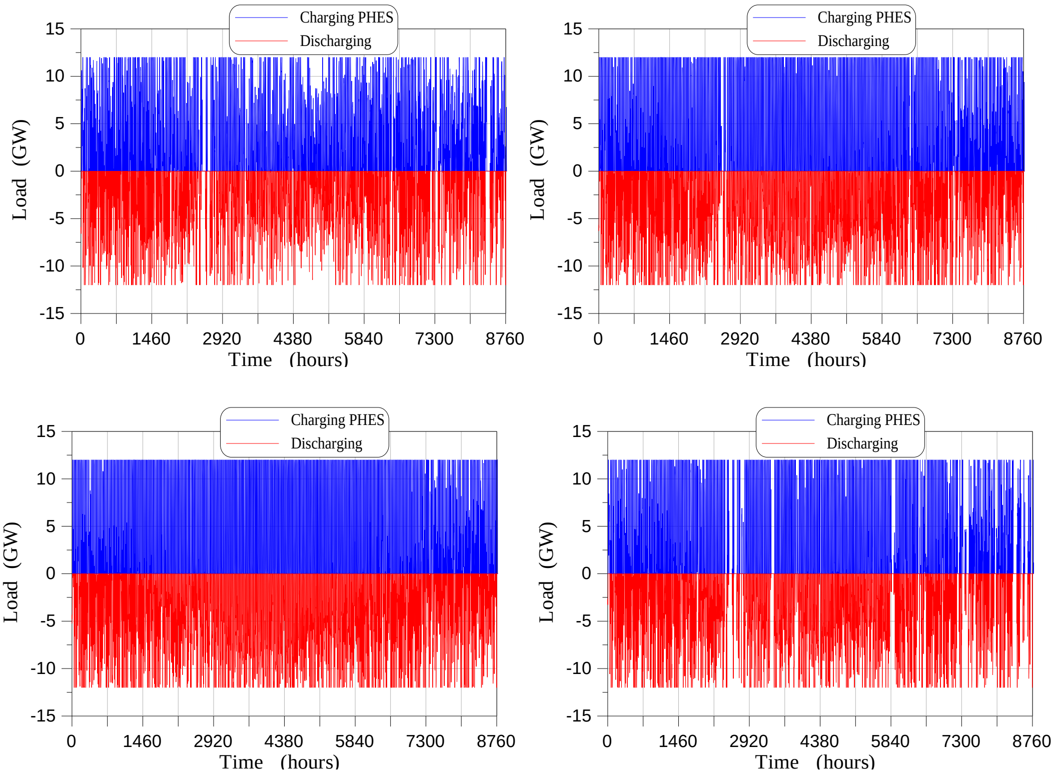


Figure 3.17. Final power level of the PHES system for 80% share – cases A, B, C and B-nuclear (top-left to bottom-right).

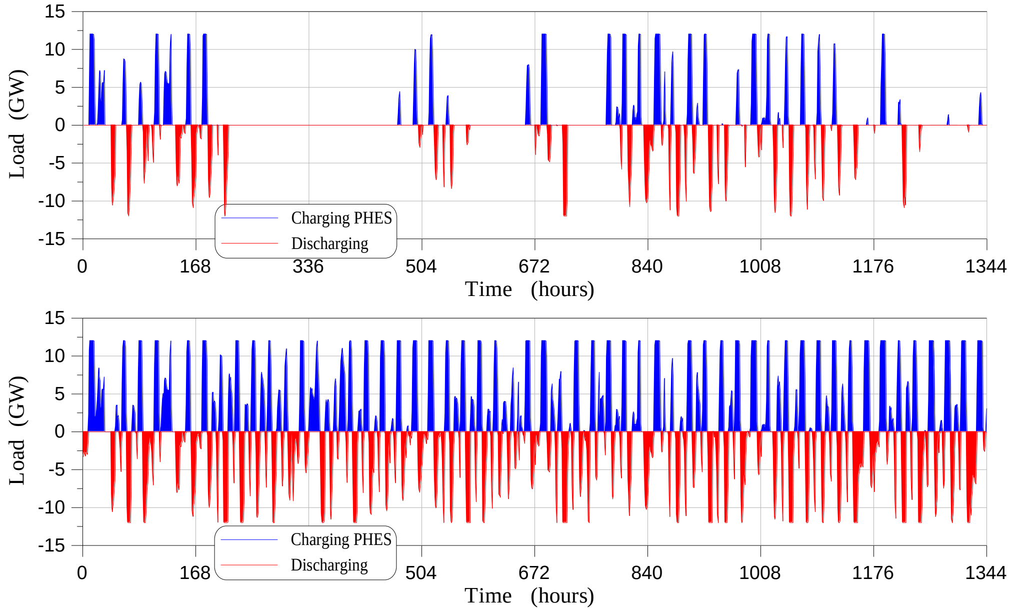


Figure 3.18. Detailed view of PHES for RES rejection (upper) and full operation (lower) – Case A.

Table 3.2. Comparative results for the cases of 80% RES development scenario.

Case	Rejected RES (GWh)	Stored RES (GWh)	Recovered portion after losses	Stored System (GWh)	Total PHES discharge (GWh)	Pumping station Capacity Factor (%)		
						RES	System	Total
A	11800	5740	36.5 %	21900	20730	5.4	20.8	26.2
B	13100	8915	51.0 %	25910	26120	8.5	24.6	33.1
C	20750	14620	52.9 %	23900	28890	13.9	22.7	36.6
Results for nuclear scenario (system feed-in limit 10 GW)								
A-n	32810	9665	22.3 %	14390	18040	9.2	13.6	22.8
B-n	34600	14975	32.7 %	15950	23190	14.2	15.1	29.3
C-n	45300	22470	37.4 %	12550	26265	21.3	11.9	33.2

The variations of the remaining load of the controllable plants after the implementation of PHES for storing the rejected RES production are not considerably reduced, as can be observed comparing the results in Fig. 3.19 with the ones in Fig. 2.9.

However, if the PHES units are fully exploited for smoothing of the CPL curve, using all the remaining capacity for night-time energy storage from the rest units, then the gain in grid stability can be significant, as can be observed in Figs. 3.20 and 3.21. The improvement becomes more evident in the wind favored Case A (Fig. 3.21, compared to Fig. 2.8), but even for the most load fluctuating Case C, the finally achieved stability degree is about the same with the initial system (Fig. 3.20).

Supported by INTELLIGENT ENERGY EUROPE

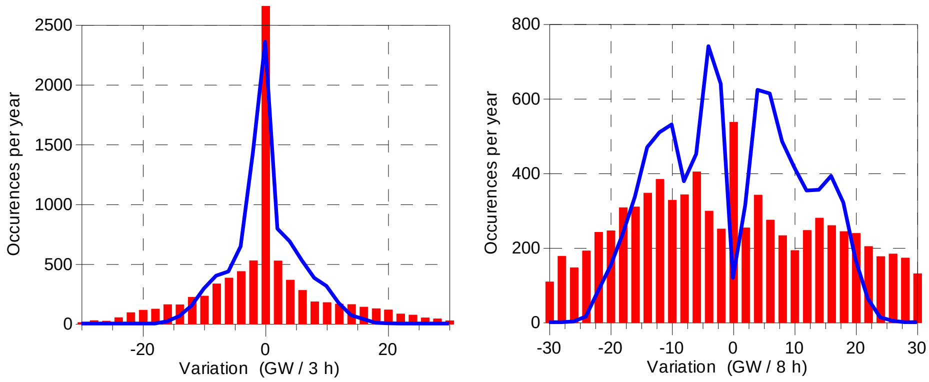


Figure 3.19. Variation of total system Load (lines) and CPL (bars) for the 80% scenario – case C, with PHES used only for RES.

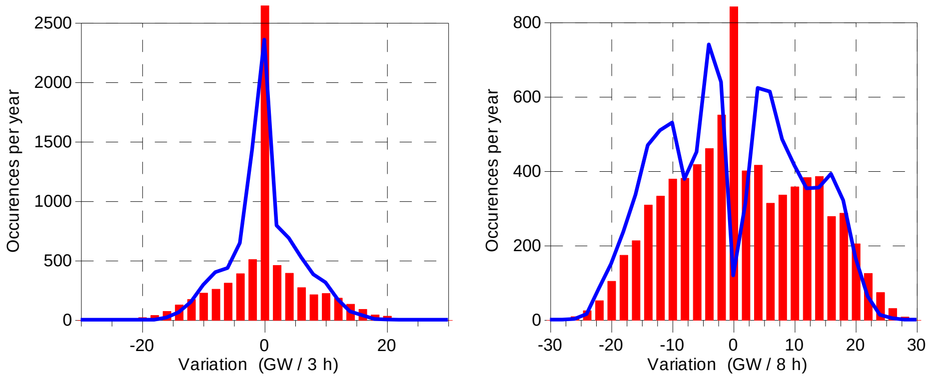


Figure 3.20. Variation of total system Load (lines) and CPL (bars) for the 80% scenario – case C, with fully exploited PHES system.

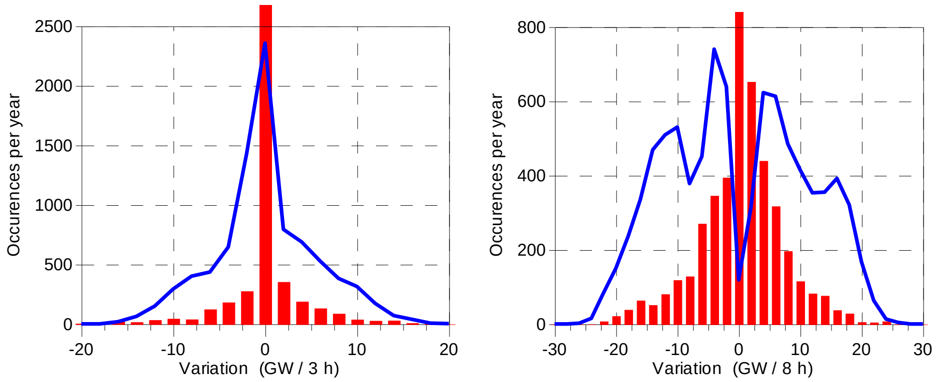


Figure 3.21. Variation of the total system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – case A, with fully exploited PHES system.

3.3 Parametric Studies

The following additional results are obtained for the 80% RES share scenario, in order to investigate the needs and the role of energy storage in the future, when the electricity system of Spain will contain only RES power plants and CCGT units, as also in case that the existing nuclear plants will remain in the system until then.

The available storage power and capacity are the major design parameters of the system. Therefore, the electricity system is simulated at first assuming unlimited storage capabilities, in order to find the maximum needs in each of the examined wind-solar development cases. Then, complete parametric computations are carried out to provide charts of the storage capability of the rejected RES production, as also of the utilization degree (capacity factor) of the PHES units.

3.3.1 Storage system with unlimited power and capacity

For these computations the reference PHES system for the 80% scenario (144 GWh and 12 GW) is replaced by a storage system with unlimited power and capacity. Hence, the system can store all RES energy rejections during the year, but the re-introduction of this energy into the electricity system is subjected to the same limitations as previously (feed-in limit due to technical minimum of the power plants). As a result, stored energy may be accumulated during large periods of the year. The overall efficiency of the charging/discharging cycle is kept the same, 75%.

Figure 3.22 shows the power variation in pumping and turbining modes of the energy storage system when used for RES rejections, as well as the corresponding energy content in its unlimited capacity reservoir. Comparing the results for the three cases A, B and C of Table 1.12, it can be observed that the maximum pumping power needs are similar (34.2 to 36.8 GW), whereas the maximum production (discharging) power is 6 GW lower in Case C. Moreover, from the load variation diagrams it is clear that the pumped-storage system utilization is substantially less in Case A, whereas the corresponding diagram for Case C is the densest one.

Concerning the stored energy in the reservoirs, maximum energy accumulations occur for all cases in the 4th month of the year (Fig. 3.22), mainly due to very high RES production. Case C shows again the smaller maximum capacity value, about 640 GWh, whereas in Case A it is more than three times higher. In all cases the stored energy variation curves exhibit frequent smaller fluctuations during the rest of the year. Most of them are below the 100 GWh line in Case A, whereas Case C exhibits higher and more frequent fluctuations, up to about 200 GWh. Consequently, a storage system with capacity of the order of 100 GWh would be quite efficient for cases A and B, and less for Case C of wind-solar mix. On the other hand, the total power needs for full PHES system implementation in the system (load curve smoothing, as well), exhibits a different trend regarding the power needs. Figure 3.23 reveals that a PHES system with maximum charging/discharging power of the order of 10 GW would be quite effective and efficient in Case A, whereas a corresponding system of similar efficiency for Case C should have about double power.

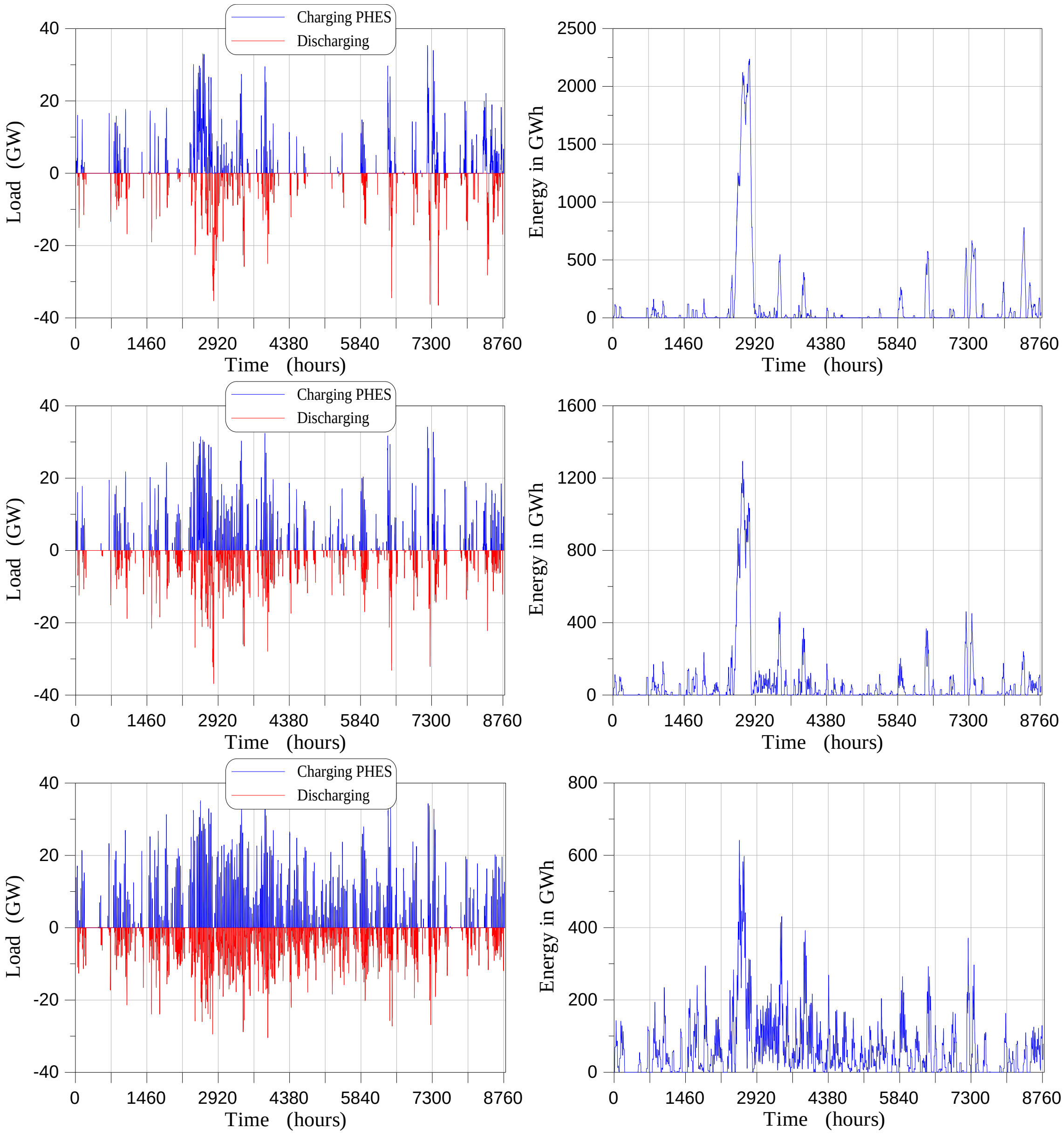


Figure 3.22. Power and charging level for storage system with unlimited power and capacity, for 80% share – cases A, B, and C (top to bottom).

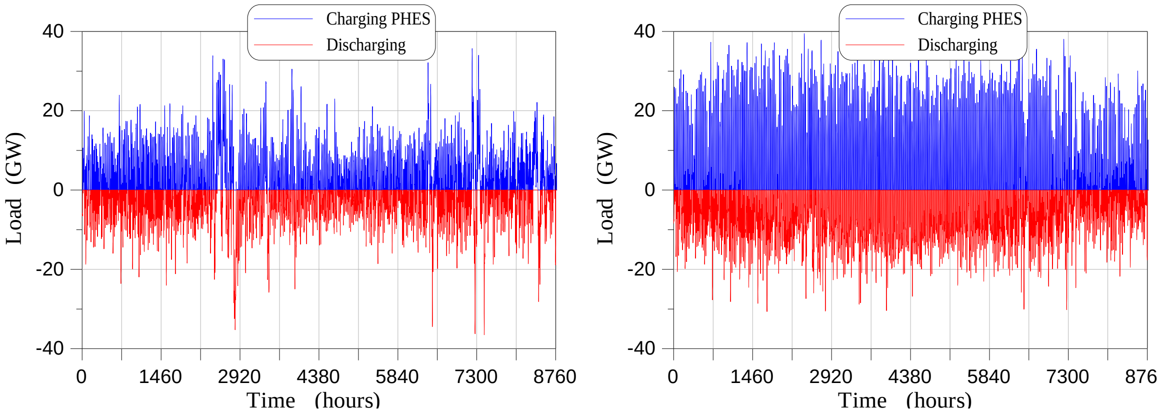


Figure 3.23. Charging and discharging power of full exploitation of an unlimited storage system, for 80% share – cases A (left), and C (right).

Similar computations were also carried out for the case of higher technical minimum of 10 GW. The results are plotted in Fig. 3.24 for Case B-nuclear, while the other two cases are similar. The pumping power is substantially increased about 10 GW, following the similar increase of RES feed-in limit of the system, but the production power remains about the same, due to the system feed-in limitations. On the other hand, however, the increased and extended RES rejections during the spring cause much higher stored energy accumulations in that period. Now, the higher feed-in limit of the system causes extended energy rejections during high RES production in the spring, which are stored but cannot be consumed as previously. As a result, the stored energy diagram shows one large and some smaller areas of increased storage capacity needs, above 4000 GWh and 1000 GWh, respectively (Fig. 3.26). In this case, even a 1000 GWh storage capacity system cannot efficiently recover the rejected RES production during the whole year.

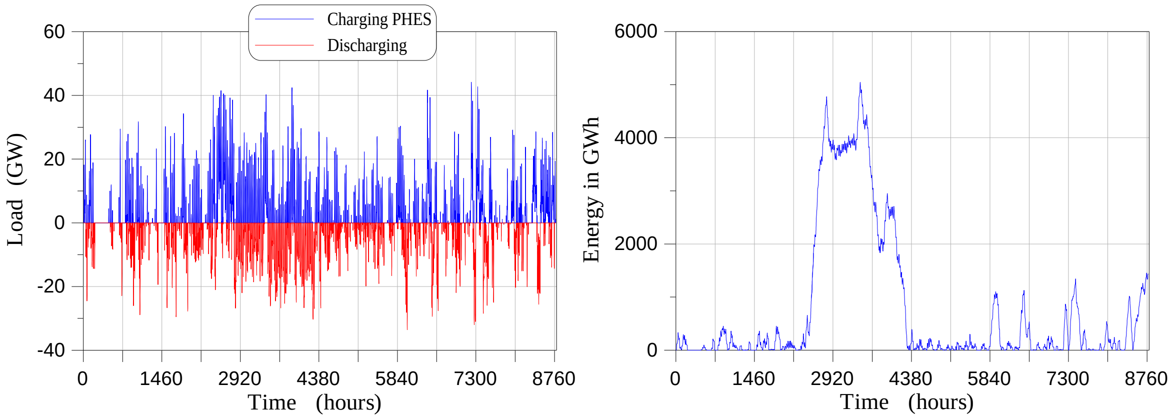


Figure 3.24. Power and charging level for storage system with unlimited power and capacity, for 80% share – case B-nuclear.

The above quantitative results for cases A, B, and C and the corresponding of nuclear scenario are concentrated in Table 3.3. Case B seems to be a good compromise of maximum storage power and capacity needs of the Spanish system for 80% RES share. It must be noted however, that the maximum needs are not indicative of the optimum RES production blending in the electricity system.

Table 3.3. Maximum power and capacity needs of unlimited storage system for 80% RES share scenario.

Case	Needed power (GW)		Needed capacity (GWh)
	Charging	Discharging	
A	35.3	36.5	2240
B	34.2	36.8	1290
C	36.8	30.4	640
Results for nuclear scenario (system feed-in limit 10 GW)			
A-n	45.3	33.6	6340
B-n	44.2	33.6	5000
C-n	46.8	34.9	4300

Supported by INTELLIGENT ENERGY EUROPE

3.3.2 Effect of storage power and capacity

The following hill charts illustrate the combined effect of the two critical design parameters of the PHES system, pumping power and storage capacity, on the two most important performance characteristics: Exploitation degree of the RES rejected energy, and annual utilization degree (Capacity Factor) of the pumping units. The latter can be directly associated with the economic results and viability of the PHES investments.

The exploitation degree of RES rejections is defined as the ratio of the stored RES energy by the PHES system, divided by the rejected production of the intermittent RES sources, during the whole year. The capacity factor of the pumping units represents their total operation during the year for storage of surplus RES production and for night-time storage of rest plants production, in order to smooth-out their loading curve.

The exploitation degree for Case A shows a continuous increase with the storage capacity, whereas it is not substantially affected by the pumping power (Fig. 3.25). The corresponding hill chart for Case C exhibits a different pattern and it can be divided in two parts (Fig. 3.27): In the left region the attainable exploitation degree maximizes up to a certain storage capacity and then remains constant, whereas in the right region it continues to increase. For the examined parametric range, 8-20 GW for pumping power and 60-240 GWh storage capacity, the maximum degree of rejected energy exploitation approaches 100% in Case C and 85% in Case B, but reaches only up to 60% in Case A.

On the other hand, the capacity factor of the pumping units exhibits a similar dependence in all cases: As expected, it decreases with the installed pumping power and cannot exceed a maximum value, here about 36 to 40%. For a given pumping power the CF increases with the storage capacity up to a certain capacity limit, above which it remains constant. This capacity limit increases with the pumping power, whereas the attainable CF decreases. Hence, assuming that a minimum CF for economically viable PHES investments is of the order of 30%, the corresponding contour line in the diagrams can be used to determine the optimum PHES sizing, depending on the wind-solar production mix.

The lowest end of that line is in all cases at 8 GW pumping power and 60-70 GWh storage capacity. However the upper end obtained for the maximum tested capacity of 240 GWh is considerably different: About 10 GW for Case A (Fig. 3.25), 15 GW for Case B (Fig. 3.26), and 21 GW for Case C (Fig. 3.27). Consequently, the RES development Case A of the 80% scenario cannot support the installation of more than 10 GW pumping power in the system, whereas this limit may increase up to 21 GW for the Case C, providing that there is available storage capacity.

Another way to use the hill charts 3.25 to 3.27 in order to select the optimum PHES system is to start from the estimated storage capacity that will be available in the 80% RES share scenario. For example, if it will be of the order of 100 GWh, then the optimum pumping power should not exceed 8-9 GW for all cases, because for higher values the exploitation degree does not increase, while the pumping CF decreases. On the contrary, if the available storage capacity will be of the order of 200 GWh, then the exploitation degree of RES rejections increases in all cases with the pumping power. Hence, the latter can be sized up to the viable CF limit (e.g. 30%), corresponding here to 10, 14 and 20 GW for cases A, B, and C, respectively.

Supported by INTELLIGENT ENERGY EUROPE

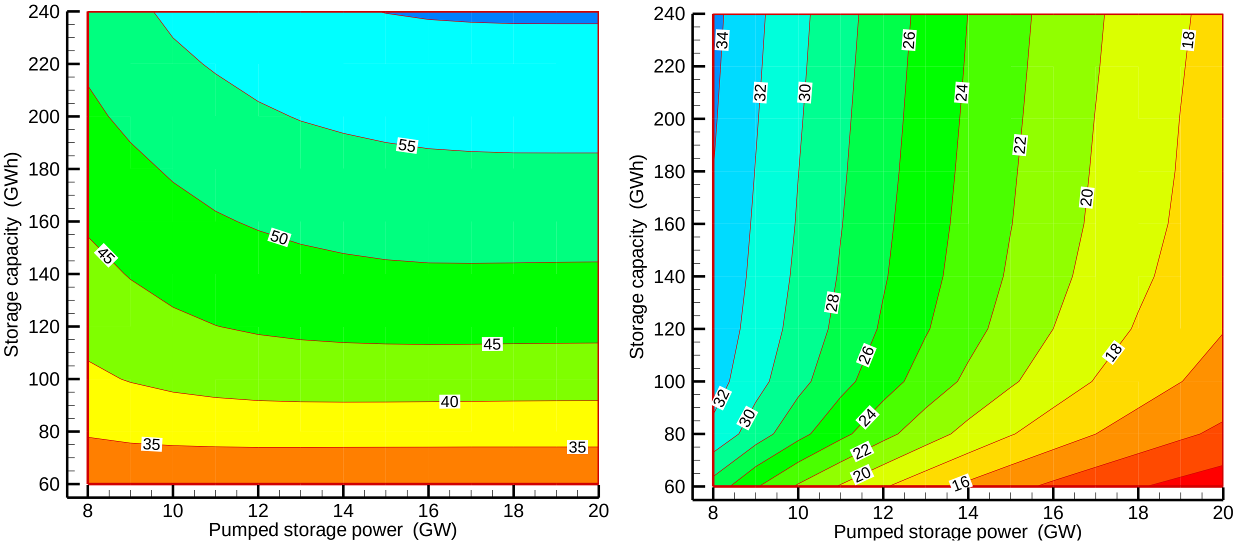


Figure 3.25. Scenario 80% - Case A: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

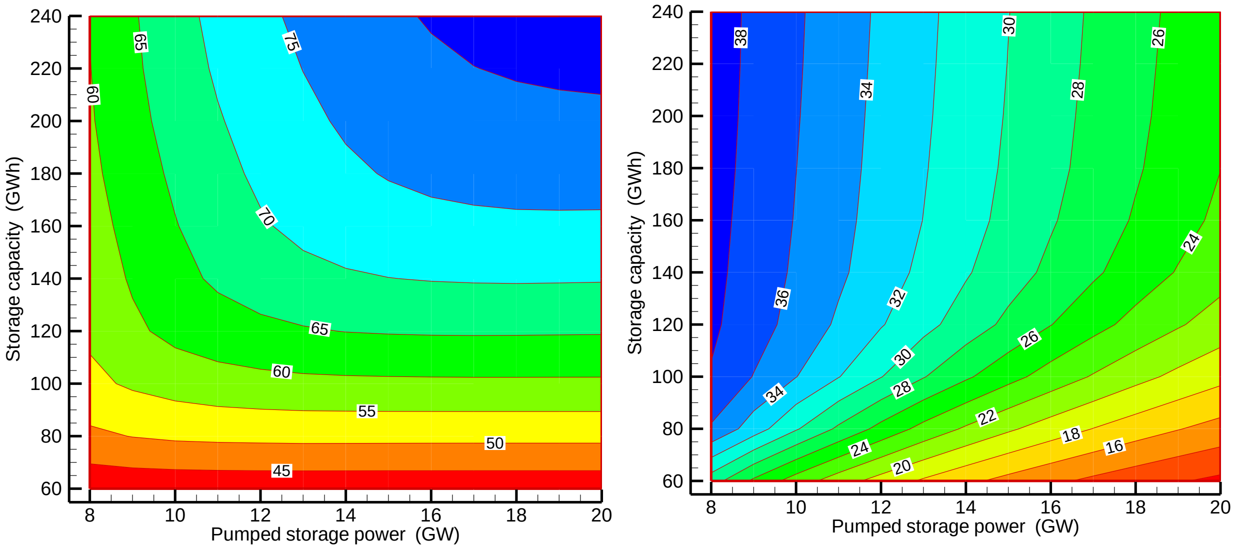


Figure 3.26. Scenario 80% - Case B: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

Supported by INTELLIGENT ENERGY EUROPE

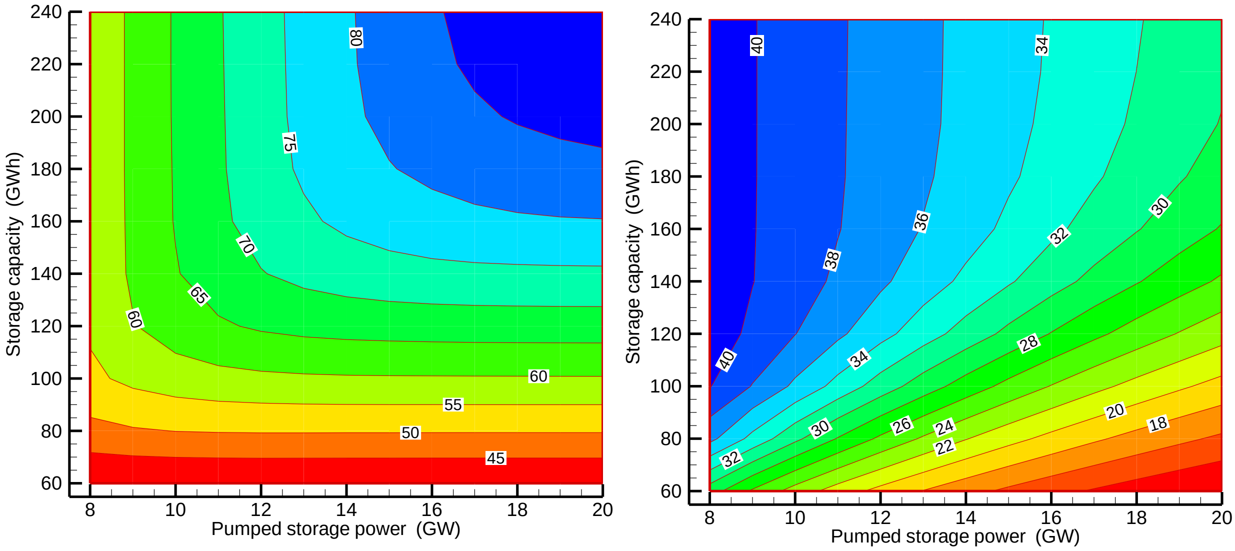


Figure 3.27. Scenario 80% - Case C: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

The corresponding results for the nuclear scenario, in which the feed-in limit for RES in the system is 10 GW, are plotted in the following Figs. 3.28, 3.29 and 3.30. As expected, the exploitation portion of the much larger RES rejections is lower by about 15-20 percentage units compared to the zero feed-in limit case, for similar PHES characteristics. The corresponding CF of pumping stations is also reduced, due to limitations in the re-injection into the system of the greater amounts of stored energy (see also Table 3.2).

The lowest end of the considered as viability threshold line of 30% CF for the smallest tested storage capacity of 8 GW is again between 70 and 80 GWh for cases B-n and C-n, (Figs. 3.29, 3.30) but quite higher in Case A-n, about 150 GWh (Fig. 3.28). The upper end, obtained for the maximum tested capacity of 240 GWh, is about 9 GW for Case A-n, 13 GW for Case B-n, and 18 GW for Case C-n, namely 1-3 GW smaller power than the corresponding cases in the zero feed-in scenario.

Finally, considering the specific pattern of the contours in these hill charts, the optimum PHES installed power for the nuclear scenario assuming available capacity of 100 GWh will be less than 8 GW in Case A-n (Fig. 3.28), and around 10 GW in cases B-n and C-n (Figs. 3.29, 3.30). The corresponding power for 200 GWh storage capacity remains small, around 8 GW, in Case A-n, but it may exceed 12 and 16 GW for cases B-n and C-n, respectively.

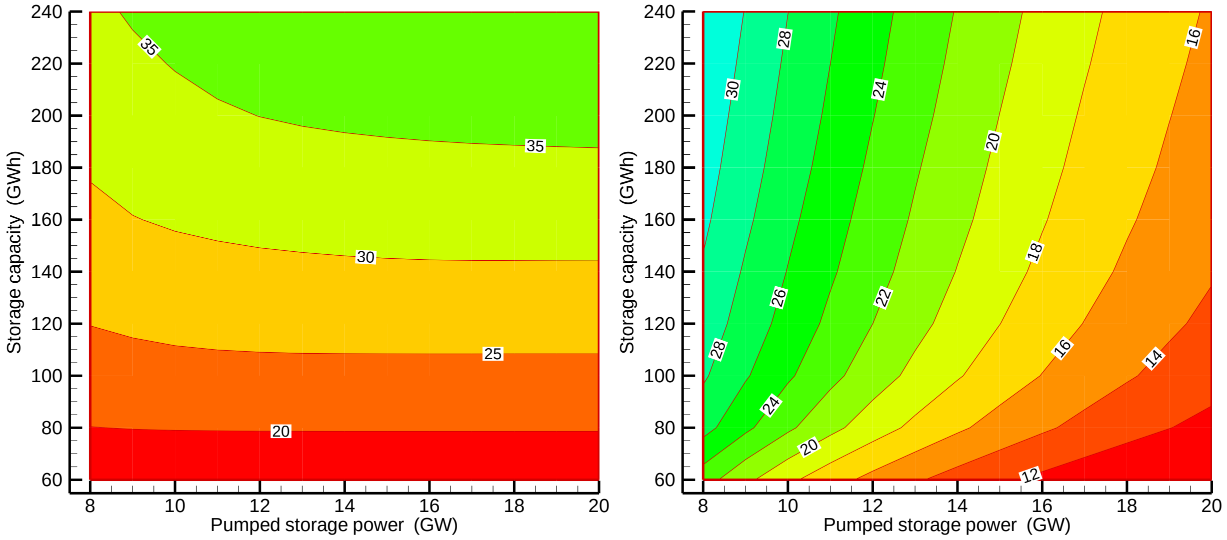


Figure 3.28. Scenario 80% - Case A-nuclear: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

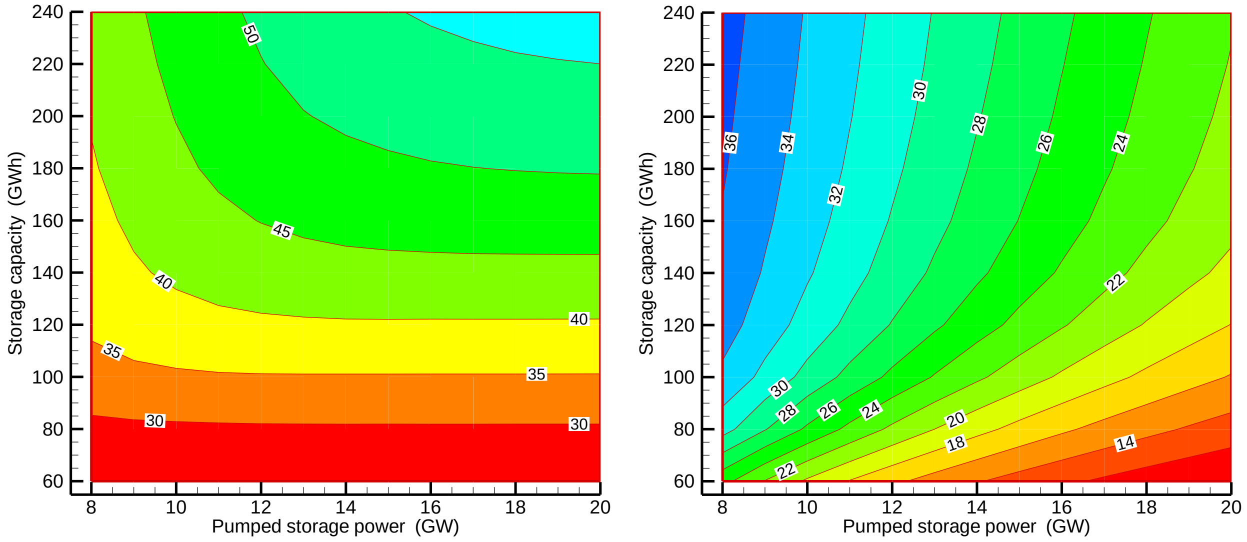


Figure 3.29. Scenario 80% - Case B-nuclear: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

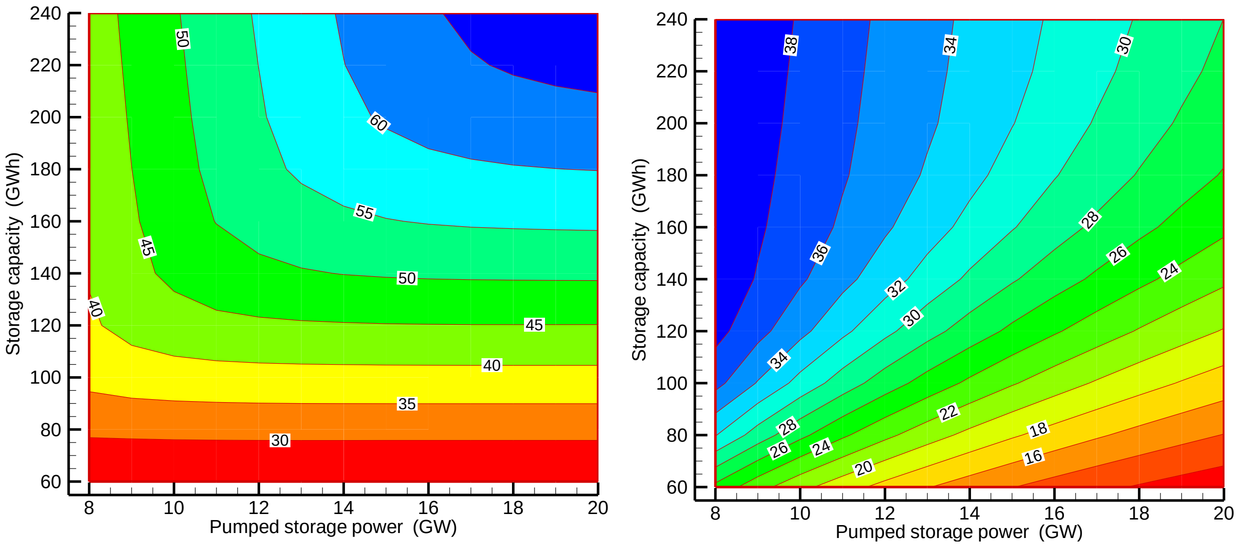


Figure 3.30. Scenario 80% - Case C-nuclear: Hill charts of RES rejections exploitation degree (left), and Capacity Factor of pumping units (right).

Supported by INTELLIGENT ENERGY EUROPE

Conclusions

The Spanish power system can be considered as an electrical island, with an exchange capacity of 3% of the installed generation capacity, far from the 10% reference recommended. However, Spain has been a good example of high renewable energies penetration in the network with new records of renewable share almost every year, due to the flexibility of the system and the operation of the existing PHES.

Nevertheless, wind power rejections have occurred during these years and will continue increasing with the growing renewable capacity installed. Although conventional plants have shown flexibility, there still exist a technical minimum of generation that blocks further renewable penetration at some moments.

The present simulations demonstrate that since it is not expected a big change in the amount of rejections for the 2020 scenario, **a fraction between 4 and 7% of the renewable generation will not be able to penetrate the system in the 80% renewable scenario**.

Pumped storage is the most suitable energy storage technology for the case of Spain, and it is already considered in the energy plans for the exploitation of excessive RES production. The capacity factor of PHES units decreases with their total installed power in the system. Consequently, there is an optimum sizing in order to recover the maximum possible RES rejections and at the same time secure the economic viability of such PHES investments.

The results of the present study show that in the 2020 scenario, the implementation of PHES for storing the rejected RES production does not cause any changes in the system stability characteristics, due to its negligible utilization in both cases 1 and 2. In the **80% RES share scenario**, the **optimum pumping power** should not exceed **8-9 GW** for all cases if calculated for a **100 GWh** storage capacity. Finally, the optimum PHES installed power for the nuclear scenario assuming an available capacity of 100 GWh will be less than 8 GW in Case A-n, and around 10 GW in cases B-n and C-n.

Regarding the different cases of wind-solar blending, Case A is the best in respect of RES production penetration for the non-nuclear scenario, whereas the blending of Case C is the worst, with almost 21 TWh of rejected energy. On the other hand, the latter case seems to achieve the highest effectiveness of the PHES system, namely, over 70% of rejections are stored compared to 49% in Case A.

The simulations show that **full exploitation of PHES units** for smoothing the system load curve can **increase significantly their capacity factor, and hence their economic results**. Moreover, this indicates that the economic results of the PHES units installed by the year 2020 will be continuously improved during the subsequent decades.

Even for the most efficient PHES design and for high storage capacities, there will always be a **remaining portion**, of the order of **25% of the rejected renewable production**, that has very short duration curve, and hence **cannot be stored** but with high capital cost systems. Channeling of this production to small distributed consumptions, like the electric vehicles, could be a possible solution. Also, additional emerging factors must be also taken into account like import/export exchange capabilities, existence of smart grids, demand management, hydrogen production by electrolysis and so on.

As a conclusion, according to the results of the present study, **PHES will play a key role to accomplish the challenging targets set in the energy scenarios for Spain**, recovering as much as 70% of the renewable energy that otherwise would be rejected.

References

---

[1] Power Statistics. 2010 Edition. Full Report (www.eurelectric.org).

[2] Grupo de Seguimiento y Planificación. September 2010.

[3] Compromisos internacionales y planificación indicativa de la generación. May 2010.

[4] Subcomisión de Análisis de la Estrategia Energética Española para los próximos 25 años. Informe de la Subcomisión. December 2010.

[5] PANER. June 2010.

[6] EU energy trends to 2030 (updated 2009).

[7] El modelo eléctrico español en 2030. Escenarios y alternativas, PWC, 2010

[8] The Spanish Electricity System, 2011, REE

[9] www.ree.es

[10] Planificación de los sectores de electricidad y gas 2008-2016, MINETUR, 2008

[11] Electricity interconnections: a step forward towards a single integrated European energy market, REE

[12] PER 2011-2020, MITyC/IDAE

[13] Prospectiva de generación eléctrica 2030, UNESA, 2007

Supported by INTELLIGENT ENERGY EUROPE