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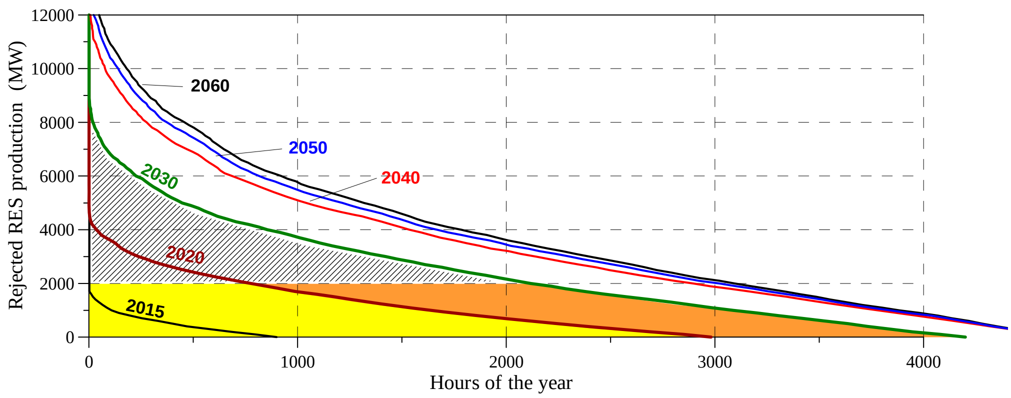
Facilitating energy storage to allow high penetration of intermittent renewable energy

D5.1 - GREECE

Overview of the electricity system status and its future development scenarios – Assessment of the energy storage infrastructure needs



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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

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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
ESS	…	Electricity Storage Systems
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

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Overview of the electricity system status and its future development scenarios – Assessment of the energy storage infrastructure needs

Executive Summary

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu), that aims to facilitate the realization of the ambitious objectives for high penetration of variable renewable energies in the European grid by 2020 and beyond, by unblocking the potential for energy storage technology implementation.

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 Greece. 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 Greece

The main characteristics of the interconnected electric grid system of Greece for the reference year 2011 are: Peak load 10.1 GW and total consumption about 53 TWh, with RES production (including hydropower) being about 11%.

The production system includes many non-flexible lignite-fired units (22 power plants, more than 5 GW in total), and about 3.5 GW of natural gas and oil-fired plants, while recently additional 1.3 GW of new CCCP plants are integrated. There are about 3 GW of hydropower reservoir plants, including 2 pumped-storage units of total 0.7 GW. Also, the cumulative wind farms, PV and other RES installed power exceeds 2 GW. The Greek TSO has issued connection offer or committed to connect wind farms of total power about 4.4 GW.

The major electricity production is still carried out by the Public Power Corporation (www.dei.gr), who owns transmission and distribution networks and is the major supplier for customers. Following the liberalization program, its legal status has recently

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changed from public to S.A. The high capital cost and the time-consuming and bureaucratic licensing procedure is a barrier for investment in generation facilities. About 10 private companies have acquired 13 generation production licenses in CCPP (cumulative capacity 5.4 GW). Some of them are also licensed for construction. The process of the liberalization is expected to be accelerated in the coming years.

Concerning the RES, a great number of production licenses have been issued during the last years by the independent Regulatory Authority of Energy (www.rae.gr), which include wind farms, PV units, small hydropower plants, and biomass/biogas combustion units, with a cumulative power approaching 30 GW.

An important transmission problem of the system is the imbalance between supply and demand, with most generation facilities being in the northern part of the country, whereas demand is mainly in the central (Attica region) and southern part. Hence, large electricity quantities are transmitted through the North-South line, which is served mainly by a central stem, consisted of three 400 kV lines. Moreover, the majority of licensed wind farms do not have the character of dispersed generation but they are high power units, with average size about 20 MW, and many projects over 25 MW.

Several large projects are under study for the next decade or being implemented to extend the 400 kV and 150 kV lines in order to serve the needs of new thermal power plants and of the extensive RES development. Also, after commissioning of the new natural gas units (up to 2015) in central and south Greece, the spatial balancing of production and demand will be significantly improved.

Concerning the autonomous Island grids, preliminary studies to connect the Aegean Islands with the mainland system and to exploit their very large wind potential have been recently carried out by the Transmission System Operator (www.admie.gr). Some of these projects are quite mature (like the Crete and Rodos Islands and the Cyclades complex interconnection), and are expected to begin in the near future.

Greece is a member of UCTE and since 2004 its system is synchronised with the European transmission system. Greece, being in the south-eastern part of Europe does not have physical interconnections with central Europe, and has characteristics of a large isolated system. The interconnections with the neighbouring countries are designed to meet annually exchanges over 7% of the needs, mainly from excess energy of Bulgaria and Romania systems. Consequently, the electricity transmission capabilities to central Europe depend also on the grid systems of the wider Balkan region. However, the latter are not yet quite consistent and robust, and hence the energy exchange capacity in the area is restricted.

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System development plans (2020 – 2050)

In 2010, the Greek Government developed the National Renewable Energy Plan (NREAP) for the period until 2020 (Law 3851/2010), for significant increase of RES share in the gross final energy consumption (up to 20%) [2-4]. According to the compliance scenario, the capacity of the intermittent sources, wind and solar PV, will reach by 2020 the amount of 7.5 GW and 2.2 GW, respectively. These estimations have recently been re-adjusted in order to take into account the reduction of gross national product and the effect of the favorable pricing policy for PVs (about 2 GW of PVs have been licensed at very high fix contract pricing, > 400 €/ kWh), and has become about 6.5 GW for the wind farms and 2.5 GW for PVs.

A recent document issued in June 2012 by the National Energy Strategy Committee following a public consultation phase, elaborated a long term analysis of the Green energy system and proposed the Energy Road Map of Greece for the period 2020-2050 [5]. The Roadmap to 2050 provides the basic guidelines of the national energy strategy in the next decades, the main objectives of which are the reduction of the dependence on imported energy and the maximization of RES penetration, achieving a significant reduction in emissions of CO_2 by the year 2050. It also includes a number of possible scenarios for the evolution of the energy system, in order to specify and evaluate alternative measures and policies for fulfillment of both national and European targets.

Among the aimed achievements of the future energy system development by the year 2050, as indicated by the two most desirable energy policy scenarios (Measures Maximization RES Penetration, MEAP, the Minimum Cost of Environmental Measures – PEK), are the following points, associated with the electric power system:

- 85%-100% electricity from RES using all commercially mature technologies.
- Total RES penetration in gross energy consumption at a rate of 60%-70%.
- Reduce greenhouse gas emissions by 60%-70% in relation to 2005.
- Complete decarbonization of the electricity production.
- Development of decentralized production units and smart grids.

There is also a conservative development scenario of Existing Policies (EP), that for moderate penetration of RES, up to 75%.

The major part of RES power to be integrated in the system will be wind and solar, the potential of which is significant in many regions, including Aegean islands. However, due to its flexibility and inter-transmission limitations, the existing grid system cannot manage and absorb large amounts of intermittent production. Some first studies showed that the current system could absorb almost the entire production of up to about 5 GW wind power. But above that, curtailments are unavoidable and they will increase analogously to the intermittent RES development, exceeding 35% by 2050 in all scenarios.

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Consequently, sufficient energy storage capacity needs to be developed during the next decades, in order to achieve large RES integration without excessive production rejections. Pumped storage is the most mature and reliable technology for large scale storage, and also it is suitable for the ground topology of Greece, therefore is considered to be the most cost-effective solution. According to the Roadmap-2050 report, in order to fulfil the RES development targets, about 1 GW of PHES capacity is required by 2020 and 2 to 5 GW up to 2050, depending on the scenario (EP or MEAP).

The existing pairs of successive reservoir hydroelectric plants are the most feasible sites for installing pumping back systems in the mainland system of Greece, requiring only a pumping station and penstock, as identified by recent studies.

A significant number of projects involving pumped storage hydro units have been submitted to the RAE for licensing, the total installed power of which exceeds 4 GW. However, the regulatory framework for such units is missing and for this reason a public consultation was distributed in 2012 by RAE. The outcome revealed several important issues that must be resolved in order to determine the status of installation and operation of PHES units in the interconnected system.

The situation is more improved concerning the Islands, for which a Completed Regulatory Framework for the Operating Principles of PHES has recently issued [11,12]. Based on that, several production licenses of cumulative power about 200 MW have been given to such plants in some large islands (Crete, Rodos, Lesvos), which moreover are accompanied by specific pricing of the produced energy. Also, applications for additional 600 MW PHES are pending today.

Finally, the outcome of recent studies is that the PHES investments should be planned and realized gradually during the next years, following the development of RES installed capacity, while a strategic long term development plan of electricity transmission should be implemented in parallel, in order to fully support the large RES integration in the electricity system of the country.

The examined future RES development scenarios

Two future scenarios for RES development are examined in the present study. The first concerns the year 2020, when, according to NREAP [4] and to latest predictions, the RES share in electricity production will approach 40%. The second case is for a much higher RES share of 80%, which, according to the National Roadmap to 2050 [5], will be reached by the year 2040-2050, with the MEAP development scenario.

In addition, the relative development of the two most important RES in Greece, wind and solar, is also investigated in the framework of the above two scenarios, since there

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are market drivers that can influence the development of one technology against the other. The main electricity system characteristics (installed power) for the various cases under consideration are tabulated as follows:

Table 1. Installed power mix of electricity production for various scenarios/cases examined.

	2011	**2020**		**80% RES share**		
		A	**B**	**A**	**B**	**C**
Thermal power plants (GW)						
Lignite	5.3	3.5		2.0		
Gas	1.8	5.2		4.5		
Oil	1.4	1.4		0.2		
RE power plants (GW)						
Wind	1.3	6.5	5.0	13.0	14.0	11.0
Solar (PV equivalent)	0.4	2.5	4.9	11.5	8.3	14.7
Hydropower	3.1	3.5		4.5		
new PHES	0	1.0		4.5		
Geothermal	0	0.1		1.7		
Other RES	0.3	0.3		0.5		
RES-E share	~14.7%	~ 40%		~ 80%		

Computer modeling

Specific software developed by the LHT/NTUA is used for the modeling of the Greek electricity system and its evolution and annual performance up to 2050. The corresponding time histories for the system load and the production of base thermal units and RES technologies are properly projected using available data to represent the foreseen state and operation of the electricity system in each of the examined cases.

A first algorithm computes on hourly basis the expected rejections of the intermittent RES sources production (W/F and PV), when it is higher than the maximum absorbable into the system. This is performed through the construction of the Residual Load (RL) curve, which is hourly time-series data obtained by subtracting all non-controllable RES production from the system load curve. The RL power variations should be covered by the left over power plants in the system (base thermal units and controllable RES, including pumped storage). Fig. 1 demonstrates the pattern of such a RL curve.

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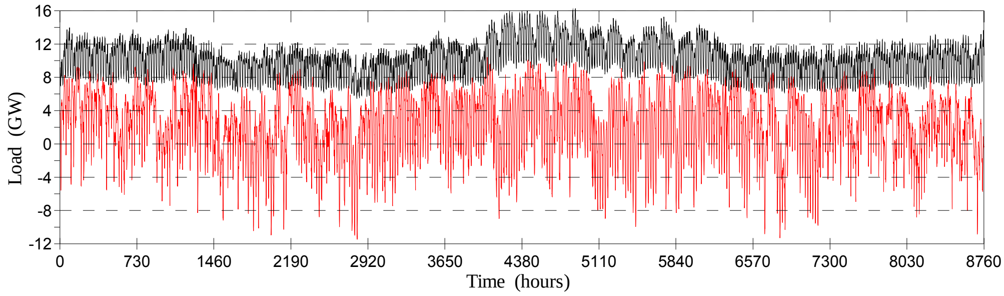

Figure 1. Load (black) and Residual Load (red) for the 80% RES scenario - case A.

The energy rejections from the intermittent RES production can then be calculated during hours when the RL is below the instant technical minimum of the power system (or below zero, in case of a very flexible production system without such limit). For the Greek system the technical limit is set to 3.7 GW for the 2020 scenario, whereas for the 80% RES scenario two such values are tested 0.4 and 2 GW, to represent a very flexible and a semi-flexible system, according the development plans of the National Roadmap.

An indicative picture of the rejected RES production throughout the year in Fig. 2 reveals a strongly fluctuating pattern, with several peaks and lows, and randomly distributed periods of continuous or zero rejections. The energy storage system must be able to follow as close as possible these variations, and this is an inherent characteristic of the pumped storage units, especially if the pumps are driven by variable speed motors.

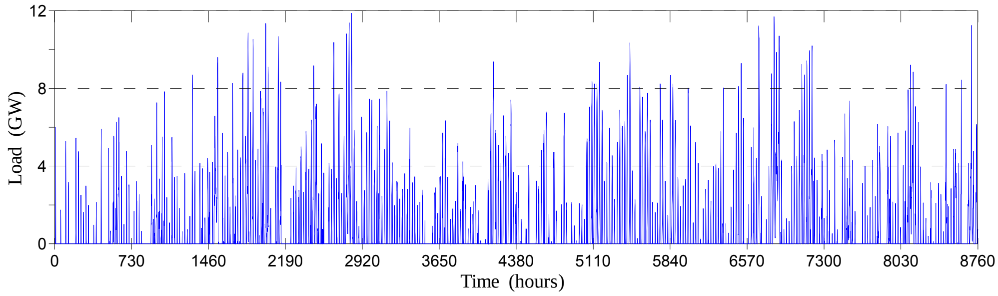

Figure 2. Rejected energy from intermittent RES for the 80% scenario - case A.

A second computer algorithm simulates the operation and performance of the PHES units incorporated in the power system, taking into account the efficiency of the cycle and various technical limitations, like the installed storage power and reservoirs capacity. In accordance to the estimations of the national Roadmap-2050, the installed PHES power is taken 1 GW for 2020 and 4.5 GW for the 80% RES share scenarios. The storage capacity is assumed in all cases to correspond to 12 hours of continuous pumping operation.

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On the other hand, the production program of the PHES units is determined by the system peak load characteristics, in order to achieve effective peak-shaving of the RL curve in high demand periods. Finally, the remaining storage power and capacity of the PHES units after the RES energy storage cycle can be exploited for further smoothing of the RL curve, following a peak-shaving and valley-filling operation strategy shown in Fig. 3. The model computes and applies this strategy on a daily basis, for the whole simulated year. More details on the modelling approach are given in Annex A.

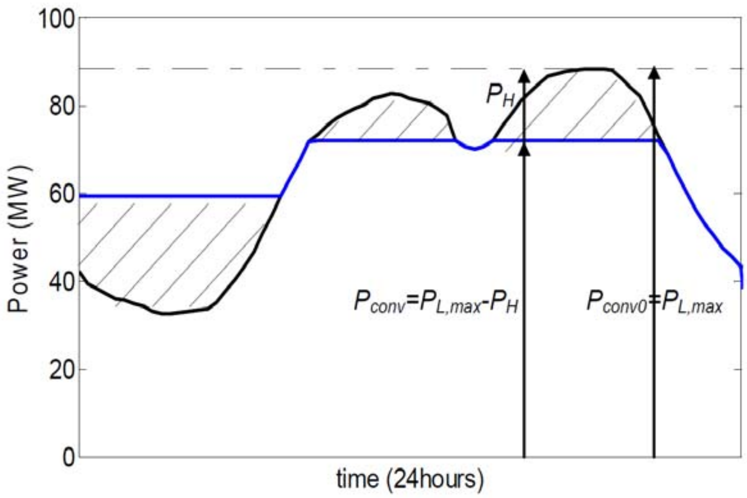

Figure 3. Indicative effects of PHES units operation on the system RL curve.

Simulation results

The results for RES production rejections and PHES operation are given in the following Table 2 for all the examined cases defined in Table 1. For the 40% RES share scenario expected by the year 2020, about 20% of the intermittent RES production will need storage at power up to 5-6 GW. The rejected portion can be quite smaller in some cases of the 80% RES scenario, in which most of the inflexible lignite units will be phased out and hence the system flexibility and RES penetration capabilities will increase. However, the corresponding rejected energy is almost double (7-8 TWh, compared to 4-4.5 TWh in 2020). Moreover, rejections may be even higher if the technical minimum of the system will lowered enough. An increase of about 50-70% is computed for technical minimum of 2 GW, instead of 0.4 GW, for the 80% scenario.

The PHES system foreseen for 2020 (1 GW) is not enough to achieve significant storage and recovery of the RES rejections by that year. For the best case B of equal wind-solar development, the storage efficiency reaches only up to 33%. On the contrary, the 4.5 GW PHES system achieves about double storage efficiencies in the 80% RES scenario. The favored wind development case B appears to be again the worst wind-solar blending in terms of efficiency (Table 2).

Concerning the capacity factor of the PHES units, the results in Table 2 show that for all examined cases it remains low, below 20%, when the units are used only for RES storage. But their full exploitation increases CF by about 12-14%. Hence, the total CF of pumping mode can reach the considered as economically viable range of 25-35%. The favored wind development cases exhibit the smallest CF for both scenarios.

Table 2. Results from the examined cases of the two development scenarios.

Case	Max. neg. power (GW)	Rejected RES prod. (%)	Total for storage (GWh)	Remaining for storage (GWh)	RE storage efficiency (%)	Pumping station Capacity Factor (%)	
						RES	System
Results for 40% RES share (2020)							
A	5.2	19.8	4130	3100	25.0	11.6	18.6
B	6.3	21.5	4470	2980	33.3	17.0	18.1
Results for the 80% RES share scenario							
A	11.5	15.1	7900	2900	63.2	12.5	13.7
B	10.2	13.1	6900	3300	52.0	8.9	13.9
C	13.1	19.0	10000	3450	65.5	16.5	11.5

The duration curve of RES energy rejections shows that rejections occur only for 3300 hours of the year in the 2020 scenario, and less frequent in 80% scenario (Fig. 4). Due to the higher storage efficiency of the latter, the duration curve of remaining energy becomes very short (up to about 1100 hours, Fig. 4b); consequently it may not be storable in a cost-efficient way by any other storage technology.

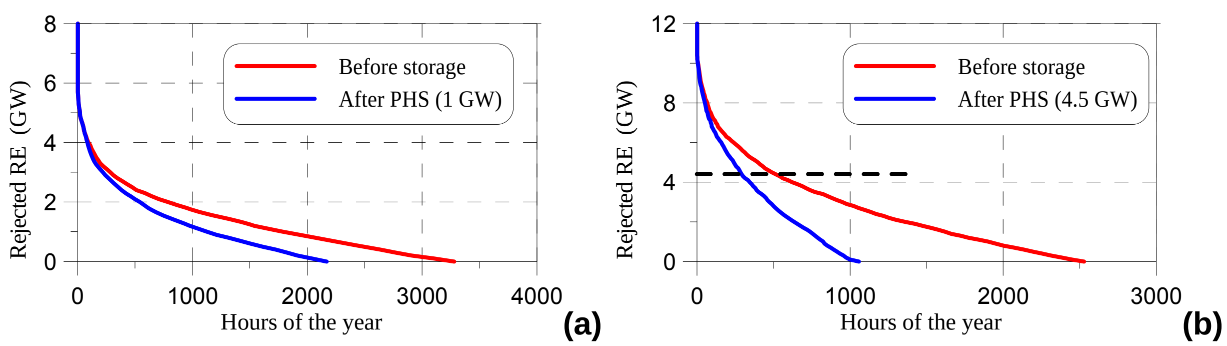

Figure 4. Duration curves of RES rejected production. a) 2020 scenario – case B, and b) 80% RES scenario – case B.

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The reduction of the highest peaks of RL is small when the PHES units are used only for RES rejections. The maximum peak shaving results are achieved for full exploitation (for both RES and the system) of the 4.5 GW PHES in the 80% scenario. In this case the RL annual peak can be reduced from 10.4 to around 7 GW for all examined cases (Fig. 5), which in turn means a considerable reduction of the left-over plants power requirements.

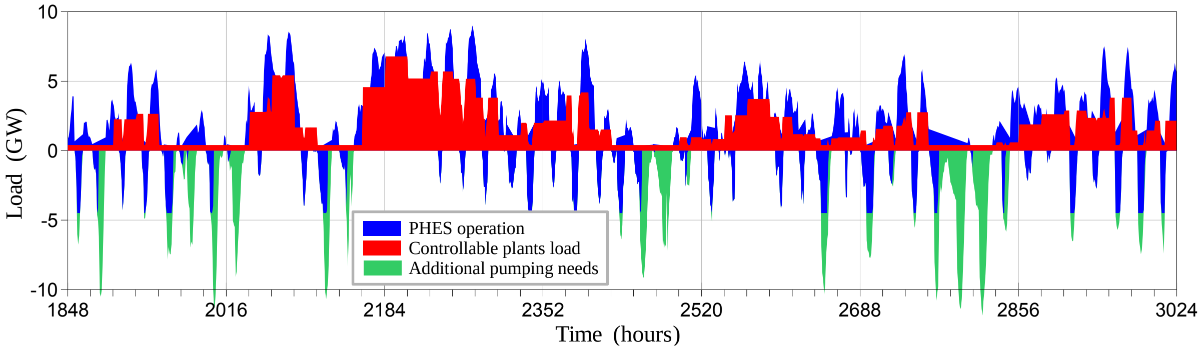

Figure 5. PHES and Controllable plants load variation for 80% scenario – case A.

The grid stability is examined in terms of the load variations of the left over power plants after RES penetration. It was found that in the 2020 scenario it is not substantially affected, because of the relatively low RES share (40%) and the compensating peak-shaving action of RES production (mainly solar) during high load demand hours. The situation changes in the 80% RES scenario, where the load variations of controllable plants are significantly increased (up to about 22 GW, compared to 10 GW in 2020), with negative effect on the grid stability (Fig. 6a). However, full implementation of PHES system of 4.5 GW can reverse this effect thanks to the considerable smoothing of the RL curve, hence resulting in remarkably improved stability of the entire system (Fig. 6b).

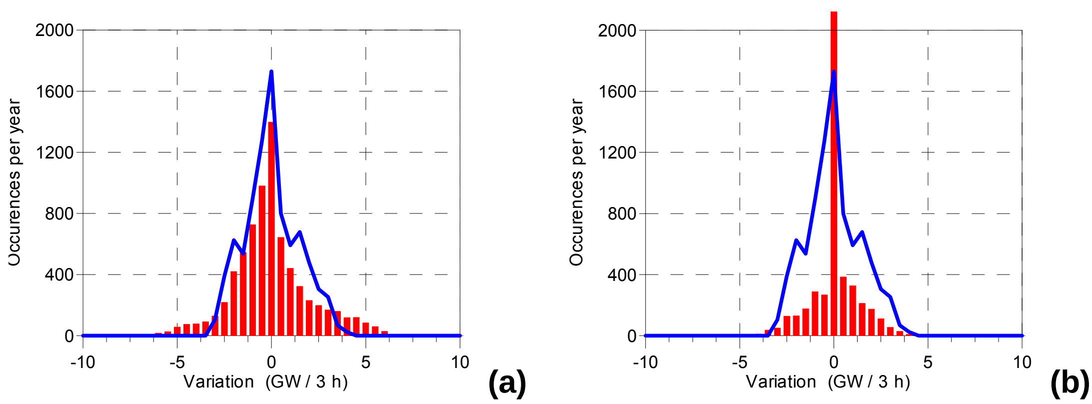

Figure 6. Variation of System Load (lines) and of Controllable Plants Load (bars) for the 80% scenario – case A. a) Without PHES, and b) after full PHES exploitation).

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Additional studies

In order to determine the storage needs of the system, a fictitious storage technology is introduced with unlimited power and storage capacity. Calculations are performed for the 80% scenario and showed the total RES energy storage needs, as well as the possibilities of returning the stored energy back to the system during the simulated period of one year.

In all three cases A, B and C, the stored energy exhibits only few high peaks at certain periods of high RES production, while its fluctuations during the rest year do not exceed 100 GWh (Fig. 7a). Consequently a storage system with that capacity would be quite effective for the 80% RES scenario. Also, Fig. 7b shows that the pumping power needs are up to about 10 GW, whereas the hydroturbines power could be much lower, 5-7 GW. This complies with the use of reversible pump-turbine machines, in which the nominal power in turbine mode is about 70% to 75% of that in pumping mode.

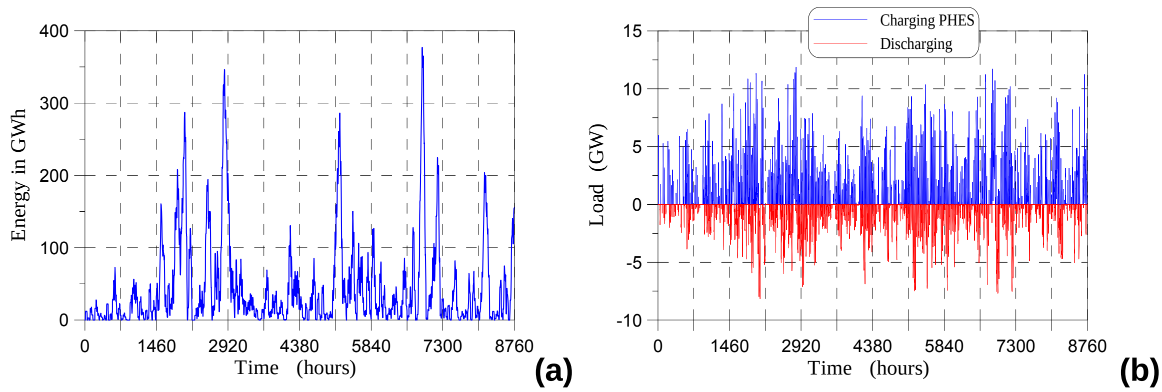

Figure 7. Charging and power level of the unlimited system, for 80% scenario – case A.

The stored energy history shows remarkable differences if the technical minimum of the system is increased (2 GW instead of 0.4 GW). In this case, the extended RES energy rejections during the spring are stored but cannot be gradually fed back to the system. On the other hand, however, the stored energy accumulation exhibits a much different pattern. As can be observed in Fig. 8, the higher feed-in limit of the system causes extended energy rejections during the high RES production in the spring, which are stored but cannot be gradually consumed. Hence, in this case even a 400 GWh storage capacity system cannot be very efficient for recovering the rejected production during the year. This reveals a decisive influence of RES feed-in limitations of the system on its storage capacity needs.

In a second investigation, the combined effect of the two main design variables of the future PHES system, pumping power and storage capacity, on the exploitation of RES rejected energy and on the CF of the pumping units is studied. The results are plotted in hill charts (Fig. 9), and show that for the foreseen PHES power in the national

Roadmap-2050 (up to 5 GW), the maximum attainable efficiency of RES rejections exploitation will not exceed 75% in all cases, even for large storage capacities up to 150 GWh (Fig. 9a).

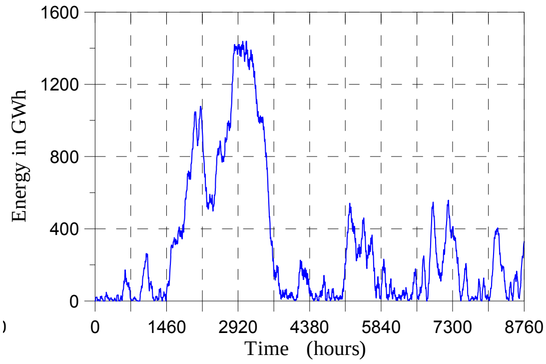

Figure 8. Storage history in case of higher technical minimum for RES penetration – case A.

Consequently, there will be always a remaining portion, about 25%, of RES rejections that could not be exploited. Installation of higher PHES power could reduce this amount (Fig. 9a), but the CF of the pumping units will be reduced (Fig. 9b), with negative effect on the economic viability of PHES system. Therefore, curtailment of this RES production may be unavoidable, since its duration curve will be very restricted (as shown previously), unless it could be channelled to small and distributed consumptions, like the electric cars.

Comparing the above results for the three examined cases of 80% scenario, it was found that case C (favoured solar development) attains the highest RES recovery efficiency and pumping units CF within the planned range of future PHES development. This advantageous behaviour was also observed for the case of higher technical minimum for RES penetration in the system.

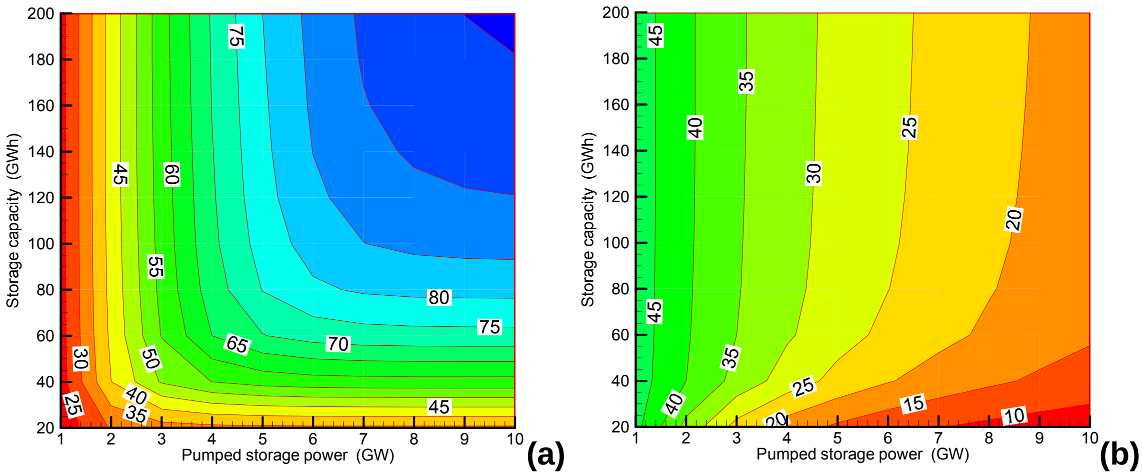

Figure 9. Hill charts of RES energy storage efficiency and CF of pumping units, for 80% scenario – case C.

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Optimum PHES sizing

The optimum size of a pumped storage plant, in terms of economic results and viability, is strongly dependent on the electricity pricing policy for the stored energy, which is not yet developed in Greece. However, reasonable size estimation can be obtained using pure energy data of the pumped storage units, and more specifically, the capacity factor (CF) of the hydraulic machinery (pumps and/or turbines). Based on results from recent studies, economically viable investment can be considered for CF in the range of 25-35%.

A specific algorithm is developed for these computations. The duration curves of RES rejections for each of the following years up to 2050 are computed at first, based on a given development scenario of the system (national Roadmap-2050). Then, the cumulative energy that can be stored and recovered by a PHES system of given power can be calculated for any desired period, starting from its commissioning year, and the average CF during the amortization period is obtained. Finally, setting as target a specific CF value, the maximum installed power for viable PHES investments can be computed.

The results for the MEAP development scenario plotted in Fig. 10 indicate that the optimum PHES installations should be realized in a progressive manner, following the development of RES plants and energy share. It is also shown that up to 2 GW of PHES could be commissioned by 2020, whereas the optimum storage power for the next decades asymptotically tends to the range between 5 and 7 GW. These results are close to the corresponding estimations of the National Energy Roadmap-2050.

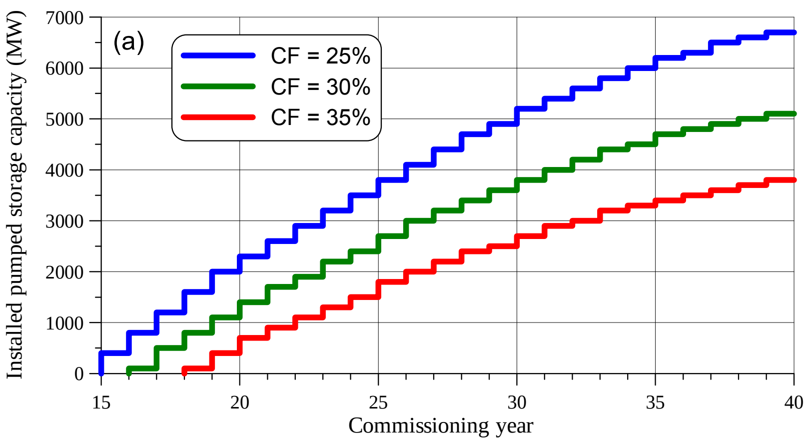

Figure 10. Optimum sizing of PHES development up to 2040 for the MEAP scenario.

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Conclusions

The electricity system of Greece exhibits characteristics of a large isolated grid, with low flexibility, production imbalances and transmission limitations. The aimed high RES integration in the system requires important modifications and improvements, most of which are foreseen in the national RES energy plan to 2020 and the Roadmap to 2050.

High penetration of intermittent renewable energy has feed-in limitations even in very flexible electric grid systems, and rejections of renewable production is unavoidable in periods of high wind and or solar potential. Moreover, the residual load that has to be covered by the left-over power plants of the system may exhibit strong variations, affecting the stability of the system.

The present simulations showed that such rejections will be of the order of 20% for the 40% RES share scenario foreseen for year 2020, which corresponds to about 8% of the total electricity consumption in the system. The rejected portion of RES production for the 80% RES share scenario is lower (13-19%, depending on the renewable production mix), but the corresponding amount of energy is higher, about 11-14% of the total consumption.

Pumped storage is the most suitable energy storage technology for Greece, and it is already considered in the energy plans for the exploitation of surplus RES production. In addition to energy storage, the integration of more PHES units in the system can significantly improve the system stability, as indicated by the present results.

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 showed that this optimum PHES power is between 1 and 2 GW for the 40% RES share scenario, and between 4 and 7 GW for the 80% scenario. The corresponding PHES needs considered in the national RE development plans are within the above ranges.

The storage capacity requirements is the second important parameter that should be optimized to support the future RE development. The present study reveals the decisive role of electricity production system flexibility on the storage capacity needs. For the 80% scenario, increasing the feed-in limit for intermittent RES production from 5% (very flexible) to 25% of the average annual load demand, the storage efficiency of the simulated PHES system (4.5 GW, 54 GWh) is reduced by 16-18 percentage units and the rejected RE that cannot be stored becomes double.

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The relative development of wind and solar energy technologies constitutes a second important parameter of the future system performance. The present simulations showed that a favored wind development scenario exhibits higher direct penetration capabilities, but it is the least efficient in terms of both rejected RE storage and capacity factor of the PHES units.

Even for the most efficient PHES design and for high storage capacities, there will be always a remaining portion, of the order of 25%, of the rejected renewable production, that has very short duration curve, and hence cannot be stored with high capital cost systems. Channeling of this production to small distributed consumptions, like the electric vehicles, could be a possible solution.

A regulatory framework for energy pricing and operation of PHES units is necessary in order to effectively schedule the RES and the entire electricity system development for the next decades. Additional emerging factors must be also taken into account in a more elaborate investigation, like the smart grid, the demand management, and the hydrogen production and utilization. The possibilities of using the existing reservoir hydroelectric plants for supporting high instant penetration of intermittent RES should be also examined.

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Overview of the electricity system status and its future development scenarios – Assessment of the energy storage infrastructure needs

Introduction

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu). stoRE aims to facilitate the realization of the ambitious objectives for high penetration of variable renewable energies in the European grid by 2020 and beyond, by unblocking the potential for energy storage technology implementation. In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies (EST), namely pumped hydro energy storage (PHES) and compressed air energy storage (CAES)[1].

Bulk EST are expected to be one of the key enabling technologies for the integration of large amounts of variable electricity generation from renewable energy sources (RES-E). In particular, the ability to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (i.e. output smoothing)[2] can mitigate many challenges that arise from high shares of variable RES-E generation in the electricity system. Furthermore, bulk EST could also play an important role in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities[3].

Work-package 5 (WP5) of the stoRE project aims to identify regulatory and market barriers to the development and operation of electricity storage systems (ESS) in the six target countries (Austria, Denmark, Germany, Greece, Ireland and Spain). For achieving that, this document, Deliverable 5.1 (D5.1), provides information about the electricity storage needs in each of the target countries necessary for integrating future RES-E generation in the incumbent electricity system.

This report is dealing with Greece (D5.1 - Greece) and is structured into three main parts. Section 1 gives an overview of the Greek electricity system – the status-quo in the year 2011 as well as future prospects until 2020 / 2050 of the electricity generation portfolio and the transmission grid system.

[1] For a complete picture of energy storage options see Deliverable 2.1 (Zach et al., 2012b) of the stoRE project, which also provides a brief overview of other (non-bulk) EST being outside the scope of stoRE.

[2] Other benefits of bulk EST, i.e. black start capability, area control, frequency response (secondary and tertiary control) etc., are described in Deliverable 2.1 in detail.

[3] See Deliverable 2.2 (Zach et al., 2012c) of the stoRE project for more details about the role of bulk EST in future electricity systems with high shares of RES-E generation.

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Section 2 of this report provides the development of the hourly residual load in the Greek electricity system until the years 2020 and 2050 – a precondition for the following modelling exercise of the electricity storage needs.

In section 3, the analysis of the future electricity storage needs in Greece is conducted, considering the existing electricity generation mix and transmission grid system (incl. planned development and reinforcements), along with the national plans for renewable energy development up to 2050. The necessity of new ESS and their feasibility from an energy 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 need of energy storage in the future electricity system of Greece and show the benefits it can bring.

Overall conclusions from the analysis carried out in this report are drawn in section 5. Finally, a brief description of the computer software used for the present analysis is provided in the Appendix.

1. System data and future scenarios

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

1.1 Power plant mix and energy production

The main characteristics of the interconnected electric grid system in Greece are (reference year 2011): Peak load 10.1 GW and total consumption about 53 TWh, with RES production (including hydro) being about 11%. The participation of the 1330 MW installed wind generators in the grid energy balance was almost 5% (Table 1.1).

Table 1.1. Resent data of the electric power system of Greece [1]

	Thermal	Hydro	W/F	PV	Other RES
Installed power (MW)					
Mainland	8500	3020	1330	400	340
Islands	1780	-	259	42	0,3
Electric energy production (TWh)					
Mainland	45	3.7	2.9	0.5	0.8
Islands	0.37	-	0.068	0.004	0,0001

The conventional thermal units consist of 22 lignite plants (5250 MW), 4 Oil plants (730 MW), 5 Combined Cycle units (2000 MW) and 3 natural gas units (510 MW). Hydropower includes 2 pumped-storage units, Thissavros and Sfikia, with 315 MW and 380 MW, respectively. Other RES include mainly small hydroelectric and combined head and power.

Today (Oct. 2012) additional new CCCP units of 1250 MW operate in the system, whereas the reservoir of a new 150 MW hydropower plant is being filled. Also, the cumulative W/F, PV and other RES installed power exceeds 2100 MW. Meanwhile, the Greek TSO has issued connection offer or committed to connect wind farms of total power about 4400 MW.

The production system is characterised of large participation of non-flexible lignite-fired units and reduced capacity of the existing hydroelectric units (hydraulic year up to about 5 TWh). Another important problem is the imbalance between supply and demand, because most generation facilities are in the northern part of the country, whereas demand is mainly in the central and southern part (Athens region), Fig. 1.1. However, after completion and commissioning of the new natural gas units (up to 2015) in central

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and south Greece, the spatial balancing of production and demand in the system will be significantly improved.

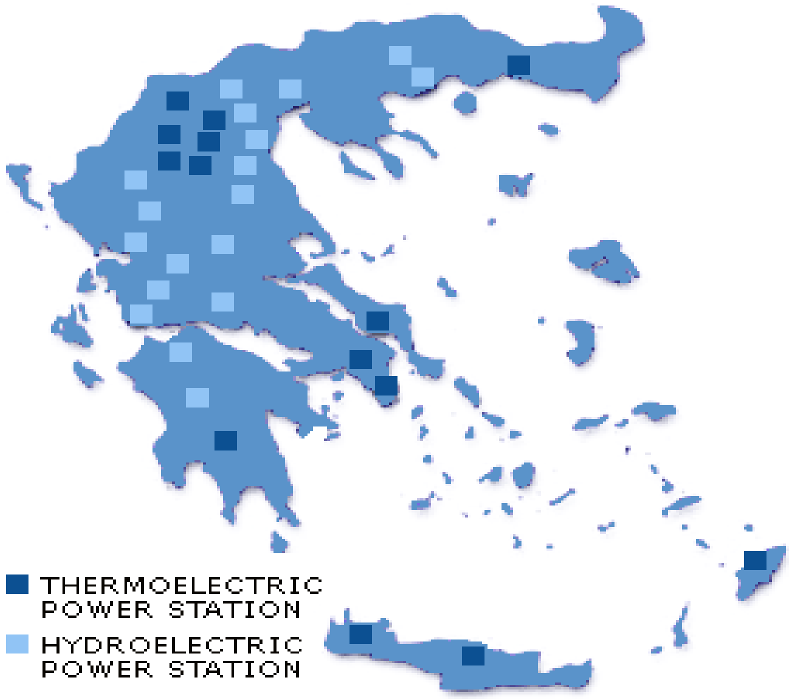

Figure 1.1. Main production units in Greece (20010).

The major production is still carried out by the Public Power Corporation (www.dei.gr), which was founded in 1950 as a monopoly company for production and distribution of electricity. Following the liberalization program, its legal status has recently changed from public to S.A.

The operation, maintenance and development of the electricity transmission system and interconnections are given to the Hellenic Transmission System Operator S.A. (HTSO), which is established in 2000 and in December 2011 was split into two separate companies: The Independent Power Transmission Operation (IPTO or ADMIE, www.admie.gr), who although 100% owned subsidiary of PPC S.A., is entirely independent from its parent company, and the Hellenic Electricity Market Operator S.A. (www.lagie.gr), which applies the rules for the operation of the electricity market in accordance with the provisions of Law4001/2011, and mainly the daily energy planning and market clearance.

In Greece there is no planning authority (e.g. National Energy Council) in charge of decision making on the strategic importance of energy projects. The authority in charge to decide whether an energy project corresponds to the national priorities for energy generation is the Regulatory Authority of Energy (RAE, www.rae.gr), an independent authority who is responsible to promote equal opportunities and fair competition, and to

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provide authorization and licensing to energy producers, suppliers and other market players.

Since 2007 all customers can choose their electricity supplier, but the actual market opening is limited, with only a few new participants. Public Power Corporation (PPC) owns transmission and distribution networks and is the major supplier for customers. Also, only minor exports are realized from Italy due to substantial pricing deviation.
The high capital cost and the time-consuming and bureaucratic licensing procedure is a barrier for investment in generation facilities. About 10 private companies have acquired 13 generation production licenses in CCPP (cumulative capacity 5.4 GW). Some of them are also licensed for construction. The process of the liberalization is expected to be accelerated in the coming years.

Concerning the RES, a great number of production licenses have been issued during the last years by RAE, which include wind farms, PV units, small hydropower plants, and biomass/biogas combustion units, with a cumulative power approaching 30 GW. (www.rae.gr)

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1.2 Transmission system and planed reinforcements

The transmission system consists of about 12000 km 150 kV lines (the 450 of them underground) και 3900 km high voltage 400 kV cables of various types. It also includes 106 km aerial line and 160 km submarine cable DC 400 kV of interconnection with Italy, while the distribution network in the country is about 217000 km and serves about 7,5 million customers. The Greek high voltage grid is shown in Fig. 1.2, along with the location of some large thermal and hydroelectric plants.

Figure 1.2. The high voltage interconnected grid of mainland Greece.

Greece, being in the south-eastern part of Europe does not have physical interconnections with Central or Western Europe. The mainland system is connected to the transmissions systems of Albania (150 kV and 400 kV lines), Bulgaria (400 kV) and FYROM (two lines of 400 kV), with total nominal capacity of about 4400 MW, as well as with Italy with a 500 MW HVDC submarine cable (Fig. 1.3). Interconnection with Turkey was implemented in 2008, with a 400 kV line. Interconnections with the neighbouring countries are designed to meet annually exchanges over 7% of the needs, mainly from excess energy of Bulgaria and Romania systems (about 6% for 2011). Greece is a

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member of UCTE and since 2004 its system is synchronised with the European transmission system.

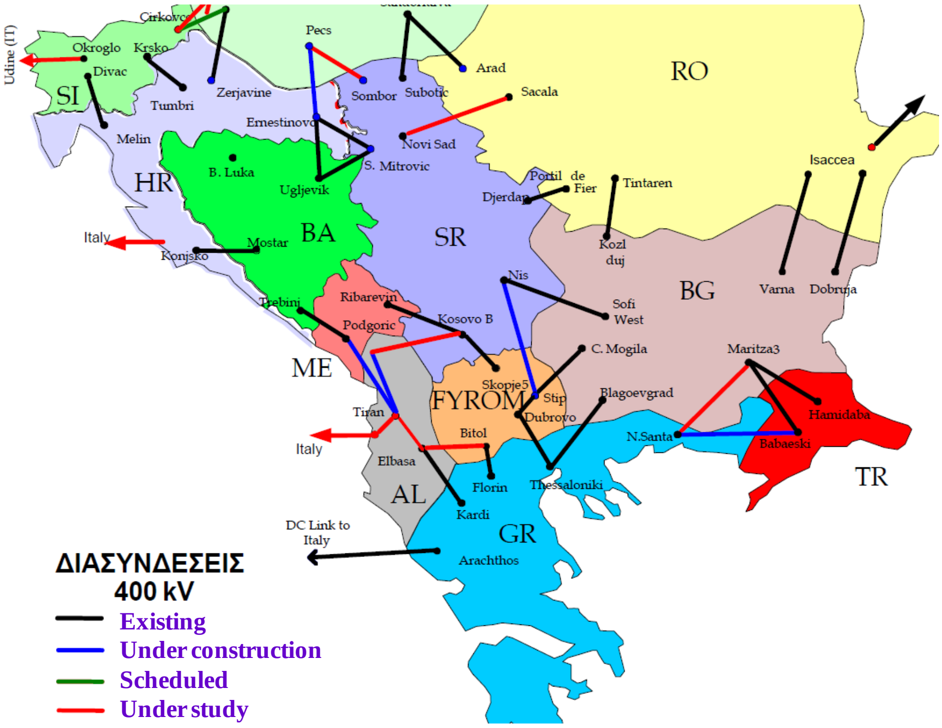

Figure 1.3. Topology of existing and future connections in the ENTSO-E system

An important problem for the transmission system is the imbalance between supply and demand, because most generation facilities are in the northern part of the country, whereas demand is mainly in the central and southern part (Athens region). Moreover, Due to the electricity imports from the northern neighbors, and the location of most large power plants in the northern Greece, large electricity quantities are transmitted through the North-South line, which is served mainly by a central stem, consisted of three 400 kV lines.

Although several important grid reinforcement works have been realized in the last years, and the very high demand during the summer has been addressed, the regions of Attika (Athens) and Peloponnese remain the most critical in the system in respect of voltage and frequency stability. Several large projects are under study for the next decade or being implemented to extend the 400 kV grid, taking into account the future evolution of the load and location of new power plants, thermal and renewable (400kV line to Thrace, and to interconnection with the system of Turkey (entire line is constructed), as well as the extension of the 400 kV line to Peloponnese and Evia, and a second interconnection line with Bulgaria). Also, considerable extensions of the 150 kV gird will be needed to cover the needs of the extensive development of RES. Also the connectivity between networks 400 kV and 150 kV is being gradually improved to

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achieve increased handling capacity of the 400kV system with reduce losses and increased voltage stability margins.

On the other hand, the electricity transmission capabilities do not depend only on the Greek system but also on the grid systems of the wider Balkan region. However, the latter are not quite consistent and robust, and the connection between east and west is weak, hence the energy exchange capacity in the area is restricted. The southern part that includes Albania, Fyrom and Greece, is usually importing region and it is interconnected with the European system through two 400 kV (Kosovo – Skopje, Blagoevgrad – Thessaloniki) and two 220 kV lines (Fierza – Prizren και Vau dejes – Podgorica), with reduced transmission capacity (about 1.1 GW). In the framework of international cooperation projects there are plans for development of interconnections in the wider Balkan area (Fig. 1.4). The new line Dubrovo-Mogila increases the reliability of the entire system and the ability to importing from Europe, and has direct benefits for the Greek system, as it almost doubles the imports capacity of the country. On the contrary, no substantial progress has been made towards upgrading the interconnection line with Italy.

Figure 1.4. Planned new transmission lines in Balkans area (UCTE – Transmission Development Plan 2009, www.entsoe.eu).

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Concerning RES integration, in several areas of high interest for RES installation (mainly W/F) the existing grids are saturated or are near saturation. For all these areas there are planned projects (some of them already in construction phase) to strengthen and expand the system to remove saturation and integrate more RES power.

It should also be noted that the majority of licensed wind farms do not have the character of dispersed generation (low power facilities, embedded in networks of low or medium voltage) but they are high power units, with average size of about 20 MW and many projects over 25 MW. Consequently, their connection to the grid usually requires the construction of large transmission projects (substations and 150 kV lines).

Therefore, in spite of the planned reinforcements, a strategic long term development plan of the electricity transmission is indispensable, given the difficulty in positioning of new transmission lines, the long duration in approval and environmental licensing and expropriation, and the continuous increase of public opposition to these projects.

1.3 Interconnection of the Islands

Several connections of Greek islands with the mainland grid exist today, but there are still more than 50 autonomous power systems in Aegean islands, including the largest ones (Crete, Rodos, Lesvos). Also, several Aegean islands are interconnected with each other.

Interconnection of these islands with the mainland grid is very expensive because of the large submarine cable lengths and advanced technology required. Moreover, the load of most islands is small and hence the economic viability of such projects is doubtful, and depends on many uncertain parameters.

Preliminary studies to connect the Aegean Islands with the mainland system and to exploit their large wind potential have been recently carried out by the Transmission System Operator (www.admie.gr). Some of these projects are quite mature (like the Crete and Rodos Islands and the Cyclades complex interconnection).

Two alternative scenarios for Crete/Rodos are considered, based on the considerable progress on the submarine interconnection technologies during the last years:

- Interconnection of Crete only, by two DC circuits 2x350=700MW total capacity and autonomous development of Dodecanese/Rodos, or
- Interconnection of Crete firstly by two DC circuits 2x550=1100MW capacity, and in a second stage extension to Dodecanese by AC 150kV.

The Cyclades interconnection is a state-of-the-art project from technological point of view, and requires high investment cost. However, due the high increasing rate of the load in these islands, the project is characterized as of great importance for the country's economy. However, the project is delayed and cannot be completed due to significant reactions of residents and local agencies, and successive prosecutions to administrative authorities and courts.

Future plans include also the interconnection of the rest large islands of the eastern Aegean (Kos, Chios, Samos, Ikaria, Lesvos, Limnos), and several smaller. An integrated picture of the interconnected system of the country with the islands is shown in Fig. 1.5.

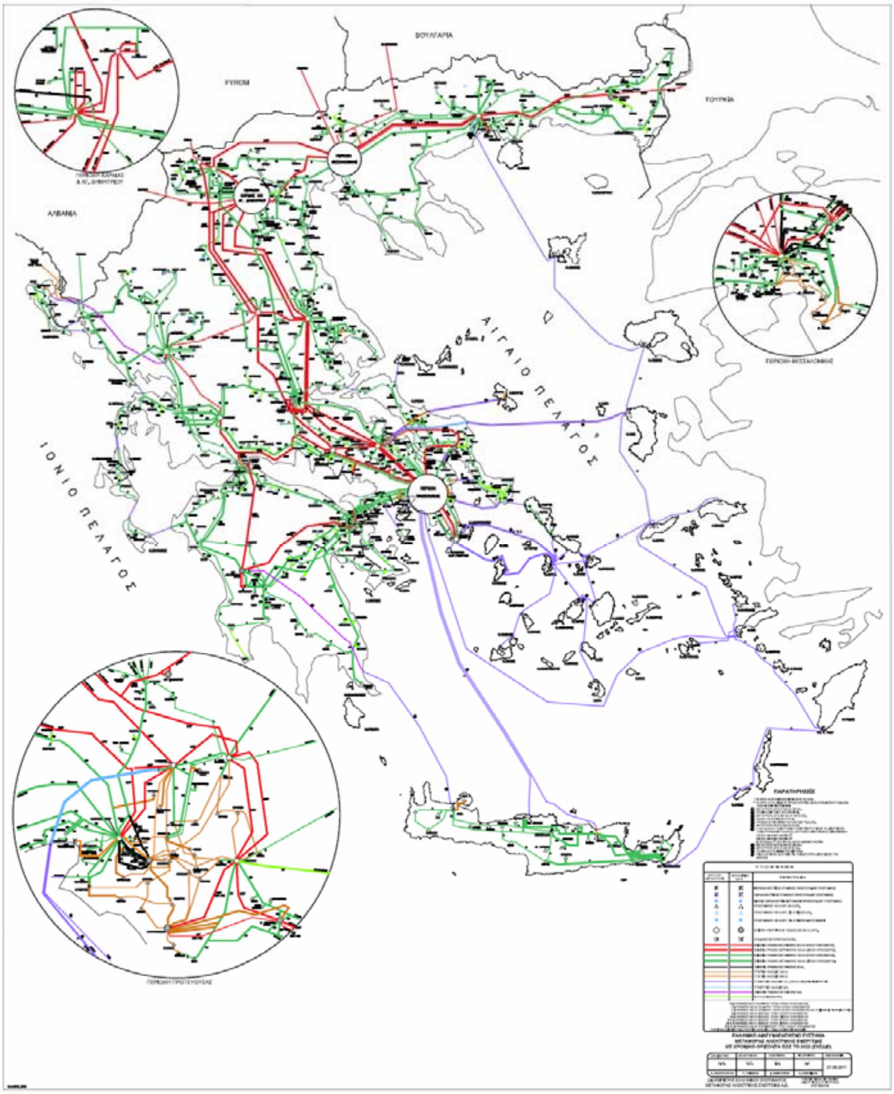

Figure 1.5. Transmission lines after interconnection of the Aegean Island (www.admie.gr)

In concluding, the implementation of the above projects within the next decade will create a robust and stable transmission grid system, that could serve the long term needs of users covering the entire continental country and the islands, and fully support the large RES integration in the electricity system.

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1.4 National Energy Plans for the future

1.4.1 Plans to 2020

Large RES penetration in the electric system of Greece has been recently considered in the scope of Directive 2009/28/EC. In 2010, the Greek Government developed a national energy plan for the period until 2020 (Law 3851/2010), for significant increase of RES share in the gross final energy consumption (up to 20%) [2-4]. This share is composed of 40% participation of RES in electricity production, 20% in heating and cooling and 10% in transport. As a result, the electricity production mix in 2020 will be much different than the current one (Fig. 1.6).

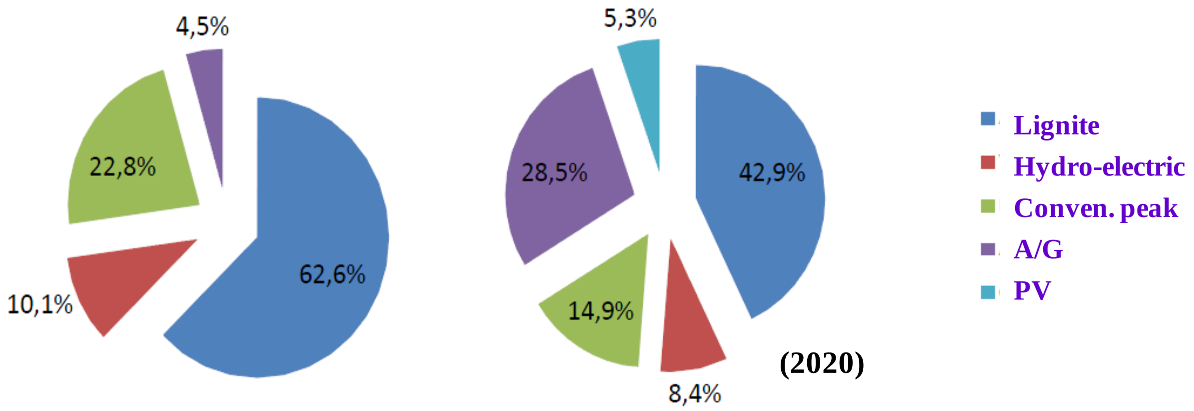

Figure 1.6. Current and modified electricity production mix in Greece by 2020.

More detailed estimations of the blending of various electricity production technologies, including conventional units and RES plants, is given in Figs. 1.7 and 1.8. According to the compliance scenario, the capacity of the intermittent sources, wind and solar PV, will reach by 2020 the amount of 7.5 GW and 2.2 GW, respectively.

However, in the last two years economic conditions in Greece and internationally followed quite different rates from the estimated ones in the above plan. Following the reduction of gross national product, the total electricity production in 2011 was about 53000 GWh, less than in previous years 2010 and 2009, and the electricity demand may remain below estimations for the next years, until the economy recovers. A comparison of the initial and the new estimations of the evolution of the main electricity quantities up to 2020 is given in Table 2 below [5].

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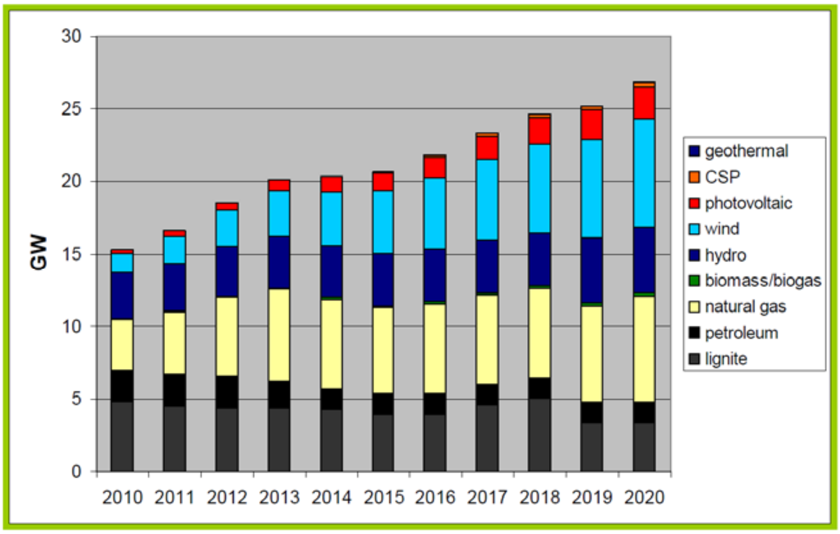

Figure 1.7. Estimated installed power for electricity production (National RES action plan 2010).

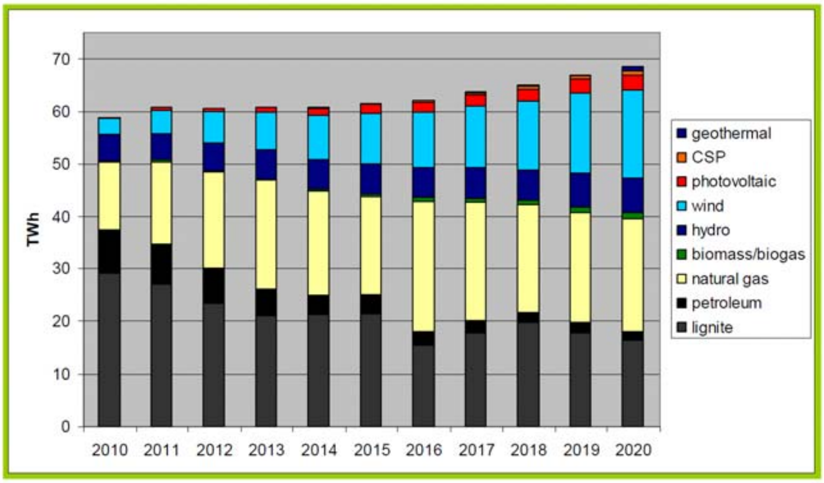

Figure 1.8. Estimated electricity generation from different technologies/fuels (National RES action plan, 2010).

Table 1.2. Initial and corrected growth estimations due to economic recession conditions.

		2011	2015	2020
Increase rate of gross national product	estim. 2010	-2.6%	2.7%	2.9%
	estim. 2012	-5%	3%	3.3%
Total electricity production (TWh)	estim. 2010	60.65	61.47	68.46
	estim. 2012	53.56	54.02	60.83
Electricity from RES (TWh)	estim. 2010	9.51	16.97	27.27
	estim. 2012	7.88	12.03	23.40

According to the new estimations the installed RES power will be reduced by 1300 MW. This reduction concerns only the wind farms installations, whereas, on the contrary, PV

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units capacity is expected to exceed initial estimations, due to the favorable pricing policy applied in the last years, during which about 2 GW of PVs have been licensed at very high fix contract pricing (> 400 €/ kWh). As a result, 2020 targets for PV development will be reached several years earlier. Consequently, the percentage targets of total RES share in the electricity production for 2020 are still feasible, and the energy mix may not be much different than the initially estimated.

1.4.2 Energy roadmap to 2050

After the above first action plan for renewable energy integration, the National Energy Strategy Committee elaborated a long term analysis of the Green energy system and proposed the Energy Road Map of Greece for the period 2020-2050 [5], taking into account the current unfavorable economic conditions in the country. The document issued in March 2012 and exposed for public consultation, which was completed at the end of June 2012.

The main objectives of the new roadmap are the reduction of the dependence on imported energy and the maximization of RES penetration, achieving a significant reduction in emissions of carbon dioxide by 2050. Zero use of nuclear energy and very limited use of Carbon Capture and Storage technology (CCS) are key options for the abovementioned planning. According to the authors of this report [5], the national energy system has the potential to differentiate significantly over the next years, fulfilling the commitments of the European energy policy, while providing security and lower energy cost to the final consumer.

The Roadmap to 2050 provides the basic guidelines of the national energy strategy towards 2050, including a number of possible scenarios for the evolution of the energy system, which were examined in order to specify and evaluate alternative measures and policies for the fulfillment of both national and European targets [5]:

- The "Existing Policies" (EP) scenario assumes a conservative implementation of environmental and energy policies, anticipating on the one hand a moderate level of CO_2 emissions reduction by 2050 (40% compared to 2005), and on the other hand moderate penetration of RES and energy saving.
- The "Measures Maximization RES" (MEAP) scenario assumes maximization of RES penetration (100% in electricity generation), so as to reduce CO_2 emissions by 60% -70% with simultaneous energy saving in buildings and transport. Increased imported electricity is also examined as a possible variation of this scenario.
- The "Minimum Cost of Environmental Measures" scenario (PEK) has the same assumptions as the previous one (MEAP) regarding the CO_2 emissions but estimates the share of renewables in the energy mix so as to minimize cost.

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Among the aimed achievements of the future energy system development, as indicated by the two most desirable energy policy scenarios (MEAP and PEK), are the following points, which are associated with the electric power system development:

- Reduce greenhouse gas emissions by 60%-70% by 2050 in relation to 2005.
- 85%-100% electricity from RES, using all commercially mature technologies.
- Total RES penetration in gross energy consumption by 2050 at a rate of 60%-70%.
- Relative increase in electricity consumption due to electrification of transport and greater use of heat pumps in the residential and tertiary sectors.
- Significant reduction of oil consumption.
- Significantly improved energy efficiency and large penetration of RES in buildings.
- Development of decentralized production units and smart grids.

The estimated evolution of the electricity production and of the installed capacity of all generation technologies involved in the production scheme up to 2050 are given in corresponding graphs [5], which are shown in Figs. 1.9 and 1.10 below.

In all the above scenarios it was adopted that the impact of the present unfavorable economic conditions will not be extended beyond the end of the current decade. Also, other important factors, as the CO_2 cost, are taken into account

From the above diagrams it can be observed that the scenario MEAP leads to complete decarbonization of the electricity production by the year 2050, whereas in the conservative scenario (EP) a remarkable portion of fossil fuels production remains in the energy blending (natural gas and lignite, Fig. 1.10).

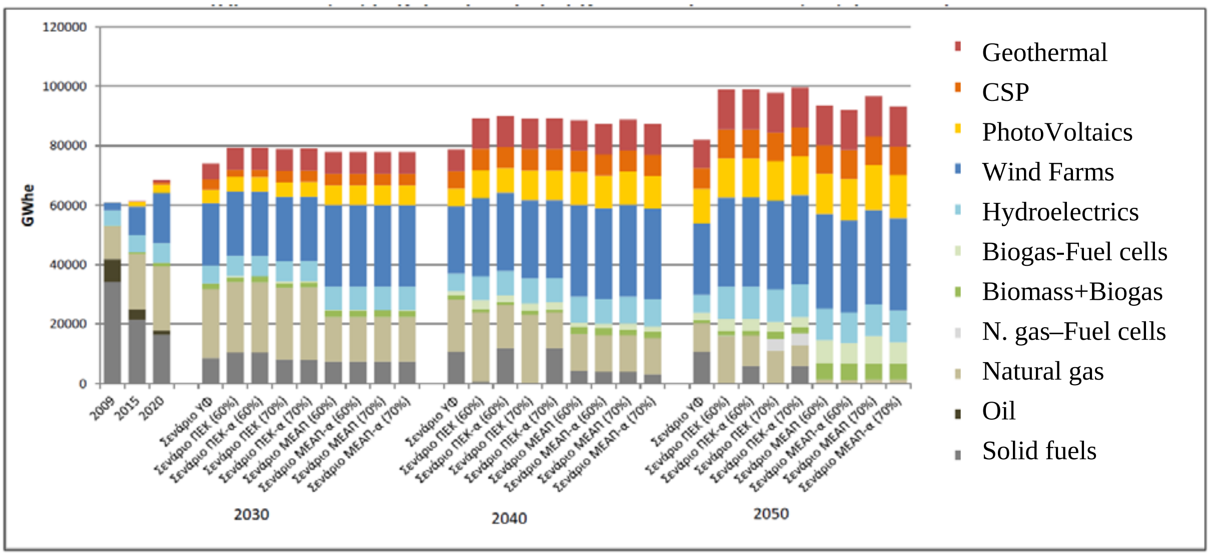

Figure 1.9. Electric energy production mix for various development scenarios [5].

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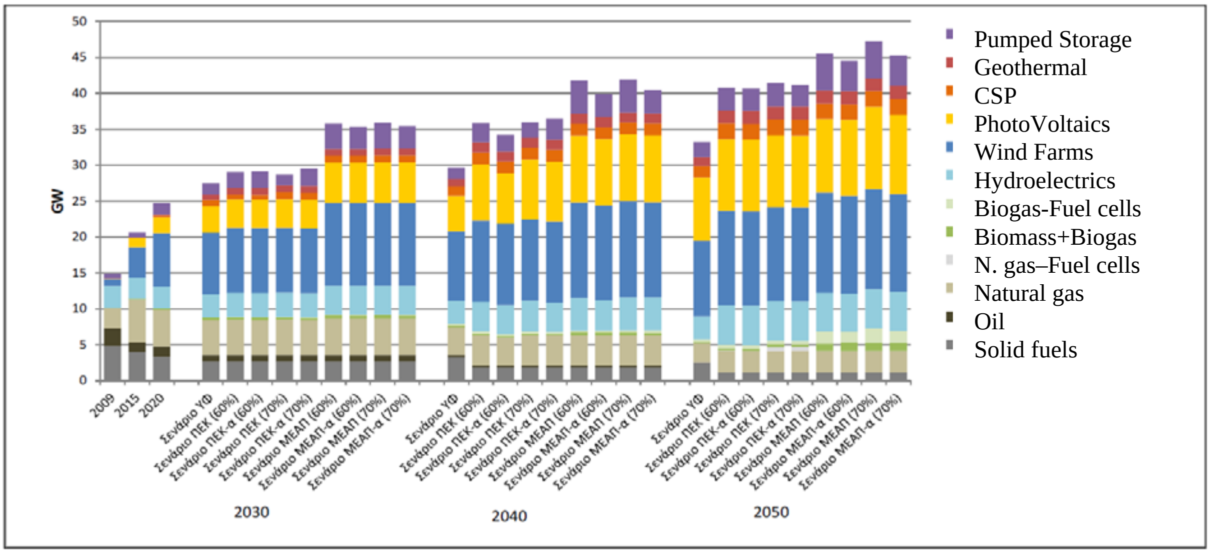
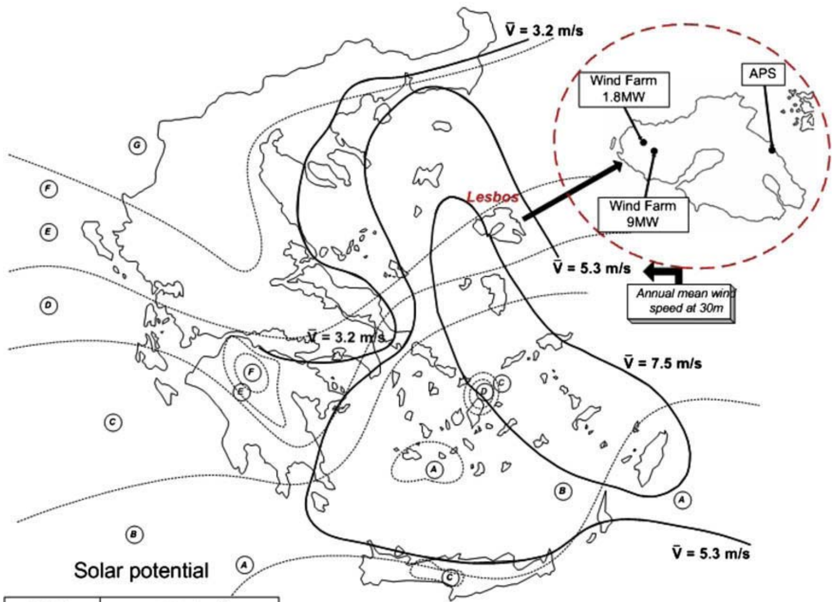


Figure 1.10. Installed capacity of electricity production technologies for various development scenarios [5].

1.4.3 PHES development plans

The major part of RES power to be integrated in the system will be wind and solar. The wind potential is significant in many regions (Fig. 1.11), and the possible sites and applications are distributed throughout the country, including the Islands, thus increasing the prospects of realization of several investments.



ZONE	kWh / m ^{2}
A	> 1650
B	1600 - 1649
C	1550 - 1599
D	1500 - 1549
E	1450 - 1499
F	1400 - 1449
G	< 1399

Figure 1.11. Wind and solar energy potential in Greek territory

However, the existing electric power system will not be able to accommodate such large amounts of intermittent production, mainly due to the inflexible conventional thermal units, as also because of the limited cross-border transmission capacity of the country. Actually, the Greek electric system could be seen as an enlarged isolated, non-interconnected grid, like the ones encountered in the Islands. Consequently, sufficient energy storage capacity needs to be developed during the next years, in order to avoid excessive rejections of RES production. Pumped storage is the most mature and reliable technology for such large storage rates, and also it is suitable for the ground topology of the country, therefore it provides to be the best solution for Greece from both technical and economic point of view.

The issue of electricity system operation for large RES penetration was the subject of special studies recently carried out at NTUA in collaboration with RAE and HTSO (Dialynas 2009, Caralis et al. 2012, Boulaxis 2009). These studies are based on decoupling the problem of electricity transmission and production, assuming that there are not restrictions in transferring electric power to and from any point of the system, which is a reasonable approach for the future transmission system, as discussed in section 1.2. Also, these studies considered high wind penetration only (and not solar). The results indicate that the system could absorb the production of up to about 5 GW wind power. However, above that quantity wind power cuts will be needed, depending on the load demand and the production mix, starting from a few percentage units and increasing exponentially with the installed wind farms power in the system. In order to fulfill the RES development target for 2020, the above studies conclude to about 1 GW of PHES capacity requirements.

According to the Roadmap-50 report, the large RES share in the electricity production is achievable with the aid of additional pumped storage installations, which for the MEAP scenarios are of the order of 5 GW for 2050, whereas for the conservative EP scenario are about 2 GW (Fig. 1.10).

Some studies have been recently performed in order to investigate potential sites and to assess the feasibility of pumped storage schemes (Stefanakos, 2009; Stefanakos et al., 2010; Anagnostopoulos and Papantonis 2011). According to their results, the most feasible sites for such plants are the existing pairs of successive large hydro power plants (HPP), in which an additional pumping station unit can recycle water from the downstream to the upstream plant reservoir. Such “pump-back” facilities have the advantage that the energy storage is generally much greater thus allowing to store large amounts of electricity.

Recently, a significant number of projects involving pumped storage hydro units have been submitted to the RAE for licensing. 17 energy production licenses for mainland sites have been granted so far, almost all to the same construction company, the total

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installed power of which exceeds 4 GW. However, Environmental terms approval cannot be granted as a consequence of the restrictions set by the Law 998/1979. Moreover, the regulatory framework for such units is missing and for this reason a public consultation has recently distributed by RAE. The outcome revealed several important issues that must be resolved in order to determine the status of installation and operation of PHES units in the interconnected system, as follows:

- Storage of RES energy or also of conventional plants excess production
- Possibility for direct collaboration with RES producers (hybrid plants)
- Inclusion of existing PHES in the new framework motivations
- Compensation of RES producers in high penetration conditions (modification of Feed-in-Tariff policy)
- Dispatch priority or other market preferential treatment of PHES production
- Pricing policy for PHES: Disconnection from Marginal System Price, pricing of ancillary services, price difference between production and storage, storage cost allocation to all electricity producers and consumers, etc.

The situation is more improved concerning the Islands, for which a Completed Regulatory Framework for the Operating Principles of PHES has recently issued [11,12]. Based on that, several production licenses of cumulative power about 200 MW have been given to such plants in some large islands (Crete, Rodos, Lesvos), which moreover are accompanied by specific pricing of the produced energy. Also, applications for additional 600 MW PHES are pending today.

Finally, the outcome of the recent studies is that new pumped storage investments should be planned and realized gradually during the next years, following the development of RES capacity, and starting from the most cost-effective pump-back plants. Moreover, pumped storage capacity should be distributed in several sites to maximize the energy and economic efficiency of the excess RES production exploitation.

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1.5 Reference and future development scenarios

Two future scenarios for RES development are examined. The first concerns the year 2020, when, according to the National energy plans (NREAP) [4] and latest predictions, the RES share in electricity production will approach 40%. The second case is for a much higher RES share of 80%, which, according to the National Roadmap to 2050 [5], will be reached by the year 2040-2050, with the MEAP (Measures Maximization RES) development scenario.

In addition, the relative development of the two most important RES in Greece, wind and solar, is also tested in the framework of the above two scenarios. The base case A (favored wind development) for 2020 is the one contained in the NREAP, whereas, a case with more increased PV installations is also considered (case B – equal development), according to the latest estimations, based on the current economic conditions in Greece and the progress in licensing procedures.

The second scenario for 80% RES share has two more cases in addition to the base case A (equal development) which is reported in the national roadmap. One with favored development of wind farms against PVs (case B), and a second with the opposite assumption, higher PV installations (case C). In all cases, the cumulative production of both wind and solar plants is kept the same. Table 1.3 summarizes the input system data for all the examined cases. The differentiation between the development of wind and PV was made because the development of renewable energies is not totally determined and there are market drivers that can influence the development of one technology against the other.

As far as the RES penetration limitations are concerned, the following method is adopted: The cumulative hourly penetration of wind and PV production cannot exceed the system load power minus the production of the non-controllable or inflexible units that are dispatched. The latter include the Lignite fired thermal units and part of some other RES production, like hydropower and geothermal.

As a first approximation, a constant minimum value of 3.7 GW is adopted to represent mostly the minimum operation of the inflexible lignite fired base units for 2020, based on the system data of Table 1.3. This feed-in limit corresponds to the current minimum load demand of the system. A quite smaller value should be used for the future 80% scenario, in which the lignite power is much reduced and the system contains more flexible thermal and RES production units, as shown in Table 1.3. In order to quantify the effect of this technical minimum, the model is applied for the 80% scenario for two different penetration limits: 2.0 GW and 0.4 GW, with the latter representing a very flexible and effective management of the whole system that could be achieved until the year 2040. According to the National Road to 2050, for year 2040 and MEAP scenario, 2 GW are the installed lignite-fired units and 0.4 GW is their mean annual production.

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For the 80% scenario of Table 1.3, the values of 0.4 and 2 GW correspond to 5% and 25% of the average annual load demand.

The reference storage (pumping) power for 2020 is taken 1 GW, whereas for the 80% scenario is taken 4.5 GW, in accordance with the corresponding estimated needs of related studies and of the national roadmap. A reference storage capacity is selected so as to correspond to 12 hours of continuous pumping operation, giving a capacity of 12 GWh for 2020 and 54 GWh for the 80% RES share scenario. Sensitivity study of the results on the values of the above critical system parameters was also carried out and the results will be also presented in this report.

Table 1.3. Overview of the main factors of the energy system for various scenarios and cases examined.

	Ref. 2011 (GW)	2020 Scenario NREAP (GW)		80% Scenario (in GW) (NR-MEAP-2040)		
		A	B	A	B	C
Thermal power plants						
Lignite	5.3	3.5		2.0		
Gas	1.8	5.2		4.5		
Oil	1.4	1.4		0.2		
RE power plants						
Wind	1.3	6.5	5.0	13.0	14.0	11.0
PV and Solar-equiv.[1]	0.4	2.5	4.9	11.5	8.3	14.7
Hydropower (semi-controllable)	3.1	3.5[2]		4.5[2]		
Geothermal (semi-controllable)	0	0.1		1.7		
Solar Thermal (semi-controllable)	0	0		1.6		
Other RES (controllable)	0.3	0.3		0.5		
Yearly peak load (GW)	10.0	11.2		16.2		
Electr. Consumption (TWh/a)	53.0	60.8		88.3		
RE production, TWh	7.9	24.5		70.6		
RE share	~14.7%	~ 40%		~ 80%		

[1] Total solar power (PV and Solar thermal equivalent)
[2] Excluding the PHES systems.

2 Development of the residual load

The Residual Load (RL) for Greece is calculated by the following method: At first, the load demand time-series is constructed by multiplying the data of the reference year so as the total electricity consumption become equal to the one given in Table 1.3 (for the corresponding scenarios 2020 and 80%). The hourly production data of wind farms, PV 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 1.3. Especially for hydropower production, the projection is done using a specific expression and not simply multiplying with the installed power ratio.

The RL is then obtained by subtracting the hourly wind, solar and hydro production from the corresponding system load. For the 80% scenario, and additional amount of 1 GW constant power is also abstracted to account for an estimated minimum power of the geothermal production (~2/3 of installed).

Although hydropower can operate flexibly to a certain degree 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 units installed in the system. This treatment is from the safe side because most of the existing hydroelectric plants are also used for water management, and their daily and seasonal production program cannot be easily modified.

Also, the existing pumped storage plants in Thissavros and Sfikia were designed and are being used for storage of the night-time surplus production of the non-flexible lignite units, therefore they are not included in the cumulative power of PHES systems considered here.

Finally, as a first approximation 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, which is quite high for wind and solar potential.

2.1 Results for the 2020 scenario

The annual load and residual load variation for the 40% RES share scenario expected by the year 2020, are plotted in Fig. 2.1 for the two cases examined. The technical feed-in limit in the system for this scenario is set to 3.7 GW, as discussed previously, and hence rejection of inflexible RES happens for RL values below that limit. In the A case the total rejected energy from renewable sources would be about 4.1 TWh, with a

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maximum negative power of 5.2 GW. This means a share of about 20% of the total wind-solar energy production. In the B case these amounts increase to about 4.5 TWh and 6 GW, respectively, due to the higher increase of solar power rejections, since solar production is less spread during the day than wind production. The corresponding rejected portion of the wind-solar production is 21.5 %. The above rejected energy corresponds to 8% of the total electricity consumption in the system (Table 1.3).

These quantitative results are also 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.

As can be observed in Fig. 2.2, rejected energy from fluctuating RES occurs throughout the whole year, over long periods, and with high gradients. However, total rejections in case B are more frequent and in general higher. In order to avoid the loss of this energy, there is a need for installation of more flexible power units, export or energy storage.

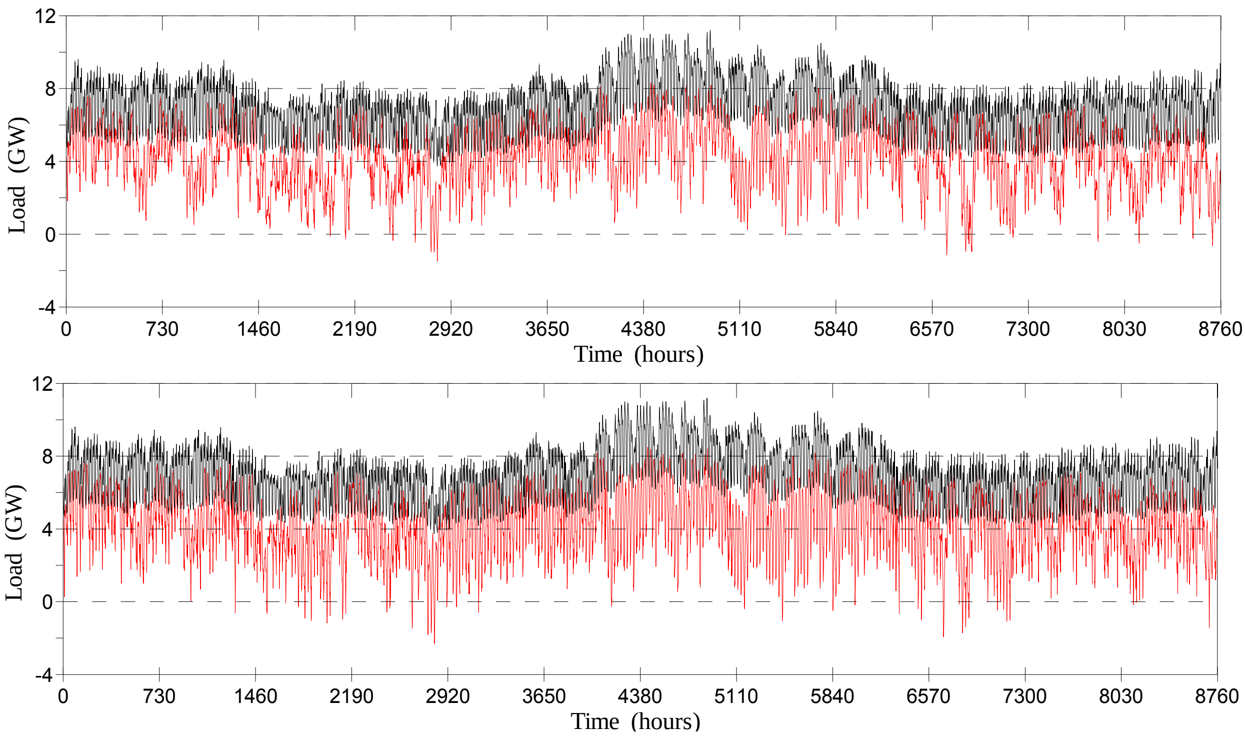

Figure 2.1. Load (black) and residual load (red) for the 40% RES share (2020-MEAP scenario), and cases A (upper) and B (lower).

Figure 2.3 shows that the variation of the load that has to be covered by the left over power plants does not change much when the wind-solar mixture of case A is considered. Stability is even slightly improved in case A, 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. The opposite is valid for the B case, in which the system stability is negatively affected.

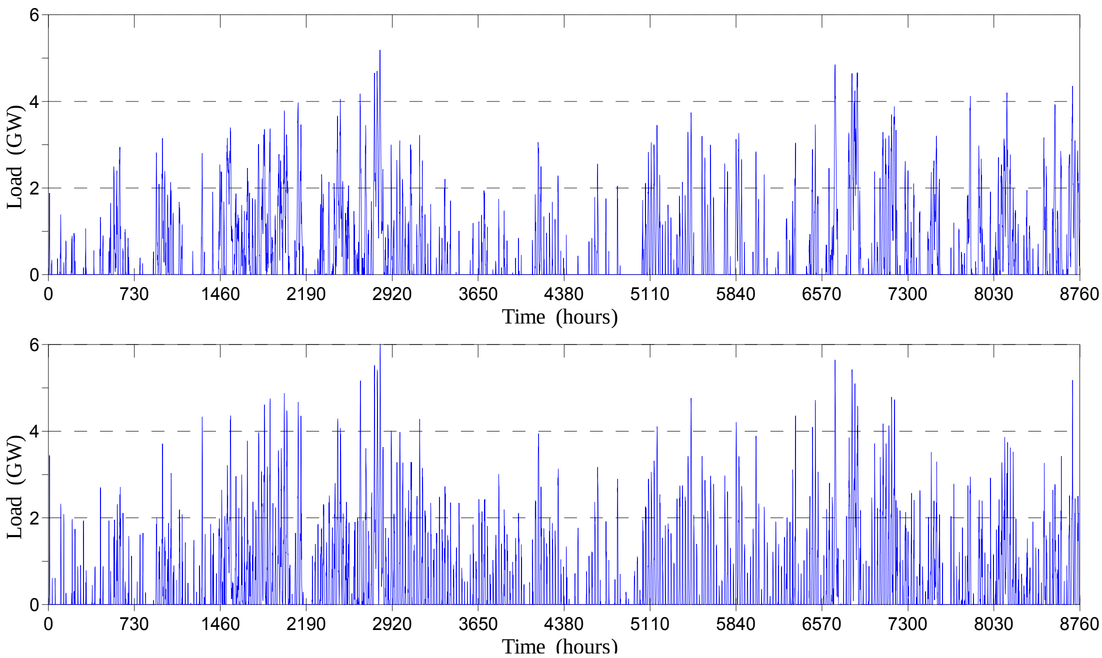

Figure 2.2. Rejected energy from intermittent RES for 40% scenario (2020), and cases A (upper) and B (lower).

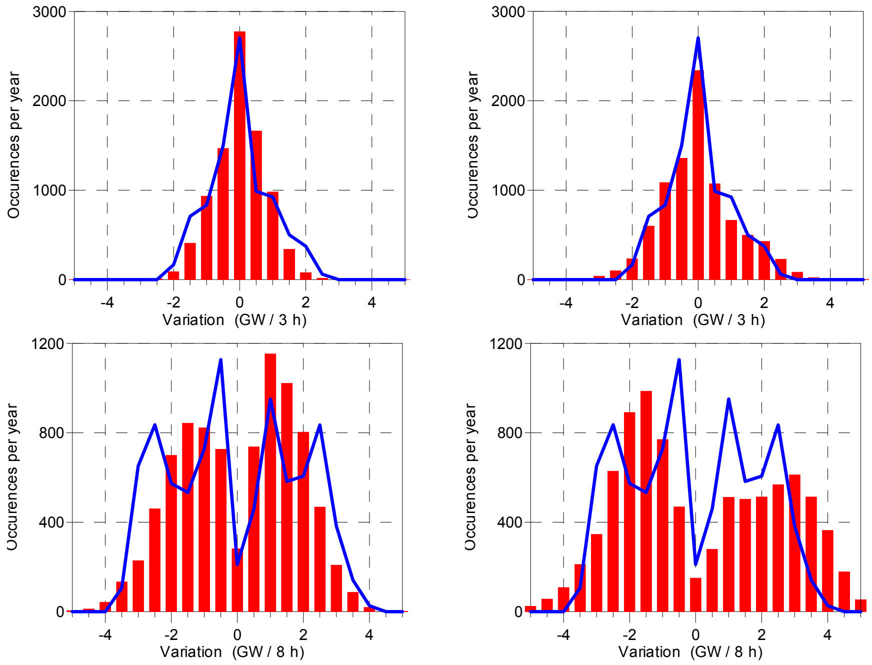

Figure 2.3 Total load variation (cont. lines) and residual load (bars) for the 40% scenario: Case A (left), and case B (right).

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Table 2.1. Comparative results for the 2 cases of the 40% RES development scenario.

Case	Max. negative power (GW)	Rejected production % Wind – PV – cumulative			Total rejected energy (GWh)
A	5.2	21.0	15.0	19.8	4130
B	6.3	18.7	26.0	21.5	4470

2.2 Results for 80% scenario

The annual load and residual load variation for the 80% RES share scenario expected by 2040-2050, are plotted in Fig. 2.4 for the three cases examined (A, B and C, Table 1.3), and for a small technical feed-in limit of 0.4 GW, assuming that the system will be very flexible and optimally managed, as discussed previously. For all three cases the variation rate of the RL is high, and the minimum-maximum power varies between +10 and -12 GW, before applying energy storage.

Even for the small technical feed-in limit of 0.4 GW (assuming that the system will be very flexible and optimally managed, as discussed previously), compared to the 40% scenario the RES energy rejections are much higher now. Also, as previously, rejections are more frequent and large in power in case C, when the installed solar power is highest (Fig. 2.5). For the same reason, the opposite trend is observed for the least solar power installations case B. The total rejected amount varies from 7 TWh for Case B to 10 TWh for case C, and the corresponding maximum negative power is 10.2 GW to 13.1 GW. The fraction of the intermittent production (wind-solar) that cannot penetrate to the system is lower than in the 40% scenario (13-19%, depending on the renewable production mix), but the corresponding amount of energy is higher, about 11-14% of the total consumption.

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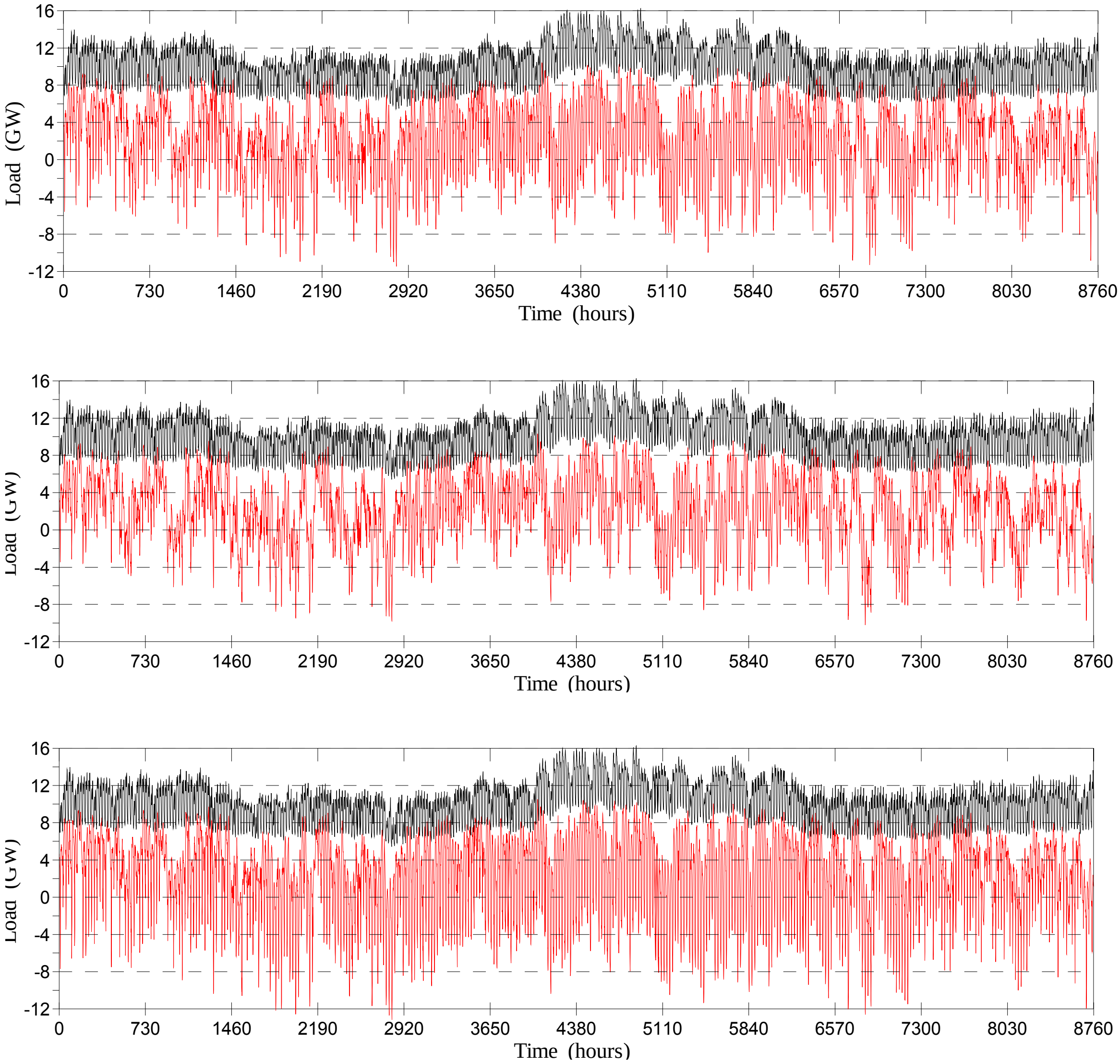

Figure 2.4. Load (black) and residual load (red) for the 80% RES share (2040-MEAP scenario), and cases A, B and C (from top to bottom).

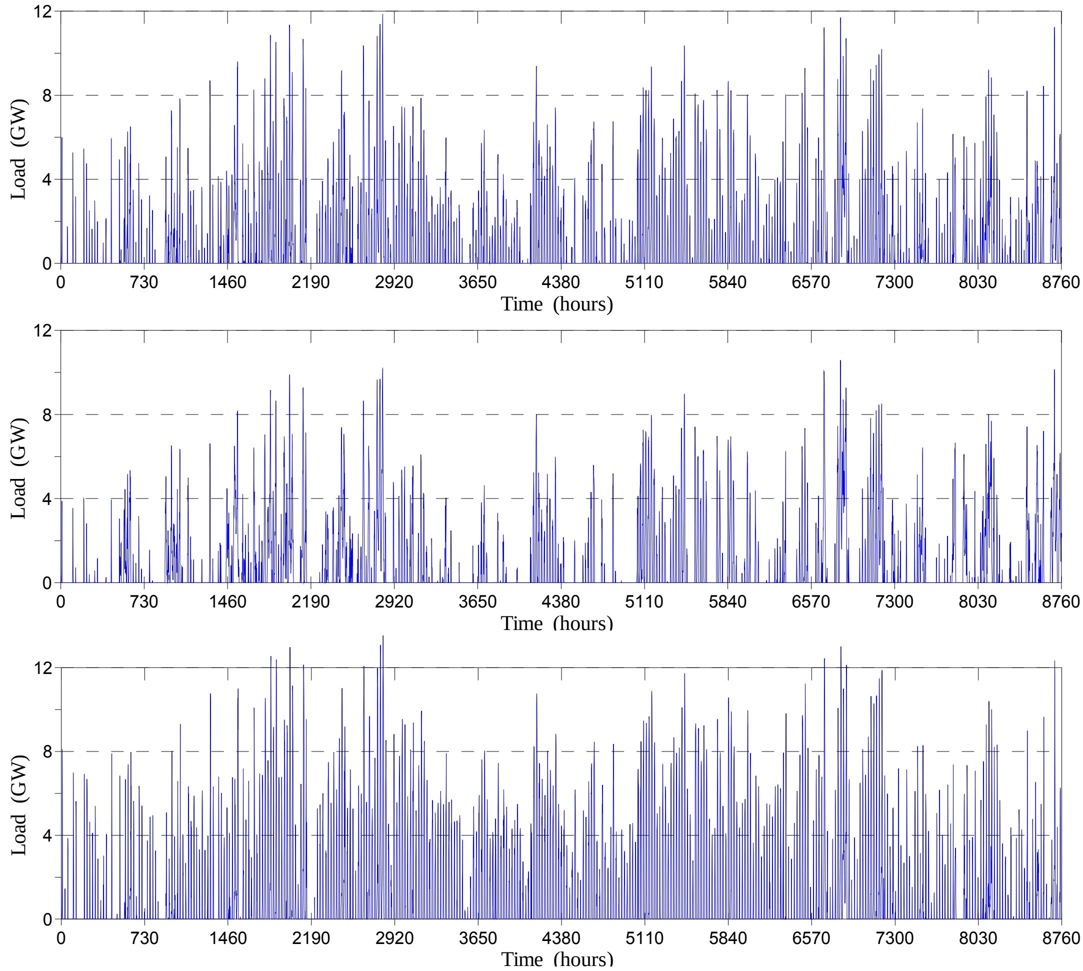

Figure 2.5. Rejected energy from intermittent RES for 80% scenario, and cases A, B and C (from top to bottom).

Due to the higher share of fluctuating energies and the larger spread of the residual load (about 22 GW compared to 10 GW in the 2020 scenario), the system load variations will increase strongly. Considering that the rest power production system cannot operate below its technical minimum (here 400 MW), the load variations of the left over controllable plants are computed and presented in Figs. 2.6 to 2.8. The initial system variations during 1 hour are less than 2 GW, whereas the influence of intermittent RES production increases this limit to about 3 GW (Fig. 2.6). Where the fluctuations of the load reaches their maximum, around 6 GW/8h, the fluctuations of the left over plants load become almost 9 GW/8h (Fig. 2.6). Hence, in all cases the penetration of intermittent production increases the load fluctuation by about 50%.

This behavior is similar in all cases B, and C, as can be observed in Figs. 2.7 and 2.8, but the increase of load fluctuation is smaller in case B and greater in case C, around 30% and 70%, respectively. 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.

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For the Greek electricity system specifically the variations within 3 hours are of interest. Old lignite fired power plants cannot start within this time and other power plants will have to cover the load during these quick changes. As the variations are increasing a higher amount of more flexible units has to be connected to the grid to cover these load changes. Energy storage systems can reduce these fluctuations an enable the left over power plant mix to adapt to the load accordingly.

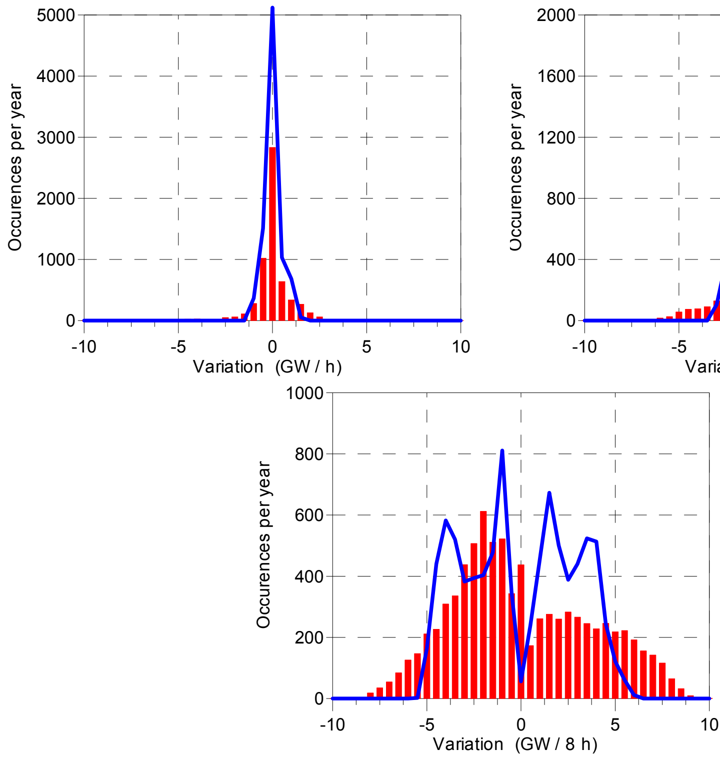

Figure 2.6. Variation of the system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – case A.

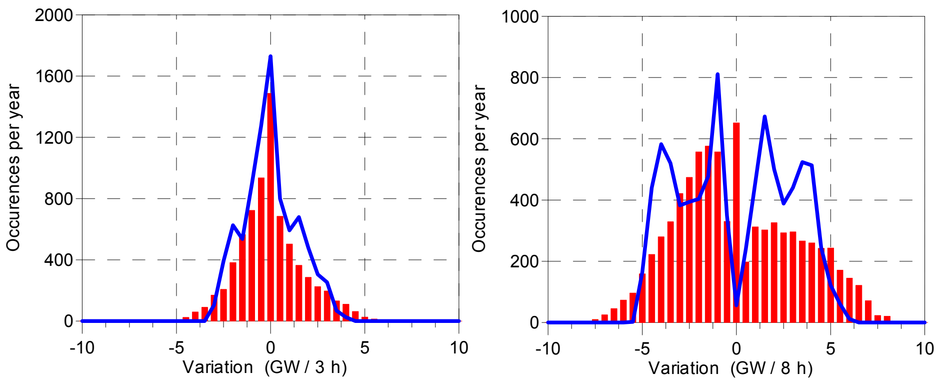

Figure 2.7. Variation of the system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – Case B.

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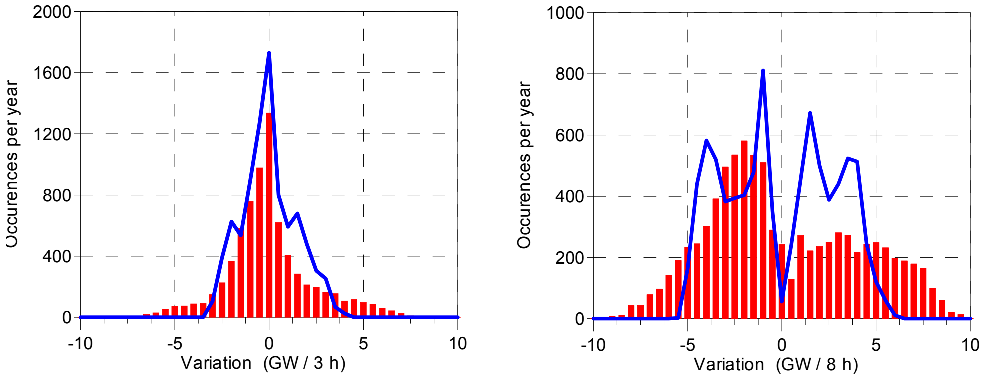

Figure 2.8. Variation of the system Load (lines) and Controllable Plants Load (bars) for the 80% scenario – Case C.

The above results reveal that the system of Case B is the most effective, 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. Consequently, the scheduled evolution of wind and solar technologies in the National Roadmap, which corresponds to the examined case A, does not constitute the optimal combination.

Table 2.1 summarizes some of the above results, and shows also the corresponding results for a higher technical minimum of the left over units of the system, equal to 2 GW, as discussed previously. It can be seen that the increase of feed-in limit from 0.4 to 2 GW has a major effect on the intermittent RES penetration. Rejections increase considerably in all cases by 47% to 73%, with the highest one being for the most efficient case B. This indicates that if the flexibility of the left over units in the system is low then the rejected wind and solar production may be significant and for any combination of installed power of these two technologies.

Table 2.1. Comparative results for the 3 cases of the 80% RES development scenario

Case	Max. negative power (GW)	Rejected production % Wind – PV - cumulative			Total rejected energy (GWh)
A	11.5	11.7	21.4	15.1	7900
B	10.2	12.6	14.7	13.1	6900
C	13.1	11.2	28.5	19.0	10000
Results for higher system technical minimum power (2 GW)					
A	13.1	20.2	32.9	24.7	12900
B	11.8	22.1	24.7	22.7	11900
C	14.7	18.3	39.8	28.1	14700

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3. Energy storage needs for future RE development scenarios

In the following section the system configuration scenarios listed in Table 1.3 are investigated with regard to the scheduled storage capacity and the maximum storage needs for total integration of rejected energy from renewables, as well as the effect of implementing and operating pumped storage plants on the electricity system of mainland Greece.

Two alternative computer algorithms were developed in parallel by NTUA and HSU to examine the optimal development and implementation of PHES system in an electricity grid, with a twofold aim: To recover the RES rejected production and to cut the peaks of the residual load to an optimum achievable with the available storage capacity during one year period. The latter is applied by a different strategy in each of the two algorithms, a brief description of which is given in Annex A.

As discussed in section 1.4, the scheduled storage power is 1 GW for 2020 and 4.5 GW for the 80% scenario, and the respective storage capacities are 12 GWh and 54 GWh (corresponding to 12 hours continuous pumping at nominal power). The corresponding total hydroturbines production power of these units is assumed equal to the pumping one.

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 annual operation of the electricity system. In this way, the real needs for new PHES installations can be estimated, along with their corresponding exploitation of RES rejected production caused by the grid limitations (grid stability, flexibility of power plant mix etc.).

The computer 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, being at the same time within economically viable range.

3.1 2020 Scenario according to NREAP

Incorporating a certain amount of non-flexible base load power plants, a fixed penetration limit of 3.7 GW is used for the investigation (like in section 2.1). This implies that the lower boundary of the residual load curve is set to 3.7 GW instead of zero, 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 and case A, before and after incorporating PHES units of total storage power 1 GW and capacity 12 GWh. The two patterns look quite similar, and the reduction of highest peaks with the PHES operation is small. This can be explained in the detailed views of Fig. 3.2, which show that the CPL curve peaks usually occur when the primary RES production is low, and therefore the stored energy in the PHES that can be used for peak shaving is also small or zero. On the other hand, during periods of very high RES production the CPL reduces to its technical minimum value (3.7 GW), whereas the PHES system is unable to store even part of that excess RES energy (Fig. 3.2, lower drawing), because the water reservoirs cannot be discharged.

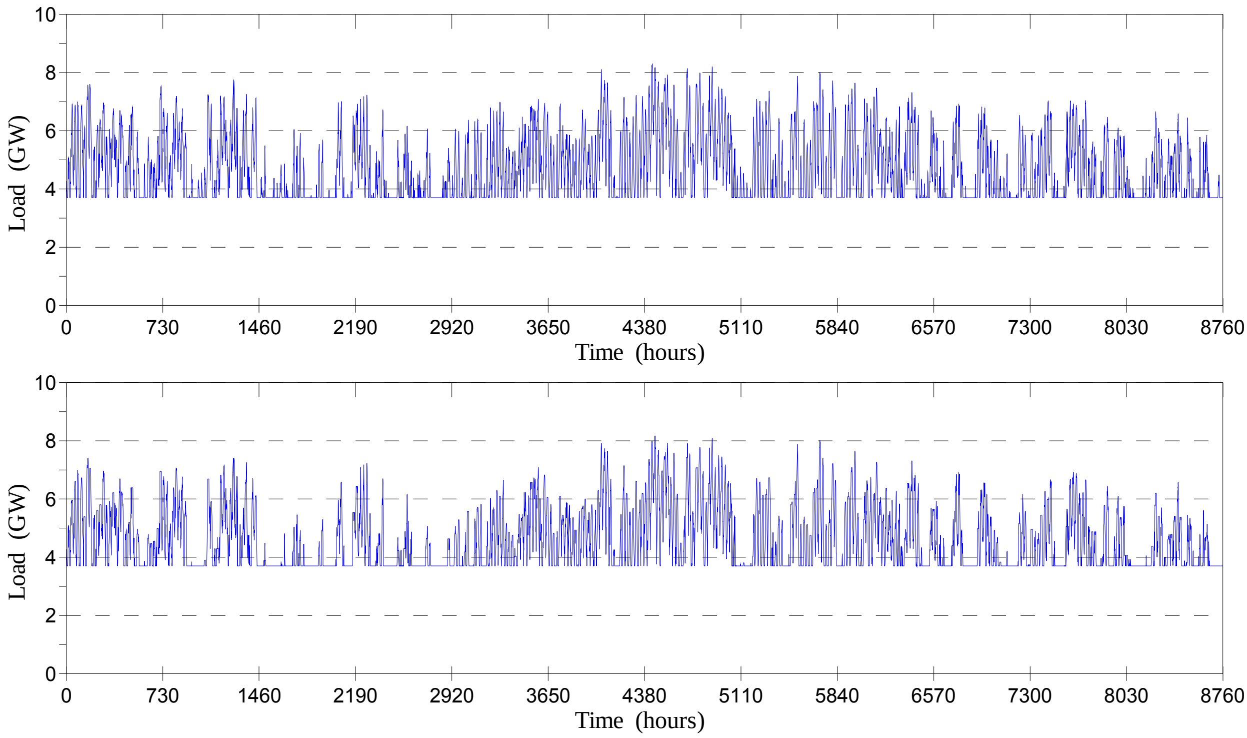

Figure 3.1. Controllable Plants Load without storage (upper), and with PHES only for RES rejections (lower), for 40% scenario – case A.

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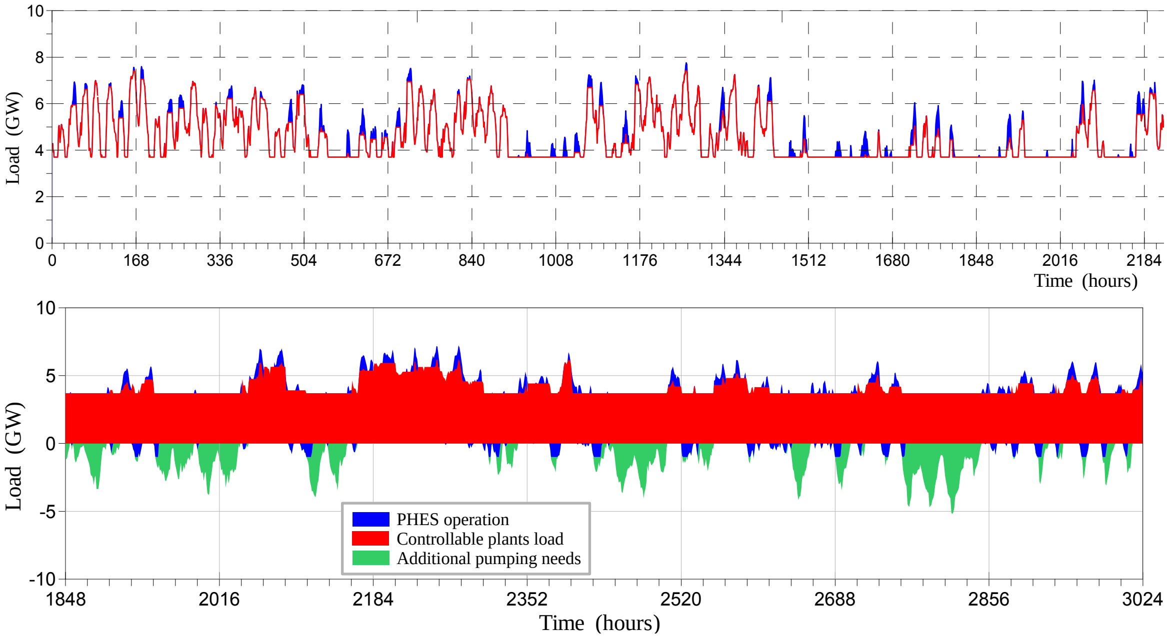

Figure 3.2. Detailed views of CPL variation and PHES performance for 40% scenario – case A.

However, the remaining capacity of PHES units after RES energy storage can be used also for peak shaving purposes, by storing energy of the other power plants of the system during the low demand (night-time) periods. Applying this strategy, the maximum peaks of the CPL curve can be considerably reduced, as shown in Fig. 3.3. In this way, the maximum annual power needed from the rest power plants of the system reduces from 8.5 GW to 7.3 GW.

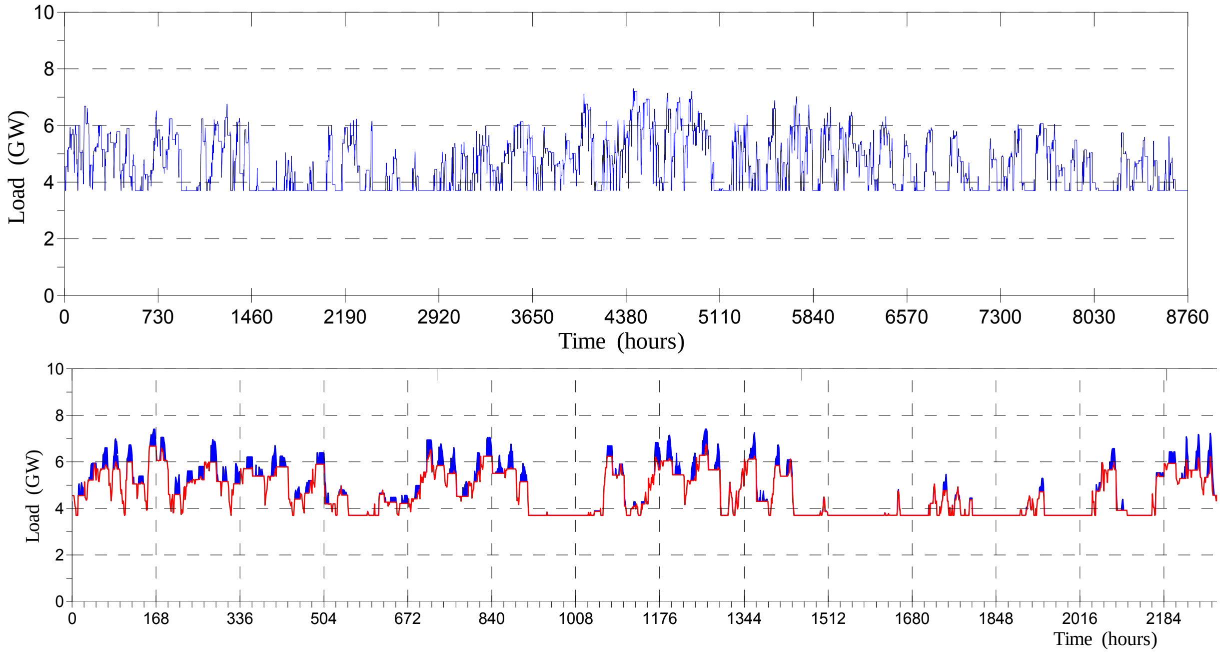

Figure 3.3. Controllable Plants Load after full PHES exploitation (upper) and detailed view of peak shaving effect (lower) – case A.

Analogous results are obtained for case B (equal development), and the final pattern of CPL curve shown in Fig. 3.4 is quite similar. The peak annual value is now slightly less reduced, to about 7.5 GW.

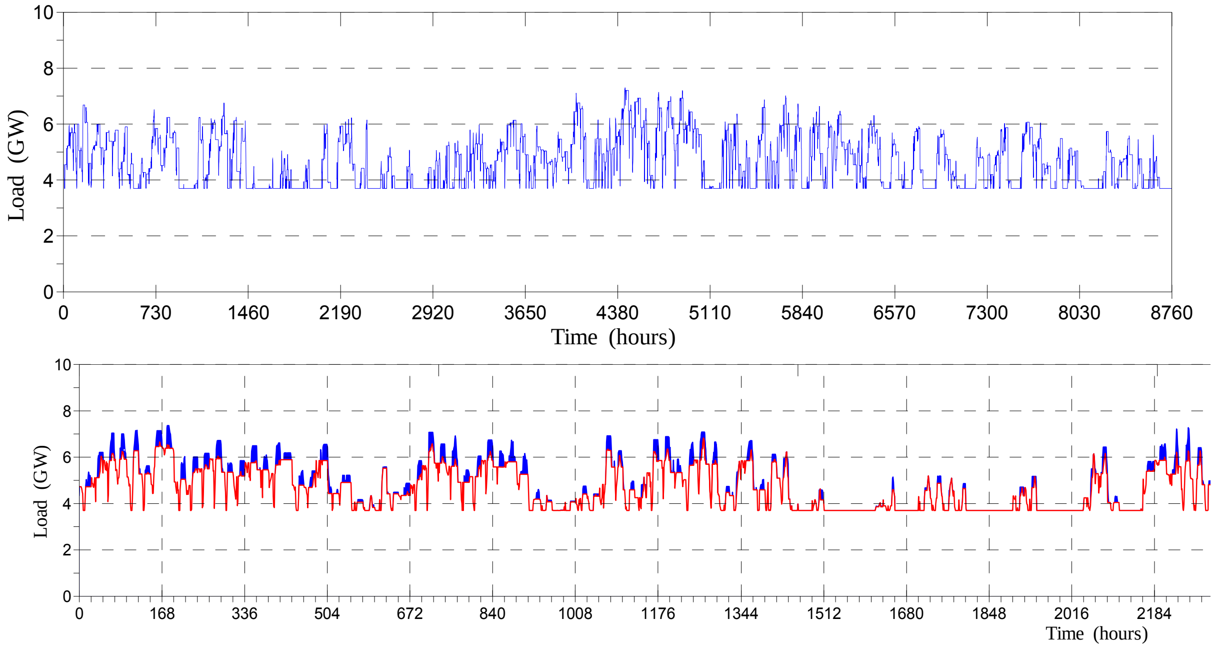

Figure 3.4. Controllable Plants Load after full PHES exploitation (upper) and detailed view of peak shaving effect (lower) – case B.

The duration curves of the rejected RES production are computed and plotted in Fig. 3.5, and are similar for both cases A and B. Rejections occur for 3000 hours of the year, and at power up to 1 GW for half of them. Only for a few hours the rejected power exceeds 4 GW. However, the assumed pumped storage system is able to exploit only part of this energy, and in both cases the remaining unrecovered energy is quite high, about 3000 GWh. The storage efficiency in case B is somewhat higher, about 33% compared to 25% in case A, but the initially rejected energy is also greater. The duration curve of the remaining energy is even shorter (up to about 2200 hours), and hence the storage of this energy in another system becomes less cost-effective.

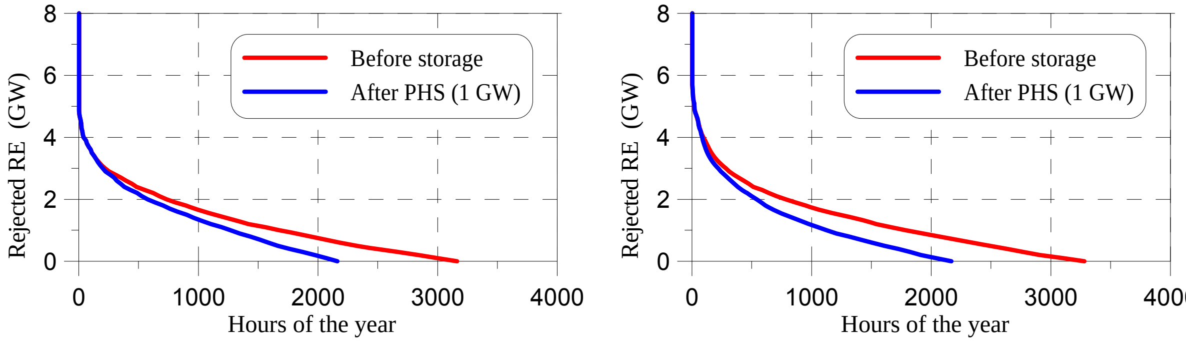

Figure 3.5. Duration curves of RES rejected production for 40% RES share (2020-MEAP), and cases A (left), and B (right).

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The accumulation of total and remaining after storage RES rejections during the year 2020 are plotted in Fig. 3.6. Their increase rate is for both cases A and B somewhat higher during the first 4 months, whereas the wind-solar blending of case A seems to be more effective (in respect of penetration ability) during the next 3-4 months.

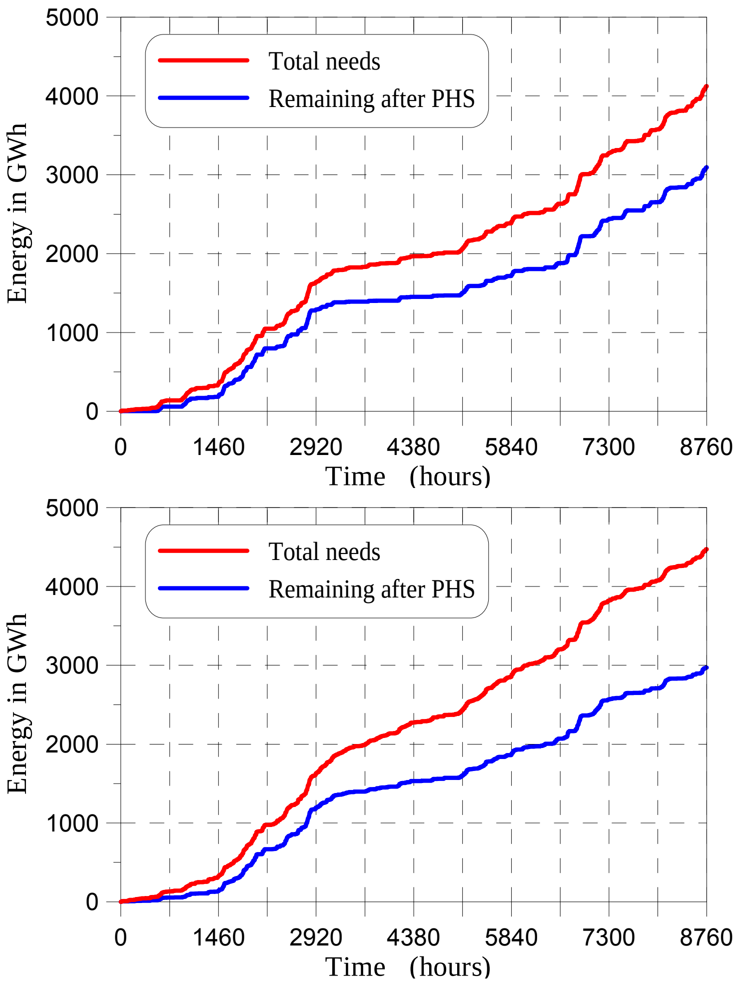

Figure 3.6. Accumulated RES energy rejections / storage needs during one year, for 40% share – cases A (upper), and B (lower).

The plots in Figure 3.7 depict the operation history of the PHES system (1 GW, 12 GWh) during the year 2020, when it is used only for storage of RES energy rejections. In both cases the load diagrams show considerable blank areas, indicating low capacity factor of the PHES machinery (pumps and hyrdoturbines). The exploitation of both power and storage capacity is better in case C, the diagrams of which are more dense. The results showed that the capacity factor of the pumping station is only 11.6% for case A and increases to 17% for case B.

Further exploitation of the PHES units for peak shaving by storing night-time production of the rest system plants results in remarkable increase of their capacity factor, by about 18%. Hence the overall CF of the pumping units reaches 30% for case A and 35% for case B. This can be observed in the dense diagrams of Fig. 3.8, while the above quantitative results are concentrated in Table 3.1.

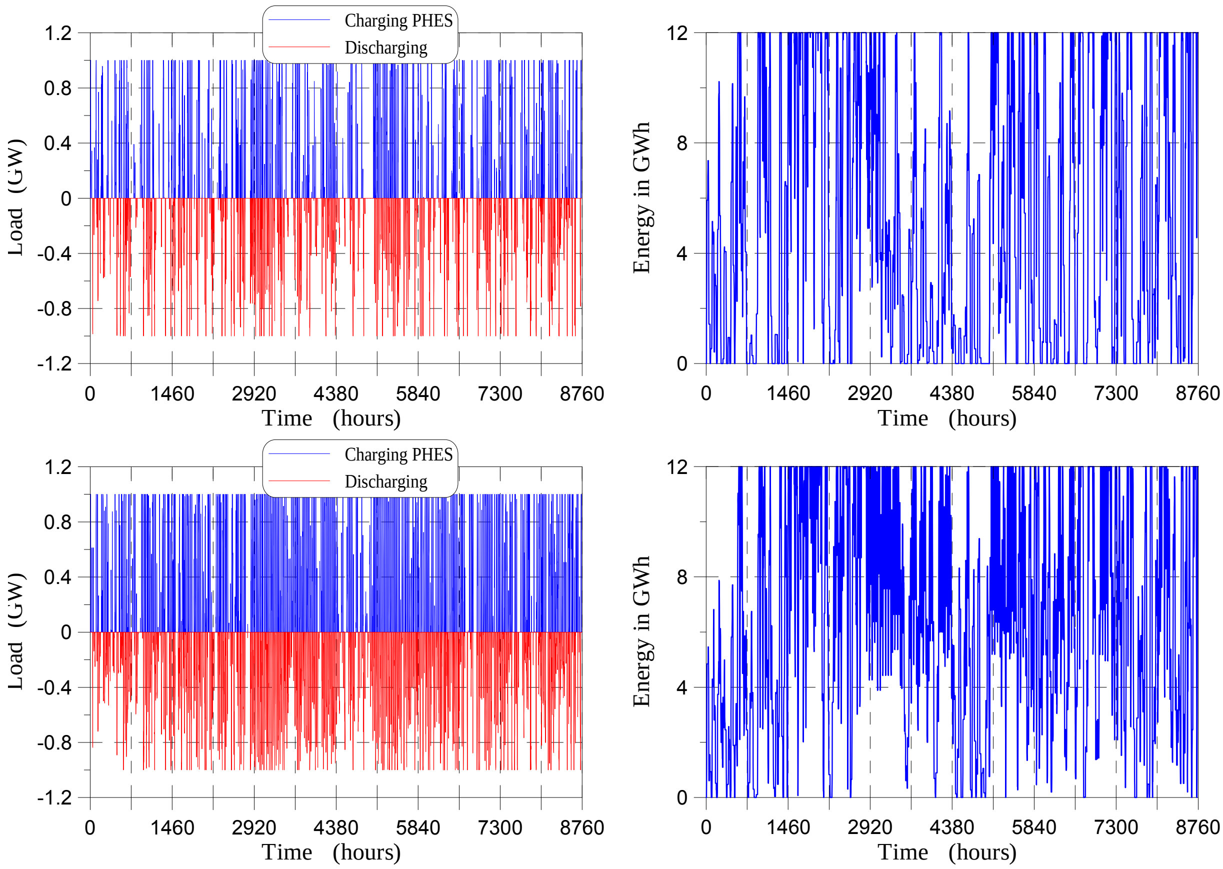

Figure 3.7. Power and charging level of the PHES system only for RES storage, for 40% share – cases A (upper), and B (lower).

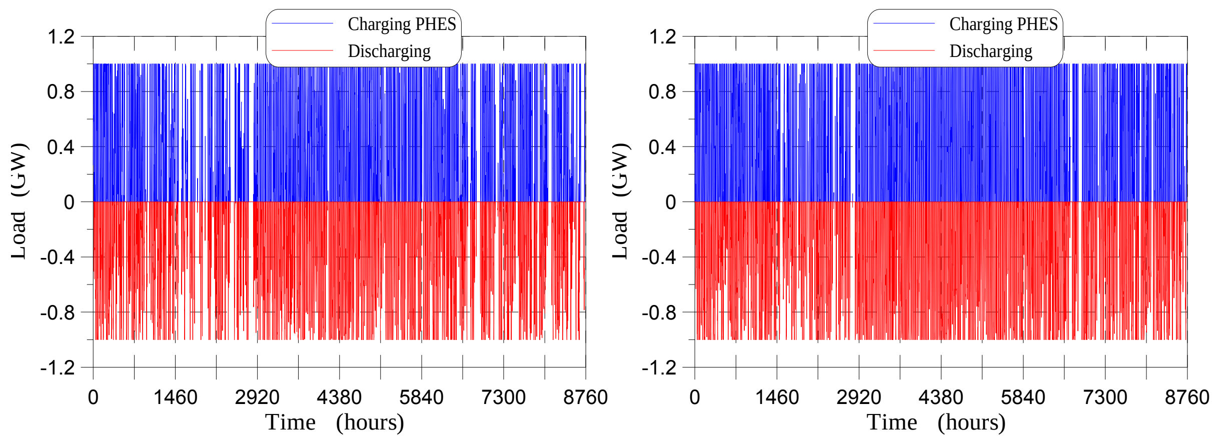

Figure 3.8. Final power level of the PHES system for 40% share – cases A (left), and B (right).

Table 3.1. Comparative results for the cases of 40% RES development scenario.

Case	Rejected RES production, %	Total for storage (GWh)	Remaining for storage (GWh)	RE energy storage efficiency	Pumping station Capacity Factor (%)	
					RE storage	System
A	19.8	4130	3100	25.0 %	11.6	18.6
B	21.5	4470	2980	33.3 %	17.0	18.1

Finally, after the implementation of PHES for storing of the rejected RES production, the variations of controllable plants load curve are remarkably reduced, and the system becomes more stable than the initial one, before the high RES penetration. This can be shown in Fig. 3.9, for the CPL curve variations within 3 and 8 hours, where case A appears to be again slightly better than case C.

It must be noticed that this improved picture of system stability is only partly due to the additional peak shaving capability with the PHES operation (see Figs. 3.2). A second reason is that the load curve reaches frequently at the system technical minimum, which is considered constant here, but it may vary in real conditions. However, if the PHES units were fully exploited for load smoothing (Figs. 3.3, 3.4), then the gain in stability would be considerably increased.

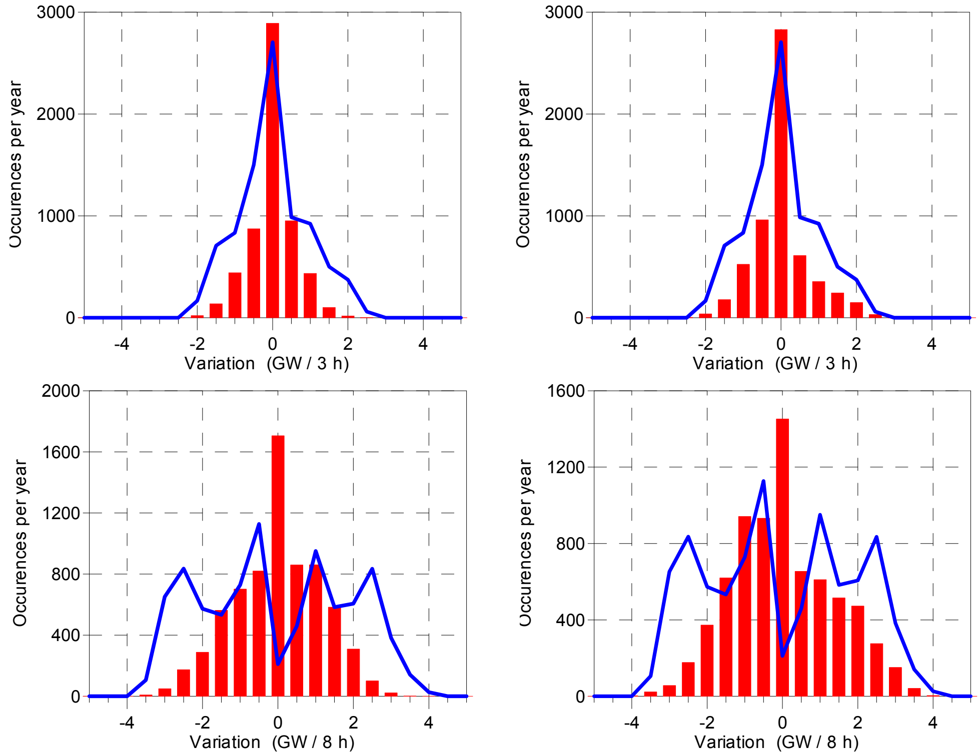

Figure 3.9. Total load variation (cont. lines) and Controllable Plants Load with the PHES (bars) for the 40% scenario: Case A (left), and case B (right).

3.2 80% RES share scenario

Three cases of different wind-solar development are examined for the 80% RES share scenario, the ‘equal development’ case A, the ‘wind favored’ case B and the ‘solar favored’ case C, as defined in Table 1.3. Case A corresponds to the estimated installed power for these technologies in the National Roadmap to 2050 [5], and the other two represent alternative possible developments, depending on the evolution of economic, social, and licensing conditions. For these 2 alternative scenarios only remarkable differences to case A are highlighted in the following results.

According to the National Roadmap, the 80% RES share in the system is estimated feasible up to the year 2040, and the corresponding installed pumped storage power will be about 4.5 GW. The storage capacity is estimated in the present study at 54 GWh, namely 12 hours of continuous pumping operation, and the penetration limit between 0.4 and 2 GW, as explained previously.

Fig. 3.10 presents the annual variation of the load of left over controllable plants (CPL curve) for case A, before and after incorporating the PHES units. Here, the contribution of these units to the reduction of CPL values and peaks shown in Fig. 3.11 is more pronounced than in 2020 (Fig. 3.2), due to the greater storage power and capacity.

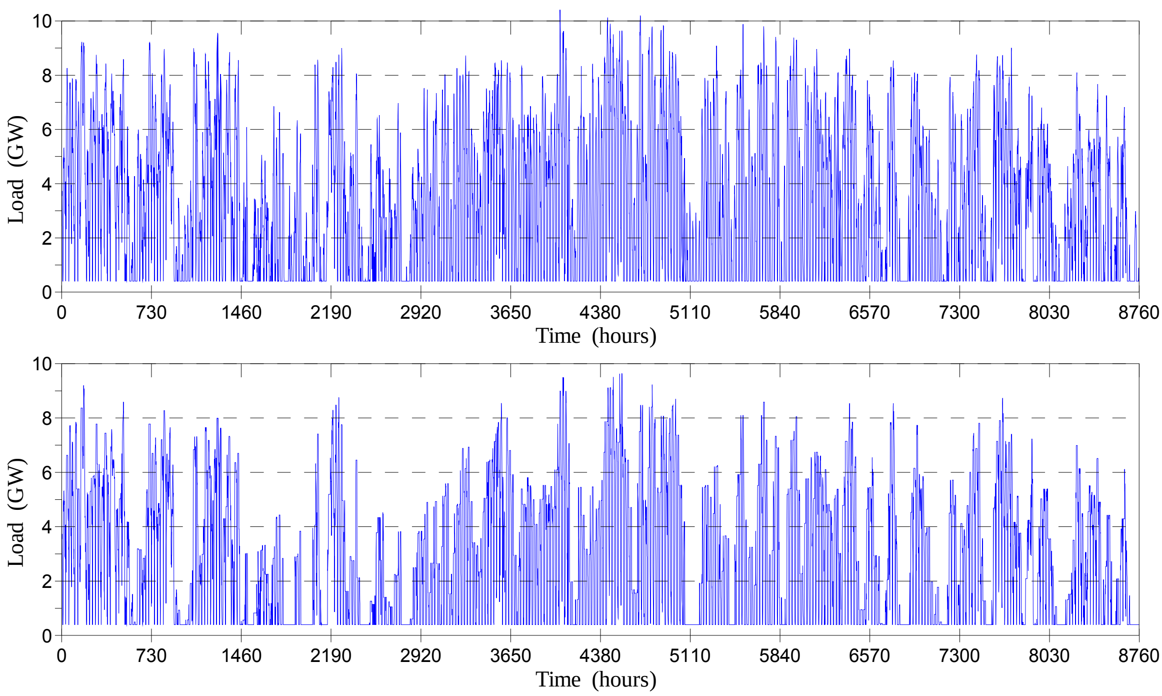

Figure 3.10. Controllable Plants Load without storage (upper) and with PHES for RES rejections (lower), for 80% scenario – case A.

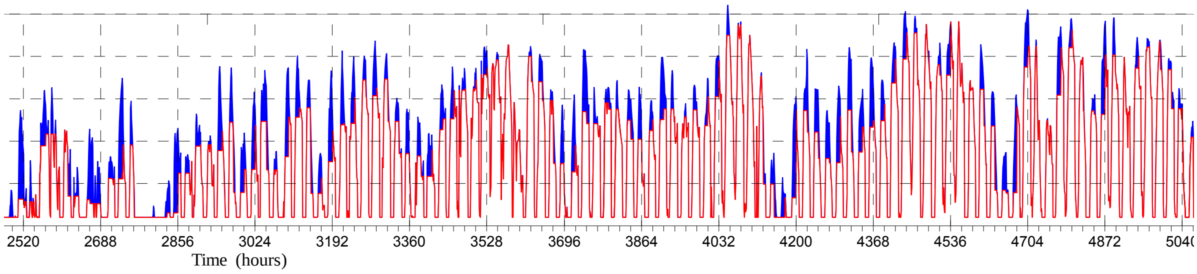

Figure 3.11. PHES and Controllable plants load variation for 80% scenario – case A.

However there are again some days of insufficient low RES production, when there is no enough stored energy to achieve this (Fig. 3.11). Hence, the maximum annual CPL value is only slightly reduced, from 10.4 GW to 9.6 GW.

If the storage units are fully exploited and are fed also with thermal plants production during the night, a greater reduction of the remaining load variation can be achieved. The smoothness on a day-basis, which is performed with the present algorithm, produces the results shown in Figs. 3.12 and 3.13. Fig. 3.12 shows that Case C exhibits stronger fluctuations in order to absorb the more significant solar production during a short period of the day (Fig. 3.9). The detailed views of Fig. 3.13 demonstrate the operation of the PHES system for cases A and C, as well as 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. The utilization of PHES units for RES storage (the additional storage of thermal plants is not shown) becomes more frequent as the installed solar power increases, towards case C.

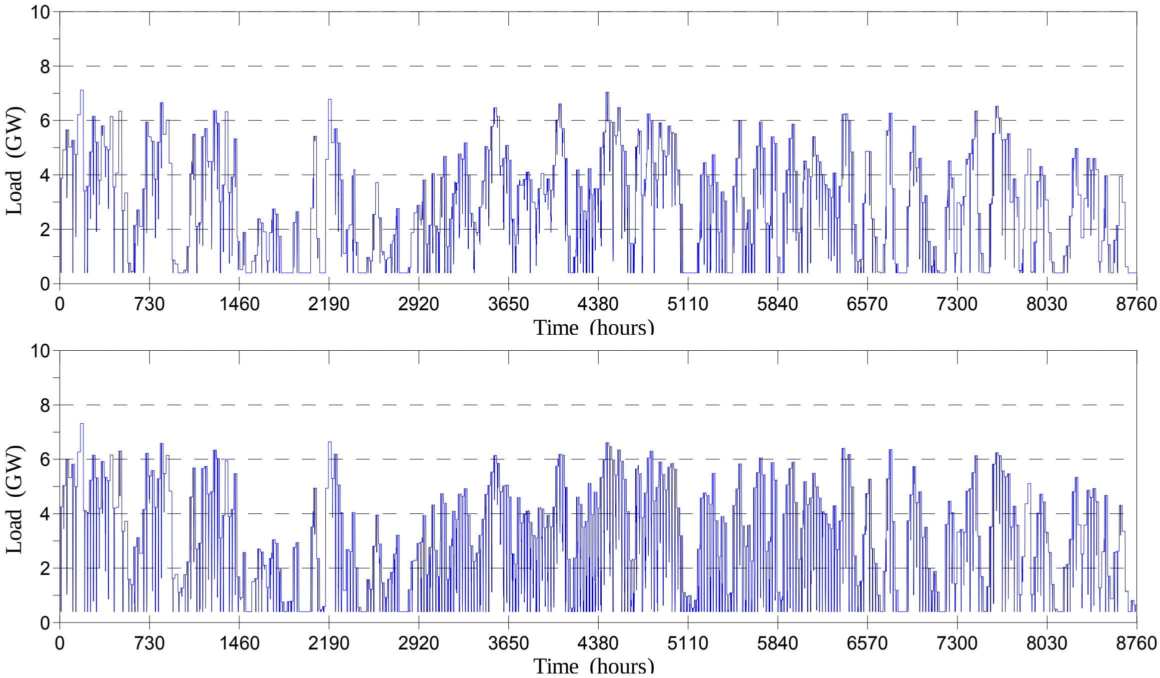

Figure 3.12. CPL curve after full PHES exploitation, for 80% RES share – case A (upper), case C (lower).

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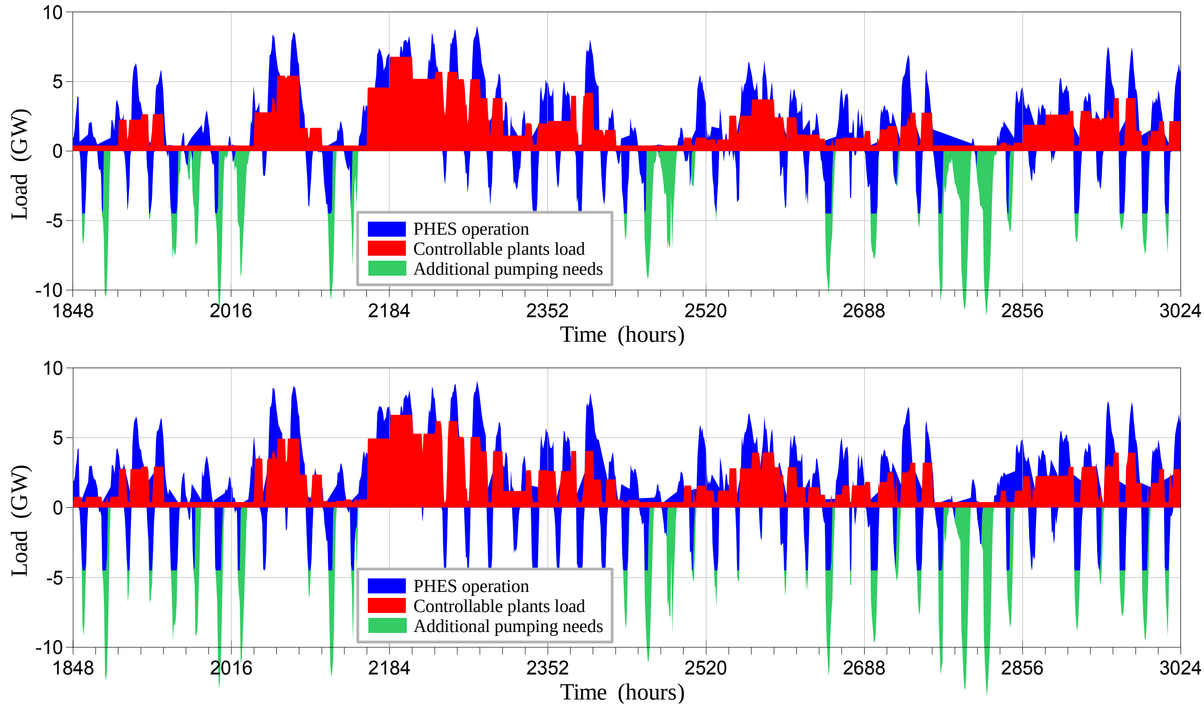

Figure 3.13. PHES and Controllable plants load variation for 80% scenario – case A (upper), case C (lower).

Applying this strategy, the maximum peaks of the CPL curve and in turn the maximum annual power of dispatchable thermal plants can be considerably reduced, as shown in Figs. 3.12 and 3.13, to around 7 GW for all cases. However, the variations of the remaining load are not similar in all cases. Case C shows much stronger fluctuations in order to absorb the more significant solar production during a short period of the day.

Due to the higher flexibility of the system in the 80% RES share scenario, energy rejections occurrence is less frequent than in 40% share scenario (about 2500 hours compared to about 3000 hours for 2020). The duration curves of the rejected RES production are plotted in Fig. 3.14 for cases B and C, whereas the results for case A are between them. A pumped storage power of 4.5 GW is capable to store the larger part of rejections (area below dotted line and red curve), and this fraction maximizes in case B and minimizes in case C (Fig. 3.14). As a result of the higher storage efficiency, the duration curve of remaining energy becomes here very short (about 1100 hours, almost half of that in 2020 scenario), consequently it would be difficult to be cost-efficiently stored by any other storage technology.

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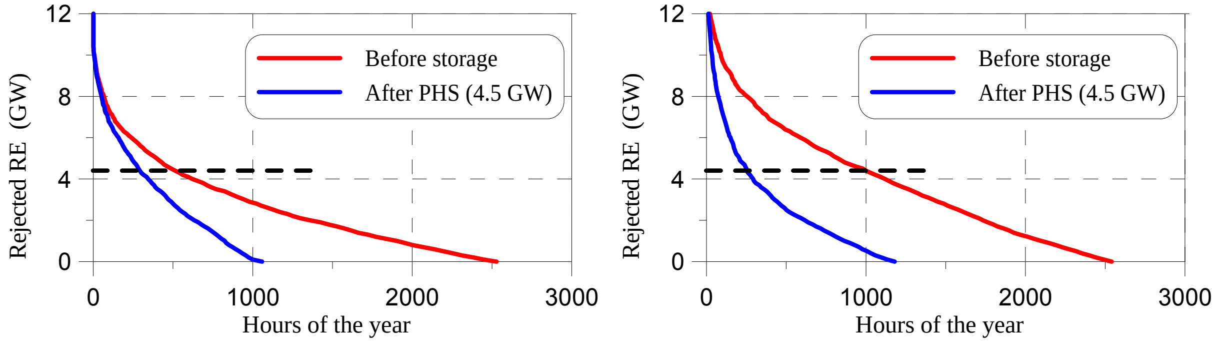

Figure 3.14. Duration curves of RES rejected production for 80% RES share and cases B (left), and C (right).

The RES rejections accumulation rate does not exhibit important variations during the year for all cases (Fig. 3.15). Fig. 3.15 depicts that the wind-solar blending of case B is the best in respect of RES production penetration, whereas the blending of case C is the worst, with almost 10 TWh of rejected energy. On the other hand, the latter case seems to achieve the highest efficiency of the installed pumped storage system (65.5% compared to 52% of case B), and can store the largest portion of rejections (Fig. 3.15).

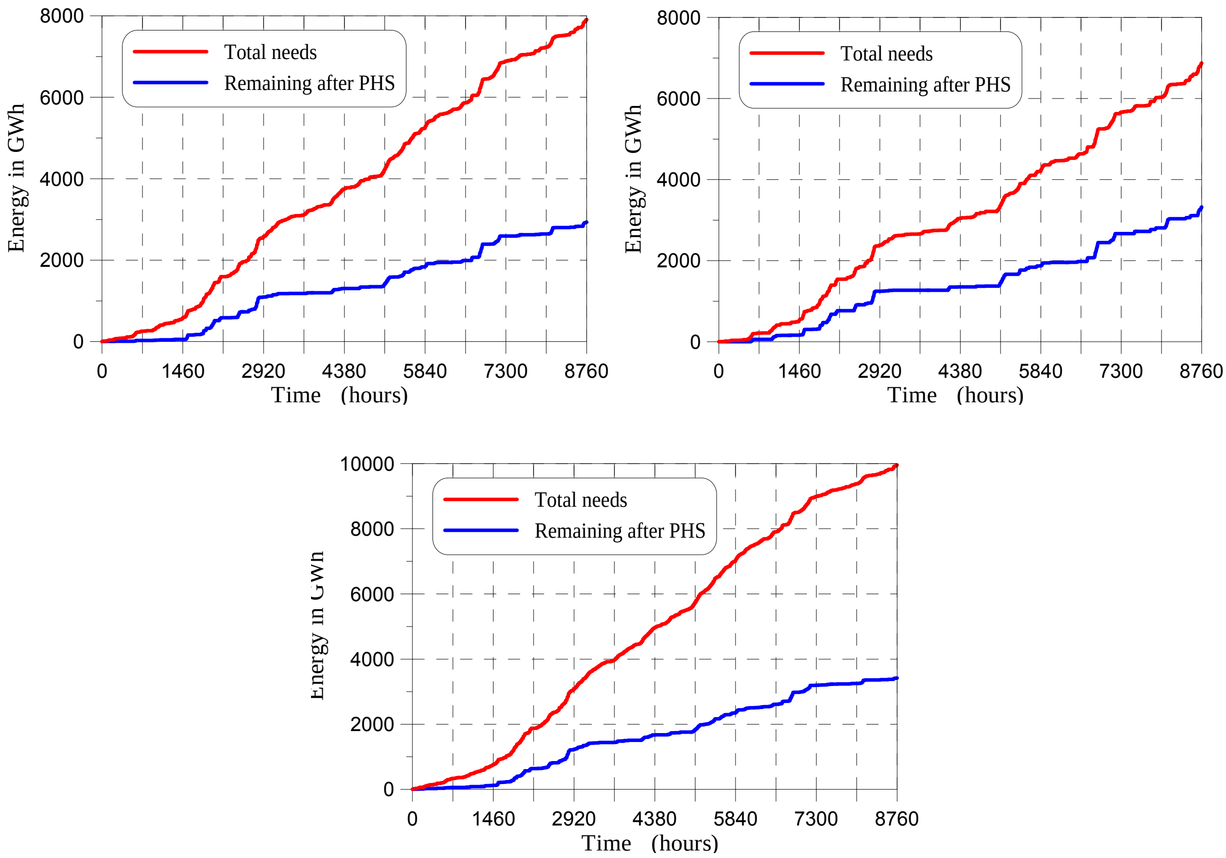

Figure 3.15. Accumulated RES energy rejections / storage needs during one year, for 80% share – cases A (upper-left), B (upper right), and C (lower).

The operation history of the PHES system (4.5 GW, 54 GWh) when it is used only for RES rejections storage for the 80% scenario is plotted in Fig. 3.16, for the reference case A. The pumping operation and the storage capacity utilization are similar with the ones of 2020 scenario. However, the nominal production power of hydroturbines (4.5 GW) is not frequently needed (Fig. 3.16), indicating that a considerably lower power can be installed without significant effect on productivity. This result complies with the use of reversible pump-turbine machines, in which the nominal power in turbine mode is about 70% to 75% of that in pumping mode.

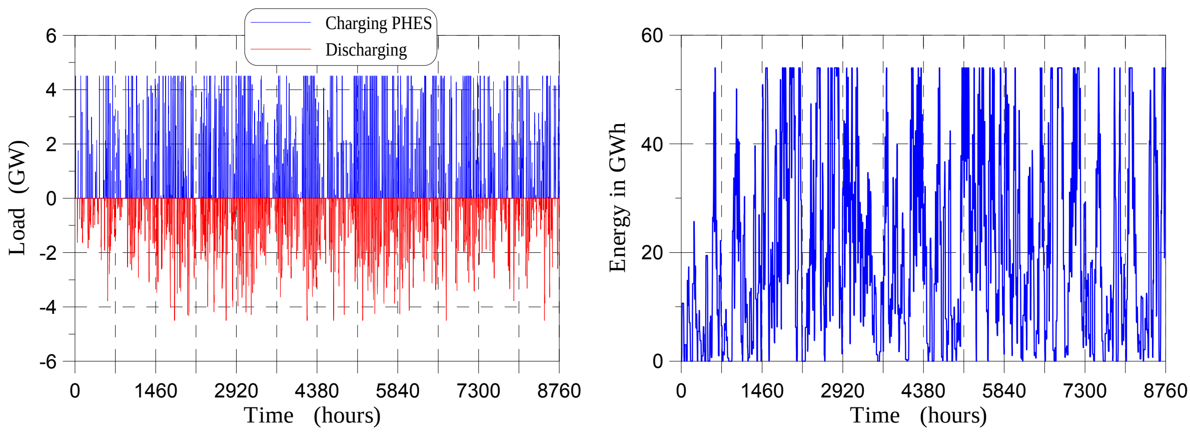

Figure 3.16. Power and charging level of PHES system only for RES storage – case A.

Full exploitation of the PHES units can increase further their capacity factor and economic results, by about 12-14%. Hence, the overall CF of the pumping units can be from almost 23% for case B to 28% for case C. Such utilization degrees are quite lower than the corresponding ones for the 1 GW storage units (30-35%) in the 2020 scenario, but they may still considered economically viable. Moreover, the reduced power needs in the production mode of the PHES units can be observed in this operation strategy too, as shows Fig. 3.17.

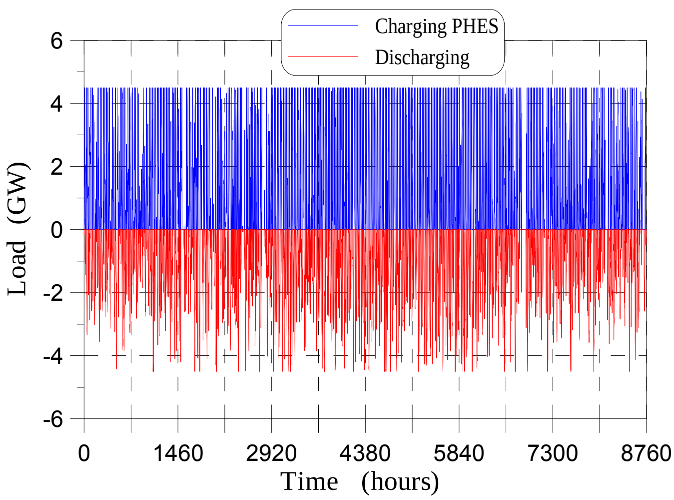

Figure 3.17. Power level after full exploitation of the PHES system – cases A

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Most of the above results are also given in a quantitatively manner in Table 3.2. This Table contains also the corresponding results that were obtained for a higher feed-in limit of the system (2 GW instead of 0.4 GW) as discussed in section 2.2 above. As expected, the higher RES rejections in both power and energy result in reduced storage efficiency of this production, which drops below 50% for all cases. On the other hand, the capacity factor of the pumped-storage units increases in all cases by about 2 percentage units (Table 3.2). However, their ability of further utilization for RL smoothing is remarkably reduced, mainly due to restricted remaining storage capacity in the reservoirs, and as a result, the total capacity factor of the pumping stations becomes smaller by 3 percentage units.

The reduced recovery efficiency of the increased amount of rejected RES production is also shown in Fig. 3.18 for case A. However, the duration curve of the remaining energy to be stored (blue curve, Fig. 3.18) is now extended to a greater time period, and this increases the possibility of its exploitation by another technology.

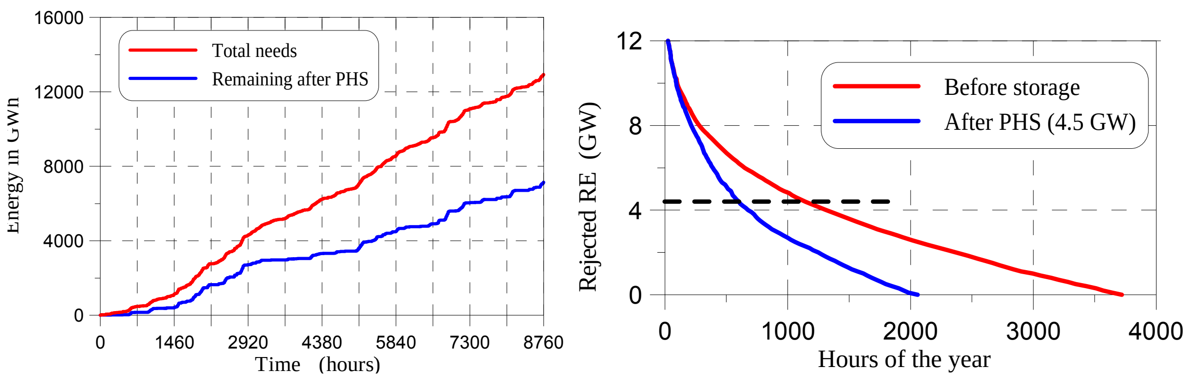

Figure 3.18. Results for higher RES penetration limit – case A. Accumulated RES rejections during one year (left), and duration curves of rejected production (right).

Table 3.2. Comparative results for the 3 cases of the 80% RES development scenario.

Case	Rejected RES production %	Total for storage (GWh)	Remaining for storage (GWh)	RE energy storage efficiency	Pumping station Capacity Factor (%)	
					RE storage	System
A	15.1	7900	2900	63.2 %	12.5	13.7
B	13.1	6900	3300	52.0 %	8.9	13.9
C	19.0	10000	3450	65.5 %	16.5	11.5
Results for higher system technical minimum (2 GW)						
A	24.7	12900	7150	44.5 %	14.6	8.2
B	22.7	11900	7650	35.7 %	10.7	9.1
C	28.1	14700	7400	49.6 %	18.3	6.7

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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, unlike in the 40% (2020) scenario, as can be observed comparing the results in Fig. 3.19 with the ones in Fig. 2.6.
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 of the system, then the gain in grid stability can be significant, as can be observed in Fig. 3.20 for case A. Similar results are also obtained for the other two cases B, and C of the 80% RES development scenario.

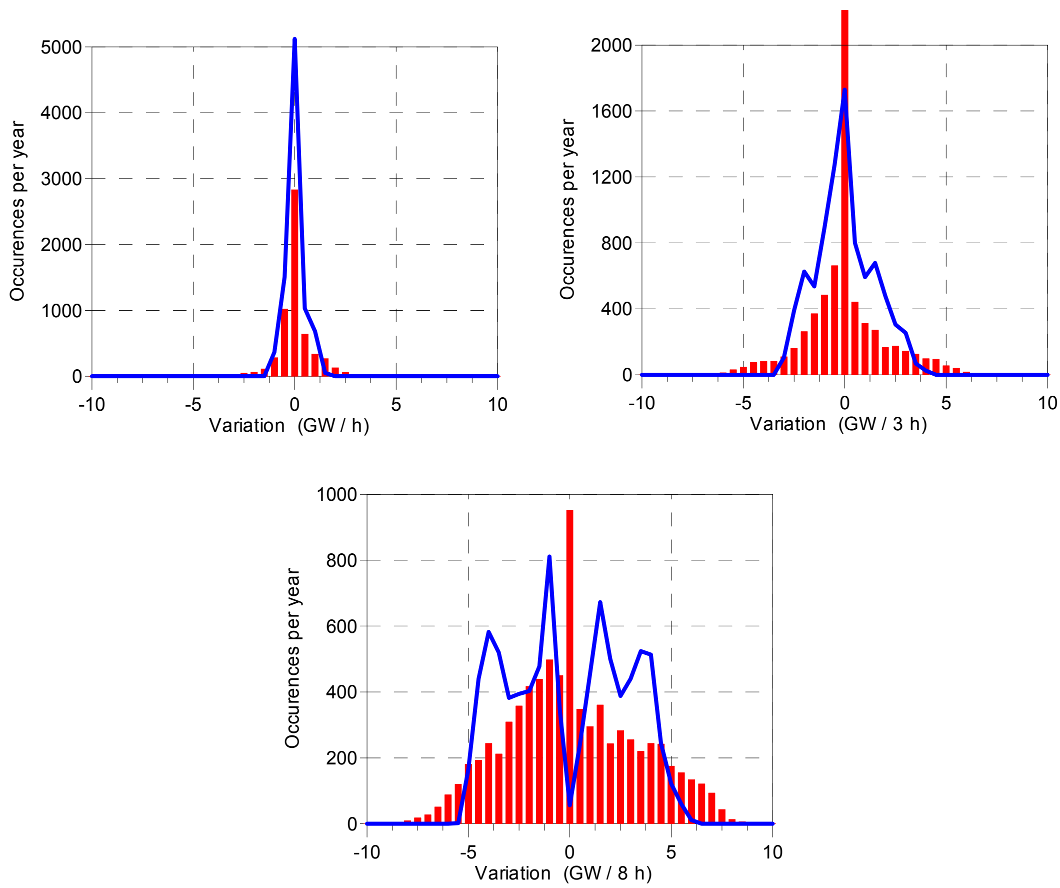

Figure 3.19. Total load variation (cont. lines) and Controllable Plants Load variation with the PHES (bars) for rejected RES production and 80% scenario – case A.

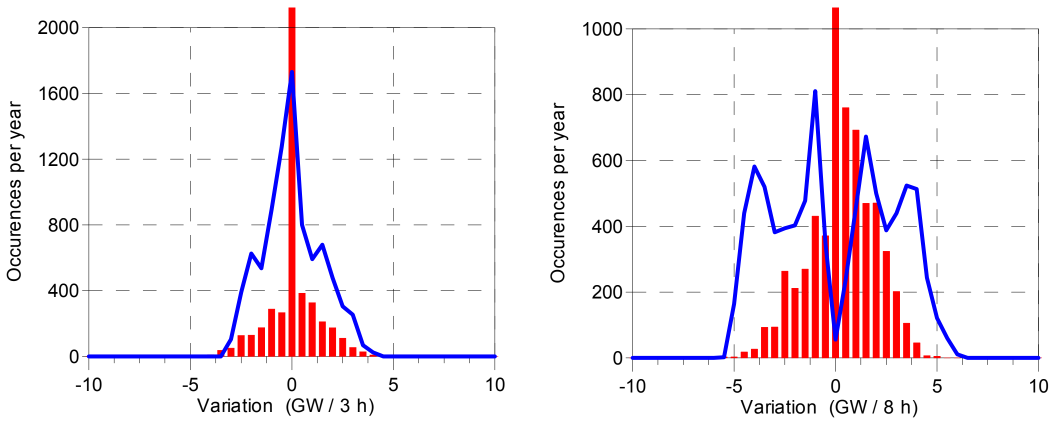

Figure 3.20. Total load variation (cont. lines) and residual load after full exploitation of the PHES system (bars), for 80% scenario – case A.

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 Greece will approach its final aimed development, which is 100% production from RES.

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 storage system.

3.3.1 Storage system with unlimited power and capacity

For these computations it was assumed that the reference PHES system for the 80% scenario (54 GWh and 4.5 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 3.25 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 the unlimited capacity reservoir. Comparing the results for the three case A, B and C of Table 1.3, it can be observed that the maximum hydroturbine production power is about the same, whereas the maximum pumping power needs are lower in case B and higher in case C. Moreover, from the load variation diagrams it is clear that the pumped-storage system utilization is substantially less in case B, whereas the corresponding diagram for case C is the densest one.

The opposite trend is observed concerning the stored energy in the reservoirs: The maximum energy accumulations occur in case B, and the minimum in case C (Fig. 3.25). In all cases the stored energy variation curves exhibit a few high peaks at certain time period of high RES production, and frequent smaller fluctuations during the rest of the year, most of which are below the 100 GWh line. Consequently, a storage system with charging/discharging power of the order of 10 GW and capacity of the order of 100 GWh would be quite effective and efficient in all examined cases.

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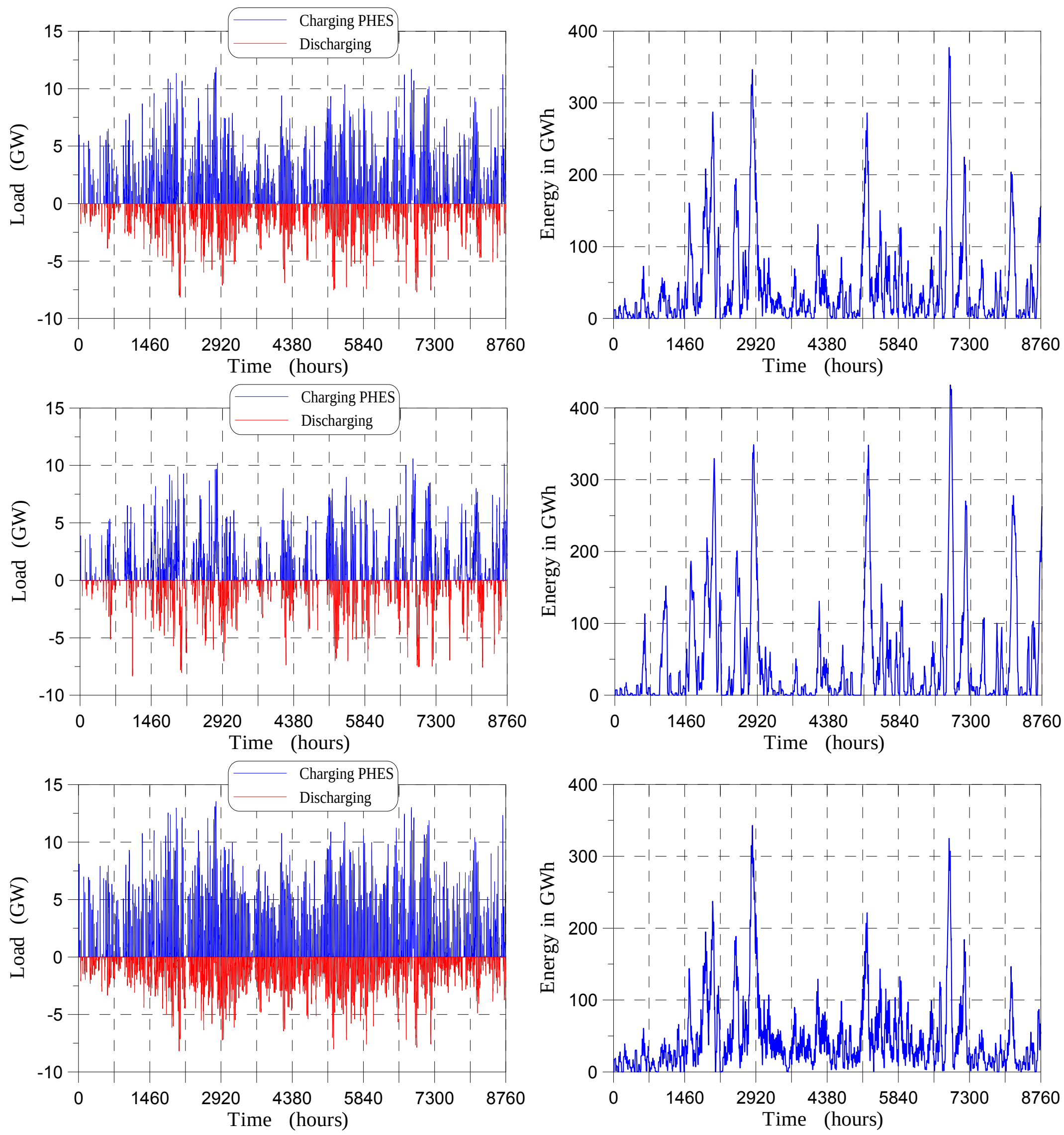

Figure 3.25. Power and charging level for storage system with unlimited power and capacity, for 80% share – cases A, B and C (top to bottom).

Similar computations were also carried out for the case of higher technical minimum of the system, 2 GW instead of 0.4 GW. The results are plotted in Fig. 3.26 for case A, while the other cases are similar. The pumping power is substantially increased, but the production power remains the same, due to the system feed-in limitations. On the other hand, however, the stored energy accumulation exhibits a much different pattern. Now, the higher feed-in limit of the system causes extended energy rejections during the high RES production in the spring, which are stored but cannot be gradually consumed as previously. As a result, the stored energy diagram shows one large and some smaller areas of increased storage capacity needs (Fig. 3.26). In this case, even a 400 GWh storage capacity system cannot be very efficient for recovering the rejected RES production during the whole year.

The above results for all three cases A, B, and C are given also in quantitative manner in Table 3.4. Case A, which is reported in the National Roadmap [5], seems to be a good compromise of moderate storage power and capacity needs of the system for 80% RES share. Also, the results reveal the decisive influence of RES feed-in limitations of the system on the storage capacity needs and exploitation of rejections.

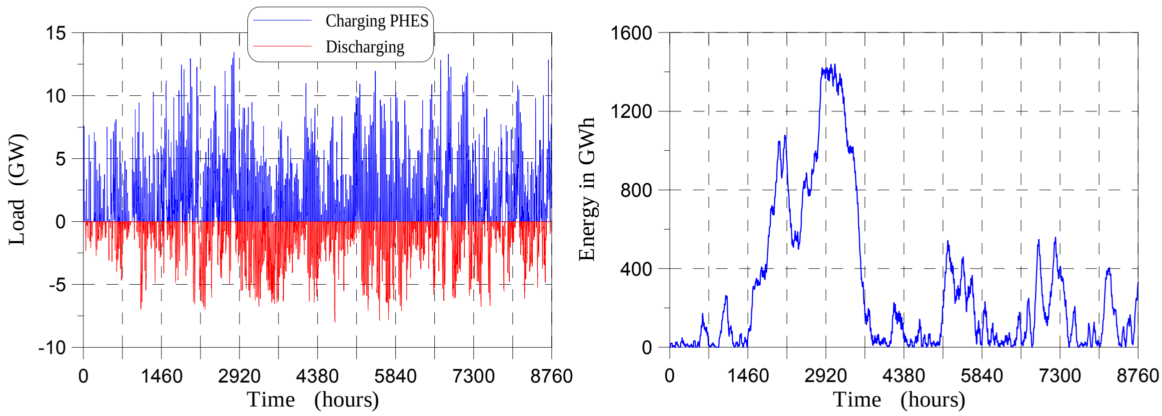

Figure 3.26. Power and charging level for unlimited storage power and capacity and higher system technical minimum – case A.

Table 3.4. Maximum power and capacity needs of unlimited storage system, for 80% RES share scenario.

Case	Needed power (GW)		Needed capacity (GWh)
	Charging	Discharging	
A	11.9	8.2	375
B	10.6	8.3	430
C	13.5	8.2	340
Results for higher system technical minimum (2 GW)			
A	13.5	8.0	1440
B	12.2	8.0	1550
C	15.1	8.1	1320

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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 future energy storage 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, as discussed in the next section 3.4.3.

The exploitation degree of RES rejections is defined as the ratio of the produced energy in the hydroturbine units of the pumped-storage 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.

A first observation is that in all cases the RES exploitation diagrams can be divided in two parts: 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 with the storage capacity. According to the National Roadmap estimations, the pumped storage installations will reach up to about 5 GW (4.5 GW for the 80% RES scenario, and ~5 GW for 100% RES share [5]). Hence, the system performance will be described by the left part of the diagrams, and the maximum attainable degree of RES rejections exploitation will not exceed 75% even for large storage capacities.

Concerning for a example a considered feasible combination of 5 GW power and 100 GWh storage capacity system, the results give exploitation degree about 75% for cases A and C (Fig. 3.27, top and bottom), whereas case B has slightly above 65%, and in order to reach the same level of 75% it needs about 50% higher capacity (about 150 GWh, Fig. 3.27, middle).

Consequently, there will be always a remaining portion, about 25%, of the RES rejected energy that could not be exploited by the pumped storage system. Curtailment of this production may be unavoidable, since its duration curve will be very restricted (as shown previously), unless it could be channelled to small and distributed consumptions, like the electric cars.

As far as the capacity factor of the pumping units is concerned, the three hill charts for cases A, B and C (right plots of Fig. 3.27), are quite similar. As expected, the CF decreases with the installed pumping power, and cannot exceed a maximum value, here about 45%. For the aforementioned example of pumped storage configuration (5 GW – 100 GWh), the smallest CF is for case B (between 20-25%), while the highest is for case C, approaching 30%.

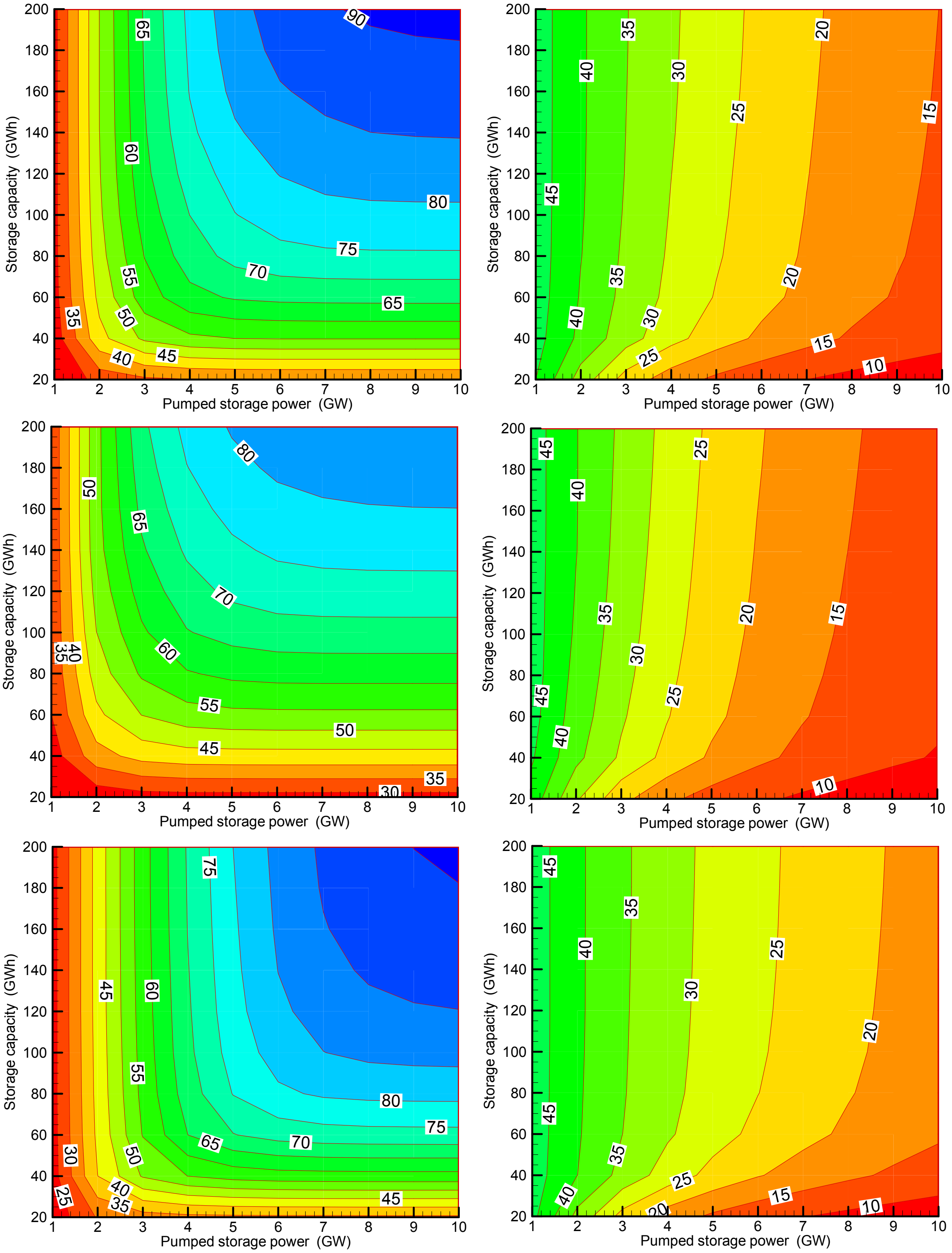

Figure 3.27. Effect of installed pumped storage power and capacity on the RES rejections exploitation degree (left), and on the capacity factor of pumping units (right). 80% RES share scenario – cases A, B, C (top to bottom).

These CF values are in all cases within the range of 25-35% of economically viable investments, as discussed in the next section 3.4.3. Eventually, the results concentrated in the above diagrams show a small advantage of RES development according to case C, which attains the highest RES exploitation degree and pumping units CF within the planned range of pumped storage development, as also for the 4.5 GW – 54 GWh configuration, which is simulated in the present report for the 80% RES share scenario (section 3.2).

Finally, the calculations are repeated for the case of increased technical minimum of the system (2 GW). The hill chart of the pumping CF is quite similar, but the exploitation degree is significantly reduced, by about 15-20 percentage units throughout the entire diagram (Fig. 3.28). Case C is again the most advantageous in terms of exploitation of rejected RES production.

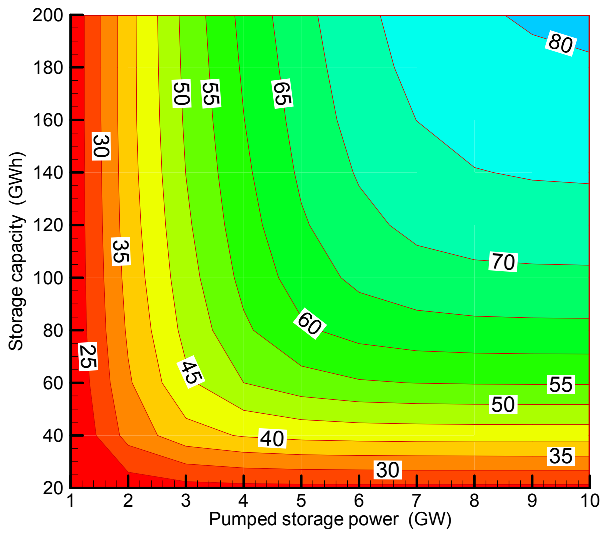

Figure 3.28. Effect of installed pumped storage power and capacity on the RES rejections exploitation degree for higher RES feed-in limit – case C.

The above hill charts facilitate the performance estimation of a selected PHES system for the 80% RES share scenario. For example, a system of 5 GW pumping power and 100 GWh storage capacity would attain about 75% exploitation degree in cases A and C, and 65% in case B (Fig. 3.27-left), but slightly above 60% in the best case C for higher technical minimum of the system (Fig. 3.28). The CF of pumping units will be around 26, 23 and 27.5% for cases A, B, and C, respectively (Fig. 3.27-right), and around 27% for case C and higher technical limit.

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3.3.3 Optimum sizing of PHES

Specific computer software is developed to estimate the energy storage capacity requirements in order to exploit as much as possible amount of the rejected WF and PV production. In order to obtain such estimations, at first the duration curves of the cumulative rejected power are computed based on the results of the first part, for several future years using the Energy Roadmap-2050 data.

The duration curves obtained for the two scenarios examined here (EP and MEAP) are plotted in the following Fig. 3.29. In both cases rejections are kept small for the next 3 years up to 2015, and then increase considerably for the next 30 years, because in both scenario the RES share in electricity production is enhanced. It is evident that power and energy rejections are quite higher for the MEAP scenario, due to the higher W/F and PV relative installed power. For the last year, 2060, where there are no available data, it was assumed that all energy values (production and load) will be increased at the same rate, 5% during the last decade. So, after 2050 energy rejections exhibit an asymptotic trend and the duration curve is only slightly moved to higher absolute values.

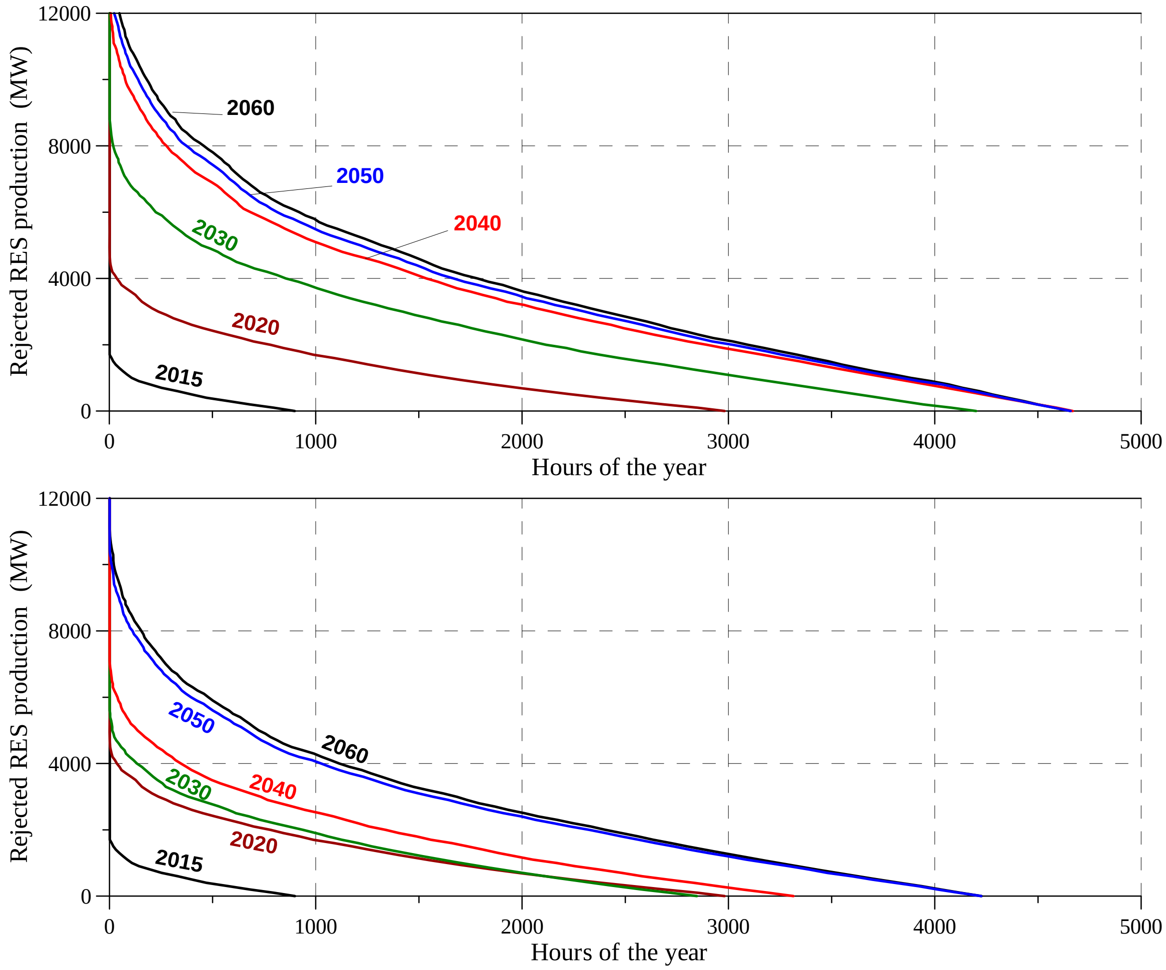

Figure 3.29. Duration curves of intermittent RES production rejections, by the energy development scenario MEAP (upper) and EP (lower), up to 2060.

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From the duration curves of rejected energy, the cumulative energy that can be stored and recovered by a pumped storage unit can be calculated for any desired period, starting from its commissioning year. In the example of Fig. 3.30, a 2 GW pumped storage exploits during year 2020 the yellow filled area below the corresponding curve, but in year 2030 the utilization of the unit becomes much higher (yellow plus orange area). On the other hand, the pattern of the duration curves indicates that an important portion of the surplus RES production cannot be stored in a cost-effective manner and will be finally rejected (e.g. hatched area in Fig. 3.30). Therefore, the emerging issue is the definition the optimum schedule of storage capacity development during the next decades.

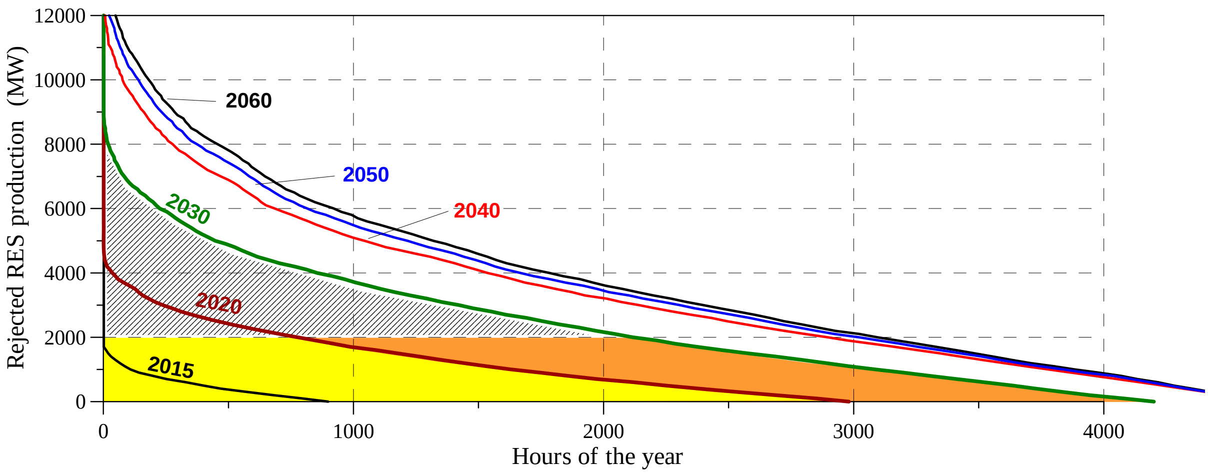

Figure 3.30. Example of rejected energy recovery by a 2 GW pumped storage unit.

The optimum size of a pumped storage plant, in terms of economic results and viability, is strongly dependent on the electricity pricing policy for the stored energy and for the subsequent controlled production in the hydroturbines of the plant. However, at present there are not any such data in Greece and neither any relative studies or estimations.

In the present study it is considered that reasonable size estimation can be obtained using pure energy data of the pumped storage units, and more specifically, based on the capacity factor (CF) of the hydraulic machinery (pumps and/or turbines). Using current operation data of existing hydroelectric plants and some results of recent studies [6, 7], it can be deduced that a reasonable value for the minimum capacity factor for a pumped storage unit in order for the investment to become economically viable is in the range of 25 to 35%. Consequently, an effective way to obtain a realistic estimation of the optimum storage capacity is the selection of the unit size so as the average capacity factor during a given amortization period is kept within the above range.

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Hence, the operation of the algorithm is as follows: Starting from the year 2015 (which can be considered as the soonest possible commissioning year for the first new PHES unit), the algorithm computes for each subsequent year the annual and average capacity factor of a new PHES unit with progressively increasing capacity (pumping power). The maximum PHES size that can provide the prescribed average capacity factor for the desired amortization period will be selected, as the optimum plant to be commissioned at that particular year. After commissioning, every PHES unit continues to operate at its nominal capacity far beyond the amortization period (lifetime of the PHES plants may exceeds 40 or 50 years), and this reduces the needs for additional storage in the next coming years. Therefore, the storage needs exhibit an asymptotic trend towards 2040, which is the last commissioning year considered in this study.

The duration curves for the years between the ones plotted in Fig. 3.30 are obtained by interpolation from the given data. Also, it is assumed that all new pumped storage units will be able to operate at their nominal power, without any limitations, like the reservoirs capacity or the capability to deliver the entire hydroturbines production to the grid. The implementation of a daily circulating operation strategy for these units is found to be very efficient: The required reservoirs size is relatively small, whereas the hydropower production can be easily absorbed in the grid during the high demand day-time period.

The results of the algorithm for the MEAP and EP energy development scenario of the Roadmap are plotted in Fig. 3.31, for three different capacity factors of the pumping station of the PHES unit. In the MEAP scenario (Fig. 3.31a) It can be observed that by adopting the smallest CF of 25% a 500 MW PHES unit would be viable even from the first commissioning year 2015, whereas for the highest CF of 35% the first viable storage unit appears 4 years later. The accumulated storage needs by the year 2040 can be served by about 5 GW PHES plats for average CF 30%. This becomes greater than 6.5 GW for CF=25% and less than 4 GW for CF=35%.

The corresponding storage requirements for the conservative EP scenario are much lower, as shown in Fig. 3.31b. For the highest CF requirement of 35% the first viable PHES plant can be integrated only after 20 years from now, whereas for the intermediate value CF=30% a relatively small PHES unit of about 500 MW can serve the system storage needs up to 2030.

The above results are obtained for a 10-years amortization period of the PHES investments. For longer amortization periods the average CF of the plant becomes higher, because rejections continuously increase over the years. Figure 3.32 shows the influence of this parameter for the MEAP scenario and fixed CF value of 30%. The increase of amortization period to 20 years makes viable from the first commissioning year a larger PHES plant of 1000 MW, and this trend continues for the next years. However, after the completion of RES development and integration into the system, the optimum PHES total size becomes independent of the amortization period (Fig. 3.32).

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Finally, an important outcome of the above analysis is that the results obtained for the optimum sizing of the PHES plants in the next decades are in agreement with the corresponding estimations of the National Energy Roadmap: In the MEAP scenario, it is estimated to about 4.5 GW for 2040 and 3 GW for 2030, which are between the CF-30 and CF-35% curves of Fig. A8a. In the EP scenario, the corresponding estimations are about 1.5 GW for both periods, which are around the CF-30% curve of Fig. 3.31b.

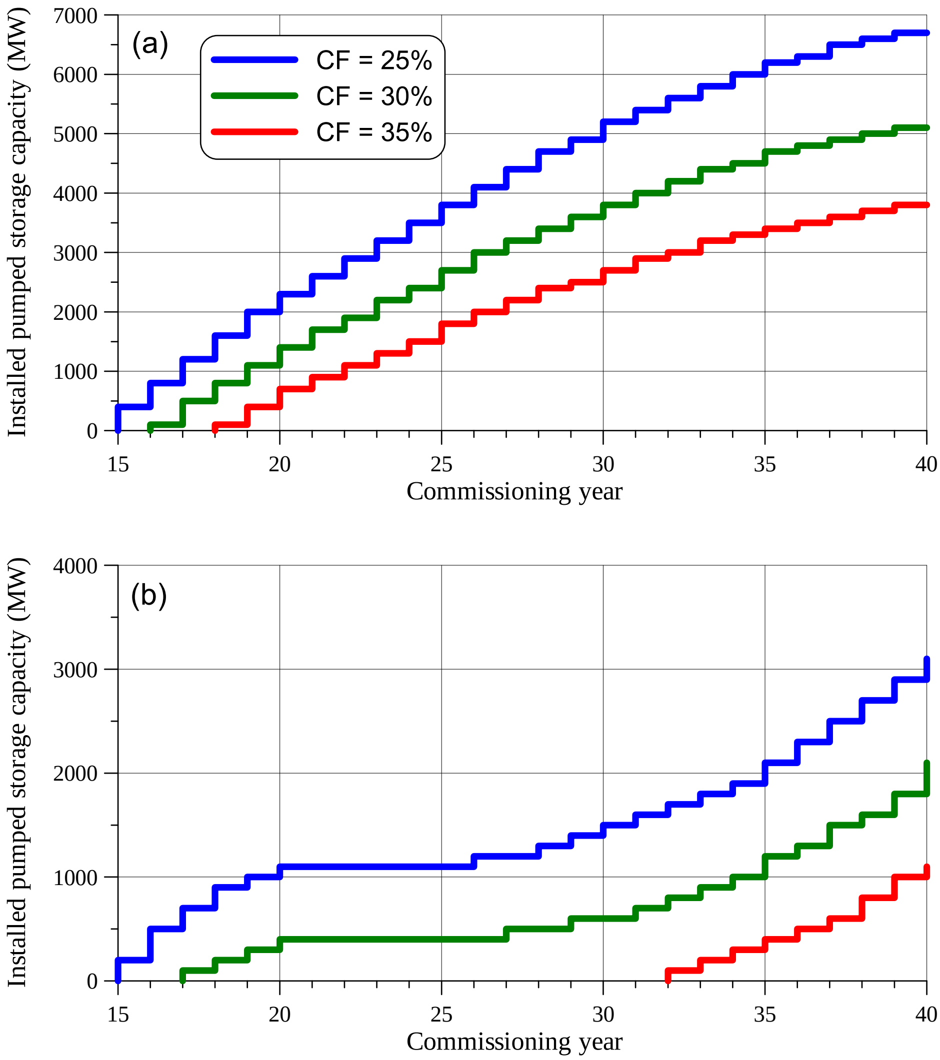

Figure 3.31. Sizing of PHES development up to 2040: a) Scenario MEAP; b) Scenario EP.

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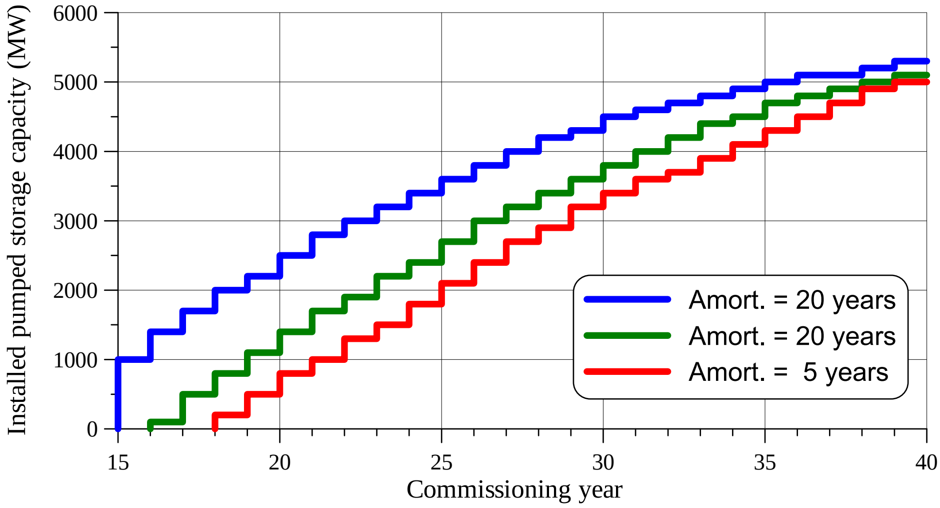

Figure 3.32. Effect of investment amortization period on the optimum PHES development.

5 Conclusions

The electricity system of Greece exhibits characteristics of a large isolated grid, with low flexibility, production imbalances and transmission limitations. The aimed high RES integration in the system requires important modifications and improvements, most of which are foreseen in the national RES energy plan to 2020 and the Roadmap to 2050.

High penetration of intermittent renewable energy has feed-in limitations even in very flexible electric grid systems, and rejections of renewable production is unavoidable in periods of high wind and or solar potential. Moreover, the residual load that has to be covered by the left-over power plants of the system may exhibit strong variations, affecting the stability of the system.

The present simulations showed that such rejections will be of the order of 20% for the 40% RES share scenario foreseen for year 2020, which corresponds to about 8% of the total electricity consumption in the system. The rejected portion of RES production for the 80% RES share scenario is lower (13-19%, depending on the renewable production mix), but the corresponding amount of energy is higher, about 11-14% of the total consumption.

Pumped storage is the most suitable energy storage technology for Greece, and it is already considered in the energy plans for the exploitation of surplus RES production. In addition to energy storage, the integration of more PHES units in the system can significantly improve the system stability, as indicated by the present results.

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 showed that this optimum PHES power is between 1 and 2 GW for the 40% RES share scenario, and between 4 and 7 GW for the 80% scenario. The corresponding PHES needs considered in the national RE development plans are within the above ranges.

The storage capacity requirements is the second important parameter that should be optimized to support the future RE development. The present study reveals the decisive role of electricity production system flexibility on the storage capacity needs. For the 80% scenario, increasing the feed-in limit for intermittent RES production from 5% (very flexible) to 25% of the average annual load demand, the storage efficiency of the simulated PHES system (4.5 GW, 54 GWh) is reduced by 16-18 percentage units and the rejected RE that cannot be stored becomes double.

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The relative development of wind and solar energy technologies constitutes a second important parameter of the future system performance. The present simulations showed that a favored wind development scenario exhibits higher direct penetration capabilities, but it is the least efficient in terms of both rejected RE storage and capacity factor of the PHES units.

Even for the most efficient PHES design and for high storage capacities, there will be always a remaining portion, of the order of 25%, of the rejected renewable production, that has very short duration curve, and hence cannot be stored with high capital cost systems. Channeling of this production to small distributed consumptions, like the electric vehicles, could be a possible solution.

A regulatory framework for energy pricing and operation of PHES units is necessary in order to effectively schedule the RES and the entire electricity system development for the next decades. Additional emerging factors must be also taken into account in a more elaborate investigation, like the smart grid, the demand management, and the hydrogen production and utilization. The possibilities of using the existing reservoir hydroelectric plants for supporting high instant penetration of intermittent RES should be also examined.

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Annexes

Annex A: Description of the computation algorithm

A.1 Calculation of the rejected renewable production

A specific algorithm developed by the LHT/NTUA is used for the modeling of the Greek electricity system and its evolution up to 2050, based on various development scenarios of the National Energy Roadmap (see Figs. 1.9 and 1.10).

The algorithm computes on hourly basis the expected rejections of the intermittent RES sources production (W/F and PV), when it is higher than the maximum absorbable into the system. The penetration limitations are set by the system administrator in order to protect the whole system from instabilities and uncontrollable power variations. In the present model these limitations are computed as follows:

The amount of intermittent RES production that cannot be absorbed in the grid system is obtained by estimating the instant penetration limit, which depends on the technical characteristics and constraints of the base thermal units in operation (e.g. technical minimum, reserve and control characteristics). For example, the maximum penetration of W/F production during the night-time hours is less than the corresponding one during the day, because during the night the production share of the less flexible lignite-fired units is much more increased, as shown in the example of Fig. A1. On the other hand, the maximum penetration limit for PV production could be taken higher than the W/F limit, due to the lower variability and better forecasting capabilities of this power technology.

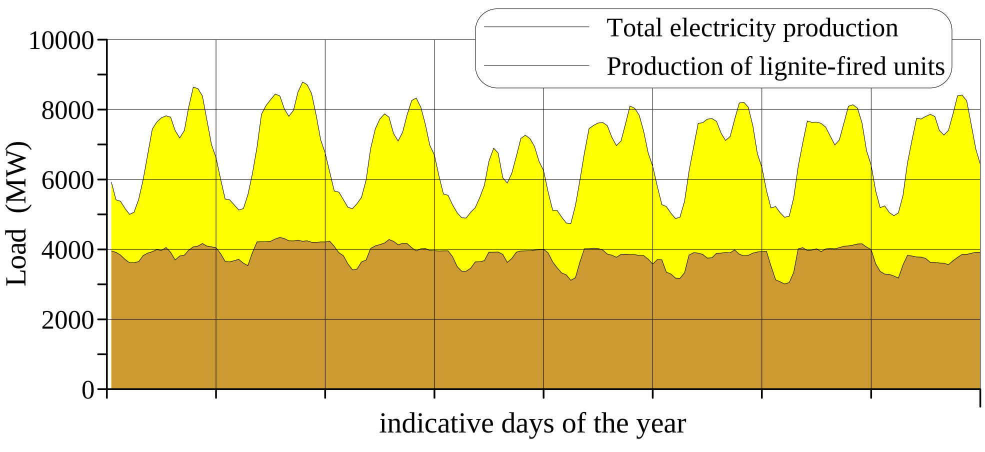

Figure A1. Indicative electricity generation history curves in the Greek system.

The maximum permissible penetration rate of intermittent sources (wind and solar) during the day is finally obtained based on the weighted production of the above sources in each time interval (here, one hour). Then, the computer algorithm calculates on hourly basis the wind and the solar production that cannot be absorbed by the grid system and hence it is available for storage.

Hourly electricity production data of all power units connected in the Greek electric power system are used for one reference year (here 2008). The corresponding time histories for total system load, base thermal units and wind farms production are extracted from this data base.

Next, since the WF and PV production is distributed on several sites all over the country, any increased installation and production scenarios of the above technologies can be obtained by multiplying the corresponding reference time series. It was found that the annually rejected production increases with the WF installed capacity and also it correlates well with the average system load of the examined year [6, 7]. A new variable, $R_{W/S}$, was defined expressing the ratio of the installed wind power divided by the mean system load. A similar variable, $R_{P/S}$, is introduced here for the PV installed power, as also a cumulative variable, $R_{I/S}$, for both intermittent RES.

In order to apply the above algorithm for the energy scenarios included in the national roadmap-2050, the following assumptions are made:

- The electricity load and production time-history for any of the examined future years will be similar to the corresponding variation of the reference year, while both instant and mean load values are modified according to the data of each specific scenario.
- The WF and PV production is distributed on several sites all over the country, and therefore any increased production scenarios of the above technologies can be obtained by multiplying their corresponding reference time-series.
- Even in the decarbonized scenario (MEAP), the electricity production blend contains some less flexible and controllable technologies (e.g. geothermal and solar concentrated), and some more flexible units (e.g. biogas and biomass). Consequently, as far as RES penetration is concerned, the former units have similar behavior to the non-flexible lignite-fired units of the reference year, whereas the latter are similar to the gas-fired plants. Consequently, certain penetration limits for intermittent RES production may be set for all scenarios.

In previous studies [6, 7] it was found that the annually rejected WF production increases with the installed capacity, and also correlates well with the average system load of the year. A variable, $R_{W/S}$, was defined expressing the ratio of the installed wind power divided by the mean annual system load. A similar variable, $R_{P/S}$, is introduced here for the PV installed power, as also a cumulative variable, $R_{I/S}$, for both intermittent RES.

The results of the algorithm for the expected rejections up to 2050 for the MEAP energy scenario of the Roadmap, are given in Fig. A2. It can be observed that rejections of both sources increase as their dimensionless installed power ($R_{W/S}$ and $R_{P/S}$) increases. However, for large RES installations, after 2040, the percentage rejections of PV production are higher than the WF ones (Fig. A2b), although the relative installed power of PVs is lower (Fig. A2a). This is because PV production is concentrated only during the day-time hours, whereas a significant portion of wind production is absorbed also during the night-time.

According to the MEAP scenario, the dimensionless RES installed power maximizes in 2040 and then remains constant, giving a cumulative value of $R_{I/S}$ about 2.25 (Fig. A2a). For that installed power the cumulative rejections are high, about 36% (Fig. A2b), revealing the need for considerable storage capacity. However, due to the higher penetration of PV production, as also because PVs always produce during high load demand periods, the above rejections are smaller compared to the ones caused if the intermittent production was only from wind, as shown in Fig. A.3, from a previous study [7].

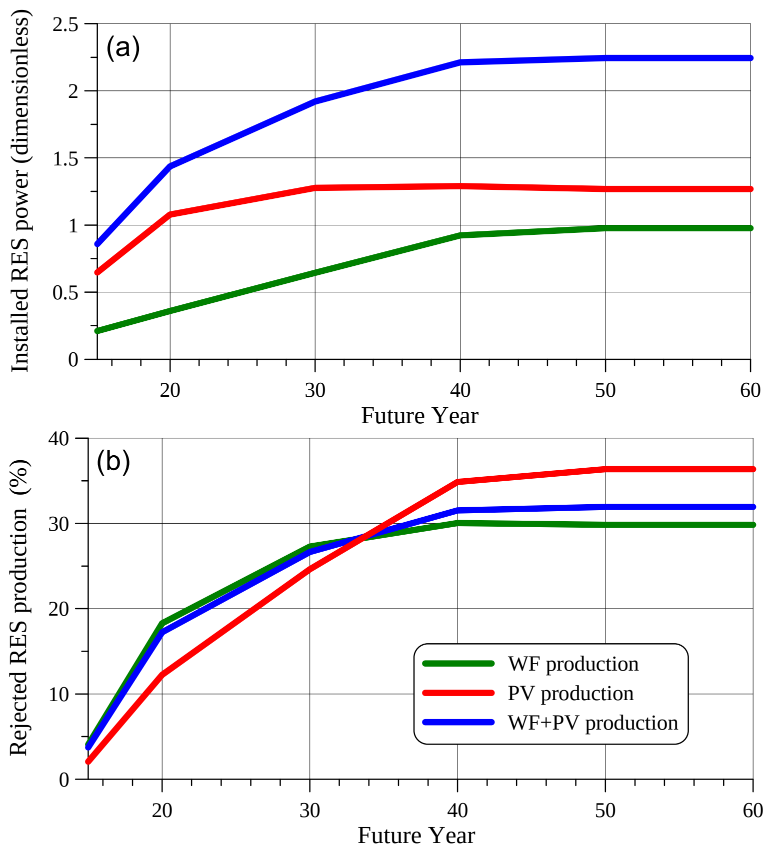

Figure A2. Intermittent RES development by scenario MEAP: a) Dimensionless installed power (R-variables); b) Annual RES energy rejections.

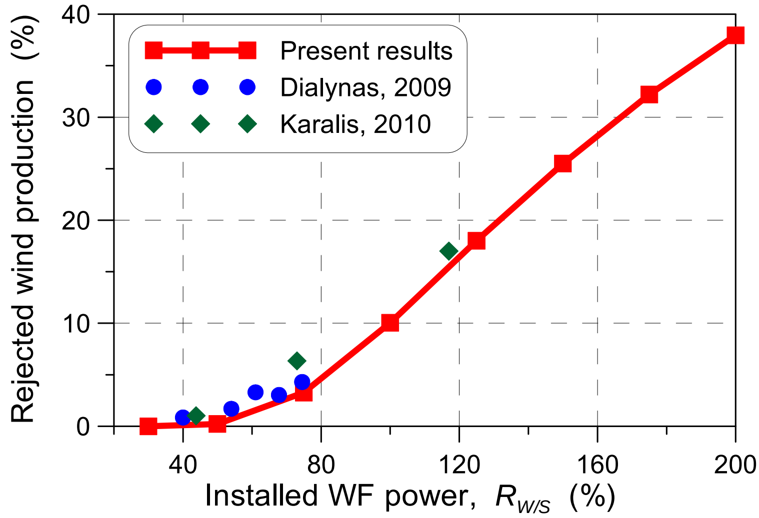

Figure A3. Annual wind energy rejection as function of the installed wind power.

An indicative picture of the wind and PV production integration in the year 2050 and with the MEAP scenario is given in Figs. A4 and A5. The corresponding installed power will be about 14 GW of wind farms and 11 GW of PV units (Fig. 1.10). Fig A4 shows that in most cases of high wind production there is a considerable amount of non-absorbable production, which is much larger during the night-time hours, as discussed previously. On the other hand, PV rejections happen almost all days of the year, as shown in Fig. A5. In this figure the combined effect of both W/F and PV productivity is more clearly shown: PV rejections are significantly affected by the parallel wind farm production, and become much higher in days when there is high wind production.

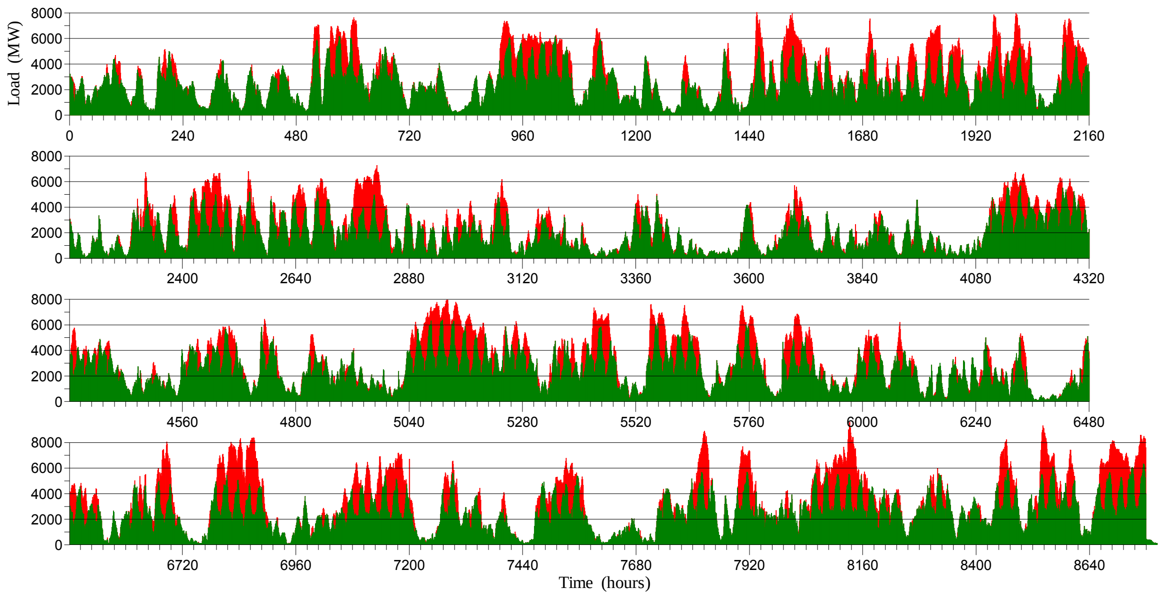

Figure A4. Time history of wind production in the year 2050 and MEAP scenario: Green=absorbed in the grid; Red=rejected, for storage.

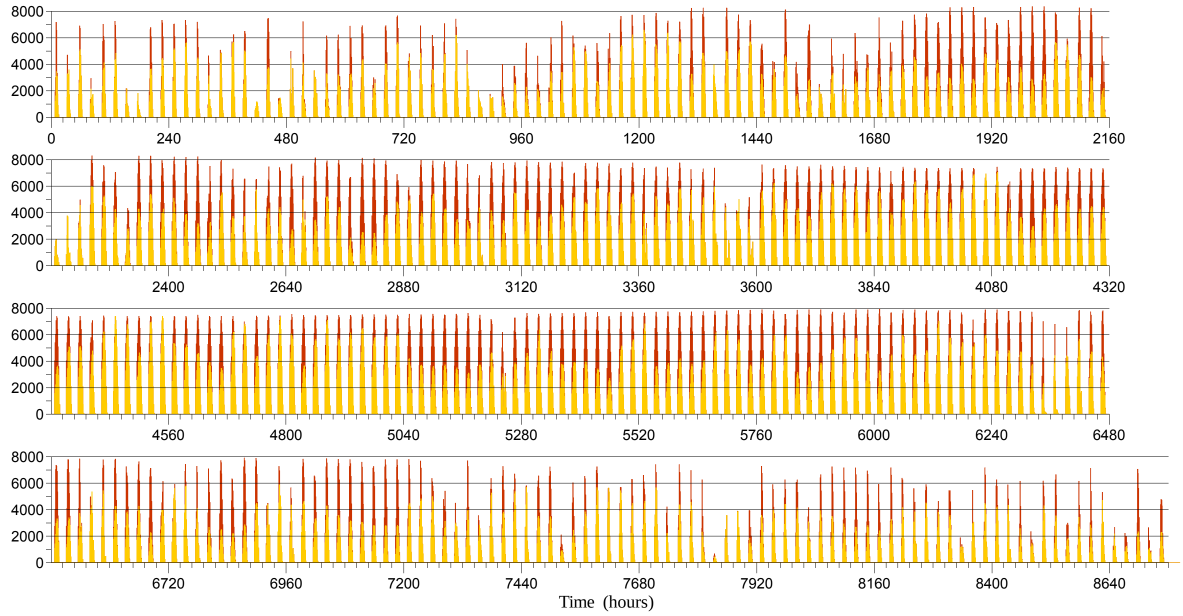

Figure A5. Time history of PV production in the year 2050 and MEAP scenario: Yellow=absorbed in the grid; Red=rejected, for storage.

A specific algorithm is developed for these computations. The duration curves of RES rejections for each of the following years up to 2050 are computed at first, based on a given development scenario of the system (national Roadmap-2050). Then, the cumulative energy that can be stored and recovered by a PHES system of given power can be calculated for any desired period, starting from its commissioning year, and the average CF during the amortization period is obtained. Finally, setting as target a specific CF value, the maximum installed power for viable PHES investments can be computed.

A.2 System performance with integrated PHES units

This algorithm is developed for the detailed modeling of the annual performance of future electricity systems with increased RES integration and PHES plants in operation. The first part of the algorithm constructs the Residual Load curve, by subtracting all non-controllable RES time-series production from the system load curve. Then, the energy rejections from the intermittent RES are computed during hours when the RL is below the instant technical minimum of the power system (or below zero, if no such limit exist).

The second part of the algorithm simulates the operation and performance of the PHES units in the system. The hourly storage power depends on the RES rejected power and the availability of storage reservoirs. On the other hand, the production program is

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determined by the system peak load characteristics, in order to achieve effective peak-shaving of the RL curve in high demand periods (Fig. A6).

Finally, the remaining storage power and capacity after the pumped storage cycle of the rejected renewable energy is exploited for smoothing the load curve of the remaining power plants following a peak-shaving and valley-filling operation strategy shown in Fig. A6: The storage and production lines can be calculated so as the pumping area multiplied by the cycle efficiency (taken here ~75%) is equal to the peak shaved area, during the same day.

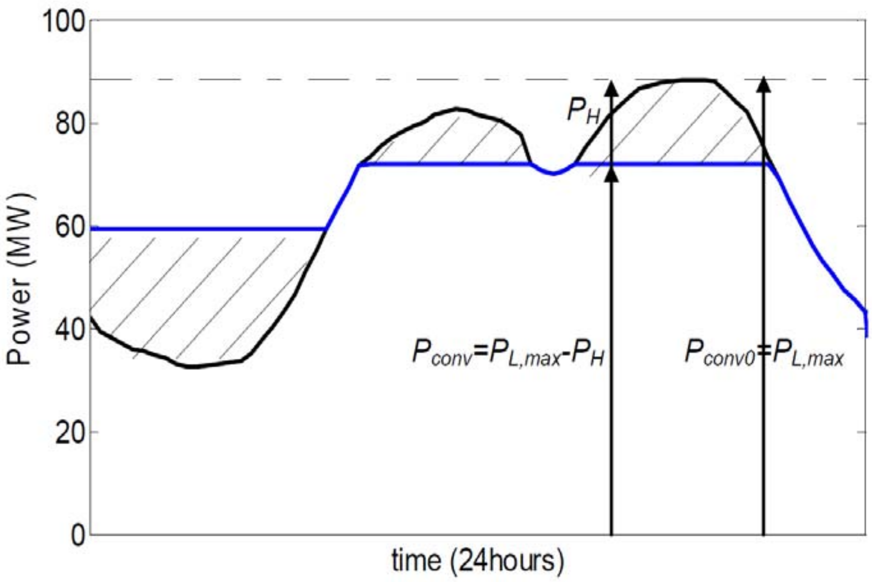

Figure A6. Indicative sketch of PHES units operation in the electric power system.

The software has the capability of multiple runs in order to conduct parametric studies of the effect of the main design and sizing quantities of the PHES system on the RES energy storage effectiveness. Moreover, it can be used to obtain complete hill charts of the PHES system annual performance and exploitation degree in the system, which can be correlated with its economic viability.

The results of the above computer modelling are presented in sections 2 and 3 of this report.

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