Towards the optimum mix between wind and PV capacity in the Greek power system

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Abstract

The achievement of the national energy targets in Greece is mainly based on the exploitation of the abundant wind and solar potential. The effective implementation of these technologies into the Greek power system requires the determination of a long-term energy planning, which takes into account the characteristics of the existing power system and the availability of wind and solar resources into the current geographical area. Technical aspects related with the reliability of the Greek power system and its ability to absorb the variable output of wind and PV are analyzed. In such a perspective, an hour by hour simulation of the Greek power system provides the energy balance of the system and the renewable energy curtailment. A second probabilistic model is used to evaluate the effect of wind and PV integration on the reliability of the Greek power supply system through the calculation of the capacity credit. Both approaches contribute on the determination of the optimum mix between the two leader technologies. Results show that the simultaneous integration of wind energy and PV could have positive effects both on the reliability and on the renewable power absorption. Apart from that, the optimum mix requires a larger wind than PV integration, which in case of the Greek case study is accounted for at least 2:1 ratio, even if financial aspects are ignored.

1. Introduction

In Mediterranean wind energy and photovoltaic systems are considered as significant contributors in reducing CO_2 emissions and protecting the environment. To meet the renewable energy national targets in Greece, effective implementation of massive wind and supplementary PV capacity into the power supply system is required. At first sight, wind energy seems to be more effective and much cheaper than photovoltaics. On the other hand, photovoltaics offer decentralized power generation always very close to the demand, provide power supply during hours of peak demand and then seem to have higher contribution on the reliability of the power system. In the National Renewable Energy Action Plan [1] the required wind and PV capacity to be installed since 2020 is estimated to 7500MW and 2200MW respectively.

Financial aspects are very important particularly in the current financial crisis, but technical restrictions should be firstly analyzed to recognize the technical limits, the conditions and the consequences from the integration of variable output renewable energy sources into the Greek power supply system. Both capacity credit and renewable power absorption (or equivalently its complement the power curtailment) are associated with the variability of wind and solar resources [2, 3]. In the specific geographical area of Greece, the annual distribution of wind power is strongly affected by the spatial distribution of wind farms [4], while solar potential is abundant in the whole territory. Dealing with renewable power absorption, technical constraints such as the units' commitment and the power dispatch should be considered to increase renewable energy contribution and ensure the safe operation of the system. The maximum safe renewable energy absorption is of crucial importance for the Greek power supply system [3] which is characterized by a rather limited cross border power transfer capacity. Additionally, the above issue clearly affects the renewable energy contribution and, consequently, the achievement of the national targets in terms of renewable energy contribution levels and reduction of the greenhouse gas emissions. On the other hand, capacity credit reflects the effect of the renewable installed capacity on the reliability of the power system and reliable estimate contribute to the long term national energy planning through the substitution of conventional power plants.

In short term the mix between the two main variable power output renewable energy sources is defined by financial issues, as soon as photovoltaics are very expensive and requires a significant feed-in tariff to represent an attractive investment. In long term, the forthcoming decrease of photovoltaics prices shows that technical issues will play a critical role in the definition of the long term wind-pv mix.

2. Required data

For the application, several data are required, such as annual time-series of load demand, characteristics of the conventional power plants (type of fuel, capacity, and availability), capacity of hydro power plants and time series of wind and PV generation.

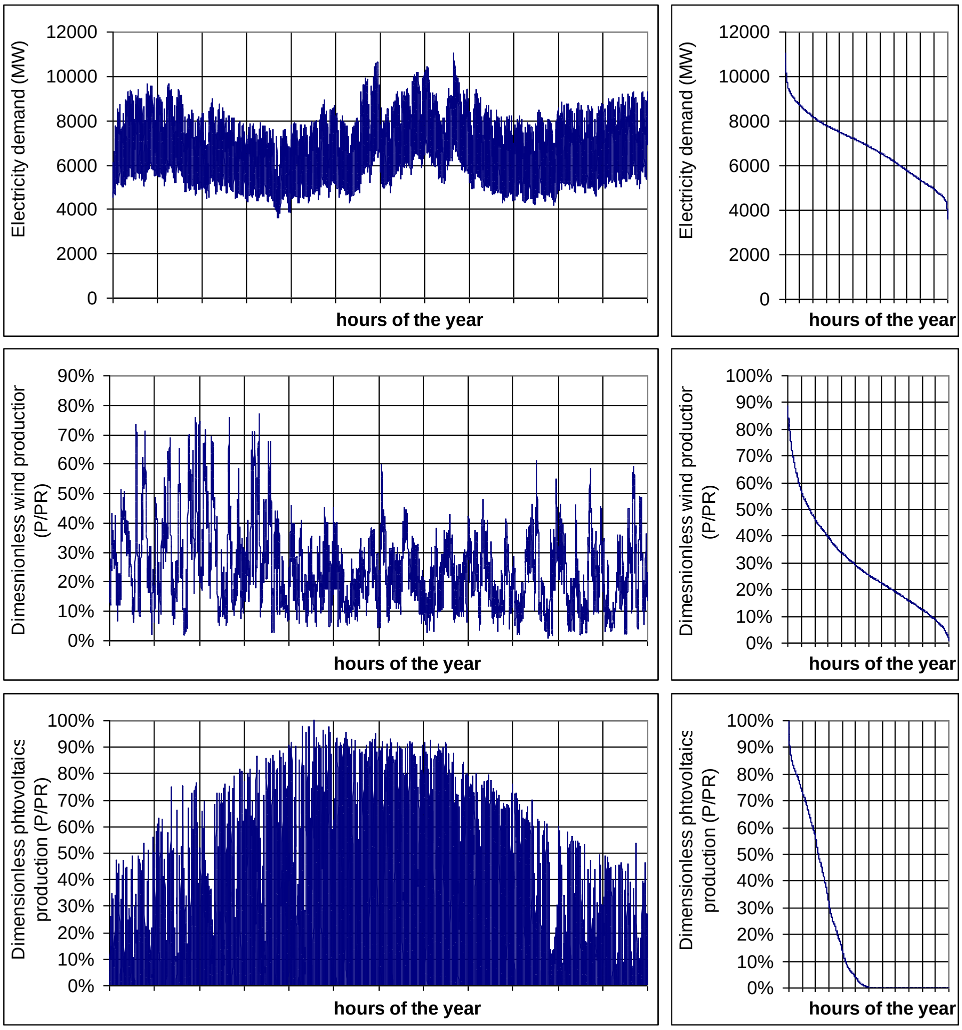

Figure 1. Annual time series and duration curves: a) electricity demand, b) wind production c) PV production

The mainland power supply system of Greece numbers a total installed conventional power capacity of 11234.3MW, consisting of 22 lignite, 4 diesel, 4 combined cycle, 3 natural gas and a number of hydro-electric units [5, 6]. Today base load lignite power plants account net power capacity of 5288MW and peak load oil or gas power plants net capacity of 2888MW. The mean availability of conventional power plants is 89%. Hydroelectric plants with net capacity 3058.5MW always provide an annual production of around 5TWh, while in a bad hydraulic year production may be reduced to almost 2TWh.

A year with annual electricity demand 60TWh, and peak demand 11.0GW is considered as a long term reference year. The analysis is based on hourly demand time series of 2006, with recorded annual energy and peak demand 49TWh and 10,3GW, after appropriate conversion. Annual data of 2006 are used, because for the same year simultaneous time series of wind power across the whole territory are available. These wind time-series have been reproduced by the systematic application of a mesoscale weather prediction model [2]. In this way, for the simulation of the power system the geographical dispersion of wind and any probable correlation between wind and load are also taken into consideration. The Numerical Weather Prediction (NWP) model, used is the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) developed at the US Naval Research Laboratory [7]. COAMPS is a three-dimensional non-hydrostatic model that has been used for operational forecasting since 1996 for a wide range of research purposes for both idealized as well as real data simulations. Appropriate adjustment of the numerical parameters, systematic application on a yearly (and beyond) basis and thorough analysis and processing of wind characteristics provide simultaneous wind speed time series at the meso-scale over the whole territory of interest. Data from existing PV installations are used in order to determine the hour-by-hour energy production throughout the year.

Figure 1 presents the annual time series of demand and electricity generation from wind and solar, and their respective duration curves.

3. Simulation of the Greek power system

3.1. Steady state energy analysis

The simulation examines the steady-state operation of the Greek power system and takes into account the specific characteristics of demand, the technical features of conventional and hydro power plants and the technical constraints for the smooth and safe operation of the system.

The aim of the methodology is to estimate the energy from renewable sources that can be absorbed directly from the Greek power system, the renewable electricity supply, the required capacity and the contribution of conventional power plants.

For the application of this methodology, the units' commitment and load dispatch should be first clarified. As long as renewable energy penetration is increased in the Greek power system, it is clear that its management rules and operation of the power system will differ from the current practice. First of all as regards the management of variable production renewable energy technologies, wind power curtailment may occur and could be established through a central control system by the Hellenic Transmission System Operator. On the contrary, curtailment of photovoltaics power can not be easily established due to distributed generation by many small units. Over and above, electricity production with Photovoltaics is too expensive type of energy to be curtailed and is absorbed in priority.

Conventional units cannot be charged under their technical minimums. For base load (lignite-fired) units, these limits are considered at least 70%, and for peak load units (gas-turbines and diesel generators) 30% of their nominal load. It is assumed that wind and load forecast models are systematically used. Then load demand, wind power availability across the Greek territory and wind power variability are considered sufficiently predictable. The power dispatch and the schedule of conventional power stations are delivered recognizing two main categories of conventional units; base load units and peak load units. The latter concerns gas turbines and diesel power units characterized by their ability for quick response and able to undertake the variability of demand and RES production. The number of base load units to be committed is defined by the expected load to be undertaken in the next 15 days. While, the minimum number of peak demand units to be committed is defined by the expected variability of demand and RES power generation for the hours ahead. This means that if high variability of load demand and RES generation is expected for the hours ahead, more flexible peak load units should be committed to ensure the safe operation of the power system.

A special methodological treatment is considered for hydropower. Today, in Greece, hydro plants operate during peak hours which always occur in summer. In the near future, their generation should be properly adjusted not only with peak demand, but also with the variability of rest RES power generation. Wind power curtailment may occur in low demand or in windy periods. During low demand hours hydro power plants are switched off. During peak demand periods, if there is wind power surplus, hydro power plants should reduce their operation saving water for peak demand periods of low wind. So, wind power plants could save water in the hydro plants' reservoirs and hydro generation will not constrain wind power absorption.

In order to have results in the safe side, a dynamic limit related with the permitted instantaneous penetration of wind power is considered to ensure the stability of the system in emergency case. For example a sudden fall of wind or a sudden storm over all the wind power plants, could lead in total loss of wind generation. Although such cases are considered improbable to occur, this dynamic limit ensures that other units, already committed, will be able to increase their production before the system collapse. In this analysis the base value of the allowed instantaneous wind power is set to 60% of the load demand.

Load demand, wind and photovoltaics' generation are taken into consideration through the annual time series. Especially the time series of wind production has been derived using wind speed time series reproduced by a meso-scale weather forecast model systematically applied in the whole country. Thus, given the installed wind power in every region and representative power curve, the output of wind power is calculated. Aggregating the output of wind power in all the different regions, the total available wind power for every time "window" (eg an hour) is derived.

The interconnections of Greece with neighboring countries have a rather small capacity, while until today the priority of such interconnections is not the cross-border transmission of wind generation. Additionally, due to similar load profiles, neighbors may not be able to absorb energy surplus. Therefore, Greek system is treated as a rather isolated power system.

The main steps of the simulation algorithm are summarized:

- $L_s(t)$ power load situation, $P_{PV}(t)$ PV production situation. For each of them, the residual load $L_{res}(t)$ is calculated as $L_{res}(t)= L_s(t)- P_{PV}(t)$
- The number of lignite units operating, $N_{ST}(t)$, is determined in an hourly basis in order to cover the 70% of the minimum load of the following 15 days.
- The number of peak-load operating units (e.g. gas turbines), $N_{GT}(t)$, is determined in an hourly basis in order to cover the load and the wind energy production variability of the following 3 hours according to the formula: $3 \cdot \sqrt{\sigma_{LRES}^2 + \sigma_{W\_PRD}^2}$
- The maximum wind energy production that can be absorbed safely, $P_{W\_ABS,uplim}(t)$, is determined as, $P_{W\_ABS,uplim}(t)=\min\{\delta^* L_{RES}\ ,\ L_{RES} - P_{min}\{\ N_{ST}(t),\ ,\ N_{GT}(t)\}$, where δ the upper limit of instant penetration in regard to the power load situation $L_s(t)$.
- $P_{W\_ABS}(t)$ the absorbed wind energy, $P_{W\_REJECTED}(t)$ the rejected wind energy are determined.
- P_{HYDRO} the hydropower production is determined in order to cover the peaks of the load.
- Additional power production of the lignite and gas turbine units is calculated to cover the total load.

The methodology calculates the ability of the Greek system to absorb renewable energy generated by wind or PV on an annual basis. Additionally, it provides results about the annual energy mix and the renewable energy contribution.

3.2. Capacity credit

For the calculation of the capacity credit of the wind and PV installed capacity, a probability analysis of the Greek power system is used. The probability functions of the three main parameters and the required convolution between them are described in the following steps:

- The main independent variables of the probability analysis are the load, the wind power production and the conventional stations availability. Hydroelectric power generation is not a stochastic variable due to hydro stations' inter-seasonal storage capability and their scheduled operation. Their power production is dependent on the power load itself and thus it is excluded from the load duration curve. Similarly, although the cumulative photovoltaic generation is variable, it is fully predictable as it depends on the day and time of the year. Then photovoltaics generation is also excluded from the load duration curve. For each of the M different power load situations, N different situations of wind power production and L different situations of conventional power availability, the power load PLi, the wind power production PWj , the available conventional power Pck and their durations in hours annually are well known. Then, the corresponding probability of occurrence is f(PLi), g(PWj) and h(Pck). Calculations for all the situations, results in the probability distribution functions and annual duration curves.

- For the calculation of the capacity credit, the convolution of f(PLi),h(Pck) and g(PWj) results in a 3-D matrix M×L×N whose elements correspond to the probability of occurrence of every possible operational mode: $\Pi ijk(PLi, PCk, PWj) = f(PLi) \cdot h(PCk) \cdot g(PWj)$, {i=1,M, k=1,L, j=1,N}.

In general, capacity credit [8, 9, 10, 11] of any power production unit is related to its capability to increase the reliability of the power supply system. The reliability of the system can be measured by the probability of power loss occurrence (Loss of Load Probability - LOLP) and corresponds to the percentage of time in which the system cannot respond to the power demand. LOLP depends among other factors on demand characteristics, availability, reliability and number of power production units etc. Certainly, the power supply systems are designed so as to keep LOLP at a very low level. When a new power unit is implemented into the system, its cost increases while LOLP decreases and its reliability rises. Its effect on system's reliability varies depending on the unit character (variable or steady) and its availability.

The Loss of Load Probability of a System $LOLP_S$ without renewable power plants is first calculated. Next, the Loss of Load Probability of a System $LOLP_R$ with renewable power plants is calculated. Obviously, $LOLP_R<LOLP_S$, i.e. wind and photovoltaics installations enhance the System's reliability. The Effective Load Carrying Capability (ELCC) of the new renewable power plants is defined as: "Which increase in power demand may occur, while the System's reliability is kept at the same level as before the renewable power plants have been installed". ELCC can be calculated via an iterative procedure. Finally, the Capacity Credit (CC) coefficient of new renewable power plants in the System is defined as $CC=ELCC/P_{R,R}$,where $P_{R,R}$ is the rated installed wind and PV capacity. The CC expresses the equivalent conventional capacity which can be effectively replaced by the wind and photovoltaics installed capacity.

4. Results

4.1. Simulation of the Greek power system

The simulation of the Greek power system is carried out for wind capacity in the range of 20% to 160% of the annual mean load. For 60TWh annual demand, the wind capacity examined is 1370-10961MW. For PV capacity the range of 20% up to 100% of the annual mean load means 1370-6851MW.

Obviously, the renewable energy target could be achieved with wind integration, or with PV integration or with several combinations (figure 2a).

Wind power curtailment may be decreased with the parallel integration of photovoltaic, due to several and important reasons (figure 2b):

- It is preferable to have in a power system the well predicted and distributed PV generation, than conventional power plants with high technical minimums, which restricts the wind power absorption.
- If there are several photovoltaics in a power system, then significant (still well predicted) variations are expected, more flexible peak power units and less heavy lignite power units will be committed. Then lower technical minimums will permit higher wind power absorption.
- Finally, although this effect can not be recorded by this simulation tool, distributed generation by photovoltaics, very close to the consumption and in the same order of capacity with the local consumption, mitigate the transfer of the power system and wind power curtailment occurred due to hypercharge of the transfer grid is avoided.

Apart from that, a very high PV integration (i.e 80-100% of the annual mean load) may cause significant wind power curtailment, even for rather low wind integration (figure 2b). This occurs due to the profile of the load demand and the availability of PV generation.

As regards the effect on the conventional power units, recorded results are not similar for the base load and for peak load conventional units. The use of heavy lignite power units is reduced steadily, as well as their required capacity (figure 2c and 2d). The required lignite power units' capacity, is not affected by the wind integration, but is reduced with the increase of the PV capacity (figure 2g). Very high PV integration leads to lower low demand which now may occur during the day and not during the night (figure 4).

On the other hand more flexible peak load power units are essential for the safe operation of the power system (figure 2h), although they will be used for only few hours per year (figure 2e). This leads to very low load factors (figure 2f) and creates skepticism about the feasibility of these plants and the operation of the liberalized market in the near future.

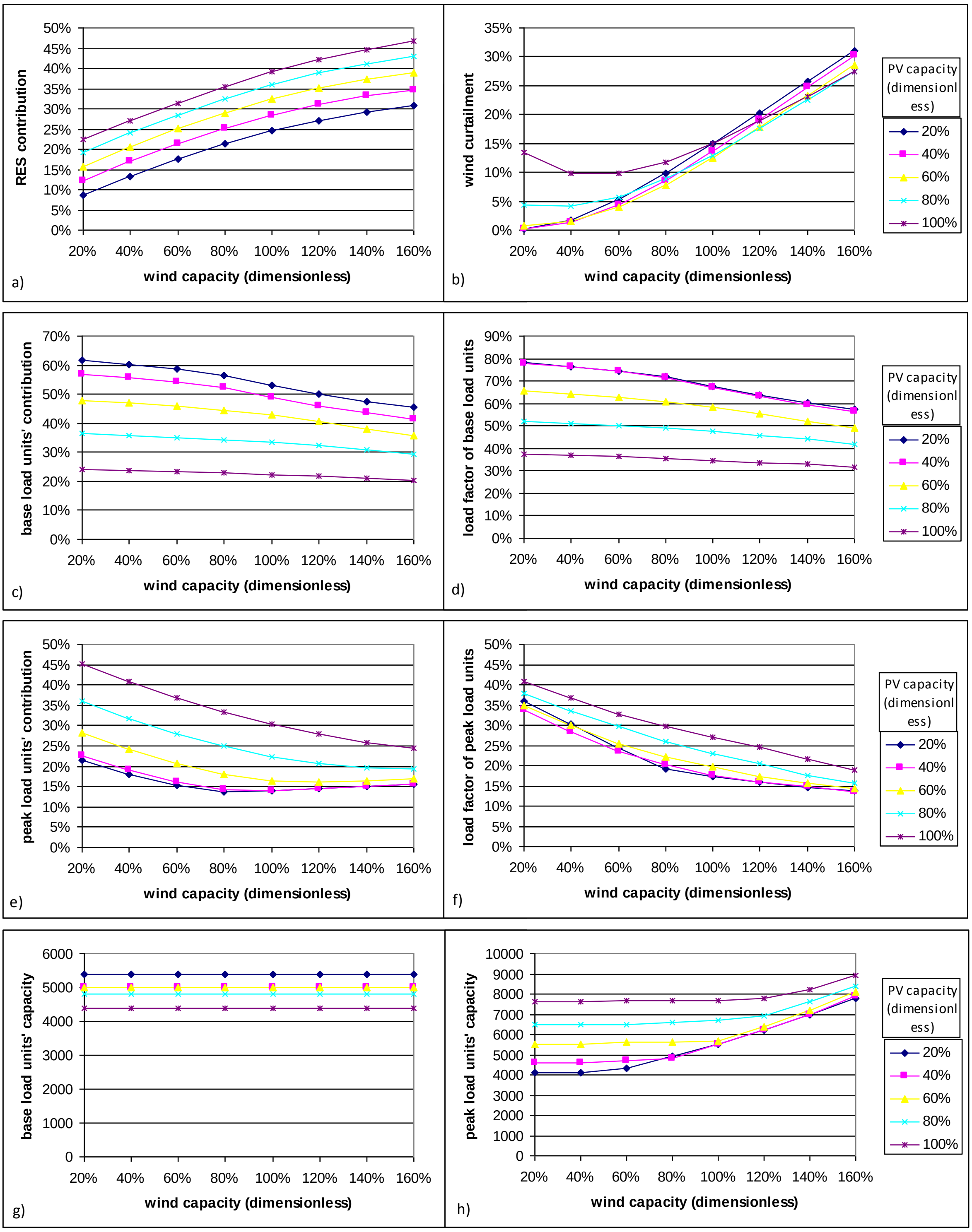

Figure 2: Results of the simulation model for wind capacity up to 160% and PV integration up to 100% of the annual mean load: a) RES (wind and PV) contribution, b) wind curtailment, c) base load units' contribution, d) load factor of base load units, e) peak load units' contribution, f) load factor of peak load units, g) base load units' capacity, h) peak load units' capacity.

4.2. Capacity credit

As regards the second part of the current approach and the calculation of the capacity credit CC of the wind and pv installations in the Greek power system, the following conclusion are drawn:

- CC is decreased as soon as the PV capacity is increased. This occurs because although photovoltaics contribute to peak demand supply for few hours of the year, for many other hours have zero production (figure 1). Additionally, in Greece, there are two peaks of the demand during the day, one in the midday and a second one around 9pm. Only for short periods during summer heat, the midday peak is higher than the other one and PV generation is invaluable.

- For a given PV capacity, the CC is increased with the increase of wind capacity up to an optimum point and then is decreased again. This point defines the optimum mix between wind and PV which leads to the optimum result regarding the effect of the installed capacity on the reliability of the system.
- The optimum mix between wind and PV is 2:1 for the Greek power system. For PV capacity 20% of the annual mean load, the optimum wind capacity is 40%. For PV capacity 60%, the optimum wind capacity is 120%. For this case CC is 17%.

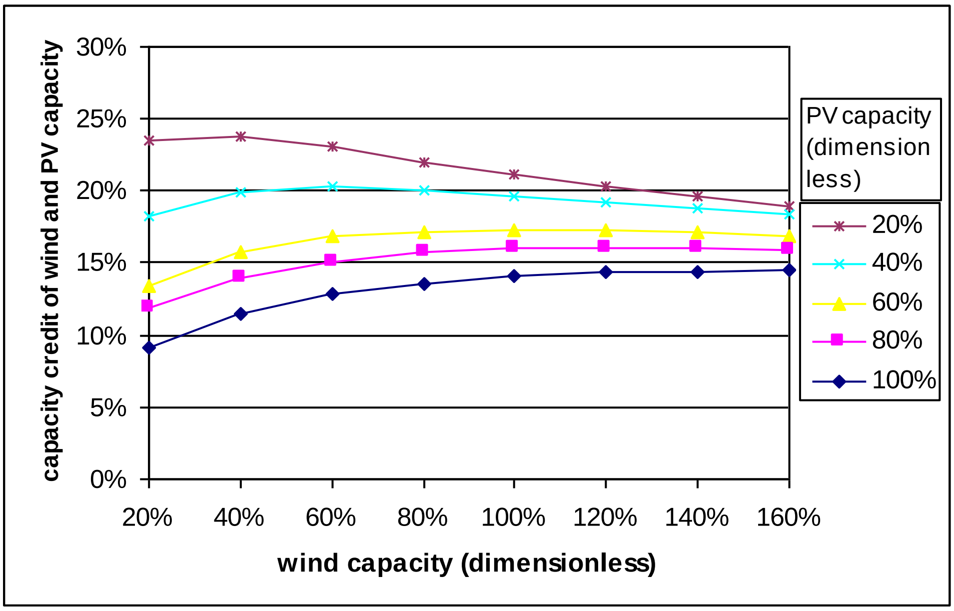

Figure 3: Capacity credit of wind and pv installations in the Greek power system for wind capacity up to 160% and PV up to 100% of the annual mean load.

5. Discussion

The above results show that there are technical issues which should be taken into consideration on the definition of the optimum mix between wind and PV for the achievement of the national targets in the Greek power system. As soon as PV power curtailment is not easy to be established due to the distributed and decentralized PV generation, high wind integration may lead to marginal cases where the absorption of PV power is problematic for the system.

In figure 4, the profile of the demand together with the profile of the residual load (load demand minus photovoltaic generation) is presented for four typical days:

- Day with peak demand of the year (15th August)
- Day with low PV generation (2nd January)
- Day with low demand (23rd April)
- Day with high PV generation (2nd June)

Several difficult situations for the system operator to deal with may occur:

- Cases with low demand and significant PV generation
- Sharp slopes of the residual load during the morning and the evening requires more peak load units to be committed
- Cases in which the residual load during the midday is lower than the low demand during the night.

In figure 5, the duration curve of the residual load shows how often events with low demand occur.

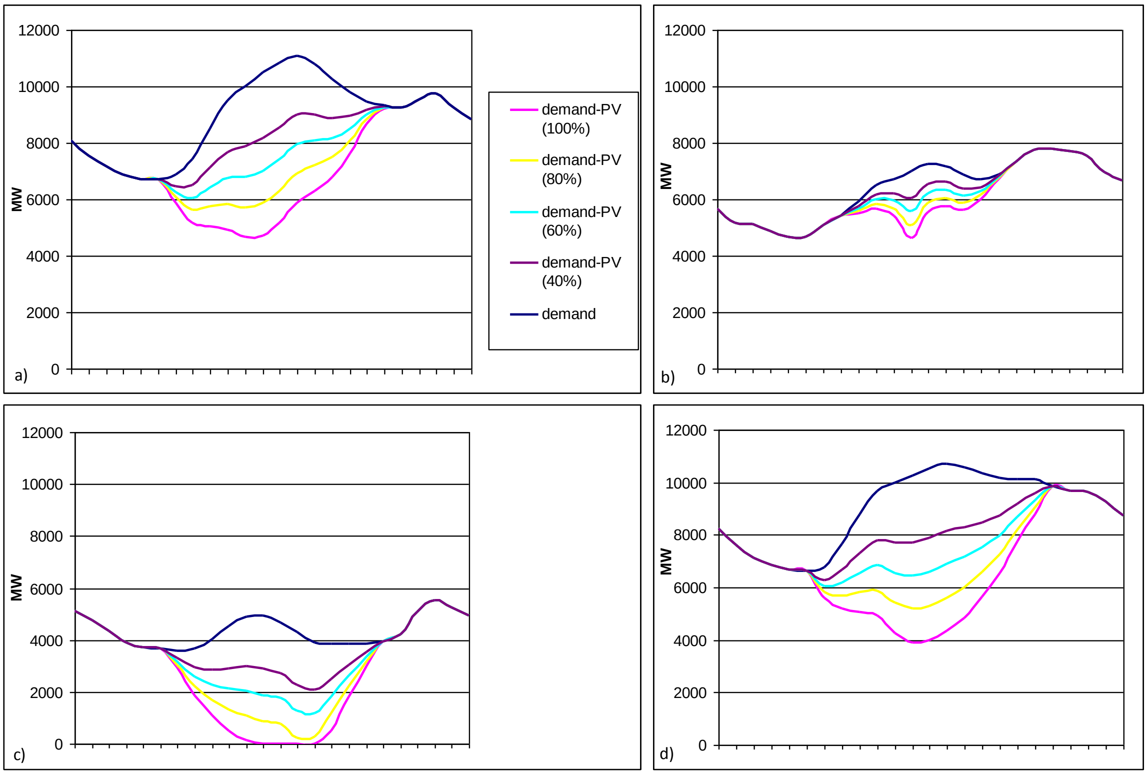

Figure 4: Profile of the demand and profile of the residual load (demand – PV generation) for PV capacity 40% up to 100% of the annual mean load: a) 15th August (peak demand of the year), b)2nd January (low PV generation), c) 23rd April (Low demand during the day) d)2nd June (high PV generation)

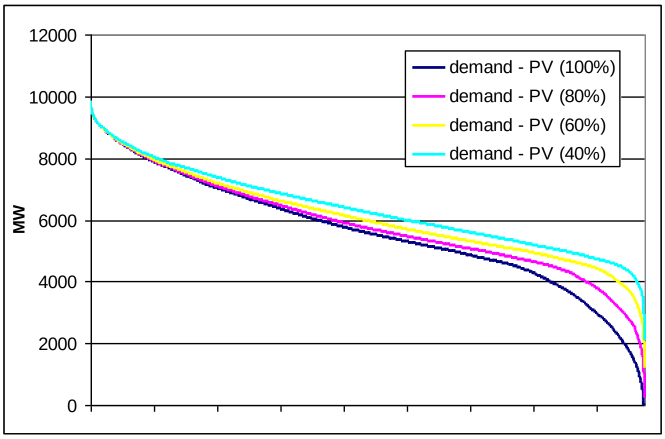

Figure 5: Duration curve of residual load (demand minus PV generation) for PV capacity 40% up to 100% of the annual mean load

In figure 6, the hourly distribution of the annual wind power curtailment is presented for wind installed capacity 120% and PV capacity 40%-100%. While the PV capacity is increased, wind power curtailment is increased during the hours with PV generation. On the other hand wind power curtailment is reduced during the night. The latter occurs because more peak load units and less heavy base load power plants are committed “thanks” to the integration of higher PV capacity. Apart from the different wind power curtailment distribution, the cumulative wind energy curtailment is initially decreased with the increase of PV capacity and is increased again for very high PV capacity. For PV 40% of the annual mean load, the annual wind energy curtailment is 3.4TWh and is reduced to 3,2TWh and 3,1TWh for 60% and 80% dimensionless PV capacity. On the contrary, wind energy curtailment is increased again for 100% PV capacity to 3.3TWh annually.

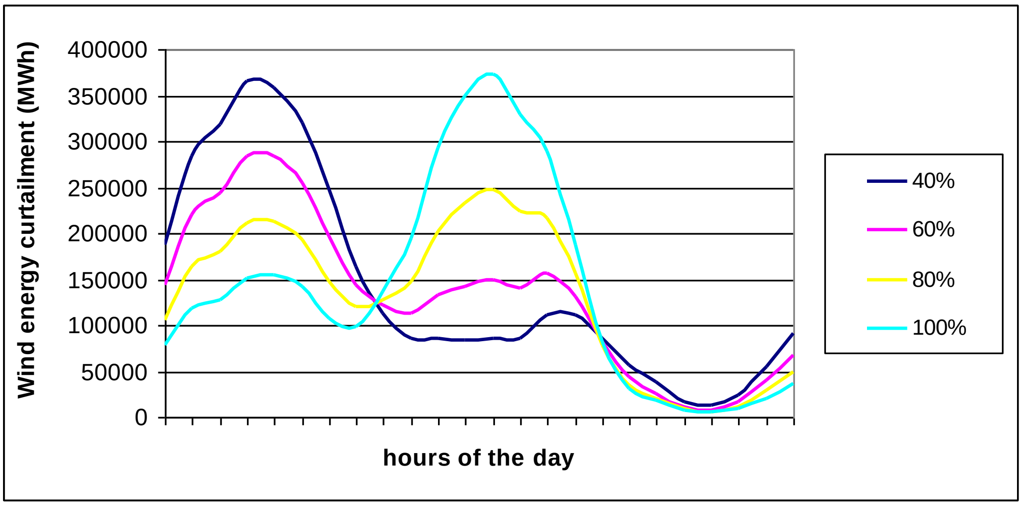

Figure 6: Distribution of wind energy curtailment for wind capacity 120% of the annual mean load and PV installed capacity 40% up to 100%

6. Conclusions

In this paper, the Greek power system was simulated under various scenarios of wind-PV integration and the capacity credit of variable output renewable energy plants was calculated. There are several benefits created by the distributed PV generation very close to the demand. The current approach proves that there are technical issues which should be taken into consideration and restrain the wind and PV development. Wind and PV integration are not independent issues, and should be together examined in the framework of an integrated energy system analysis. The current approach shows that the optimum mix between wind and PV is 2:1 in the Greek power system for the specific wind and solar potential. The upper technical limit of wind integration is higher that the similar one of the PV integration due to the duration curve of the wind power output and establishment of wind power curtailment. Although a rational PV development has a positive contribution to the operation of the power system and almost facilitates wind power absorption, incontrollable PV integration leads to further wind power curtailment and sets troubles for the system operator. The safe operation of the Greek power system requires the significant increase of peak demand power plants which offer flexibility and are able to undertake the increased variations of demand and renewable power output. One of the main challenges is to prove the feasibility of such plants in the framework of a liberalized market.

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