Determining the Maximum Feasible Amount of Photovoltaics in the European Transmission Grid Under Optimal PV Utilization

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Abstract—**In the past few years a significant growth of the number of photovoltaic (PV) systems has been observed worldwide and particularly in Europe. Increasing maturity of this technology and growing manufacturing capacities have led to a considerable decline in prices. Looking at a future possible development of installed PV capacities in Europe, the paper at hand investigates how well the available PV energy is made use of when the installed capacity of PV reaches nearly 2000 gigawatt-peak (GWp). A methodology is presented that aims at optimal placement of PV plants taking into consideration region-specific irradiation conditions in Europe and restrictions imposed by the transmission network. Additionally, a method for optimized placement and dimensioning of storage systems along with their best possible operation strategy is applied for assessment of the effect on PV utilization.**

Keywords:photovoltaics utilization, European transmission grid, storage, DIgSILENT PowerFactory

I. INTRODUCTION

Recent developments in prices for photovoltaic (PV) systems have demonstrated that grid parity for this electricity source might be reached sooner than expected even in regions with less favorable irradiation conditions. Germany alone currently accommodates around 30 GWp of installed PV capacity taking the leading position worldwide [1]. This development has been largely stimulated by increasing manufacturing capacities, feed-in tariffs and growing retail electricity prices. Assuming further price decline of PV systems and growing electricity prices along with the governmental goals towards a considerable reduction of greenhouse gas emissions, a big increase in the number of PV installations can be anticipated in Europe. Therefore, this renewable electricity source has the potential to cover a substantial amount of load in the upcoming decades.

So far grid-connected PV installations in Europe have taken place predominantly on the low and medium voltage levels distributed quite homogenously, leading to a situation where electricity produced by PV is consumed for the most part in the vicinity of the producers without having to be transported over large distances utilizing the transmission system. However, with increasing PV capacity at certain locations this situation will at some point change as PV-generated electricity will be able to cover the complete regional demand in certain hours and even provide excess PV generation. Assuming that such a region is coupled to the interregional transmission system this excess energy can either be transported away over large distances to supply consumers in other regions, be stored for later use or be curtailed. Clearly the former two options would require the availability of transmission capacity and storage systems as prerequisites, which, if not existent or existent to insufficient degree, would require investments in the corresponding infrastructure. The curtailment of PV, on the other hand, requires no additional infrastructure but decreases the number of full load hours and may decrease economical attractiveness of PV, let alone wasting a valuable source of renewable electricity, which, although not usable locally, could replace fossil generation elsewhere. Already today lack of adequate transmission system capacity leads to curtailment of wind power in Northern Germany as described in [2]. Although issues associated with PV systems currently predominate on the distribution system level, large expansion of PV could lead to similar effects as for wind power, especially if current postponements of grid expansion measures are taken into account. Large-scale storage limitations are currently given by location scarcity for e.g. pumped hydro storage plants, limited maturity of certain technologies and their high price. The latter two have a large improvement potential whereas the former has only limited potential for additional exploitation, partly due to environmental aspects and resistance by the population.

In the light of restrictions imposed by the transmission network and storage options described above, utilization of electricity produced by an increasing number of PV plants in the future may suffer setbacks leading to a decreasing number of full load hours. In order to assess the influence of the mentioned factors, simulations using Energynautics' European transmission grid model were carried out in DIgSILENT PowerFactory looking at future utilization of grid-connected PV in Europe while taking into consideration possible restrictions imposed by the electricity network and storage infrastructures. Optimal placement of PV generation capacities is determined by means of optimal power flow simulations allowing for diverse solar insolation properties of different European regions and transmission network limitations. Several possible projections of future PV capacity growth were then developed, starting with the amount required to supply the complete European load on a sunny summer weekend, then increasing this amount linearly. Furthermore, the effect of optimally placed and operated storage on PV utilization was investigated in several scenarios representing various amounts of storage. The results for each investigated case present the annual load coverage through PV and the amount of curtailed PV energy and offer reflections on the maximum feasible amount of installed PV capacity in Europe aimed at maximizing load coverage through PV on the one hand and minimizing curtailed PV energy on the other.

It should be emphasized here that distribution system issues associated with large amounts of installed PV generating capacities, such as inadmissible voltage increase and overloading of power systems equipment, are not taken into consideration. Similarly, issues concerning power system operation based on large amounts of nonsynchronous generation are assumed to be solvable, permitting the operation of the power system on the basis of inverter-coupled generation.

Section II details the approach taken for modeling and calculations while section III presents calculations results. Conclusions are drawn in section IV.

II. METHODOLOGY

The principal question aimed to be answered in this study is how efficiently power available from PV installations can be utilized on the European level. This depends on how much power generated by PV is consumed locally, how much of the excess power can be transported to other locations and how much power can be stored provided storage capabilities are in place. Several projections concerning the installed capacity are considered with the goal to increase PV's share in supply of the demand. Simultaneously, more PV capacity may lead to large amounts of local excess PV power at certain locations in the system in certain hours in relation to demand on the same nodes. The limitations for power exchange between distant regions by means of the transmission system given by the limited thermal capacity of transmission lines lead to curtailment of PV power. It is assumed that sufficient reactive power compensation for the transmission network is in place so that neither voltage stability nor voltage angle stability are an issue. When PV is curtailed at one location due to transmission grid restrictions other generating capacities need to be present to supply load at another location if there is not enough PV to cover demand locally. These generating capacities could be constituted by other renewable resources, fossil fuel plants and storage systems. The present study focuses on photovoltaics and system planning defined by its behavior. No correlation with other volatile resources of renewable energy, such as wind power, is considered.

The calculations that are described subsequently were carried out using a detailed model of the European transmission grid, which is described in section II.A. In the first step, suitable locations and appropriate amounts of PV installations are identified under the assumption of demand supplied completely by PV for a specific hour as explained in section II.B. Next, section II.C describes the methodology applied for calculations of a complete year for determination of utilized and curtailed PV energy while considering different scenarios in terms of available storage capacity.

A. European transmission grid model

Calculations were conducted with Energynautics' high voltage transmission network model, which was developed with the power system calculation tool DIgSILENT PowerFactory. The model covers all ENTSO-E member countries and is designed for calculations of load flow and optimal load flow. Having over 200 nodes the model represents the load and generation centers in Europe in an aggregated fashion. The load across the nodes is distributed using a dedicated distribution key which is based on factors such as population density and the location of heavy industry. Aggregated transmission routes between and inside the individual countries are mostly modeled as 380 kV high voltage AC lines. In addition, high voltage DC lines are present as well summing up to 450 lines in total for both technologies. Although the model is capable of AC load flow calculations and can determine losses, reactive power flows and the necessary compensation, optimal power flow calculations (OPF) were conducted on DC basis for this study owing to the fact that the principal interest here lies in the active power balancing of PV power on the European level.

This study deals with large amounts of installed PV capacity in Europe that could be reached at a certain point in time in the future. As the exact time point depends on a variety of factors it cannot be predicted with certainty. Hence, the year 2050 was chosen as a rough target for estimating the development of electricity consumption. Moreover, a prediction concerning the expansion of the transmission network was made. It is based on the assumption that all projects in a mid-term planning horizon from the ENTSO-E's Ten Year Network Development Plan (TYNDP) [3] will be built. The transmission system model was upgraded by implementing most of these projects. In total 82 GVA of additional capacity were added to account for new HVAC lines and 13 GVA for new HVDC lines representing the state of year 2020. From this point onwards no further expansion of the transmission grid is considered until the year 2050. This setting will provide understanding of the role that the transmission grid plays in terms of curtailment of PV. For a joint optimization of transmission and generation systems please refer to a companion paper [4]. The model's aggregated nodes and lines are shown in Figure 1 having the predicted year-2020 status. It is furthermore assumed that Europe is able to fully cover its electricity needs without importing solar-generated power from North Africa.

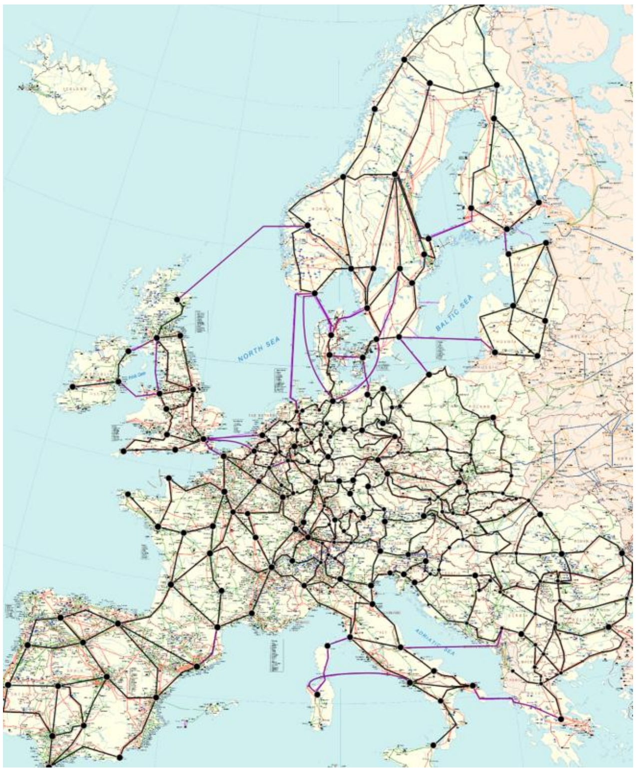

Figure 1: Aggregated model of the European high-voltage transmission grid (Source: Energynautics)

B. *Determination of minimum PV capacity*

The study at hand aims to determine the upper reasonable limit for installed capacity with regard to utilized PV energy. However, before calculations of PV usage are conducted, a starting point for the installed PV capacity needs to be found. This has been done using the methodology that is described in the following.

PV is set to supply 100% of demand in all modeled countries (EU27 excluding Malta and Cyprus, including Norway and Switzerland) on a clear-sky summer weekend day at noon. The rationale behind this approach is that the power produced by PV plants at this hour is at its maximum while the demand in the system is relatively low compared to, for example, a winter weekday. If PV were set to supply a certain hour on a day that bears the highest demand in a year, such as a winter weekday, there would be a large number of hours in a year with excess PV generation, i.e. lots of hours when total European demand is smaller than total PV produced. This setting would lead to inefficient PV sizing from the outset. Dimensioning PV according to the light-load day, in contrast, implies that none or only little curtailment is expected throughout the year. Some curtailment might still take place due to inhomogeneous weather situation in different European regions and local grid congestion. By setting the time point to noon, the resulting PV capacity thus corresponds to one of the day's load peaks.

As mentioned previously, load assumptions are made for 2050 serving as the reference year and were developed by EWI based on ENTSO-E data for 2011 weighted according to region-specific GDP growth.

PV generation capacities determined using the described approach were not set equal to the demand at the nodes in the model they are installed at. Instead, in order to have PV benefit from locations with best irradiation conditions placement of generation capacities was carried out in accordance with region-specific average annual solar insolation data. To this end, generators on all nodes in the grid model were assigned one of six possible production costs representing six solar regions of distinct average annual insolation amount. Essentially, those regions with better irradiation properties were set to have lower production cost and those exhibiting less irradiation were assigned higher production cost. These regions are shown in Figure 2. The segmentation was done by the Institute of Energy Economics at the University of Cologne (EWI) and is based on [5]. Darker regions represent locations with high solar irradiation whereas the lighter ones stand for regions with a smaller yield.

In the next step, after this cost setting was fed into the model by allocating the production cost to all generators, a DC optimal power flow (OPF) calculation with the objective function set to minimization of generation costs was performed. This optimization mode maximizes the power output of those generators that are able to produce at lower cost, which are in our case situated in areas with high irradiation.

The transmission system limitations play a key role in cross-border long-distance balancing of PV and demand. Hence, the OPF was configured to respect the thermal limits of the lines while still prioritizing generation at sunny locations. With grid restrictions in place this yields a distribution of PV similar to that of demand totaling 770 GWp in installed capacity. This number represents the base case to be used for simulations of the complete year. PV plants could be made up by both small and large PV systems situated at all voltage levels underlying the corresponding node in the transmission network. Table I summarizes the relative distribution of PV and demand per country.

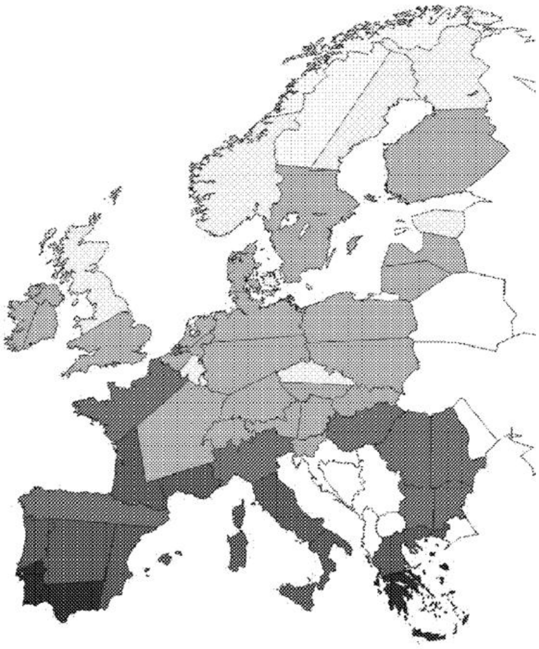

Figure 2: Solar regions (Source: EWI)

TABLE I RELATIVE DISTRIBUTION OF INSTALLED PV CAPACITY AND DEMAND IN EUROPE

Country	Installed PV, %	Demand, %
Austria	1.6	1.9
Belgium	1.3	2.7
Bulgaria	1.1	1.1
Czech Republic	0.9	2.3
Denmark	0.7	0.9
Estonia	0.0	0.3
Finnland	2.1	2.1
France	13.4	14.1
Germany	11.8	12.7
Great Britain	9.0	9.5
Greece	2.7	2.4
Hungary	2.8	1.5
Ireland	1.0	0.9
Italy	12.9	11.7
Latvia	0.6	0.3
Lithuania	0.0	0.4
Luxembourg	0.0	0.2
Netherlands	5.4	3.2
Norway	1.3	2.5
Poland	6.4	5.6
Portugal	2.5	2.1
Romania	1.9	2.4
Slovakia	0.9	1.0
Slovenia	0.0	0.4
Spain	13.1	12.9
Sweden	4.6	3.7
Switzerland	2.1	1.3
Total	**100**	**100**

C. *Whole-year calculation scenarios*

With the determined amount of installed PV in Europe in the base case, simulations of the complete year can be started. Under several different scenarios each of these calculations yields relevant quantities concerning the utilization and curtailment of available PV energy. These calculations comprise hourly OPF simulations using hourly demand and irradiation data for Europe for model input.

Hourly irradiation data were taken from the Satel-Light database [6] that offers access to solar radiation data all over Europe based on measurements from a geostationary satellite and estimations of cloud cover. As the exact locations of the aggregated nodes in the model are known, corresponding irradiation data were applied on the installed PV capacity yielding PV power available hourly at each network node. The data used here is based on irradiation measurements for the year 2000. The 2050 load data were extrapolated from 8 typical days to represent a complete year.

Next, the PV power and demand data were fed into the model for each node of the transmission network and for each hour. An OPF calculation series of the complete year was then performed, whose output showed how much PV power was actually used at each node, how much needed to be curtailed due to grid restrictions or excess PV generation and how much power needed to be provided by other sources of electricity in order to ensure that entire demand is supplied. This process was applied a number of times to allow for three scenario settings. Each of the scenarios contained four options in terms of installed PV capacities, which started with the base case and assumed proportional increases in steps of 385 GWp (being 50% of the base case) until the maximum of 1925 GWp. In scenario 1 no storage was considered that would enable capturing PV power that was curtailed owing to restrictions imposed by the thermal capability of the lines or if excess PV power was being generated at a certain hour in the complete system. This is the most pessimistic scenario and leads to highest amount of curtailed PV.

In scenario 2 storing PV energy was allowed in today's pumped hydro power plants, whose locations are known and are placed on the corresponding nodes in the model. In addition, some extra storage was added at nodes that exhibited PV curtailment after simulations according to scenario 1 with installed PV capacity in Europe corresponding to that determined in the base case (770 GWp). Dimensioning was carried out based on the amount of energy curtailed in spring as this represents a compromise between winter when only a small amount of storage would be needed due to low PV irradiation and summer when the needed storage would be too large for other seasons. The determined amount of required storage capacity totals to around 290 GWh. These strategically placed units could be constituted both by small and large units dispersed throughout the sub-transmission and distribution level underlying the corresponding transmission node. A prominent representative of a small unit is an electric vehicle (EV). EV are expected to be present in large numbers in the future of mobility and power systems. These storage systems would absorb PV power that could neither be consumed locally nor transported through the transmission system to other locations and inject it back into the network whenever required at a later time point.

Last, scenario 3 incorporated storage that was dimensioned and placed in accordance with PV curtailment as seen in the year calculated in scenario 1 having around 1155 GWp PV in the system. Clearly, the resulting amount of storage capacity of about 1540 GWh is substantially higher than the one derived from calculations with 770 GWp PV installed in Europe. Table II gives an overview of the considered scenario settings. As can be seen from the table the number of conducted whole-year calculations adds up to 12.

TABLE II CALCULATION SCENARIOS

Installed PV, GWp	**Total storage capacity in Europe in GWh**		
	Scenario 1	***Scenario 2***	***Scenario 3***
770; 1155; 1540; 1925	none	290	1540

The calculation of quantities associated with storage operation implemented in the model takes place according to the rules described in the following. In the equations below $P_{i,h}$ stands for the active power dispatched by the OPF algorithm at a particular node i on a particular hour h. $P_{PVi,h}$ denotes residual PV power after netting of PV power available a priori with the demand. This a priori netting ensures that as much PV power as possible is consumed by the demand in the network at the corresponding transmission node. $P_{N,STORi}$ denotes the nominal power of the aggregated storage unit at node i whereas $SOC_{i,h}$, $SOC_{i,h-1}$ and SOC_{MAXi} stand for current state of charge (SOC), SOC in the previous simulated hour and the nominal storage capacity of the storage unit at node i, respectively. The hourly time resolution means that hourly power and energy values are mutually interchangeable. Consider the case where dispatched power on a particular hour and node is below the available PV power:

$$SOC_{i,h} = \min\{SOC_{i,h-1} + \min(P_{N,STORi}, (P_{PVi,h} - P_{i,h})), SOC_{MAXi}\} \quad \text{if } P_{i,h} \leq P_{PVi,h} \tag{1}$$

Here the following applies for PV power stored $P_{PVSTOREDi,h}$, utilized $P_{UTILi,h}$ and curtailed $P_{CURTi,h}$:

$$P_{PVSTOREDi,h} = SOC_{i,h} - SOC_{i,h-1} \tag{2}$$

$$P_{UTILi,h} = P_{i,h} + P_{PVSTOREDi,h} \tag{3}$$

$$P_{CURTi,h} = P_{PVi,h} - P_{UTILi,h} \tag{4}$$

Hence, if only a part of available PV power is dispatched by the OPF algorithm, the remaining part will be stored by a unit at the same node if within the limits imposed by storage's nominal power and capacity.

For the case that power dispatched by the OPF algorithm at a particular node on a particular hour exceeds the available PV power, storage is dispatched to discharge and free up capacity, so that when PV is in excess again sometime later it can be stored again instead of being curtailed due to the fact that the storage is full.. This also means that storage is prioritized over other plants, which is surely a reasonable operation strategy when a lot of PV is present in the system. Weather forecasts will definitely play an important role when deciding how to operate storage in the future power system management. For the described case the following equations apply:

$$SOC_{i,h} = \max\{SOC_{i,h-1} - \min(P_{N,STORi}, (P_{i,h} - P_{PVi,h})), SOC_{MINi}\} \quad \text{if } P_{i,h} > P_{PVi,h} \tag{5}$$

where SOC_{MINi} stands for the minimum allowed storage state and

$$P_{PVSTOREDi,h} = 0 \tag{6}$$

$$P_{UTILi,h} = P_{PVi,h} \tag{7}$$

$$P_{CURTi,h} = 0 \tag{8}$$

Last, in the case that no PV but only residual load is present at a node, storage is set to cover the load limited by its nominal power and remaining capacity. If the load could be completely covered, remaining storage capacity is made available to the rest of the system.

III. WHOLE-YEAR CALCULATION RESULTS

This section presents results obtained after calculations of complete years in accordance with the distribution of PV installations given in Table I and scenarios described in section II.C.

A. *Scenario 1: no storage*

In scenario 1 no storage was considered to be available meaning that PV power that is present in abundance at one node can only be transported by means of the transmission grid to other locations up until the thermal limits of the lines are hit. Relevant quantities can be seen in dependence of total installed PV capacity in Europe in Figure 3.

Starting with 770 GWp of installed PV, less than 1% of annual PV energy available in abundance at certain nodes cannot reach other locations to be utilized solely due to grid restrictions, as there is not a single hour in the year when total power available from PV exceeds the total demand in the system. This is the result of PV dimensioning for a light-load day in summer as described in section II.B. In this case PV is able to supply around 17% of the yearly load. As the installed PV capacity increases by 50% to 1155 GWp, curtailment can be seen to have increased to over 6% in total, and the largest part of it is still caused by the grid restrictions. However, there are some hours in a year now where the total energy available from PV exceeds the total amount of load in the system such that the surplus amount could not be consumed even if the grid were not the limiting factor and is therefore ascribed to missing load. This quantity grows further with increasing PV capacity and at some point shortly after 1700 GWp, PV curtailed due to missing load exceeds the amount of curtailed energy caused by grid restrictions. The latter share exhibits a saturation behavior staying relatively constant at 10% of total available PV energy from about 1550 GWp on. This means that up to this amount of curtailed PV could be saved by enforcing the grid appropriately.

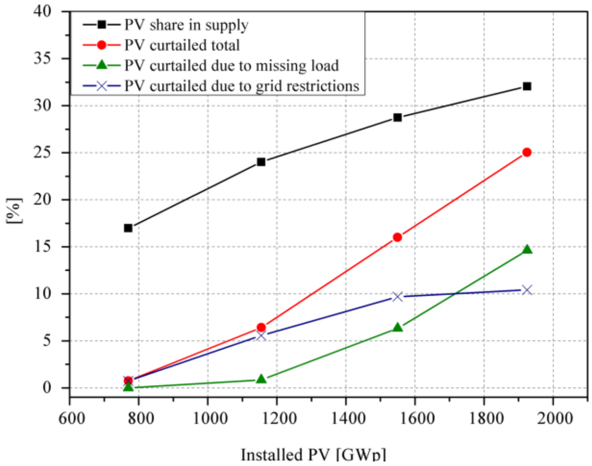

Figure 3: Calculation results for scenario 1 with no storage

The results of this scenario show that if the installed capacity of grid-connected PV systems should reach 1925 GWp without any grid enforcement after 2020 or storage options, 25% of available PV energy would be wasted. The PV's share in load coverage does not follow the proportionality of increasing installed capacity and thus only supplies about 32% of demand with 1925 GWp installed as compared to 17% being supplied by a 2.5 times smaller capacity of 770 GWp.

B. *Scenario 2: 290 GWh storage*

Storage simultaneously fixes the two factors that influence the amount of curtailed PV energy, namely the grid restrictions and excess of PV energy in relation to demand in the system in certain hours. The wasted energy caused by the latter factor can only be reduced through storage, while the effect of the former, in contrast, can be rectified either through storage or through grid enforcement. Hence, in the evaluation of annual curtailment figures the difference between the curtailed PV energy and excess PV energy on a particular hour is attributed to inadequate grid resources rather than to excess PV amount.

Figure 4 illustrates the quantities related to PV usage in this scenario. As can be seen, storage introduced into the system is now able to reduce the amount of curtailed PV energy to around 23% compared to 25% seen in scenario 1 for 1925 GWp of installed PV. This seems to be a modest number, however the absolute amount of avoided curtailed energy still adds up to nearly 51000 GWh per year, which corresponds to electricity consumed by Portugal in 2011 [8]. Storage essentially shifts the curtailment curves to larger values of installed PV capacity by a certain degree.

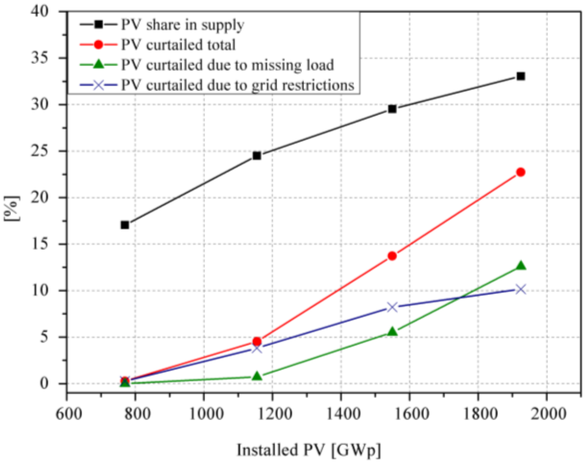

Figure 4: Calculation results for scenario 2 with 290 GWh of storage

C. Scenario 3: 1540 GWh storage

The effect of a larger storage than the one considered in the previous scenario is visible in Figure 5.

Up until 1155 GWp the storage which has been dimensioned to attend this very amount of PV installed in the system is able to capture almost the complete excess PV energy on all nodes and inject it into the system at a later time thus effectively keeping the curtailment down at well below 1%. It also significantly contributes to reduction of curtailed PV energy caused by grid restrictions. With 1540 GWp PV in the system the curtailment totals to 5%. In the end, with 1925 GWp present in the system the PV's share in load supply adds up to about 38% under a curtailment of about 12% which is mostly attributed to grid restrictions. In the present case appropriate grid enforcement would contribute significantly to reduction of the total curtailed PV energy.

The results show that even about 2000 GWp of PV in the system could be feasible provided that the grid is expanded in appropriate locations so as to enable transport of abundant PV energy at some nodes to others where this resource is scarce. A large damping effect is provided by storage with a total capacity across Europe of 1540 GWh, which is equivalent to the full capacity of nearly 31 Mio. electric vehicles, which is a quite significant number although it could underlie significant variations considering possible breakthroughs in terms of higher energy density of future batteries[1]. Besides, Germany alone plans to have 6 Mio. electric vehicles rolling on its streets by 2030 as stated in [7] such that the above number of 31 Mio. in total for the whole of Europe appears to be a realistic number by 2050. In addition, other storage technologies, such as compressed air energy storage could be available on a wide scale by then.

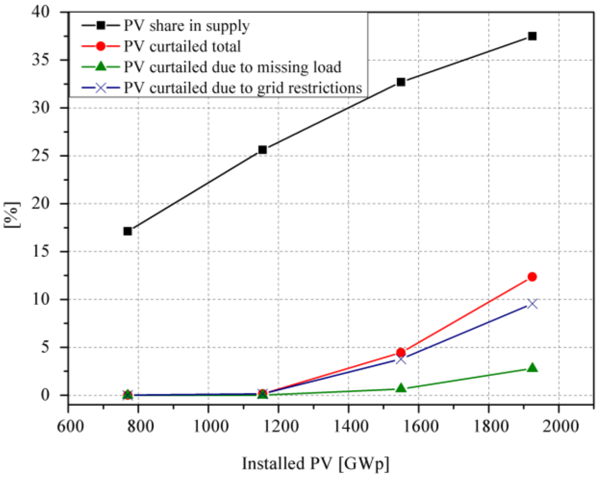

Figure 5: Calculation results for scenario 3 with 1540 GWh of storage

Figure 6 compares the number of annual average full loads hours reached by PV in all Europe for the three considered storage scenarios. Compared to scenarios 1 and 2 storage dimensioned for 1155 GWp of installed PV in the European power system in scenario 3 is able to increase PV usage substantially, even for larger installed capacities.

Summarizing, it has been shown in the present study that curtailment of PV energy can be reduced significantly if storage is dimensioned and placed strategically on specific nodes in the transmission system. It can be thus concluded that around 30 to 40% of annual demand in Europe can be feasibly covered by PV. That is, the amount of curtailed PV energy is acceptable in relation to the amount of storage that needs to be built. Any further expansion of PV capacity is likely to represent a high economic burden owing to the disproportionately high amount of required storage capacity.

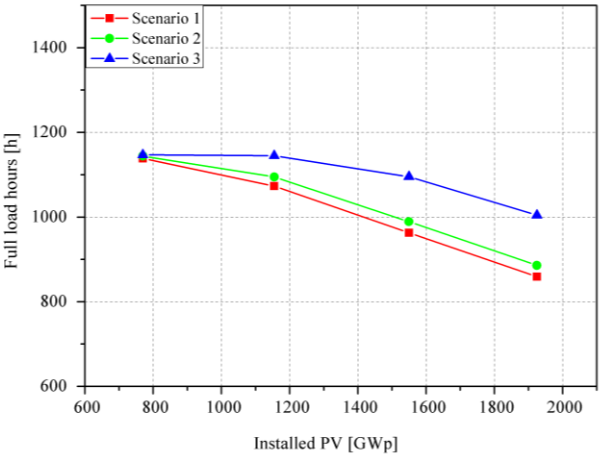

Figure 6: Comparison of full load hours of PV in Europe for different scenarios

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[1] 50 kWh per EV were assumed with reference to the Tesla Roadster

IV. CONCLUSIONS

In this work a methodology is presented that aims at an optimal placement of a large amount of grid-connected photovoltaic installations according to the solar irradiation potential in Europe and under consideration of restrictions imposed by the European transmission network.

The transmission restrictions lead to a well-distributed placement of PV capacities to match the distribution of the demand. The resulting distribution is kept while the total installed capacity is increased proportionally up until nearly 2000 GWp of installed PV while conducting optimal power flow simulations of a complete year in order to assess the curtailment of PV associated with excess PV energy and insufficient transmission capacity. The influence of strategically placed and dimensioned storage capacities is determined in several simulations scenarios demonstrating a potential for significant reduction of curtailed PV energy in the interconnected European grid under a large-scale deployment of distributed storage systems. With 1540 GWh storage capacity in the system, which could be constituted by, for example, electric vehicles, compressed air energy storage and others, approximately 1550 GWp of PV covering about 33% of the annual demand can be accommodated by the system with a 5% annual curtailment of PV energy. Demand side management could provide for a shift in diurnal load cycle helping to keep the PV power and demand in the system well-correlated. Appropriate grid enforcement could further reduce the amount of curtailed PV energy. For example, PV's share in load coverage could be increased to 38%, which however would lead to 12% curtailment unless necessary grid extension or additional storage capacity is provided. Further expansion of installed PV capacity aimed at increasing PV's share in load supply would necessitate disproportionately high storage and grid extension to keep the amount of curtailed energy low.

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