Value of PV energy in Germany

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ABSTRACT

This paper presents a detailed assessment of the value of photovoltaic energy within the German energy supply structure, taking into account the correlation between actual consumption and local power generation. Contrary to previous statistical approaches, this paper takes a new dynamic approach, modelling the dynamic behaviour of the PV power generation as a one-year time series. A comparison with the time series of the power demand allows assessment of the value of PV energy. The value of PV energy mainly results from its ability to substitute conventional power generation and the benefit of this kind of decentralized power generation for network stability and quality. An evaluation of these aspects is carried out for the year 2005 and a likely scenario in 2015.

Introduction

Power generation using PV power plants has achieved an order of magnitude in Germany that has become relevant for energy supply within a short period of time. Assuming a continuation of the enormous growth rates of previous years, PV will have a secure place in power supply. Its role must therefore be more carefully assessed from the point of view of energy provision, especially considering its correlation with actual consumption and local power generation. In order to give a detailed evaluation of PV supply, its temporal and spatial variations have to be considered.

This new approach was developed in a recent study entitled 'Rolle der Solarstromerzeugung in zukünftigen Energieversorgungsstrukturen – Welche Wertigkeit hat Solarstrom?' ('The Role of Solar Power Generation in Future Energy Supply Structures – What Value Has PV Energy?'). The study was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the German Solar Industry Association (BSW) and the European Photovoltaic Industry Association (EPIA) and includes contributions from Fraunhofer Institute for Solar Energy Systems (FhG-ISE) and meteocontrol GmbH.

Appropriate evaluation of PV energy

The differential costs of EEG [1], calculated as the feed-in tariff reimbursements minus costs of alternative power generation, were examined in a BMU Report [2]. This report established that detailed analyses of the most appropriate sources of electricity from renewable energy are urgently required in order to draw conclusions about further development of the EEG. Based on this recommendation, investigations into the value of PV energy were carried out in the actual study in order to make the requested proper assessment.

Two important points have to be considered:

- The potential of PV to substitute conventional electricity production and power plant capacity where not only base load, but medium and peak load can be supplied through correlation with actual consumption; and
- The potential of decentralised energy generation to save costs in grid operation, by avoiding losses in transmission, and to allow a more secure and efficient operation of the distribution network.

This approach allows a more detailed description of the use of power generation by PV systems than was possible in [2] for pragmatic reasons. This newly developed procedure correlates the dynamic of PV power generation and the dynamic of electricity consumption allowing for a better quality assessment for the value of PV energy than has so far been possible using statistical approaches. To represent the development of the value of PV energy, a scenario for 2015 was developed along with the reference scenario for 2005.

Modelling Germany's PV power generation

In order to account for dynamic effects, a high-resolution model capable of computing the supply of PV throughout the year with a temporal resolution of 15 minutes was developed. Figure 1 shows the procedure schematically. Based on irradiation and temperature data for 120 locations in Germany (from the University of Oldenburg and the German Meteorological Service DWD), time series of standardized PV power generation were computed for every location and for different installation types. In regards to installation, two different technologies (crystalline and non-crystalline), 17 different orientations and five different installation environments (ground-based, flat-roof, on-roof, integrated in-roof, façade) were examined and weighted statistically according to surveys of the German Solar Industry Association (BSW).

A parameterized transforming algorithm is used to extrapolate the PV power generation of several representative sites to PV power generation in grid regions as well as throughout Germany. This algorithm uses two types of entry parameters:

- the standardized PV power generation for the representative sites (result of the first step); and
- the spatial distribution of installed PV capacity.

In 2005 a PV capacity of 1,893MWp was installed. According to statistics published by Photon, the spatial distribution is connected to 875 distribution networks. An installed PV capacity of 12GWp is assumed for 2015. As no forecast on spatial distribution adjusted to distribution networks is available, a distribution adjusted to federal states is chosen, using the scenario assumptions of the BSW for this study.

The calculated time series of power generation were compared to data of PV installations measured by meteocontrol in 2005. The analysis of different sites reveals only low differences between computed and measured data (difference in whole energy generation 1-10% and root mean square error (RMSE) 23-25W/kWp). For this reason, the computing method and the models were assumed to be appropriate for this study and the following analyses.

Substitution of conventional power generation

The assessment of the substitution of conventional power generation requires more than solely taking an average price at the European Energy Exchange (EEX) for comparison or the costs of base load power plants. A new approach was developed to ameliorate the value of comparison. It allows the electricity generation to be classed by power plant type (base, medium and peak load power plants). In this way, the saved generation costs for the different types of power plants can be individually determined.

For such a detailed approach, a one-year time series with a temporal resolution of 15 minutes of PV supply were taken for the year 2005 (2GWp installed PV capacity) and for the projected scenario of 2015 (12GWp installed PV capacity) and contrasted with the load curve. The load curve data for 2005 can be collected from public information on grid load provided by the four transmission network operators.

To assess the time series of load in 2015, it is assumed that the following two parameters cause a variation from the load curve in 2005:

- the increase of electrical power used for air conditioning (summer peak load increases by approximately 3.5GWp between 2005 and 2015); and
- the increase of wind power generation from 17 to 30GW [3].

Using this dynamic approach, the effects of the substitution of conventional power generation were investigated. The benefit of this substitution consists of four different components:

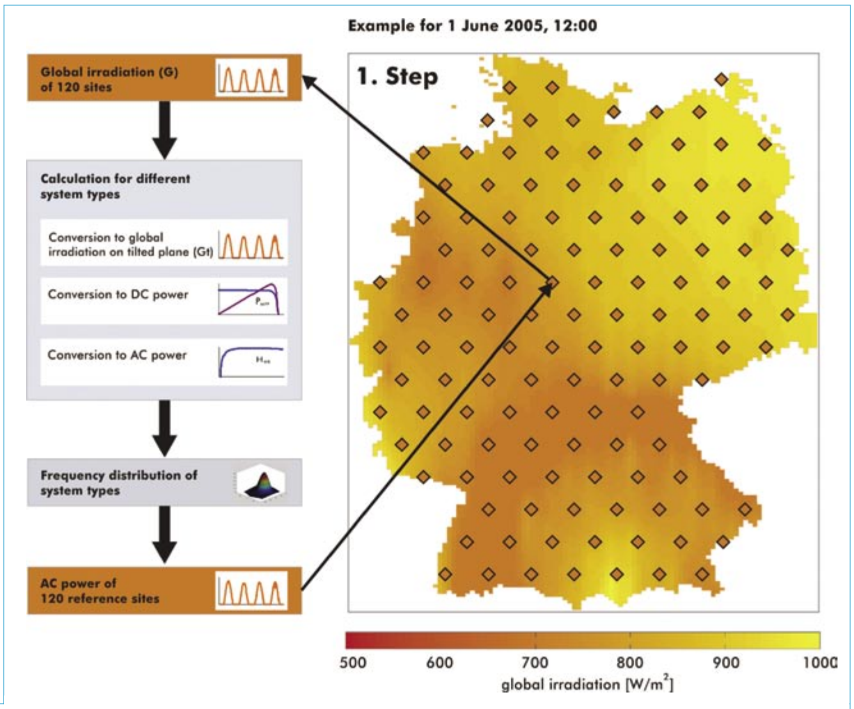
1. Avoided variable power generation costs of the conventional base, medium and peak load power plants;
2. Avoided damage costs of CO_2 emissions by substitution of fossil fuels;
3. Avoided fixed power generation costs of the conventional power plants (power plant capacity effect); and
4. Additional balancing costs caused by the variations of PV power generation.

Avoided variable power generation costs

The dynamic approach for the investigation of avoided variable power generation costs demands that power generation be classed by power plant type. According to the different types of power plants (base, medium and peak load) and the different types of fuel used to supply the electric power in the different load sectors, the savings differ.

Coal-fired and gas-steam power plants are both used to supply medium and peak load. The study does not attempt to form a detailed distinction between medium and peak load power plants, thus allowing a clear view of the substitution effect in summation. Further, it is assumed that base load is constant during working days within one season. The capacity results from the minimum of the weekly averaged hourly profile; accordant assumptions are made for the weekend base load.

Two cases are taken into consideration in the examination of savings accrued by use of PV power generation: a reference case without PV power generation and a scenario with a distinguished installed PV capacity. For these two cases, the consumption is classed in base, medium, and peak load and accumulated over the year. The contrast between the consumption in the two scenarios classed



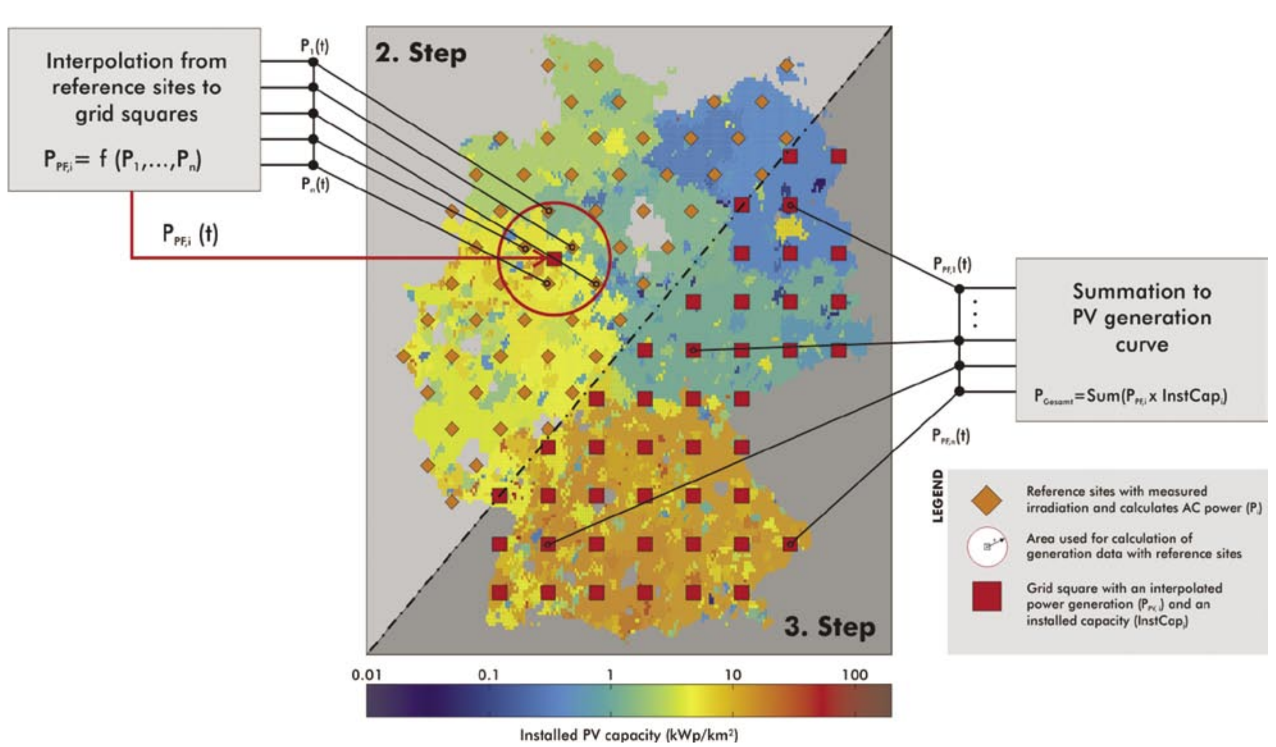


Figure 1. Calculation approach for time-series generation of PV energy in Germany.

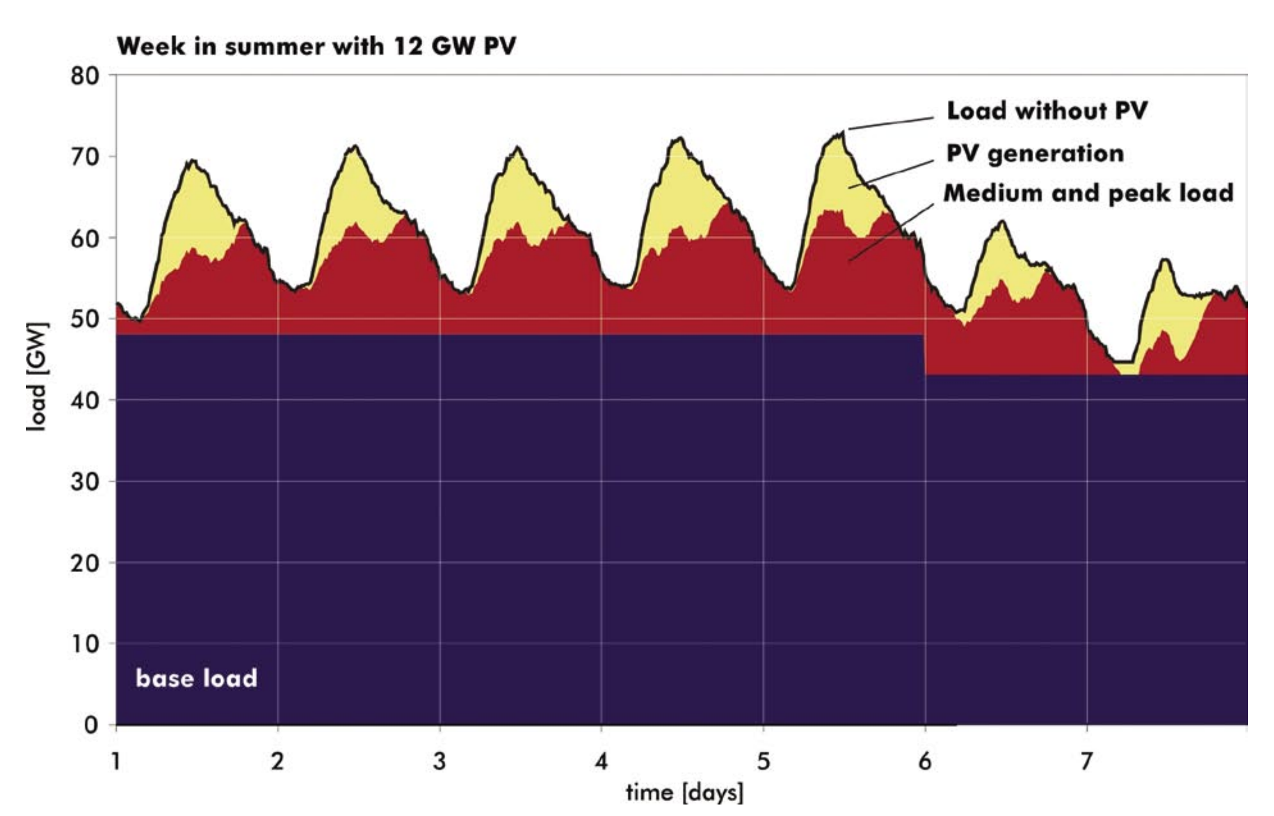


Figure 2. PV generation substitutes highlighting medium and peak load.

by load sectors represents the avoided power generation from conventional power plants caused by PV power generation.

Figure 2 gives an example of the distribution of the total load to base load (blue) and medium/peak load (red) in a summer week assuming an installed PV capacity of 12GWp. The reduction of consumption of medium/peak load due to PV power generation is evident. In the years 2005 and 2015, annual PV power generation is split into 7% base load energy and 93% medium/peak load energy.

The predominant part of PV energy is used to supply medium/peak load. For this reason, solar energy will contribute to a large extent in supplying the variable part of the load, which is conventionally supplied by coal-fired and gas-steam power plants. The power generation costs of these technologies range from 30% (coal-fired power plants) to 50% (gas-steam power plants) higher than the costs of base load power generation.

A range of fuel costs (only lignite/coal-energy-mix – lignite/coal/natural gas-energy-mix 2005 – lignite/natural gas-energy-mix) is taken into consideration to allow differentiation between coal-fired and gas-steam power plants. These three energy mixes allow calculation of the real substitution effect. Three different rates of price trends are considered for the scenario of 2015 [4]. With these basic assumptions, avoided variable power generation costs (respective to energy mix used) amount to approximately 2.5; 3.7; 5.1c€$_{2005}$/kWh$_{PV}$ (2005) and approximately 2.5; 4.4; 6.8c€$_{2005}$/kWh$_{PV}$ (2015) (excluding external costs).

In this context it must not be ignored that avoided fuel costs are minimal at a 100% level of coal use, but saved damage costs of CO_2 emissions are at the maximum. Accordingly, at a 100% level of use of natural gas, the saved fuel costs are maximal but avoided damage costs of CO_2 emissions are minimal. This trade-off has to be taken into consideration to allow a proper assessment of cumulated benefits later in this study. Therefore, saved CO_2 emission costs and avoided variable power generation costs cannot be considered independently. Both cost components were added for each technology, resulting in a combined range. Therein, the range of avoided variable power generation costs is 2.5; 3.1; 4.4c€$_{2005}$/kWh$_{PV}$ (2005) and 2.7; 3.6; 5.9c€$_{2005}$/kWh$_{PV}$ (2015).

Avoided damage costs of CO_2 emissions by substitution of fossil fuels

The most important factor regarding the avoided power generation costs using PV power generation is the saving of external costs. It is assumed that the damage costs resulting from CO_2 emissions comprise the biggest part of external costs. Using the damage cost range of 15; 70; 280€$_{2005}$/t$_{CO_2}$ [5] and assuming avoided CO_2 emissions from conventional medium load power plants of 323; 622; 783g$_{CO_2}$/kWh$_{PV}$, the result is 0.5; 4.4; 21.9c€$_{2005}$/kWh$_{PV}$ avoided damage costs of CO_2 emissions in 2005 and 2015. This calculation also includes CO_2 emissions with a range of 30; 65; 100g$_{CO_2}$/kWh$_{PV}$ during the life cycle of the PV plant.

Avoided fixed power generation costs (power plant capacity effect)

The power plant capacity effect of PV describes the capacity of conventional power plants that can be substituted by the installation of PV systems. Different approaches allow an investigation of the influence of PV energy on the necessary installed power plant capacity. By noting the PV power generation at the moment of annual peak load (1995-2005), it is ascertained that the effect of power plant capacity of PV is insignificant, as no PV system could supply power at the moment of annual peak load.

An alternative method to investigate the effect of power plant capacity is the so-called 'Effective Load Carrying Capability' (ELCC) [6]. The ELCC of a power plant is defined as the rise of load without further decrease of security of supply (here assumed to be 99%), which is made possible by this power plant. Applying the ELCC method, the power plant capacity effect amounts to 230MW in 2005 (11.5% of installed PV capacity) and 3,600MW in 2015 (30% of installed PV capacity) through the use of PV.

The use of wind energy mostly reduces load in winter and decreases the difference

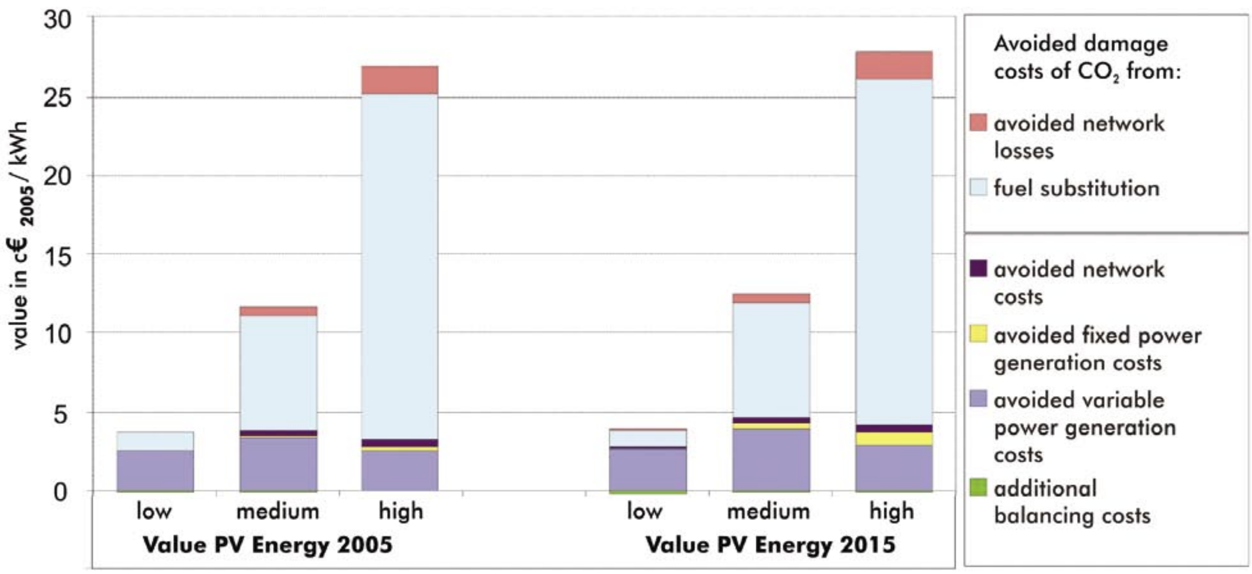


Figure 3. Value of PV energy split into the different value components.

between summer and winter peak load. This leads to a higher effect of power plant capacity of PV in 2015 (30GW wind) than in 2005 (17GW wind). Assuming the same boundary conditions, an effect of wind energy on power plant capacity of 6% in 2005 and 11% in 2015 is identified.

In evaluating the power plant capacity effect of PV, it is assumed that PV systems substitute gas-steam and coal-fired power plants, which are typically used to provide medium/peak load. They have investment costs of 550; 800; 1300€/kW. Assuming a lifecycle of 40 years, a discount rate of 5% and an average annual PV energy production of 900kWh$_{PV}$/kWp, the resulting benefits of substituted power plant capacity lie in the range of 0.0; 0.15; 0.3c€$_{2005}$/kWh$_{PV}$ in 2005 and 0.0; 0.4; 0.8c€$_{2005}$/kWh$_{PV}$ in 2015.

Additional balancing costs

As balancing group management does not have the ability to track the actual load exactly, balancing capacity is required. The available balancing capacity can be positive (increase of power generation) as well as negative (reduction of power generation). Three sources of error are known: errors in load forecasts, unplanned outages of power plants and errors in forecasts of wind power generation. In the course of the increasing relevance of PV power generation, the accuracy of its forecasts becomes equally important.

The examination of actual and future costs of errors in forecasts of PV power generation led to the determination of the balancing capacity range based on the approach and assumptions that were used in the German DENA study [3]. The statistical approach is based on an interaction of the probability functions of the different forecast errors. A forecast error of 10% of normalized root mean square error (NRMSE) was assumed for 2005 and 6% of NRMSE for 2015. This corresponds to the predicted improvement of wind forecasts [7].

Assuming a deficit level of 0.01%, the additional range of balancing capacity due to PV power generation is determined to be +19MW and -20MW (-1.0%/+1.2% of installed PV capacity) in 2005 and +280MW and -220 MW (-1.8%/+2.3% of installed PV capacity) in 2015. Under the assumptions of an average tariff for positive reserves of 65€$_{2005}$/(kW year) and for negative reserves of 25€$_{2005}$/(kW year) [8], the additional balancing costs are approximately 0.1c€$_{2005}$/kWh$_{PV}$ in 2005 and 0.2c€$_{2005}$/kWh$_{PV}$ in 2015.

Potential benefits for network operation

Due to their local/decentralized power generation, PV systems have the potential to generate benefits for network operation in three ways:

1. Reduction of network losses: power losses can be reduced as locally generated power substitutes power generated by more distant producers. Saved damage costs of CO_2 emissions caused by reduced power losses are closely linked to this.
2. Network capacity effect: local generation reduces the network's loading and releases additional transmission capacities. This allows a delay or even avoidance of grid extensions.
3. Benefit from the active provision of local ancillary services for network operation to improve its quality, security and efficiency.

Reduction of network losses

The analysis of transmission losses of German network operators shows that an upper limit of 10% in all layers of network and in annual average can be assessed. In the actual study, a lower range of avoided power losses of 2-8% is assumed due to PV power generation. This lower range is caused by the topological distribution of installed PV capacity that constrains the achievable reduction of network losses compared to an ideal topological distribution. Assuming costs of 6c€$_{2005}$/kWh$_{PV}$ for network losses (according to internet publications of network operators), the result is avoided network losses in the range of 0.1; 0.3; 0.5c€$_{2005}$/kWh$_{PV}$ (excluding avoided external costs).

Network capacity effect

A comparison to standard VDEW load curves (for households and for agriculture) shows that there is no PV power generation at the moments of annual peak load (typically in winter evenings). Data from enterprises with peak load during the day yields a different situation. However, a reduction of annual peak load cannot be guaranteed in this case because PV power generation can be near to zero at the moment of annual peak load.

An approach with the ELCC also shows that the network capacity effect can be neglected in this study. In future, different behaviour of use (e.g. air-conditioning and energy management) could lead to more correlation with PV power generation and the benefit of the network capacity effect could increase. Distribution networks are usually not fully loaded.

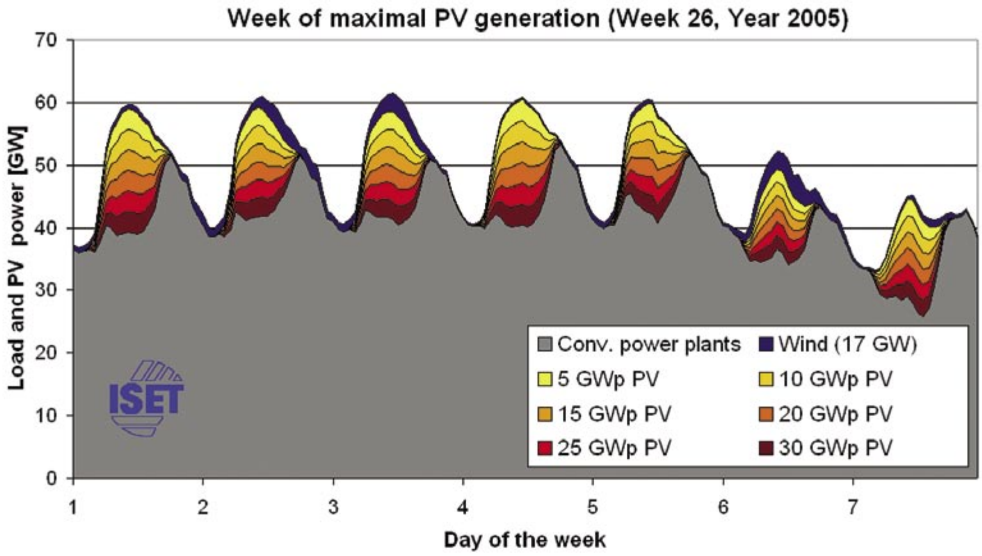


Figure 4. Influence of PV energy production to the load curve dependent on installed PV capacity. The load curve is shown for the week of maximal PV energy production (database: 2005, 17GW installed wind capacity).

This means that there is no benefit from any network capacity effect; this may change considerably with an increasing load in the future.

Benefit of active provision of ancillary services for network operation

Possible ancillary services as well as the economic attractiveness of their provision were examined in the course of this study. With the exception of primary control and positive balancing capacity [8], PV systems are suited to the provision of ancillary services due to their decentralized installation. In many cases, a quantification of the benefit is difficult to achieve because the possibilities of contribution and respective reimbursements are absent. In the overall result of this study, the benefit from providing ancillary services is currently assumed to be insignificant. In the future, an enormous increase of this benefit value is possible, especially with regard to active distribution network management. Power quality and reliability can be improved by the use of PV systems and reactive power can be provided very cost-efficiently [9].

Avoided costs of network operation

The avoided costs of network operation result mainly from the avoided costs of network losses in the range of 0.1; 0.3; 0.5c€$_{2005}$/kWh$_{PV}$. The other two factors are considered to be insignificant to the actual study. As with the substitution of conventional power generation, the avoided damage costs of CO_2 emissions from the avoided network losses must also be taken into consideration. This leads to avoided damage costs of CO_2 emissions from avoided network losses in the range of 0.0; 0.2; 1.8c€$_{2005}$/kWh$_{PV}$.

In this context, it must be emphasised that the investigations in this report are targeted at average benefits in Germany, though case studies with considerably

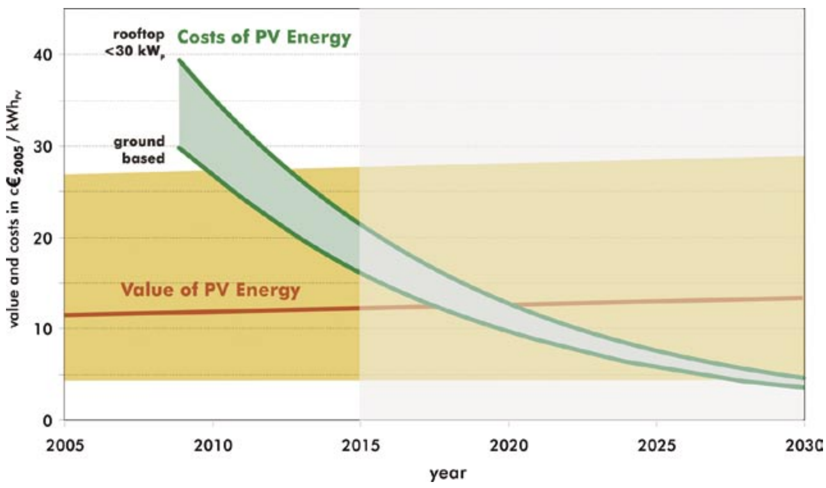


Figure 5. Comparison of costs (reference: EEG feed-in tariffs according to the blueprint for EEG 2009, including 2% inflation) and the range of value of PV energy determined in this study (in €$_{2005}$).

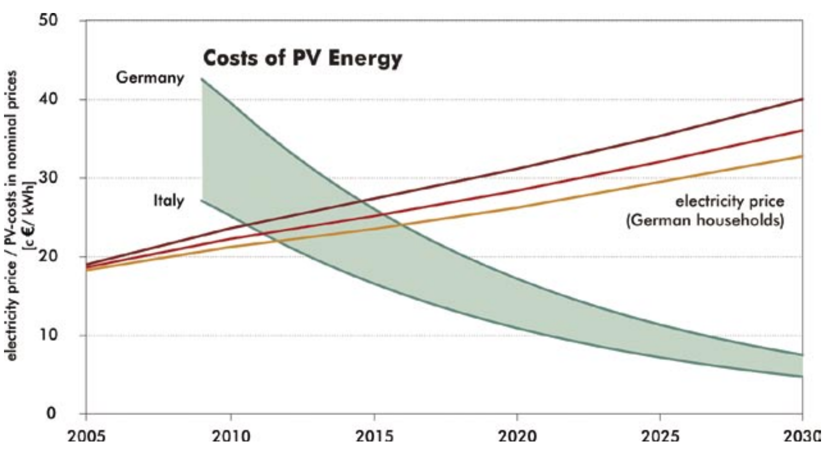


Figure 6. Comparison of the value of PV energy and the electricity tariffs for households in determination of grid parity.

Power Generation

higher benefits are possible. It is assumed that the results of the presented approach can be applied for 2005 and 2015.

Conclusion

The result of the study with the given scenarios for 2005 and 2015 is shown in Figure 3. A total value of PV energy in a range of 3.5; 11.5; 26.9c€$_{2005}$/kWh$_{PV}$ in 2005 and 3.6; 12.3; 27.7c€$_{2005}$/kWh$_{PV}$ in 2015 is identified. (Value given in 2005 prices.)

The effect of avoided damage costs of CO_2 emissions is evident. The underlying assumptions for these values are associated with great uncertainties and are not further examined in this study. An alternative approach of these costs using the avoidance costs of CO_2 emissions may show an increase of these costs in the future.

A number of factors of the value of PV energy were not considered in this study. Among these are hedging of price fluctuations, taxes and duties, and external economic influences such as the labour market. A combined investigation that includes wind energy and other renewable energies is recommended. It can reveal further synergy effects that can increase the total value significantly.

An important finding of this study is the high correlation with the demand curve that allows integrating PV into the existing power supply structure up to an installed capacity of 30GWp without important structural changes in the portfolio of power plants (Figure 4) because of the predominant replacement of controllable medium/peak load power plants. Poorly controllable base load power plants, on the other hand, are affected in their operation at low rates. Therefore, any additional storage capacity is not necessary.

Furthermore, a predominant decentralized and local PV power generation reduces costs for the network operation, especially with regard to the transmission network. An additional advantage of PV power generation is the cost-efficient possibility of providing ancillary services. They can be integrated effectively in network management systems and can contribute to an improvement of network stability and quality.

In conclusion, Figure 5 compares the assessed value of PV energy with the feed-in tariff reimbursements. The feed-in tariffs according to the blueprint of the new EEG of December 5th, 2005 are used as reference. Viewed in relation to PV energy costs for 2009, the range is between 32c€/kWh$_{PV}$ for ground-based PV installations and 42.48c€/kWh$_{PV}$ for rooftop installations <30kWp. This blueprint envisages a reduction of 7% for 2010 and 8% starting from 2011. An inflation rate of 2% is assumed and calculated at 2005 prices in an attempt to represent the actual remuneration. Depending on the assumptions made, especially regarding avoided damage costs of CO_2 emissions, the value of PV energy will reach the costs according to the feed-in tariff between 2011 and 2030 as shown in Figure 5. The ascertained values for 2005 and the scenario in 2015 are therefore continued proportionally until 2030. The medium value intersects during the years 2017 and 2020.

Alternative approach: grid parity

This newly developed approach for the determination of the value of PV energy complements other existing and commonly-used approaches. One approach takes the point of view of a household and calculates the so-called grid parity (in relation to date) when generation costs or feed-in tariffs are below private power purchase tariffs. From the date of grid parity, the use of generated PV energy will be more economic than its feed-in. For this reason, this date also represents the point at which the EEG-reimbursement could be replaced by other types such as Net-Metering.

For example, a household with an annual electricity consumption of 3500kWh and power purchase costs according to Eurostat, with three different inflation scenarios [4]. The expected feed-in tariff of PV energy generation according to the blueprint of EEG of December 5th, 2007 is taken for reference for the costs of German PV feed-in. In Italy, where higher irradiation would lead to an additional energy production of approximately 57%, the costs of PV feed-in are considerably lower.

Figure 6 shows the comparison between Germany and Italy. In Germany, grid-parity will be reached in 2014-2016. Assuming the same acquisition tariffs, but taking into account the Italian irradiation levels, grid parity would already be reached in 2010-2011.

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References

[1] German Parliament 2004, 'Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich vom 21. Juli 2004,' Bundesgesetzblatt, Jahrgang 2004, Teil I, Nr. 40, Bonn.

[2] Nitsch, Staiß, Wenzel & Fischedick 2005, 'Ausbau Erneuerbarer Energien in Stromsektor bis zum Jahr 2020 - Vergütungszahlen und Differenzkosten durch das Erneuerbare-Energien-Gesetz,' BMU, 2005.

[3] DEWI/E.ON Netz/EWI/RWE Transportnetz Strom/VE Transmission: 'Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020' (in a study commissoned by Deutschen Energie-Agentur GmbH (dena), Köln, Germany).

[4] Nitsch 2007, 'Leitstudie 2007' (in a study commissioned by BMU).

[5] Krewitt, Schlomann 2006, 'Externe Kosten der Stromerzeugung aus erneuerbaren Energien im Vergleich zur Stromerzegung aus fossilen Energieträgern' (in a study commissioned by BMU).

[6] Perez, Margolis, Kmiecik & Schwab, 2006, 'Effective Load-Carrying Capability of Photovoltaics in the United States,' Solar Conference, Denver.

[7] ISET 2007, 'Optimierungsmöglichkeit en der Windenergieprognose und die Entwicklung des Prognosefehlers'(in a study commissioned by BMU: 'Bewertung der Optimierungspotenziale zur Integration des Windstroms in das Verbundnetz').

[8] Braun, M. 2007, 'Systemdienstleistungen für den Netzbetrieb,' *BWK*, Vol. 59, pp. 53-58.

[9] Braun, M. 2007, 'Reactive Power Supplied by PV-Inverters – Cost-Benefit-Analysis,' 22nd European Photovoltaic Solar Energy Conference, Milan, Italy.

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