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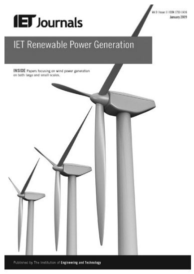

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Market value of solar power: Is photovoltaics cost-competitive?

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Abstract: This paper reviews the economics of solar power as a source of grid-connected electricity generation. It is widely acknowledged that *costs* of solar power have declined, but there is disagreement how its economic *value* should be calculated. 'Grid parity', comparing generation costs to the retail price, is an often used yet flawed metric for economic assessment, as it ignores grid fees, levies, and taxes. It also fails to account for the fact that electricity is more valuable at some points in time and at some locations than that at others. A better yardstick than the retail price is solar power's 'market value'. This paper explains why, and provides empirical estimates of the solar market value from a literature review, German spot market analysis, and the numerical electricity market model EMMA. At low penetration rates (<2–5%) solar power's market value turns out to be higher than the average wholesale electricity price – mainly, because the sun tends to shine when electricity demand is high. With increasing penetration, the market value declines – the solar premium turns into a solar penalty. In Germany, the value of solar power has fallen from 133% of the average electricity price to 98% as solar penetration increased from zero to 4.7%. This value drop is steeper than wind power's value drop, because solar generation is more concentrated in time. As a consequence, large-scale solar deployment without subsidies will be more difficult to accomplish than many observers have anticipated.

1 Introduction

Electricity from solar photovoltaics (PV) currently plays a limited role in global power generation, supplying not more than 0.4% of global electricity. However, it has been growing rapidly during the last years, driven by technological progress, economies of scale and deployment subsidies. By end of 2013, global PV capacity has reached 140 GW, a 14-fold increase since 2007, with most capacity being installed in Germany, China and Italy [1]. Many observers expect a continuous capacity growth, driven by a variety of factors ranging from climate policy and security of supply to industrial policy and local energy independence. In particular markets, PV plays a significant role today, supplying close to 7% of Italy's and 5% of Germany's power demand.

Technological learning as well as economies of scale have reduced costs throughout the PV value chain. Competition has helped to drive down equipment prices dramatically. Costs for turnkey small-scale rooftop installations are now 1600 €/kW in Germany, down by two-thirds since early 2006, corresponding to levelised electricity costs (LEC) of about 140–200 €/MWh. [20 years life-time, 3–8% real discount rate, 850 full load hours (10% capacity factor) and O&M costs 15 €/MWh.] This is less than household retail electricity prices in many markets – hence solar PV has already reached 'grid parity'. Does this mean solar power is competitive with other electricity generating technologies?

This paper reviews the economics of solar PV by appraising its (private) competitiveness and (social) efficiency as a source of grid-connected electricity generation. Section 2 reports on recent cost development. Section 3 argues that the concept of 'grid parity' is flawed as it compares generation costs to retail prices. Section 4 proposes 'market value' as an economically sound yardstick for efficiency analysis. Section 5 reports market value estimates from empirical prices and a literature review. Section 6 introduces the numerical model EMMA and presents model-based market value estimates. Section 7 concludes.

2 Riding down the learning curve? Solar power's impressive cost drop

The remarkable growth of solar power has been accompanied by a decrease of equipment cost [2, 3]. Prices for solar panels have decreased, a reason for and most probably also a consequence of the deployment boom. Retail prices for small-scale roof-top installations in Germany have fallen by 15% p.a. during the last 7 years and reached 1600 €/kW [4]. However, both retail and wholesale prices seem to have stopped falling since the end of 2012 (Fig. 1). Large regional cost differences continue to exist, with prices in the U.S. being twice as high as in Germany [5, 6]. Solar LEC varies widely, depending on resource quality, equipment prices and discount rate. Under favourable circumstances, they might be as low as 100 €/MWh. Nemet [7], Hernández-Moro and Martínez-Duart [8] and Bazilian *et al.*

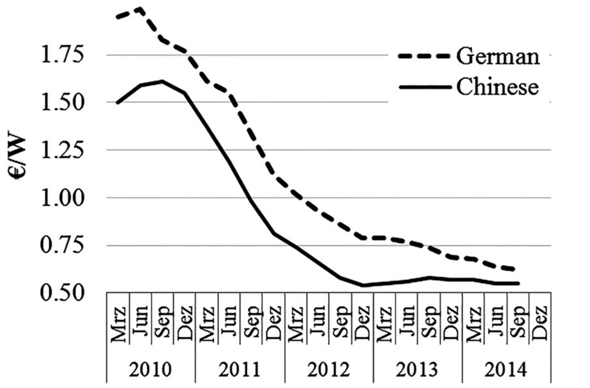

Fig. 1 *Wholesale prices for PV modules have levelled off since late 2012, after falling dramatically the years before*

Source: own figure, data from pvxchange.com

[9] discuss and quantify the drivers for solar cost reductions, such as learning curves. Nordhaus [10] provides a sharp critique of the econometric identification strategy of such as learning curves. After decades of research, there is still no consensus in the literature to what extent the price drop reflects technological learning, and if learning can be expected to continue. In any case, assessing future cost development is beyond the scope of this paper. Instead, we focus on the value side of the competitiveness equation.

3 Grid parity: what is the right yardstick?

To assess the economics of solar power, one needs to compare the costs of generating electricity to the value of that electricity. Unlike most other electricity generation technologies, solar PV is modular. That means, it can be applied at small scale without major specific cost penalties. In contrast, coal, hydro and wind power plants feature significant economies of scale, such that they cannot efficiently be deployed in household size. Household PV assets often have a rated output of below 10 kW. A state-of the art double-block coal plant has a rated output of 1.5 GW – more than five orders of magnitude larger.

Naturally, small PV investors who also consume electricity locally compare solar generation costs to the price they pay for electricity on the retail market. In many cases, solar generation costs have dropped below retail prices. This phenomenon is called 'grid parity' or 'socket parity'. Household prices are now above 250 €/MWh in Germany and Denmark and above 150 €/MWh in most other European markets. Hence, it is cheaper for a household to generate electricity from solar power than buy it from a retailer. Some authors seem to suggest that once a technology has reached grid parity, its deployment is economically efficient [11–15]. This might sound straightforward, but is not the case. Grid parity compares generation costs to the retail price, but for economic assessments this is not the right yardstick.

Only about 20–40% of European retail electricity prices represent the cost of electricity generation. Grid fees, taxes and levies, and sales margins comprise the rest. Households' solar investments are profitable only because they avoid paying these items. However, grid operation costs are virtually independent from PV deployment [16]. In some cases, PV deployment might defer distribution grid investments [17, 18], in other cases it might increase investment needs [19–21]. Beyond a certain threshold, it certainly increases investment needs, even though there exist a wide range of technical measures to push this threshold [22, 23].

In economic terms, replacing electricity from retail markets with 'self-produced' solar power constitutes a negative externality: generating solar power locally has a negative impact on other economic actors, as they have to pay more for electricity networks, levies and taxes. Hence the concept of grid parity corresponds to a private, not a social, perspective: reaching grid parity might indicate that investments are profitable for the individual investors, but it does *not* indicate that they are efficient for society. [24] provides a model-based assessment of German solar externalities. To align private interests with society's needs, self-consumed solar PV generation should be subject to the same taxes as other generation, and grid fees should include capacity payments to reflect the true cost structure of electricity grids.

The economically correct yardstick to evaluate electricity generators, including distributed generation, is its 'opportunity costs', the costs of the generator that it replaces. Opportunity costs are quite well represented by wholesale electricity prices – to the extent that externalities of power generation [25–27] are internalised. However, even then, the valuation of solar power is not trivial: the temporal and spatial pattern of solar generation as well as its forecast errors need to be taken into account to construct an economically correct yardstick. One way of doing this is to derive solar power's 'market value'.

4 The concept of 'market value': accounting for variability

The market value of solar power is the average spot market value of electricity (€/MWh) generated by solar power. The wholesale price of electricity is different in every hour and can be different at every transmission node of the power system. To understand why this is the case, it helps to dig a little into the physics and economics of electricity.

4.1 Some physics and economics of electricity

It seems that electricity, being a perfectly homogeneous good, is the archetype of a commodity. Electricity, like other commodities, is traded via standardised contracts on exchanges. However, the laws of electromagnetism impose a number of constraints, which require an appropriate treatment of the good 'electricity' in economic analysis [28].

Particularly, electricity storage, transmission and supply flexibility is constrained. As an immediate consequence, the equilibrium wholesale spot electricity price varies over time, across space and over lead-time between contract and delivery: (i) since inventories cannot be used to smooth supply and demand shocks, the equilibrium electricity price varies (strongly) over time. Wholesale prices can vary by two orders of magnitudes within one day, a degree of price variation that is hardly observed for other goods, (ii) similarly, thermal constraints and Kirchoff's laws limit the amount of electricity that can be transmitted, leading to sometimes (very) significant price spreads even between close locations and (iii) moreover, because frequency stability requires demanding and supply to be balanced at every instant, but fast adjustment of power plant output is costly, the price of electricity supplied at short notice can be (very) different from the price contracted with more lead-time. Across all three dimensions, price spreads occur both randomly and with predictable patterns.

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In other words, electricity indeed is a perfectly homogenous good and the law of one price applies, but this is true only for a given point in time at a given location for a given lead-time. Along these three dimensions, electricity is a heterogeneous good. Fig. 2 visualises the three dimensions of heterogeneity by illustrating the wholesale spot prices in one power system in one year as a three-dimensional array.

Three-dimensional heterogeneity can be observed in real-world power markets. For example, at most European power exchanges, the market is cleared for every hour for each bidding area at three different lead-times (day-ahead, intra-day and real-time). American ISO-markets often feature an even finer granularity, clearing the market every 5 min for each of several thousand transmission nodes. Hence there is not *one* electricity price per market and year, but 100 000 prices (in Germany) or three billion prices (in Texas). This heterogeneity of electricity prices needs to be accounted for when estimating the value of electricity generated by solar power.

4.2 Market value of solar power

The varying price of electricity needs to be taken into account in any welfare, cost-benefit or competitiveness analysis of variable renewables [30–32]. In fact, it needs to be taken into account in the economic analysis of any generation technology [28]. It is in general *not* correct to assume that (i) the average price of electricity from solar power is identical the average power price or that (ii) the price that different generation technologies receive is the same. Specifically, the fact that the marginal costs of solar power are below the average electricity price or below the marginal costs of any other generation technology does *not* indicate that solar power is profitable. Still, this seems to be suggested by interest groups, policy makers and academics [33–35] (it might well be that the authors are aware that this is not the case, but readers frequently interpret figures in this way). The market value of solar can be below or above the average electricity price and above or below another generation technology. Comparing different technologies in LEC terms does not imply anything about efficiency of these technologies.

Formally, the solar market value $\bar{p}^s$ can be written as the solar-weighted electricity price of all T time steps in all N price areas at all T lead-times

$$\bar{p}^s = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{\tau=1}^{\mathrm{T}} s_{t,n,\tau} \cdot p_{t,n,\tau} \tag{1}$$

where $s_{t,n,\tau}$ is the share of solar generation in time t at node n that was sold at lead-time τ and $p_{t,n,\tau}$ is the respective price, one of the elements of the price array displayed in Fig. 2.

In some cases, the relative price of electricity from solar power is of interest. We define the 'value factor' [36, 37] of solar power here as the market value over the time-weighted average electricity price, the so-called 'base price'. Solar's value can be higher than the base price ('solar premium', [38] this issue), or lower ('solar penalty').

4.3 Approximation of market value

Facing incomplete information about the full matrix of electricity prices, we use a framework proposed by [39, 40] to approximate the solar market value. The framework rests on the idea that three intrinsic characteristics of variable renewables affect their market value, along the three dimensions of electricity heterogeneity introduced above (Fig. 3).

- The supply of solar power is *variable* (over time). At low penetrations, solar's market value is usually higher than the average price because of positive diurnal correlation with the load (correlation effect), at high penetration it falls below the

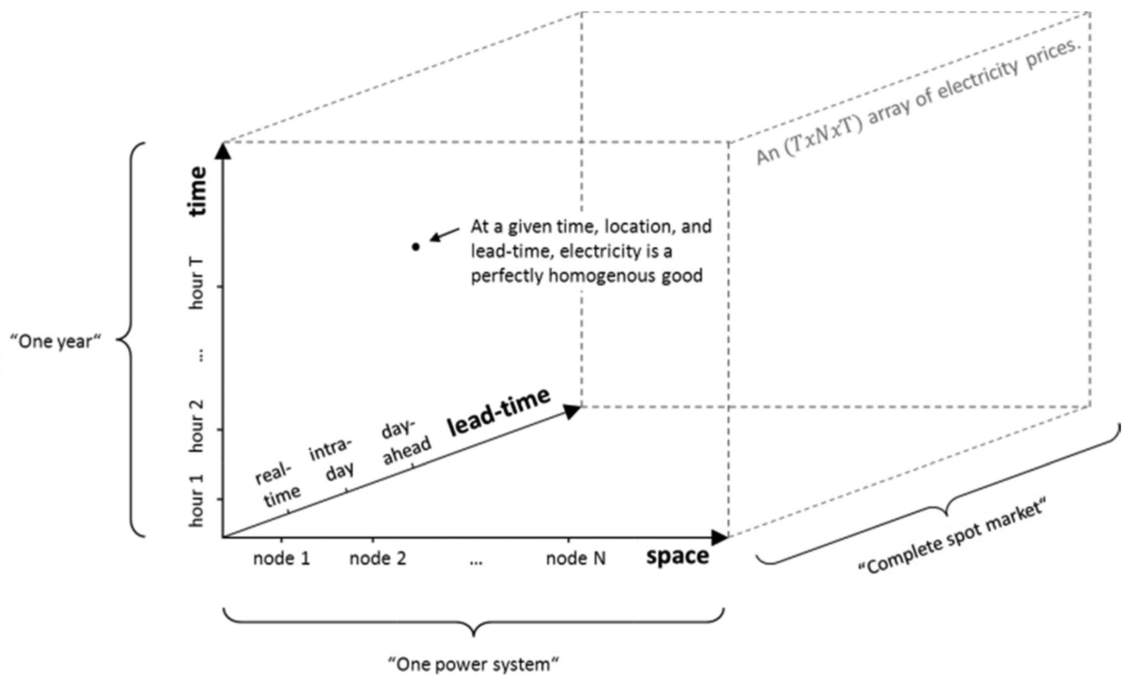

Fig. 2 *Array of wholesale spot electricity prices. Electricity price varies along three dimensions: time, space and lead-time*
Source: updated from [29]

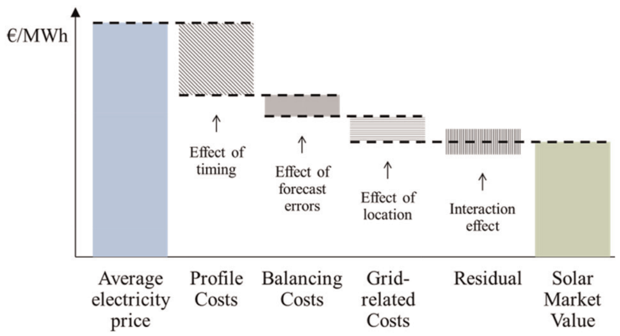

Fig. 3 *Average electricity price minus profile, balancing and grid-related costs gives approximately solar power's market value*
Source: updated from [39]

average electricity price because of the price-depressing effect of additional supply during sunny hours (supply effect). The impact of variability is called 'profile costs'.

- The output of solar power is *uncertain* until realisation. Forecast errors of solar generation need to be balanced at short notice, which is costly. These 'balancing costs' reduce the market value.
- Installations are bound to certain *locations*. Small-scale solar PV generators, if installed close to loads, typically benefit from supplying to a high-price area. This is called 'grid-related costs'.

All three 'costs' can materialise in the form of (increased) costs or (decreased) revenue, and they can be positive or negative

There are at least two separate branches of the literature that discuss the economic implications of wind and solar variability [41]. Economists often assess the 'energy value' of generation [30–32], while engineers estimate 'integration costs' [42, 43]. The framework used here allows for a unified and economically sound assessment of energy value and integration costs.

5 Market value estimates: market and literature

This section presents empirical evidence on solar PVs market value from observed market data and a meta-analysis of previously published studies.

5.1 Market data estimates

We use German market data for the years 2006–2013 to estimate the market value of solar power. Profile costs are calculated from day-ahead spot prices, balancing costs from imbalance prices. Solar forecasts and generation were taken from TSOs, spot prices from the power exchange, and imbalance prices from the TSOs. As Germany is a uniform bidding area, grid-related costs cannot be estimated from observed prices.

Fig. 4 shows the value factor calculated from spot prices. At low penetration rates, the solar factor was around 1.3 in Germany, driven by the positive diurnal correlation of solar power with demand. As the solar market share increased from 0 to 4.7%, the value factor declined by 35 percentage points. An OLS fit estimates the drop to be 5.5 percentage-points per percentage-point market share, more than twice as much as for wind power.

An alternative way of visualising the impact of solar generation on relative prices is the structure of spot price

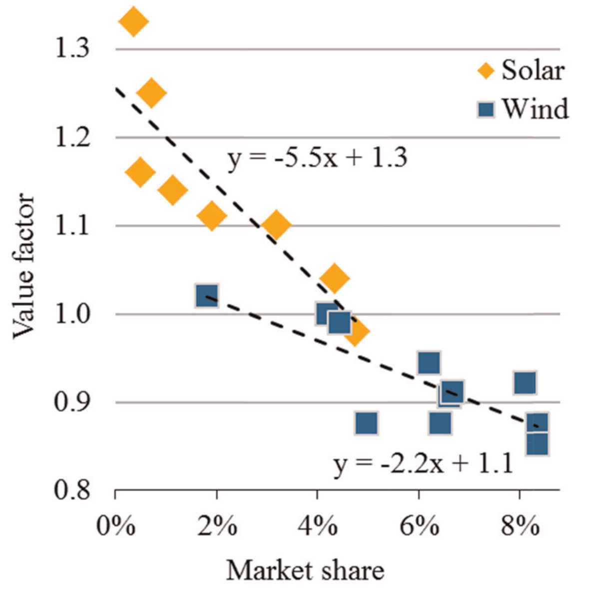

Fig. 4 *Historical wind and solar value factors in Germany from spot prices (reflecting profile costs). As solar penetration increased from 0 to 4.7%, its value factor decreased from 1.33 to 0.98*

during the day (Fig. 5). Over the years, the price peak around noon disappeared, 'shaved' by the additional electricity supply from solar power.

For deviations from schedules, all German generators have to pay the quarter-hourly 'imbalance price' [44]. We evaluate quarter-hourly TSO forecast errors for solar power with these prices to estimate balancing costs. Solar forecast errors are available for the years 2011–2013. The solar balancing costs for these years were 1.9, 3.0 and 1.9 €/MWh, respectively, or 4–7% of the base price.

5.2 Quantitative literature review

Table 1 summarises a number of studies that quantify the market value of solar power. Virtually all studies find value

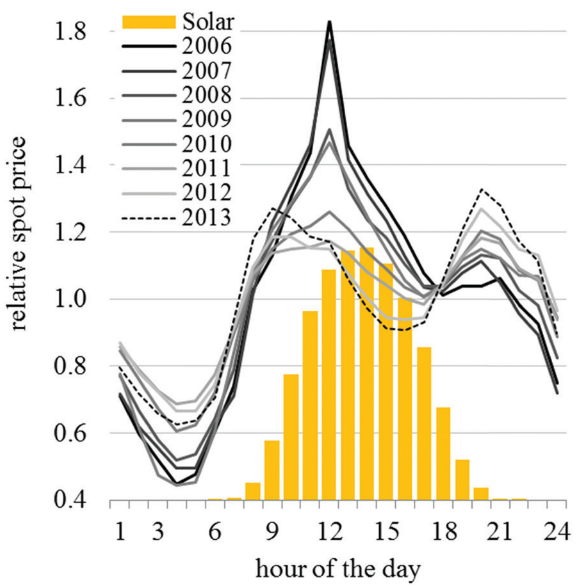

Fig. 5 *Daily spot price structure in Germany during summers from 2006 to 2013. Bars display the distribution of solar generation over the day*

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Table 1 Empirical literature on the market value of solar power

Prices	Reference	Region	Value factors estimates, at different market shares
historical prices	Borenstein [16]	California	1.0–1.2 for different market design (small)
	Sensfuβ [48], Sensfuβ and Ragwitz [49]	Germany	1.33–1.14 (0% and 2%)
	Brown and Rowlands [50]	Ontario	1.2 (small)
	Gilmore *et al.* [38]	Australia	1.4–1.8 in different states (small) 1.0–1.1 in different states (1.3%)
prices from dispatch model	Bouzguenda and Rahman [51], Rahman [52], Rahman and Bouzguenda [53]	'Utility'	only absolute value reported
	ISET [54], Braun *et al.* [55]	Germany	only absolute value reported
	Energy Brainpool [56]	Germany	1.05 (6%)
	Gilmore *et al.* [38]	Australia	1.0–0.85 (1.3–6%)
dispatch and investment model	Lamont [30]	California	1.2–0.9 (0–9%)
	Gowrisankaran *et al.* [45]	Arizona	0.9–0.7 (10–30%)
	Mills and Wiser [32], Mills [46]	California	1.3–0.4 (0–30%)
	Nicolosi [47]	Germany	1.02–0.7 (0–9%)

factors above unity at low (<2–5%) penetration, but significantly lower value factors at higher penetration. The methodologically most sophisticated studies by [30, 32, 45–47] report value factors in the range of 0.7–0.9 at 10% penetration and about 0.4–0.7 at 30% penetration. Fig. 6 summarises all studies. An OLS fit of all estimates results in a drop of 3.6 percentage-points value factor per percentage-point market share. At 15% penetration rate, solar's value factor is estimated to be 0.7.

The loss in market value potentially jeopardizes the long-term competitiveness of solar power. In the following section, we assess what can be done to mitigate the value drop.

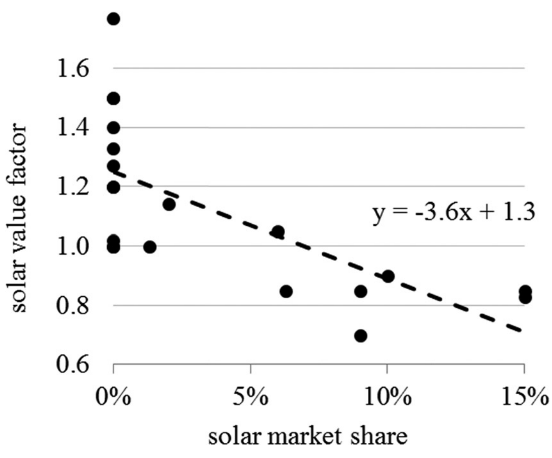

Fig. 6 *Solar market value literature. OLS-fit of all studies estimates the solar value factor to fall from 1.3 at zero penetration to 0.7 at 15% penetration*

List of references is provided in Table 1

6 Market value estimates: model results

This section gauges the solar market value using the European Electricity Market Model EMMA. Key levers are identified that help mitigating the value drop.

6.1 Model EMMA

EMMA is a stylised numerical dispatch and investment model of the interconnected Northwestern European power system that covers Germany, Belgium, The Netherlands, France and Poland. In economic terms, it is a partial equilibrium model of the wholesale electricity market. It determines optimal or equilibrium yearly generation, transmission and storage capacity, hourly generation and trade, and hourly market-clearing prices for each market area. Model formulations are parsimonious while representing wind and solar variability, power system inflexibilities and flexibility options with appropriate detail. Solar in-feed series are derived from weather data taken from the re-analysis model ERA-Interim.

All results shown in this paper are long-term value factors, corresponding to the long-term economic equilibrium. For each model run, the amount of solar PV capacity is set to a level between 0 and 15% market share in energy terms, and the thermal capacity mix is determined endogenously ('greenfield approach'). If not stated otherwise, no wind power is added.

EMMA considers both profile and balancing costs. The former are implicit in the hourly electricity prices the model calculates. The latter is approximated by a spinning reserve requirement that is a function of installed solar capacity and a constant activation charge of 4 €/MWh. The value factors hence represent both the cost of forecast errors and the declining energy value as solar penetration increases. The model considers constraint interconnector capacity, but no internal grid constraints. Hence, grid-related costs are only partially accounted for.

EMMA has been applied previously in [29, 37, 57]. The model is open source; model documentation, equations, GAMS code and input data are available at http://www.pik-potsdam.de/members/hirth/emma.

6.2 Model results

Fig. 7 shows estimates of the solar value factors for market shares between 0 and 15% under benchmark (central value) parameter assumptions. 'Benchmark' estimates refer to best-guess parameter assumptions, such as a CO_2 price of 20 €/t, a natural gas price of 25 €/MWh, a hard coal price of 125 $/t, current demand level and structure, current storage capacity, inflexible heat-and-power and balancing power provision, summer maintenance of thermal plants and median assumptions on thermal investment costs. These assumptions are varied one-by-one in the following. At low penetration, the value factor is 1.3, consistent with market data. It drops to 0.6 at 15% market share. This corresponds to 4.6 percentage-points value factor per percentage-point market share, just between the market estimate (5.5 percentage-points) and the literature review (3.6 percentage-points). A reason for the estimated curve to be flatter than market estimates is that the long-term nature of the model allows the capacity mix to adjust. [With increasing solar shares, the base price level itself might also drop, such that in absolute terms the value drop is even larger. However, in the long-term, the base price is rather

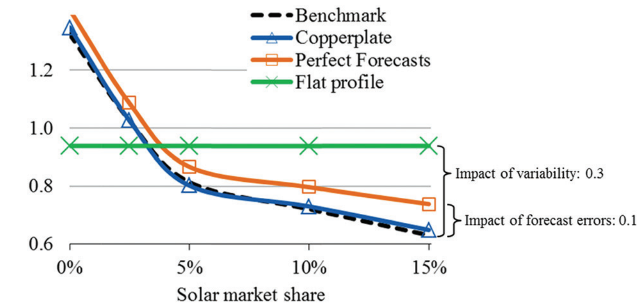

Fig. 7 *Long-term solar value factor drops to 0.6 at 15% penetration rate*

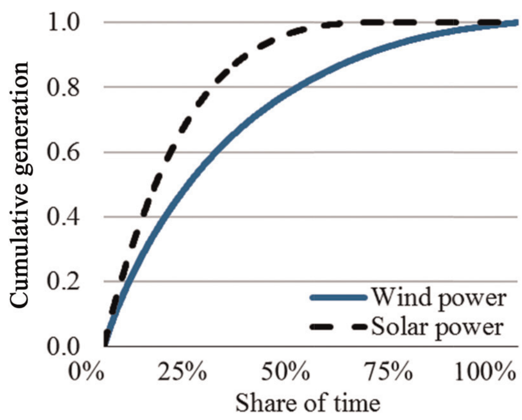

Fig. 9 *Cumulative distribution functions of solar and wind power. Solar is more concentrated than wind*

stable. In the benchmark run, it decreases by 5% when moving from zero solar to 15%.]

Next, we test the impact of the three properties of variable renewables one by one: forecast errors, location constraints, and temporal variability. Perfect forecasts (no balancing costs) would increase the market value of solar power by about 0.1. In contrast, turning Northwestern Europe into a copper plate by removing all interconnector constraints has virtually no impact. If solar power would generate constantly, its value would be reduced at low penetration (because the favourable demand correlation disappears) but strongly increased at high penetration (because the supply effect disappears). In this sense, the economic impact of variability is much larger than the impact of forecast errors – at 15% penetration, it is about three times as large.

The solar value factor drops quicker than that of wind power (Fig. 8). While solar power is of higher value than wind power at low penetration, at higher penetration the raking is reversed. This is in line with the market data presented above and confirms previous studies [16, 32, 45, 47]. Solar loses value quicker because solar power is concentrated in a few hours (Fig. 9): 80% of all solar power is produced in 26% of all hours of the year, while 80% of all wind power in 47% of all hours. As the solar generation is more concentrated, the supply effect is stronger.

In turn, we estimate the impact of individual price and technology assumptions and test the effect of integration measures.

Thermal plant *maintenance scheduling* significantly impacts the results. For the benchmark, we assumed reduced plant availability during the summer, when maintenance is scheduled. This is beneficial for solar generator: they produce most electricity when competitors are offline. If availability would be flat during the year, solar's value would be reduced (Fig. 10). However, the estimates for higher penetration rate are robust with respect to maintenance assumptions.

Climate policy has a non-monotonic impact on the value factor of solar power, as previously observed for wind power [29, 37]. A benchmark CO_2 price of 20 €/t was assumed – this price was reduced to zero and increased to 100 €/t. At high solar penetration, *both* high and low CO_2 prices reduce the value of solar (Fig. 11). This surprising finding is driven by the fact that both high and low carbon prices increase the convexity of the merit-order curve by favouring base load technologies – lignite and hard coal at low carbon prices, nuclear and CCS at high carbon prices. High prevalence of base load technologies reduces the value of solar at high penetration, because the spot price falls to their (low) marginal costs, whenever significant solar power is generated. This effect is so strong, that even the absolute solar market value at high penetration is lowered by a high carbon price: counterintuitively, ambitious climate policy can acerbate, rather than alleviate, the loss of solar power's market value. If a high CO_2 price is combined with a ban on nuclear and CCS, this effect is eliminated and solar power's market value is increased.

There exist a number of options to integrate variable renewables into power systems, such as storage, flexible generation and transmission expansion [58]. Previously, we reported in [37] that the impact of *electricity storage* on wind power is small, because wind fluctuates mainly on

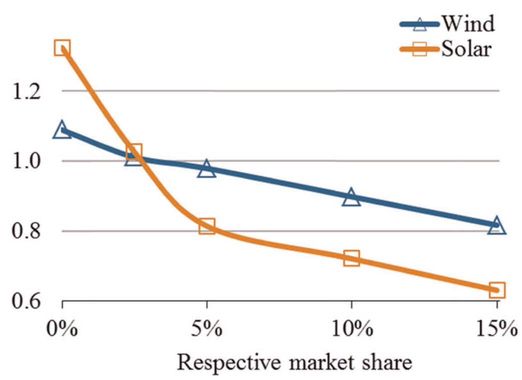

Fig. 8 *Low penetration, the market value of solar is higher than that of wind – but it decreases faster*

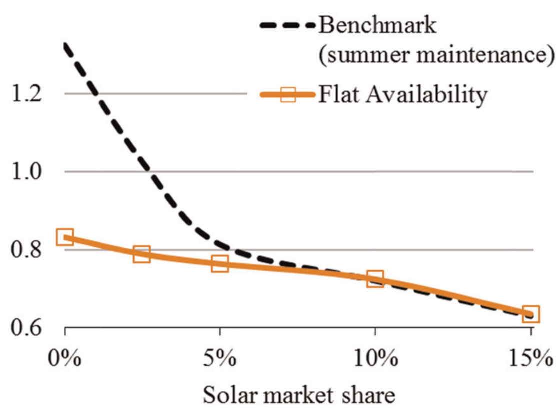

Fig. 10 *Value of solar power is as high, because power plants are less available during summer times*

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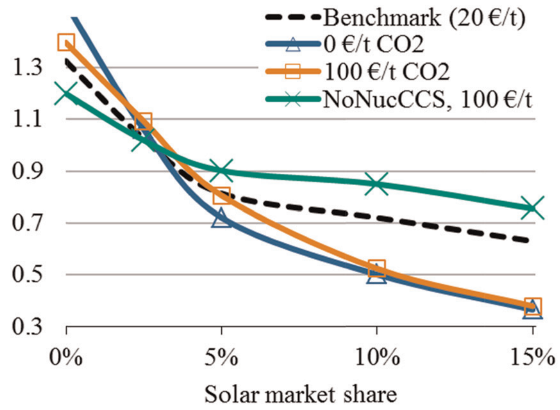

Fig. 11 *Both high and low CO_2 prices reduce solar's value factor, because both induce investment in base load technologies*

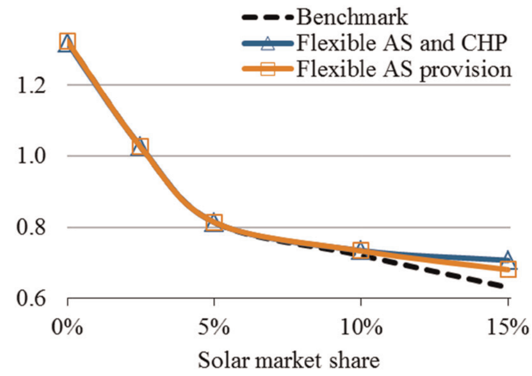

Fig. 13 *More flexible thermal power plants increases solar's value at high penetration significantly*

longer time scales of weeks, not fitting well to pumped hydro storage that has been designed to balancing diurnal-scale load fluctuations. However, such a design matches well to the properties of solar power. With double storage capacity (14 GW), the 15%-penetration value factor is 7 percentage-points higher than without the storage – for wind power, this delta is only 3 percentage-points. At low penetration, storage shaves the price peak at noon, thereby reducing solar's value (Fig. 12). Only at a penetration rate of 15% solar power benefits from pumped hydro storage.

Similarly important might be the impact of *flexible thermal generation*. EMMA dispatches thermal generation subject to two must-run constraints: ancillary service provision and combined heat and power (CHP) generation. Dropping these constraints increases the value factor by 5 percentage-points each, dropping them jointly increases the factor by 9 points (Fig. 13).

Expanding *interconnections* has a small impact on the value of solar (recall Fig. 10). There seems to be a remarkable difference between wind and solar power: wind power benefits from more interconnection capacity, but hardly benefits from pumped hydro storage. The opposite is the case for solar power. In that sense, wind and solar power require complementary integration efforts.

Also *fossil fuel prices* affect solar's market value. A common measure for their impact is the cross price elasticity, the relative change of solar's value factor as fossil fuel prices increase by 1%. At high solar penetration, the solar-coal price cross-elasticity is +1.0%, which has intuitive: an increase in the competitor's cost increased solar's relative price. Surprisingly, the solar-natural gas price cross-elasticity is negative (−1.5%). That means that an increase in the gas price 'reduces' the value of solar power. Mid-merit gas-fired plants are complementary technologies to solar power, since they efficiently 'fill the gap' during times of little renewable generation. Hence, one can think of natural gas and solar generators as a gas/solar 'package'. Coal plants are a substitute technology to the gas/solar package. Increasing coal prices increase both the share of gas/solar. Increasing gas prices reduce the share of gas/solar. Of course, solar power becomes more competitive vis-à-vis gas as well, but this effect is too weak to make solar benefit from higher gas prices.

Overall, 20 parameter tests were conducted. The range of value factor estimates is 1.2–1.6 for low penetration, consistent with empirical data assessed here and reported in the literature. At 15% penetration, the factor is estimated to drop to 0.4–0.8 (Fig. 14).

6.3 Comparing empirical evidence

Table 2 summarises the results from analyses of market date, the existing literature, and EMMA model results. The consistency of such diverse methodology increases confidence in the robustness of findings.

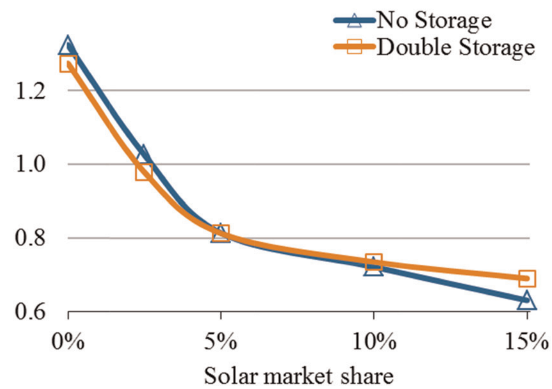

Fig. 12 *Additional storage capacity increases solar's value at high penetration significantly*

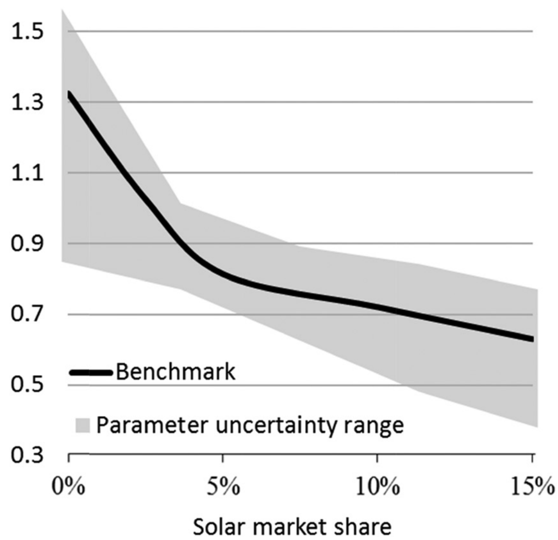

Fig. 14 *Long-term solar value factor drops to 0.4–0.8 at 15% penetration rate*

Table 2 Empirical literature on the market value of solar power

	Market data	Literature review	EMMA model results
value factor at low penetration, <1%	1.1–1.3	1.0–1.8	0.9–1.5
value drop in percentage-point value factor per percentage-point market share	5.5 (OLS)	3.6 (OLS)	4.6 (benchmark)

7 Conclusions

For socio-economic assessments of solar power, one needs to account for solar's temporal variability, location, and forecast errors. 'Grid parity', while being a widespread concept, ignores these factors (moreover, it conceals the fact that grid fees, levies, taxes comprise a large share of retail prices). For policy assessment, it is not a useful indicator. 'Market value' is a more complete evaluation metric.

In this paper, the market value of solar power was estimated from three different data sources: observed market prices, numerical model results, and a quantitative literature review. Results are consistent and striking: at low penetration rates (<2–5%) solar's market value is higher than the average electricity price. With increasing penetration it rapidly declines – it relative price decreases by 3.3–5.5 percentage-points per percentage-point market share. This value drop is steeper than for wind power, because solar generation is concentrated in fewer hours. Model results indicate that at a market share of 15%, 1 MWh of solar power is worth only 60% of an MWh from a constant electricity source, with a parameter uncertainty range of 40–80%. This estimate already accounts for the long-term adaptation of the thermal capacity mix.

The market value of solar power might be much higher in regions closer to the equator, where solar generation is less variable and electricity consumption is stronger correlated with solar radiation because of more prevalent air conditioning. Assessing the solar market value in different power systems is a promising direction of future research.

Model results identify electricity storage and more flexibly dispatched thermal power plants as promising options to integrate variable renewables into power systems. Pumped hydro storage seems to be more helpful to mitigate the value drop of solar than of wind power, while the opposite is true for interconnector expansion.

Stricter climate policy can, counterintuitively, reduce the market value of solar power. A high price on CO_2 incentivizes investment in low-carbon base load power generation technologies, such as nuclear power or CCS. Such technologies are capital-intensive and therefore no good complements for solar PV. Less capital-intensive technologies could play an important role, such as natural gas-fired plants with carbon capture and storage.

The findings imply that, without a major technological breakthrough, it will be quite costly to drive up the share of solar power beyond 10% or 15% of Northwestern Europe's electricity consumption, even if equipment costs keep falling. It seems unlikely that such shares will be reached without long-lasting subsidies. This puts doubts on some of the very ambitious European policy targets for renewable energy.

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