The Market Value of Solar Power

Is Photovoltaics Cost-Competitive?

Lion Hirth

hirth@neon-energie.de

This is a post-print version of an article forthcoming in IET Renewable Energy Generation (http://dx.doi.org/10.1049/iet-rpg.2014.0101). Brought to you by neon.

Please cite as: Hirth, Lion (2015): "The Market Value of Solar Photovoltaics: Is Solar Power Cost-Competitive?", *IET Renewable Power Generation* 9(1), 37-45.

The market value of solar power:
Is photovoltaics cost-competitive?

– August 2014 –

– submitted to IET Renewable Power Generation –

*Lion Hirth**

neon neue energieökonomik GmbH | Potsdam-Institute for Climate Impact Research

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.

Keywords – variable renewables; solar power; power system modeling; market integration of renewables; electricity markets; intermittency; competitiveness of renewables; distributed generation.
JEL – C61, C63, Q42, D40

*Lion Hirth, neon neue energieökonomik GmbH | hirth@neon-energie.de | +49 1575 5199715 | www.neon-energie.de. The paper was presented at the 2013 Solar Integration Workshop in London. I would like to thank two anonymous reviewers for helpful and constructive comments. Part of this research was conducted while Lion Hirth was employed at Vattenfall GmbH. The findings, interpretations, and conclusions expressed herein are those of the author and do not necessarily reflect the views of Vattenfall or the Potsdam-Institute.

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 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, photovoltaics 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 levelized electricity costs (LEC) of about 140-200 €/MWh.[1] This is less than household retail electricity prices – 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. The following section 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 seven years and reached 1600 €/kW [4]. However, both retail and wholesale prices seem to have stopped falling since end of 2012 (Figure 1). Large regional cost differences continue to exist, with prices in the U.S. being twice as high as in Germany [5], [6]. Solar levelized electricity costs (LEC) vary widely, depending on resource quality, equipment prices, and discount rate. Under favorable circumstances, they might be as low as 100 €/MWh.

---

[1] Assuming 20 years life-time, 3-8% real discount rate, 850 full load hours (10% capacity factor) as in central Europe, and 15 €/MWh O&M costs. At 3% discount rate and 1500 full load hours, LEC are as low as 80 €/MWh.

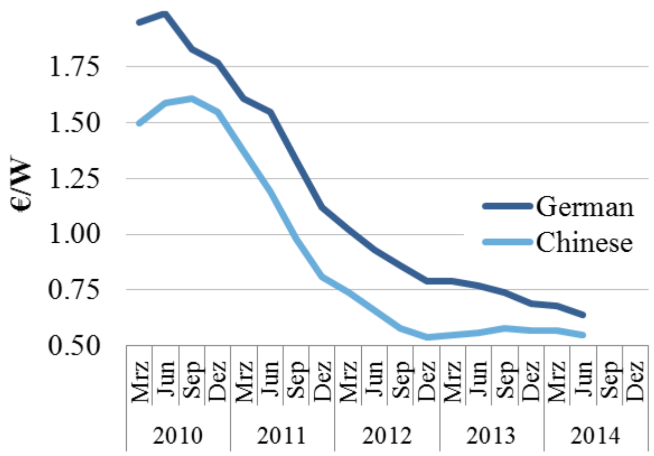

Figure 1. Wholesale prices for PV modules have leveled off since late 2012, after falling dramatically the years before. Source: own figure, data from pvxchange.com

[7]-[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 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. 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 generation costs to the electricity's value. Unlike most other electricity generation technologies, solar PV is modular. That means, it can be applied at small scale without major specific cost increases compared to large-scale applications. In contrast, coal, hydro, and wind power plants feature significant economies of scale, such that they cannot efficiently be deployed in household size.[2]

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 one 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

---

[2] 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. In terms of energy, the difference might even be six orders of magnitude.

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, subsidies, and taxes. Hence the concept of grid parity corresponds to a private, not a social, perspective: depending on tax rules and grid fee tariff structures, crossing grid parity might indicate that investments are profitable for the individual investors, but it does *not* indicate that they are efficient for society.[3] 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 internalized. 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 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.

a) 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 standardized 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. (iii) Moreover, because frequency stability requires demand 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.

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

---

[3] For a quantitative assessment of the externalities of German solar PV, see [24].

dimensions, electricity is a heterogeneous good. Figure 2 visualizes the three dimensions of heterogeneity by illustrating the wholesale spot prices in one power system in one year as a three-dimensional array.

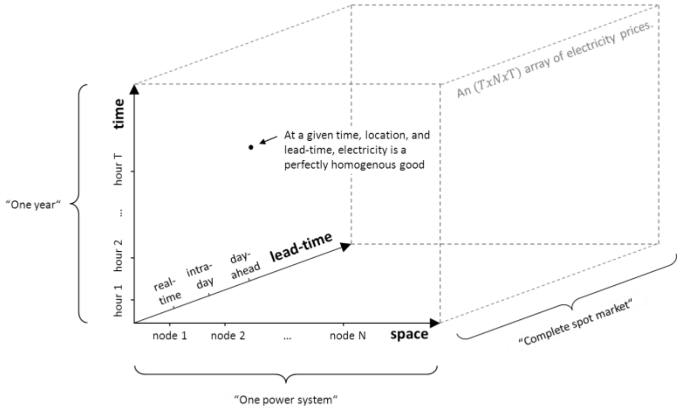

Figure 2: The array of wholesale spot electricity prices. The electricity price varies along three dimensions: time, space, and lead-time. Source: updated from [29].

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, real-time). American ISO-markets often feature an even finer granularity, clearing the market every five minutes 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).[4] This heterogeneity of electricity prices needs to be accounted for when estimating the market value of solar power.

b) *The 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 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 competitive; still this is repeatedly suggested by interest groups, policy makers, and academics [33]-[35] (it might well be that 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 allow to infer anything about efficiency of these technologies, still such comparisons are regularly done.

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

---

[4] Prices in Germany (EPEX Spot) are determined for each quarter-hour in three sequential markets for one uniform bidding area ($35000 \cdot 1 \cdot 3 \approx 105'000$). Prices in Texas (ERCOT) are determined for each five minutes for all 10,000 bus bars of the system ($105'000 \cdot 10'000 \cdot 3 \approx 3'000'000'000$).

$$\bar{p}^{s} = \sum\nolimits_{t=1}^{T} \sum\nolimits_{n=1}^{N} \sum\nolimits_{\tau=1}^{\mathrm{T}} s_{t,n,\tau} \cdot p_{t,n,\tau} \qquad (1)$$

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 Figure 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").

c) *An approximation of market value*

Facing incomplete information about the full matrix of electricity prices, we use a framework proposed by [39] and [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 (Figure 3).

- The supply of solar power is *variable* (over time). At low penetrations, solar's market value is usually higher than the average price due to positive diurnal correlation with load (correlation effect), at high penetration it falls below the 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 realization. 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 materialize in form of (increased) costs or (decreased) revenue, and they can be positive or negative

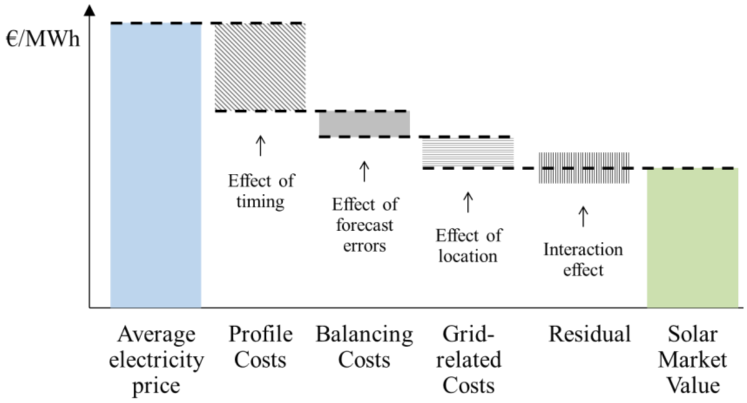

Figure 3. The average electricity price minus profile, balancing, and grid-related costs gives approximately solar power's market value. Source: updated from [39].

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]. Reference [44] argues that integration costs cannot necessarily be attributed to a single technology. The framework used here allows for a unified and economically sound assessment of energy value and integration costs.

5. *Market value estimates: market & literature*

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

a) Market data estimates

We use German market data for the years 2006-13 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 observe prices.

Figure 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 zero 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.[5]

An alternative way of visualizing the impact of solar generation on relative prices is the structure of spot price during the day (Figure 5). Over the years, the price peak around noon disappeared, "shaved" by additional electricity supply from solar power.

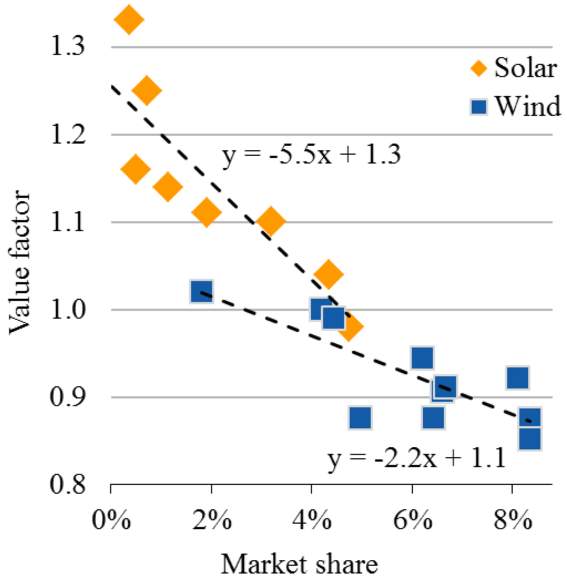

Figure 4. Historical wind and solar value factors in Germany from spot prices (reflecting profile costs). As solar penetration increased from zero to 4.7%, its value factor decreased from 1.33 to 0.98.

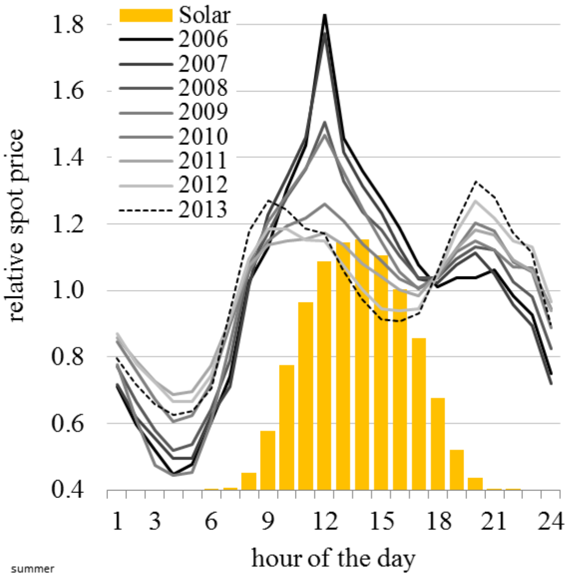

Figure 5. The daily spot price structure in Germany during summers from 2006 – 2013. The bars display the distribution of solar generation over the day.

For deviations from schedules, all German generators have to pay the quarter-hourly "imbalance price" [45]. 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 2011-13. 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] Note that over time, not only solar capacity changed, but many other parameters in the power system. Due to lack of observations, controlling for more variables was not feasible.

b) *Quantitative literature review*

Table 1 summarizes a number of studies that quantify the market value of solar power. Virtually all studies find value factors above unity at low (<2-5%) penetration, but significantly lower value factors at higher penetration. The methodologically most sophisticated studies by [30], [32], [46]-[48] report value factors in the range of 0.7-0.9 at 10% penetration and around 0.4-0.7 at 30% penetration. Figure 6 summarizes the 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.

Table 1: Empirical literature on the market value of solar power

Prices	**Reference**	**Region**	**Value Factors Estimates (at different market shares)**
Historical Prices	Borenstein 2008 [16]	California	1.0 to 1.2 for different market design (small)
	Sensfuß 2007, Sensfuß & Ragwitz 2011 [49], [50]	Germany	1.33-1.14 (0% and 2%)
	Brown & Rowlands 2008 [51]	Ontario	1.2 (small)
	Gilmore et al. 2014 [38]	Australia	1.4-1.8 in different states (small) 1.0-1.1 in different states (1.3 %)
Prices from Dispatch Model	Rahman & Bouzguenda 1994, Rahman 1990, Bouzguenda & Rahman 1993 [52]-[54]	"Utility"	*only absolute value reported*
	ISET et al. 2008, Braun et al. 2008 [55], [56]	Germany	*only absolute value reported*
	Energy Brainpool 2011 [57]	Germany	1.05 (6%)
	Gilmore et al. 2014 [38]	Australia	1.0-0.85 (1.3-6%)
Dispatch & Investment Model	Lamont 2008 [30]	California	1.2-0.9 (0-9%)
	Gowrisankaran et al. 2011 [46]	Arizona	0.9-0.7 (10-30%)
	Mills & Wiser 2012, Mills 2011 [32], [47]	California	1.3-0.4 (0-30%)
	Nicolosi 2012 [48]	Germany	1.02-0.7 (0-9%)

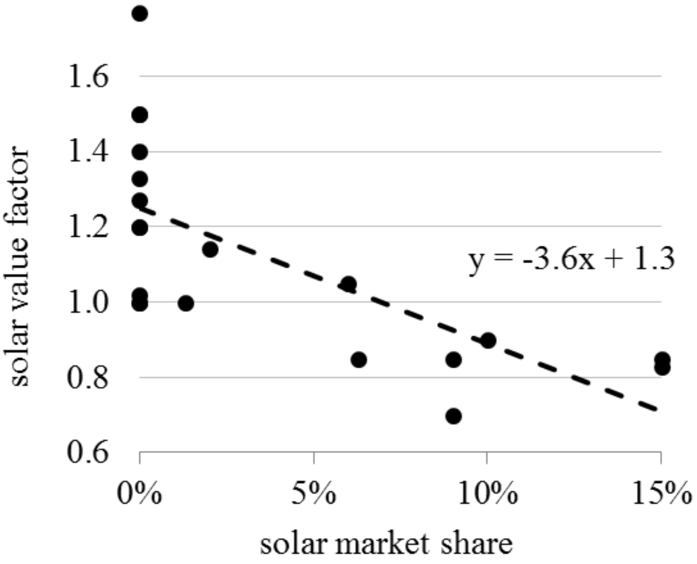

Figure 6. The solar market value literature. An OLS-fit of all studies estimates the solar value factor to fall from 1.3 at zero penetration to 0.7 at 15% penetration. A list of references is provided in Table 1.

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.

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.

a) The model EMMA

EMMA is a stylized 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 zero 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 are 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], and [58], where more model details can be found. The model is open source; model documentation, equations, GAMS code, and input data are available at http://www.pik-potsdam.de/members/hirth/emma.

b) Model results

Figure 7 shows estimates of the solar value factors for market shares between zero and 15% under benchmark (central value) parameter assumptions.[6] 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

---

[6] “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.

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.[7]

Next, we test the impact of the three properties of variable renewables one by one. Perfect forecasts (no balancing costs) would increase the market value of solar power by about 0.1. In contrast, turning North-western Europe into a copperplate by removing all interconnector constraints has virtually no impact. If solar power would generate constantly, it value would be reduced at low penetration (because the favorable demand correlation disappears) but strongly increased at high penetration (because 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.

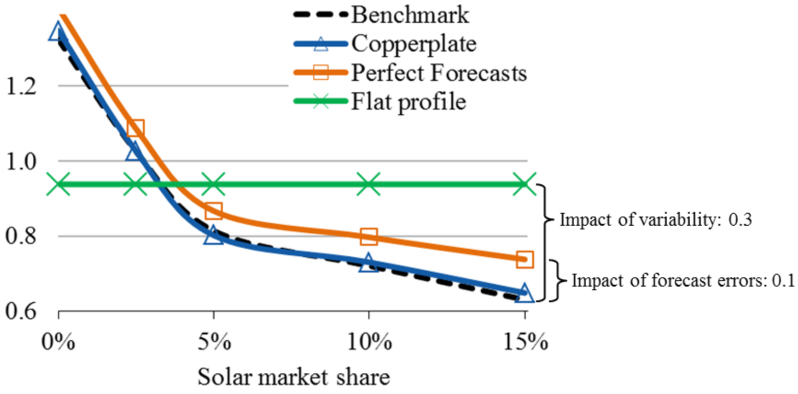

Figure 7. Long-term solar value factor drops to 0.6 at 15% penetration rate.

The solar value factor drops quicker than that of wind power (Figure 8). While solar power is of higher value than wind power at low penetration, at higher penetration this raking is reversed. This is in line with the market data presented above and confirms previous studies [16], [32], [46], and [48]. Solar loses value quicker because solar power is concentrated in few hours (Figure 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. Because solar generation is more concentrated, the supply effect is stronger.

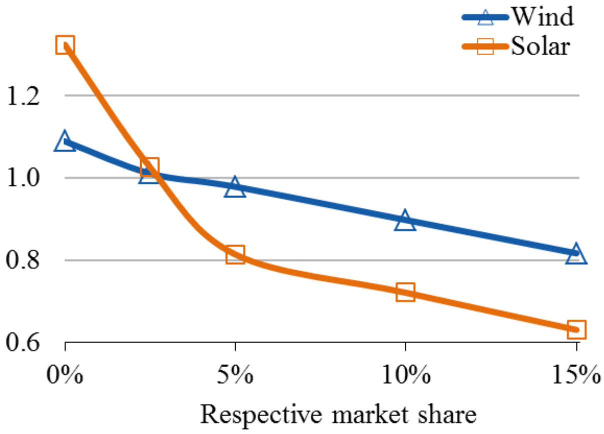

Figure 8. At low penetration, the market value of solar is higher than that of wind – but it decreases faster.

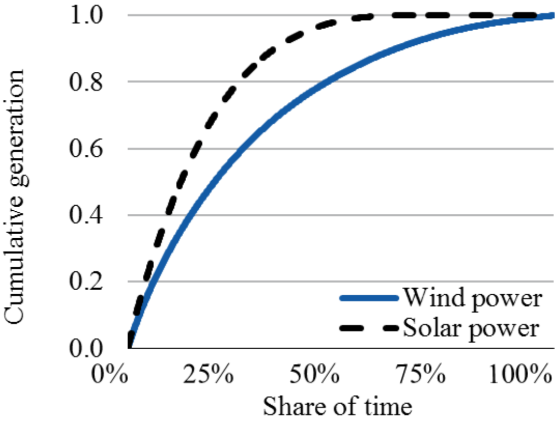

Figure 9. Cumulative distribution functions of solar and wind power. Solar is more concentrated than wind.

---

[7] With increasing solar shares, the base price level itself might also drop (merit-order effect), such that in absolute terms the value drop is even larger. However, in the long-term, the base price is rather stable. In the benchmark run, it decreases by 5% when moving from zero solar to 15%.

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 generators: they produce most electricity when competitors are offline. If availability would be flat during the year, solar's value would be reduced (Figure 10). However, the estimates for higher penetration rate are robust with respect to maintenance assumptions.

Climate policy has an interesting and 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 (Figure 11). This reason is that both high and low carbon prices increase the convexity of the merit-order curve by favoring base load technologies – lignite and hard coal at low carbon prices, nuclear and CCS at high carbon prices. High prevalence of base load technologies reduce 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 much more stable.

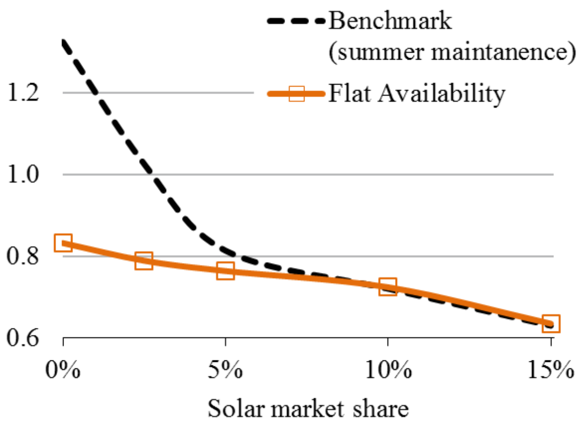

Figure 10. The value of solar power is as high, because power plants are less available during summer times.

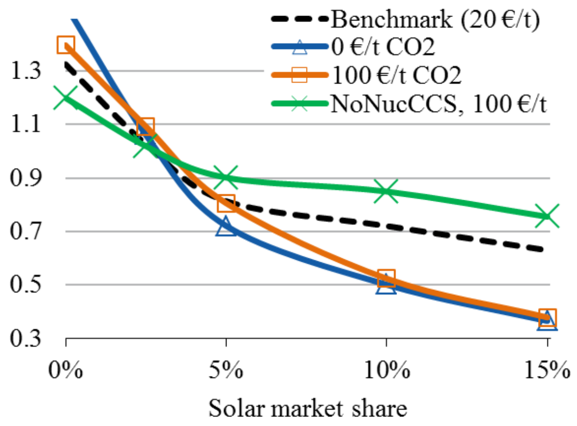

Figure 11. Both high and low CO_2 prices reduce solar's value factor, because both induce investment in base load technologies.

There exist a number of options to integrate variable renewables into power systems, such as storage, flexible generation, and transmission expansion [59]. Previously, we reported in [37] that the impact of *electricity storage* on wind power is small, because wind fluctuates mainly on longer time scales of weeks, not fitting well with 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 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 (Figure 12).

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 together increases the factor by 9 points (Figure 13).

Expanding *interconnections* has remarkable little impact on the value of solar (recall Figure 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.

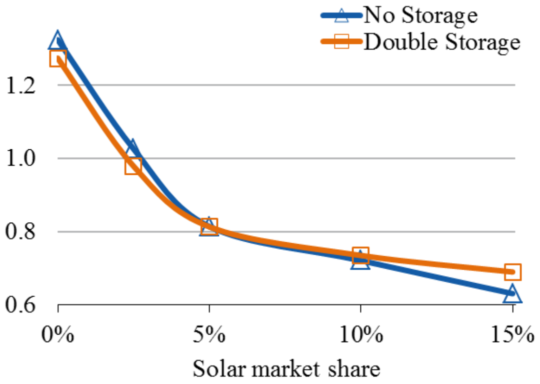

Figure 12. Additional storage capacity increases solar's value at high penetration significantly.

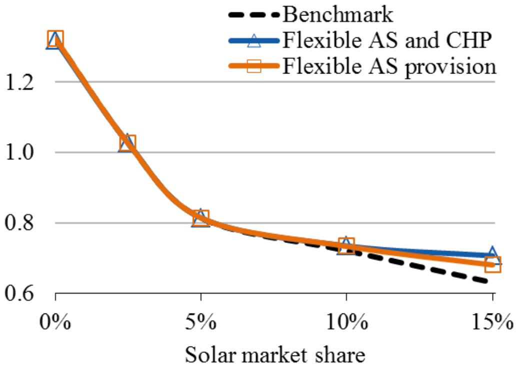

Figure 13. More flexible thermal power plants increases solar's value at high penetration significantly.

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 one percent. At high solar penetration, the solar-coal price cross-elasticity is +1.0%, which is intuitive: an increase in the competitor's cost increases solar's relative price. Surprisingly, the solar-gas price cross-elasticity is -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 gas and solar generators as a gas/solar "package". Coal plants are a substitute technology to the gas/solar package. Increasing coal prices increases both the share of gas and solar. Increase gas prices increases the share of coal and reduces the share of gas/solar. Of course, solar power becomes more competitive versus 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 to 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 to 0.8 (Figure 14).

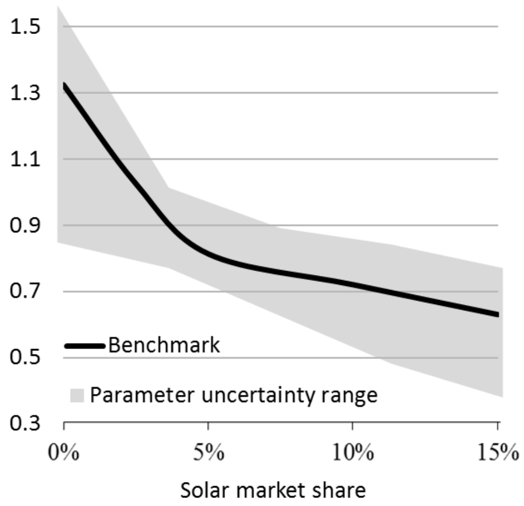

Figure 14. Long-term solar value factor drops to 0.4 – 0.8 at 15% penetration rate.

c) *Comparing empirical evidence*

Table 2 summarizes 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.

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.

For 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. However, 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%, one MWh of solar power is worth only 60% of a 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 quantitative 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..

References

[1] REN21 (2014): *Renewables 2014 Global Status Report*, REN21 Secretariat, Paris.

[2] Barbose, Galen, Naïm Darghouth & Ryan Wiser (2013): "Tracking the Sun VI. An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012", *LBNL report* 6350E.

[3] Schindler, Roland & Werner Warmuth (2013): *Photovoltaics Report*, Fraunhofer ISE, www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf

[4] BSW (2014): BSW Preisindex 1401.

[5] IEA (2013a): *Tracking Clean Energy Progress 2013*, International Energy Agency, Paris.

[6] IEA (2013): *Renewable Energy Mid-Term Market Outlook*, International Energy Agency, Paris.

[7] Nemet, Gregory (2006): "Beyond the learning curve: factors influencing cost reductions in photovoltaics", *Energy Policy* 34, 3218-3232.

[8] Hernández-Moro, J & J Martínez-Duart (2013): "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution", *Renewable and Sustainable Energy Reviews* 20, 119-132.

[9] Bazilian, Morgan, Ijeoma Onyeji, Michael Liebreich, Ian MacGill, Jennifer Chase, Jigar Shah, Dolf Gielen, Doug Arent, Doug Landfear, Shi Zhengrong (2013): "Re-considering the economics of photovoltaic power", *Renewable Energy* 52, 329-338.

[10] Nordhaus, William (2014): "The Perils of the Learning Model For Modeling Endogenous Technological Change", *The Energy Journal* 35(1), 1-13.

[11] BSW (2011): *Solarenergie wird wettbewerbsfähig*, Bundesverband Solarwirtschaft, www.solarwirtschaft.de/fileadmin/media/pdf/anzeige1_bsw_energiewende.pdf.

[12] EPIA (2011): *Solar Photovoltaics competing in the energy sector*, European Photovoltaic Industry Association, www.epia.org/publications/photovoltaic-publications-global-market-outlook/solar-photovoltaics-competing-in-the-energy-sector.html

[13] Koch, Oliver (2013): "Capacity mechanisms", *Paper presented at the 13th European IAEE Conference*, Düsseldorf.

[14] Fraunhofer ISE (2013): *Photovoltaics report*, Fraunhofer Institute for Solar Energy Systems, www.ise.fraunhofer.de/mwg-internal/de5fs23hu73ds/progress?id=94T8LFoGsA&dl.

[15] Breyer, Christian & Alexander Gerlach (2013): "Global overview on grid-parity", *Progress in photovoltaics* 21(1), 121-136.

[16] Borenstein, Severin (2008): "The Market Value and Cost of Solar Photovoltaic Electricity Production", *CSEM Working Paper* 176.

[17] Hoff, T & D Shugar (1995): "The value of grid-support photovoltaics in reducing distribution system losses", *IEEE Transactions on Energy Conversion* 10(3), 569-576.

[18] Gil, Hugo & Geza Joos (2006): "On the Quantification of the Network Capacity Deferral Value of Distributed Generation", *IEEE Transactions on Power Systems* 21(4), 1592-1599.

[19] E-Bridge, IAEW & BET (2011): *Abschätzung des Ausbaubedarfs in deutschen Verteilungsnetzen aufgrund von Photovoltaik- und Windeinspeisungen bis 2020* , report for BDEW, Bonn.

[20] dena (2012): *dena-Verteilnetzstudie. Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030*, Deutschen Energie-Agentur GmbH, Berlin.

[21] IEA (2014): *The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems*", International Energy Agency, Paris.

[22] Lödl, Martin, Georg Kerber, Rolf Witzmann & Michael Metzger (2010): „Comparison of energy storage and grid enforcement in low-voltage distribution grids with a high degree of decentralized generation", *Proceedings of VDE-Kongress*, Leipzig.

[23] Fraunhofer IWES (2012): *Vorstudie zur Integration großer Anteile Photovoltaik in die elektrische Energieversorgung*, Kassel.

[24] Jägemann, Cosima, Simeon Hagspiel & Dietmar Lindenberger (2013): "The economic inefficiency of grid parity: The case of German photovoltaics", *EWI Working Paper* 13/19.

[25] Borenstein, Severin (2012): "The Private and Public Economics of Renewable Electricity Generation", *Journal of Economic Perspectives* 26(1), 67–92.

[26] Fischedick, M, R Schaeffer, A Adedoyin, M Akai, T Bruckner, L Clarke, V Krey, I Savolainen, S Teske, D Ürge-Vorsatz & R Wright (2011): „Mitigation Potential and Costs", in: O Edenhofer, R Pichs-Madruga, Y Sokona, K Seyboth, P Matschoss, S Kadner, T Zwickel, P Eickemeier, G Hansen, S Schlömer and C v Stechow (Eds.): *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge University Press, Cambridge, UK.

[27] ExternE (2005): *External Costs of Energy*, project for the EU commission, www.externe.info.

[28] Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2015): "Integration Costs Revisited – An economic framework of wind and solar variability", *Renewable Energy* 74, 925–939.

[29] Hirth, Lion (2015): "The Optimal Share of Variable Renewables", *The Energy Journal* 36(1), 127-162.

[30] Lamont, Alan (2008): "Assessing the Long-Term System Value of Intermittent Electric Generation Technologies", *Energy Economics* 30(3), 1208-1231.

[31] Joskow, Paul (2011): "Comparing the Costs of intermittent and dispatchable electricity generation technologies", *American Economic Review* 100(3), 238–241.

[32] Mills, Andrew & Ryan Wiser (2012): "Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot case Study of California", *Lawrence Berkeley National Laboratory Paper* LBNL-5445E.

[33] IEA & NEA (2012): *Projected costs of generating electricity*, International Energy Agency and Nuclear Energy Agency, Paris.

[34] Kost, Christoph, Thomas Schlegl, Jessica Thomsen, Sebastian Nold & Johannes Mayer (2012): *Stromgestehungskosten Erneuerbarer Energien*, Fraunhofer ISE, www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/presseinformationen-2012/erneuerbare-energietechnologien-im-vergleich

[35] Clover, Robert (2013): "Energy Mix In Europe to 2050", *paper presented at the 2013 EWEA conference*, Vienna.

[36] Stephenson, Hans (1973): "Valence of Electric Energy", *IEEE Transactions on Power Apparatus and Systems* 92(1), 248-253.

[37] Hirth, Lion (2013): "The Market Value of Variable Renewables", *Energy Economics* 38, 218-236.

[38] Gilmore, Joel, Ben Vanderwaal, Ian Rose & Jenny Riesz (2014): "Integration of solar generation into electricity markets: An Australian National Electricity Market case study", *IET Renewable Power Generation* (this issue).

[39] Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2014a): "Integration Costs Revisited – An economic framework of wind and solar variability", *Renewable Energy* (forthcoming). Also available as *USAEE Working Paper* 13-149.

[40] Ueckerdt, Falko, Lion Hirth, Gunnar Luderer & Ottmar Edenhofer (2013a): "System LCOE: What are the costs of variable renewables?", *Energy* 63, 61-75.

[41] Ueckerdt, Falko, Lion Hirth, Simon Müller & Marco Nicolosi (2013b): "Integration costs and Marginal value. Connecting two perspectives on evaluating variable renewables", *Proceedings of the 12th Wind Integration Workshop*, London.

[42] Milligan, Michael & Brendan Kirby (2009): "Calculating Wind Integration Costs: Separating Wind Energy Value from Integration Cost Impacts", *NREL Technical Report* TP-550-46275.

[43] Holttinen, Hannele, Peter Meibom, Antje Orths, Bernhard Lange, Mark O'Malley, John Olav Tande, Ana Estanqueiro, Emilio Gomez, Lennart Söder, Goran Strbac, J Charles Smith, Frans van Hulle (2011): "Impacts of large amounts of wind power on design and operation of power systems", *Wind Energy* 14(2), 179 – 192.

[44] Milligan, Michael, Hannele Holttinen, Brendan Kirby, Juha Kiviluoma, Ana Estanqueiro, Sergio Martín-Martínez, Emilio Gómez-Lázaro, Iván Pineda & Charlie Smith (2013): "Wind integration cost and cost-causation", *Proceedings of the 12th Wind Integration Workshop*, London.

[45] Hirth, Lion & Inka Ziegenhagen (2013): "Balancing power and variable renewables", *USAEE Working Paper* 13-154.

[46] Gowrisankaran, Gautam, Stanley S. Reynolds & Mario Samano (2011): "Intermittency and the Value of Renewable Energy", *NBER Working Paper* 17086.

[47] Mills, Adrew (2011): "Assessment of the Economic Value of Photovoltaic Power at High Penetration Levels", paper presented to UWIG Solar Integration Workshop, Maui, Hawaii, www.uwig.org/mwg-internal/de5fs23hu73ds/progress?id=XDyBuJov9m.

[48] Nicolosi, Marco (2012): *The Economics of Renewable Electricity Market Integration. An Empirical and Model-Based Analysis of Regulatory Frameworks and their Impacts on the Power Market*, Ph.D. thesis, University of Cologne.

[49] Sensfuß, Frank (2007): *Assessment of the impact of renewable electricity generation on the German electricity sector. An agent-based simulation approach,* Ph.D. thesis, University of Karlsruhe.

[50] Sensfuß, Frank & Mario Ragwitz (2011): „Weiterentwickeltes Fördersystem für die Vermarktung von erneuerbarer Stromerzeugung", *Proceedings of the 7th Internationale Energiewirtschaftstagung*, Vienna.

[51] Brown, Sarah & Ian Rowlands (2009): "Nodal pricing in Ontario, Canada: Implications for solar PV electricity", *Renewable Energy* 34, 170-178.

[52] Bouzguenda, Mounir & Saifur Rahman (1993): "Value Analysis of Intermittent Generation Sources from the System Operator Perspective", *IEEE Transactions on Energy Conversion* 8(3), 484-490.

[53] Rahman, Saifur (1990): "Economic Impact of Integrating Photovoltaics with Conventional Electric Utility Operation", *IEEE Transactions on Energy Conversion* 5(3), 422-428.

[54] Rahman, Saifur & Mounir Bouzguenda (1994): "A model to Determine the Degree of Penetration and Energy Cost of Large Scale Utility Interactive Photovoltaic Systems", *IEEE Transactions on Energy Conversion* 9(2), 224-230.

[55] ISET, Frauenhofer ISE & Meteo Control (2008): *Wertigkeit von Solarstrom. Untersuchung im Auftrag des Bundesministeriums für Umwelt*, Institut für Solare Energieversorgungstechnik, www.iset.uni-kassel.de/abt/FB-A/publication/2008/2008_Braun_Staffelstein_Wert_PV_Strom.pdf.

[56] Braun, Martin, Stefan Bofinger, Thomas Degner, Thomas Glotzbach & Yves-Marie Saint-Drenan (2008): „Value of PV in Germany. Benefit from the substitution of conventional power plants and local power Generation", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Sevilla.

[57] Energy Brainpool (2011): *Ermittlung des Marktwertes der deutschlandweiten Stromerzeugung aus regenerativen Kraftwerken*, www.eeg-kwk.net/de/file/110801_Marktwertfaktoren.pdf.

[58] Hirth, Lion & Falko Ueckerdt (2013a): "Redistribution Effects of Energy and Climate Policy", *Energy Policy* 62, 934-947.

[59] Hirth, Lion & Falko Ueckerdt (2013b): "The Decreasing Market Value of Variable Renewables: Integration Options and Deadlocks", in: Deltlef Stolten & V Scherer (eds.): *Transition to Renewable Energy Systems*, Wiley.