ECONOMICS OF HYBRID PV-FOSSIL POWER PLANTS

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ABSTRACT

Fuel-parity is a very important milestone for further photovoltaic (PV) diffusion. A fuel-parity model is presented, which is based on levelized cost of electricity (LCOE) coupled with the experience curve approach. Preconditions for a successful hybridization of PV and fossil fuel power plants are discussed. The global fossil fuel power plant capacity is analysed for the economic hybridization market potential on a georeferenced localized basis for all fossil fuel power plants. LCOE of fossil fuel power plants are converging with those of PV in sunny regions, but in contrast to PV are mainly driven by fuel cost. As a consequence of cost trends this analysis estimates an enormous worldwide market potential for PV power plants by the end of this decade in the order of at least 900 GWp installed capacity without any electricity grid constraints leading to a fast diffusion of hybrid PV-Fossil power plants. The complementary power feed-in of PV and wind power plants might result in hybrid PV-Wind-Fossil power plants in regions of good solar and wind resources. In the mid- to long-term the remaining fossil fuels might be substituted by renewable power methane by using the existing downstream natural gas infrastructure. In conclusion, PV is on the pathway to become a highly competitive energy technology.

Keywords
Fuel-Parity, Hybrid Power Plant, Economic Analysis, Energy Options, PV Markets

1 Introduction

Installations of Photovoltaic (PV) power plants have shown high growth rates around the world.[1] As a consequence of this growth PV electricity generation cost continuously decreases. The contrary trend is shown by power generation cost due to increasing fossil fuel prices. The intersection of these two trends is defined as fuel-parity and indicates cost neutral PV power plant investments. The purpose of the presented study is a detailed analysis of global fuel-parity dynamics for nearly all fossil fuel fired power plants in the world in the years to come. Key motivation of this work has been to learn more about the geographic and temporal distribution in the occurrence of fuel-parity in the world.

This paper presents a detailed analysis of fuel-parity dynamics based on the levelized cost of electricity (LCOE) concept coupled with the experience curve approach (sections 2 and 3) including a discussion of the preconditions of PV hybridization (section 4) and an overview on the global fossil fuel power plant capacity (section 5). Results for the fuel-parity of PV and fossil fuel power plants are presented (section 6) and integrated to a global hybrid PV-Fossil power plant demand curve (section 7). A broader perspective is given by including wind power and renewable power methane (section 8) and the conclusion for the presented insights (section 9).

This conference contribution presents results of Q-Cells research. Initially the research focus was led on grid-parity event dynamics [2], however the grid-parity concept is no help in case of highly subsidized electricity markets being prevalent in several regions in the world [3]. Nevertheless, the true power generation costs are typically significant in those countries, hence the grid-parity concept had to be complemented by the fuel-parity concept for covering the economic market potential of PV power plants mainly starting in very sunny but heavily subsidised markets. First fuel-parity insights have already been published [4-6], but this paper is the first comprehensive PV hybridization analysis for all major fossil fuel fired power technologies on a global scale. Hybrid PV-Fossil power plants are the major part of an even more comprehensive work on hybrid PV power plants.[7]

2 Major PV Diffusion Phases - Consequence of High Growth Rates and Learning Rates

Average annual growth rates of global PV production increased from about 33% in space age and during off-grid diffusion to 45% for the last 15 years during on-grid diffusion (Figure 1).[8] In history of PV three major inventions led to new and sustainable markets for PV systems. In the 1950s the introduction of PV power supply in space as least cost option started the first PV market diffusion phase. The second PV diffusion phase was driven by off-grid PV applications and started a fast growth in PV production in the 1970s. The third PV market diffusion phase has been enabled by the political invention of roof-top programmes and feed-in tariff laws in the 1990s. By end of 2010 about 40 GWp of cumulated PV power capacity has been globally installed and most interestingly PV products found their markets in all countries in the world.[9] This paper intends to give some insights for the fourth diffusion phase: commercial utility-scale PV power plants.

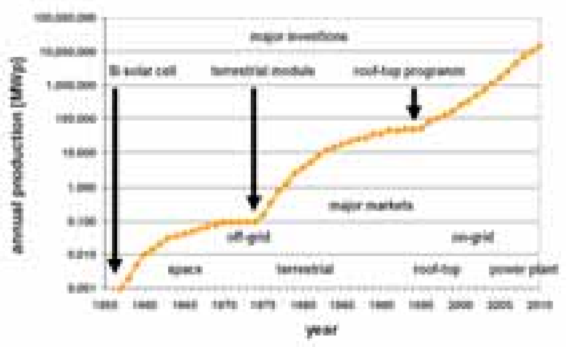


Figure 1: Historic PV production in dependence of major inventions and market segments.[8]

The sustainable PV market growth over more than five decades has been possible due to the favourable fundamental economics of PV technology. The basis for this development is the modular and scalable nature of PV applications and production. Modular PV products can be found in the market from the sub-watt class (e.g. solar calculators), in the watt range (e.g. pico systems and solar home systems) [10], in the kilowatt size (e.g. residential roof-top systems) [2] up to the multi megawatt dimension (utility-scale power plants) [5,6]. The industrial value chain of PV is highly scalable and characterized by nearly continuous production flows for all production steps from metallurgical silicon (Si), to Si refinery, ingoting, wafering, cell and module manufacturing (or integrated PV thin film module production), inverter production and even system assembly, in particular of large scale power plants. Most industries based on modular and continuous production flows are characterized by an enormous cost reduction as a consequence of historic industrial production.[11] Accordingly, PV technology shows a stable long trend of reducing PV module cost per doubling of cumulated production of about 20% for the entire period from the mid 1970s until 2010 (Figure 2). Stable learning rates can be expected in the years to come due to fast increasing corporate PV research and development investments.[8] A broader discussion of the PV learning curve can be found elsewhere [8,12].

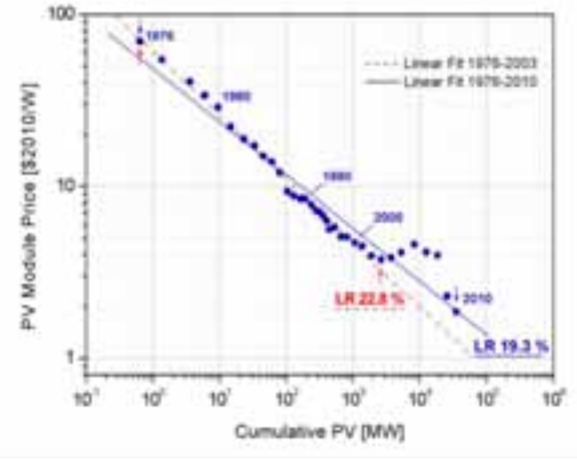


Figure 2: Learning curve for PV modules for the mid 1970s - 2010. Best approximation for the cost is the price curve as information rated in Wp. Oscillations around this trend are mainly caused by varying PV industry market dynamics and therefore profit margins, documented by applying different learning rates of 22.8% and 19.3% for the periods 1976 – 2003 and 1976 – 2010, respectively.[8]

3 Fuel-Parity Concept of PV Power Plants

As a consequence of fast decreasing PV levelized cost of electricity (LCOE), PV power plants become more cost competitive than fossil fuel fired power plants. Beyond fuel-parity further cost reduction in power generation can be realized by combining PV and fossil power plants, i.e. for the periods of sunshine the conventional power plant can be reduced in power output or completely shut down.

The most appropriate method for cost calculation is the LCOE approach [13] summarized and adapted to PV and fossil fuel fired power plants in Equation 1:

$$LCOE_{PV} = \frac{Capex}{Y_{ref} \cdot PerfR} \cdot \left(crf + k\right) \qquad \text{(Eq. 1a)}$$

$$k = k_{ins} + k_{O\&M} \qquad \text{(Eq. 1b)}$$

$$LCOE_i = \frac{Capex_i \cdot crf + Opex_{i,fix}}{FLh_{i,el}} + Opex_{i,\mathrm{var}} + \frac{fuel_i}{PE_{th,i} \cdot \eta_{i,el}} + \frac{carbon \cdot GHG_i}{\eta_{i,el}} \qquad \text{(Eq. 1c)}$$

$$crf = \frac{WACC \cdot \left(1 + WACC\right)^N}{\left(1 + WACC\right)^N - 1} \qquad \text{(Eq. 1d)}$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \qquad \text{(Eq. 1e)}$$

$$fuel_i = fuel_{crudeoil} \cdot cf_i \qquad \text{(Eq. 1f)}$$

$$fuel_{crudeoil} = fuel_{crudeoil,2010} \cdot \left(1 + r_{crudeoil}\right)^{y-2010} \qquad \text{(Eq. 1g)}$$

Equation 1: Levelized cost of electricity (LCOE) for PV and fossil fuel fired power plants. Abbreviations stand for: capital expenditures (*Capex*), reference yield for specific PV system at specific site (Y_{ref}), performance ratio (*PerfR*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual cost of Opex in percent of Capex (*k*), annual insurance cost in percent of Capex (k_{ins}) and annual Opex in percent of Capex ($k_{O\&M}$), oil/ natural gas and coal fossil plants as index (*i*), annual fix Opex of fossil plants ($Opex_{i,fix}$), variable Opex of fossil plants ($Opex_{i,var}$), annual full load hours of fossil plants ($FLh_{i,el}$), fuel cost for fossil plants ($fuel_i$), thermal energy conversion factor of fossil plants ($PE_{th,i}$), primary to electric energy conversion efficiency of fossil plants ($\eta_{i,el}$), carbon emission cost (*carbon*), carbon emission intensity per thermal energy of fossil plants (GHG_i), weighted average cost of capital (*WACC*), lifetime of plants (*N*), equity (*E*), debt (*D*), return on equity (k_E), cost of debt (k_D), fuel cost ($fuel_i$), fuel cost of crude oil ($fuel_{crude\ oil}$), ratio of fossil fuel to crude oil as coupling factor (cf_i), fuel cost of crude oil in the year 2010 ($fuel_{crude\ oil,2010}$), annual escalation rate of crude oil price ($r_{crude\ oil}$) and year (*y*).

From an end-user perspective grid-parity is a good definition for sustainable PV economics. This must be regarded differently from utility point of view. Large power generation companies are mainly used to operate large power plants, which is also possible by operating several large scale multi 10-100 MW PV power plants. PV power plants can be built in the 10 MW scale but also for a power capacity of more than 1 GW.[14] Large scale PV power plants become attractive for utilities in case of favourable economics. Consequently, PV power plants are competing with fossil fuel fired power plants, in particular oil, natural gas and coal fired power plants. Competitiveness is best measured by calculating and comparing LCOE for all power plants at all relevant locations. Fuel-parity is therefore defined by the parity of PV LCOE to the LCOE of respective fossil fuel fired power plants plus the cost of reduced full load hours (FLh) of fossil power plants. Relative competitiveness of PV and oil power plants is depicted exemplarily in Figure 3 for typical conditions on the Arabian Peninsula.[5] Fuel-parity is no future projection anymore, it is a matter of fact. Moreover, being beyond fuel-parity automatically implies economic benefits of CO_2 reduction, as fossil fuel fired power plants emit large quantities of greenhouse gases (GHG) in contrast to PV power plants contributing only 2% to 5% of specific GHG per kWh compared to fossil power plants on basis of total life cycle analysis.[15]

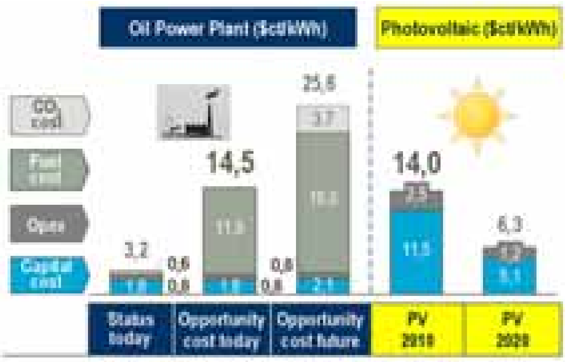
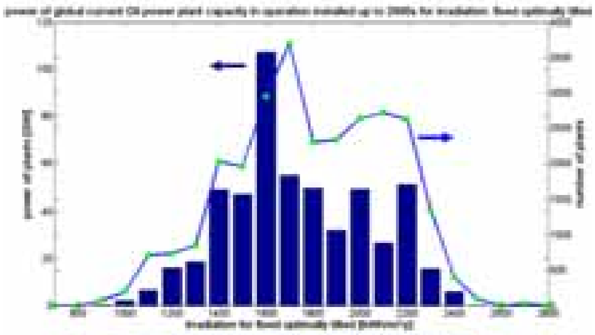


Figure 3: Cost structure of oil and solar PV power plants for very sunny and oil rich regions.[5] LCOE of oil power plants are largely dominated by fuel cost and relative low capital cost and operational expenses (Opex). LCOE of solar PV power plants are dominated by capital cost, whereas solar fuel is for free. Assumptions for oil power plant LCOE are: fuel cost of 4, 80 and 160 USD/barrel, full load hours of 4,000 h, 4,000 h, and 3,500 h, net efficiency of 40%, 40%, and 50%, CO_2 cost of 0, 0 and 70 USD/t_{CO2}, for status today, opportunity cost today and opportunity cost future, respectively. Capital expenditures (Capex), fixed Opex and variable Opex for oil power plants are 800 €/kW, 17 €/kW and 1 €/MWh_{el}, respectively. Assumptions for solar PV power plant LCOE are: full load hours of 1,725 h and 1,800 h, Capex of 2,000 €/kW and 1,000 €/kW, Opex of 1.5% of Capex, for PV power plants built in 2010 and 2020, respectively. Weighted average cost of capital are 5% for oil and solar PV power plants. Life time of oil power plants is 30 years. Life time for solar PV power plants built in 2010 and 2020 is 25 years and 30 years, respectively.

Conditions for the LCOE comparison in Figure 3 seem to be very optimistic, as solar resource for PV is excellent and oil power plants are known to be the most expensive fossil power plants. For better understanding of the global market potential of hybrid PV-Fossil power plants, the solar conditions are derived for all oil, natural gas and coal fired power plants in the world (Figure 4).

Necessary input for the evaluation of the global market potential are globally distributed and georeferenced solar resource data for fixed optimally tilted PV systems [16] and the coordinates of all fossil fuel fired power plants in the world [17]. The georeferenced power plants are sorted by solar irradiation of fixed optimally tilted PV modules and depicted in Figure 4.



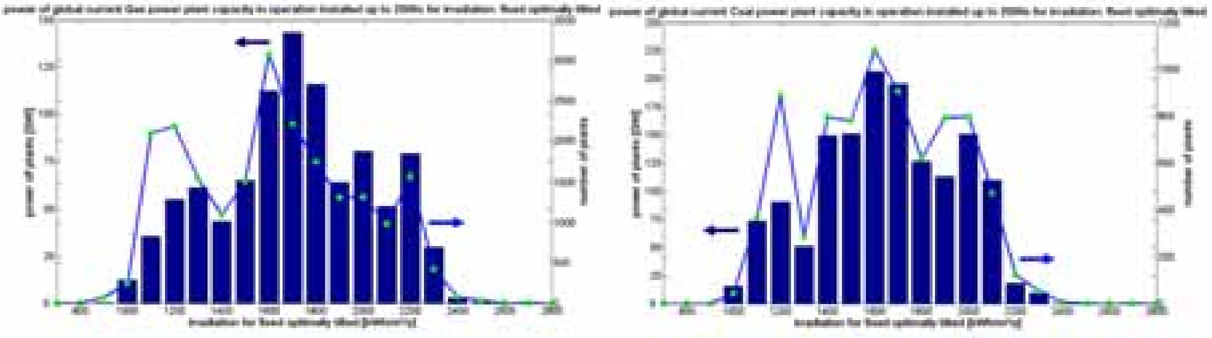


Figure 4: Solar location of oil (top), natural gas (bottom, left) and coal power plants (bottom, right) as of end 2000s. Power plants are georeferenced [17] and sorted by solar irradiation of fixed optimally tilted PV modules [16]. Total power plant capacities are 560 GW (oil), 1,100 GW (gas) and 1,470 GW (coal) of which about 150 GW (oil), 250 GW (gas) and 290 GW (coal) are located in very sunny regions of more than 2,000 kWh/m²/y of solar irradiation.

There are thousands of oil, gas and coal fired power plants located in very sunny regions of more than 2,000 kWh/m²/y (Figure 4). Total fossil fuel fired power plant capacity in the world is about 560 GW (oil), 1,100 GW (gas) and 1,470 GW (coal), of which more than 150 GW (oil), 250 GW (gas) and 290 GW (coal) being located at very sunny sites of more than 2,000 kWh/m²/y. By combining PV power plants with fossil fuel fired power plants to hybrid PV-Fossil power plants the fuel consumption of the respective fossil power plant can be reduced. Both, oil and gas fired power plants are able to adjust their power generation on a minute scale, i.e. by using state-of-the-art energy meteorology being able to forecast 24 hours ahead. Thus, there is no fundamental problem in combining PV power plants with oil and gas power plants to hybrid power plants. In the case of coal power plants excellent energy meteorology has to be applied, or new plants have to be built as integrated gasification combined cycle (IGCC) coal plants, since they are as flexible as oil and gas fired power plants.

4 Preconditions for PV Hybridization

Several requirements need to be fulfilled for a successful hybridization of PV and fossil fuel fired power plants. Therefore the fundamental concept of hybridization needs to be applicable for hybrid PV-Fossil power plants. Due to the fluctuating resource of PV power plants, the fossil fuel fired power plant has to be very flexible in its operation modes. However, the fluctuating characteristic of the PV sub-component would be much better manageable in case of good predictability in the range of some days and in particular for the next 24 h for a well-adjusted operation of the different sub-components. The economics of different fossil fuel fired power plant options for hybridization with PV power plants can be better analysed by applying a price coupling of the major fossil fuels. These preconditions for composing and analysing hybrid PV-Fossil power plants are illustrated in this section.

Hybrid power generation systems contain two or more power generation sources in order to balance each other's strengths and weaknesses. There are several definitions for hybrid power systems, but one of the best is as follows: small set of co-operating units, generating electricity or additionally heat or potable water, based on diversified renewable and non-renewable energy sources, while the co-ordination of their operation takes place by utilisation of advanced power electronics systems.[18] Hybrid power systems are a good way to increase availability and flexibility of power supply systems and to have available flexible sources of electricity which optimize utilisation of energy sources.

There are various types of fossil fuel fired power plants like natural gas or oil fired combined cycle gas turbines (CCGT) in the typical power range of 60 – 800 MW, natural gas or oil fired gas turbines (GT) in the typical power range of 60 – 250 MW and coal fired steam power plants (ST) in the typical power range of 60 – 800 MW.[19] In the last two decades the CCGT power plant has been the most commonly built power plant in the world (Figure 5), with the exception of China being more focused on coal fired ST power plants.

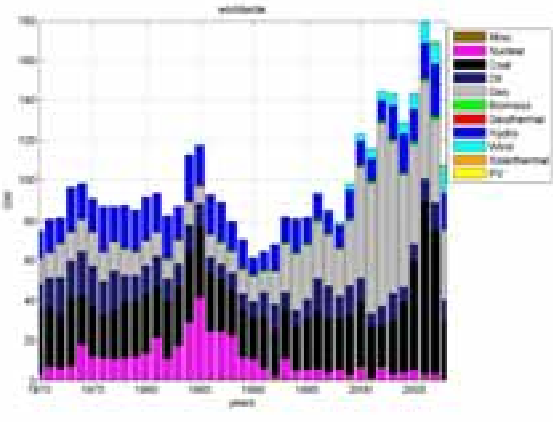


Figure 5: Global new power plant capacity commissioned in the years 1970 – 2008 and still in operation. Fossil fired power plants dominate the new investments over the entire period. Hydro power receives stable investments, whereas nuclear power plants significantly lost attraction. Wind power is the only new renewable energy source which achieved considerable market share. Data are taken from Platts [17], but about 35 GW of wind power and 13 GW of solar PV are missing in the dataset.

The fundamental reason for the substantial growth in new CCGT power plant capacities had been power market liberalization in various markets, relative cheap natural gas fuel, increased risk level in parameters driving the power plant economics, relatively reasonable performance in emissions and rather low capital requirements. All this provides a flexibility being described by the capability to follow the market on the supply side, e.g. fuel price and fuel availability, and the demand side, e.g. hourly, daily or seasonal power revenue and ancillary services. The operational flexibility comprises fast start-up and shutdown, fast load changes and load ramps, high start-up reliability and load ramps, high start-up reliability and load predictability, frequency control and ancillary services. The ramp rates of modern flexible CCGT power plants are 2.5% of full capacity per minute and even higher during the start-up sequence.[20]

The power plant energy conversion efficiency is typically substantially reduced in case of part load operation, however an appropriate power plant design allows relative part load efficiencies not lower than 90% - 95% of full load efficiency even for a part load of 20%. This is an enormous contribution for a high operational flexibility while hardly increasing power generation cost. The success in increased flexibility of GT and CCGT is extended to coal fired power plants and realised in the IGCC power plant which can be fuelled with any type of fossil fuels, in particular any types of coal.[19]

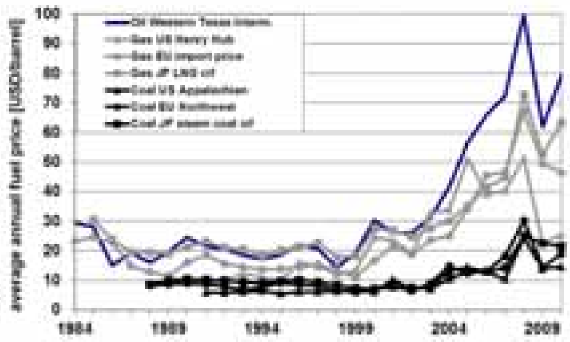
Besides the flexibility requirement of the last two decades the arising need for flexibility due to fast growing fluctuating renewable PV and wind power plants can be provided by these plants which positions them as nearly ideal balancing power plants. In the near term even coal fired power plants will be able to be operated in such a flexible manner. This will not be the case for nuclear power plants, hence they are structurally not suitable for future flexibility requirements and therefore will have to be substituted.

The interdisciplinary field of energy meteorology integrates the physics of the atmosphere and energy system engineering for tackling the various impacts of weather and climate on conversion, transmission and consumption of energy. The need for high quality energy meteorology is becoming very relevant for PV, since fast increasing cumulative installed PV capacities need to be properly integrated into existing local power systems. The operation modes of existing peaking power plants, e.g. oil and natural gas fired power plants, intermediate load power plants, e.g. natural gas and hard coal fired power plants, but also storage facilities need to be adapted to fluctuating feed-in power sources like wind power and PV. By accurate forecasting of solar resource availability and hence PV power feed-in the operation necessity for conventional power plants can be planned at least one day ahead. Furthermore, good prognosis tools significantly reduce the cost of PV integration into conventional power systems, already documented by respective tools for wind power prediction which lowered the regulation cost by 40% and even the knowledge on the uncertainty on the short-term reduced the cost by further 40% [21].

In Germany the first PV power forecasting tool was introduced in the year 2006 [22] and the prognosis quality steadily increased ever since. The relative root mean square error (rmse) of the day-ahead (24 hour) forecast has been continuously reduced from about 35% - 40% in the year 2004 to less than 4% in the year 2011.[23,24] Technically it is possible to reduce the current one hourly forecast interval to the 15 minutes interval typically used in the power industry but even a 5 minutes interval as is used in the US is manageable. Lorenz et al. [23] give an overview on further relevant literature.

The forecast deviations for PV power feed-in in Germany can still be further optimized but has already achieved a relatively sophisticated level. The prognosis tools could be spread all around the world, currently performed for the US, by adaption to special local weather conditions, and should be not a large obstacle. Finally, the energy meteorology tools available for PV power feed-in are an excellent basis for well performing hybrid PV-Fossil power plants.

Fossil fuel prices for crude oil, natural gas and steam coal considerably deviate in different markets in the world, but the overall price trend is similar and relative price differences have decreased in the last decade (Figure 6). Long-term price escalation as a consequence of increase in demand and degrading and diminishing resources is reflected in fossil fuel prices. Dependence of natural gas and coal price on crude oil price can be found within market fluctuations over the entire period of time. For comparison reasons all fossil fuel prices have been recalculated to thermal energy units in USD per barrel. The long-term price ratio of natural gas to crude oil is about 0.7 – 0.9, whereas the ratio of coal to crude oil is about 0.2 – 0.4. The coupling of natural gas and coal to crude oil is sensible because both are used for their thermal energy content but factors such as relative availability, local energy logistics and respective power plant efficiencies create price offsets. Long-term price coupling of natural gas on crude oil is expected by International Energy Agency to be about 0.9 for the US and 0.8 for Europe and Japan [25].



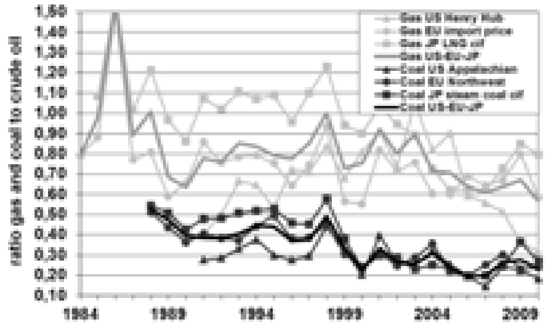


Figure 6: Fossil fuel prices in absolute money of the day units (top) and normalized to crude oil (bottom) on thermal energy units for major trade centres in the years 1984 to 2010. Long-term price escalation as a consequence of increase in demand and diminishing resources is reflected in prices. Dependence of natural gas and coal price on the crude oil price can be found within market fluctuations over the entire period of time. Long-term price ratio of natural gas to crude oil is about 0.7 – 0.9, whereas ratio of coal to crude oil is about 0.2 – 0.4. Data are taken from BP [26].

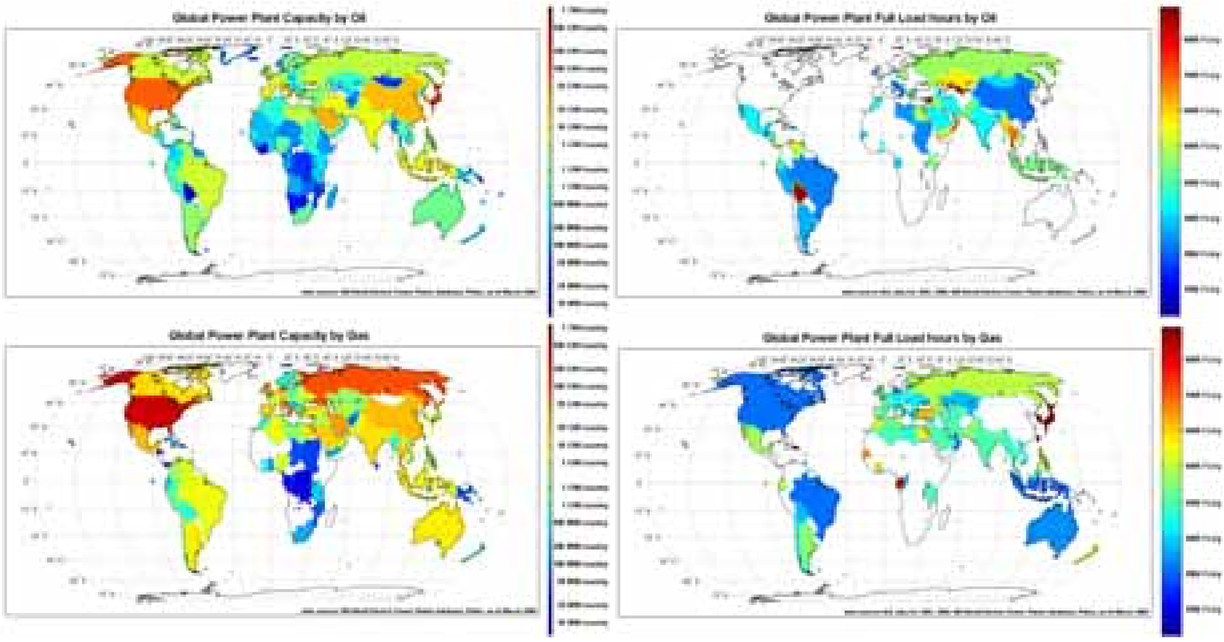
Summing up, the preconditions for hybrid PV-Fossil power plants are very good, since most fossil fuel fired power plants are very flexible and the improvements in energy meteorology enable a well-adjusted operation of hybrid PV-Fossil power plants. The fossil fuels are coupled to the crude oil price, thus the following analysis is performed on basis of the crude oil price.

5 Overview on Global Fossil Fuel Power Plant Capacity and Economic Scenario

The total global installed fossil fuel power plant capacity is about 3,180 GW, being about 67% of total global installed power plant capacity (Figure 5), by end of 2008 composed by about 440 GW (oil), 1,230 GW (gas) and 1,510 GW (coal). These fossil power plants generated 13,683 TWh, being about 68% of total global power generation in 2008. The contribution by fuel was 1,104 TWh (oil), 4,303 TWh (gas) and 8,273 TWh (coal). Comparing the installed capacity and the generated electricity makes it possible to characterize the power technologies by their full load hours (FLh), being 2,520 FLh (oil), 3,500 FLh (gas) and 5,460 FLh (coal).[3]

The distribution of the global installed fossil fuel power plant capacity and the respective FLh are depicted in Figure 7. In this paper the hybridization potential of PV and fossil fuel power plants is analysed, hence power plants in peaking operation modes have to be neglected. For practical reasons only power plants are considered in the following in case of at least 2,000 FLh of all power plants in one country per fuel type (Figure 7). This limit reflects a high probability that the respective power plants are also in operation during daytime when the PV power plants feed-in their power.

The applied economic scenario for fossil fuel power plants is defined in Table 1. In general the assumptions in Table 1 reflect a realistic estimate of all major economic drivers, except the price for fossil fuels being very likely too conservative. The range of the most fundamental price, crude oil, is between 80 to 107 USD/barrel from 2010 to 2020. If the depletion and degradation rate of fossil fuels stays at the rate of the 2000s, the real price could be twice as high at the end of 2010s as assumed in the applied scenario.



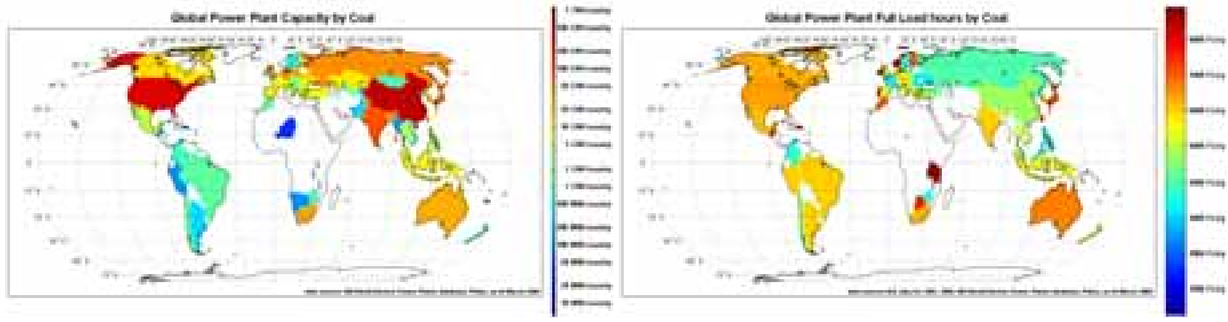


Figure 7: Global fossil fuel power plant capacity (left) and average full load hours (right) of at least 2,000 FLh for oil (top), gas (center) and coal (bottom) per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database [17] and International Energy Agency [3].

Parameters	**units**	**oil**	**gas**	**coal**
Capex	[€/kW]	800	750	1,500
Opex$_{fix}$	[€/kW/y]	17	15	20
Opex$_{var}$	[€/MWh$_{el}$]	1	1	1
power plant lifetime	[y]	30	30	40
power plant efficiency 2010	[%]	40%	50%	35%
power plant efficiency 2020	[%]	50%	55%	45%
power plant efficiency increase	[%/y]	1%	0.5%	1%
coupling factor fuel	[-]	1.0	0.80	0.30

Table 1: Scenario assumptions for fossil fuel power plant economics. Further scenario settings are: weighted average cost of capital of 6.8%, exchange rate USD/€ of 1.40, crude oil fuel price of 80 USD/barrel in 2010, annual crude oil price escalation rate of 3% in real terms, no cost for existing CO_2 emissions over the entire scenario period and a thermal energy conversion of 1.6806 MWh$_{th}$/barrel. The scenario covers a business-as-usual approach, whereas the assumptions on the crude oil price and its escalation as the most relevant cost factor might be too conservative. Price coupling of gas and coal to crude oil fluctuates over time (Figure 6). Numbers mentioned are for fossil fuel power plants of multi-100 MW. Abbreviations stand for: capital expenditures (Capex), operational expenditures (Opex), annual fix Opex (Opex$_{fix}$) and variable Opex (Opex$_{var}$). Data are taken from various sources described elsewhere [7].

6 Fuel-Parity of PV and Fossil Fuel Power Plants

Cost dynamics of PV power plants show a fast reduction in LCOE which is fundamentally coupled to the high market growth rate (Figure 1) and the high learning rate (Figure 2). Cost projection of PV power plants can be modelled by combining LCOE approach and learning curve approach, shortly discussed in section 1 and described in more detail elsewhere [2]. Due to several uncertainties a realistic scenario is used assuming that the future development of PV industry will stay on a business-as-usual path, i.e. a lower growth rate than the average of the last 15 years (Figure 1) and a cost reduction according to the PV learning curve.

The PV scenario assumptions are: PV power plant Capex of 1.80 to 2.00 €/Wp (depending on local least cost conditions), Opex of 1.5% of Capex, performance ratio of 80%, local irradiation of fixed optimally tilted systems [16], weighted average cost of capital of 6.8%, plant lifetime of 25 years, annual power degradation of 0.4%, learning rate for modules and inverters of 20% (2010 to 2012) and 15% (2013 to 2020) and for remaining BOS components no further learning to be conservative, global PV growth rate of 40% (2010 to 2012) and 30% (2013 to 2020).

The PV scenario setting can be considered as realistic, maybe slightly too conservative. The PV growth rates have been higher for the last 15 years (Figure 1), hence the cost reduction in time might be faster. The most competitive utility-scale market segments in the world are China and Germany, which show average fully-loaded PV system Capex of about 1.9 – 2.1 €/Wp in the year 2010 [27] being in line with the realistic scenario assumptions. Most competitive PV industry leaders achieve an even better cost level. True costs of PV power plants in Germany equipped with CdTe modules from First Solar are found to be slightly below 1.6 €/Wp. The two c-Si module cost leaders achieve fully-loaded module cost in average of about 1.02 €/Wp. The fully-loaded average non-module cost in China and Germany for c-Si PV power plants are 0.67 and 0.72 €/Wp, respectively. As a consequence the fully-loaded system cost for very competitive c-Si PV power plants have been about 1.7 €/Wp, composed by c-Si module cost leaders and the two most cost efficient PV markets. In total leading PV industry players have been able to offer PV power plants for 1.6 – 1.7 €/Wp for the conditions of cost efficient PV markets.[27]

Comprehensive hybridization economics of PV and fossil fuel power plants can be derived on basis of the scenario assumptions for PV power plants (this section) and fossil fuel power plants (section 5), the LCOE modelling (section 3), the experience curve approach (Figure 2) and described in more detail elsewhere [2,8] and the georeferenced dataset of all fossil fuel power plants. Key assumption is the close physical location of PV and fossil power plants. Therefore no additional storage is needed, no substantial grid constrains have to be feared and electricity supply security is provided.

Upgrading existing fossil fuel power plants by PV power plants to hybrid PV-Oil, PV-Gas or PV-Coal power plants is economically favourable for PV LCOE lower than respective oil, gas or coal LCOE. The precise calculation need to include slightly higher capital cost of fossil power plants by reducing their FLh in order of the PV FLh. This effect can be calculated by Equation 1c and has to be generated additionally by the PV component, i.e. lower PV LCOE, of the hybrid PV-Fossil power plant. All breakeven, i.e. parity, analyses in this paper take this effect into account. The year of PV and oil power plant parity is illustrated in Figure 8.

The fair comparison of PV and fossil fuel power plants would be on a total plant LCOE basis, i.e. including all cost components. However, for estimating the competitiveness of the PV hybridization approach a fuel-only LCOE calculation is helpful, since only the marginal cost of the fossil fuel of the power plants are taken into account, i.e. in case of lower PV LCOE than fuel LCOE a non-hybridization strategy of respective power plant owners would definitely cause higher power generation costs and lead to higher prices for the end-users, thus loosing competitiveness either to competitors or to other regions on a macro-economic level.

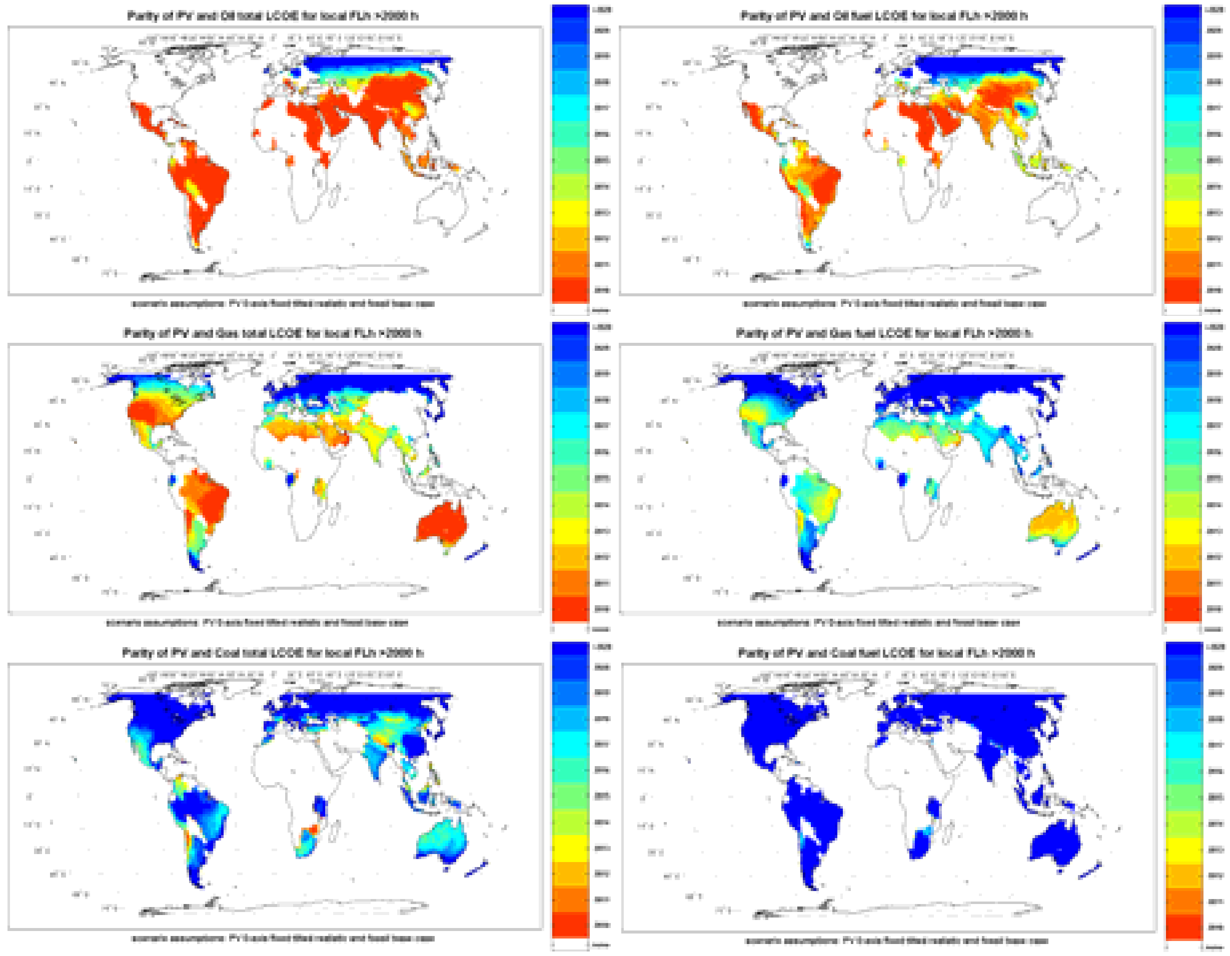


Figure 8: Parity of PV and fossil fuel power plants for total plant LCOE (left) and fuel-only LCOE (right) for oil (top), gas (centre) and coal (bottom) fired power plants for the 2010s. Power plant scenario assumptions are defined in sections 5 and 6. Countries operating respective fossil fuel power plants in average of at least 2,000 FLh are included in the analysis. The calculation is performed on a mesh of 1°x1° of latitude and longitude.

In nearly all sunny regions in the world, PV power plants are lower in LCOE than oil power plants already in the year 2010 (Figure 8). In most sunny regions PV LCOE are even lower than fuel-only LCOE of oil fired power plants. The calculations are performed without any subsidies, i.e. fossil fuels have to be taken into account for their world market price. Fossil fuel producing countries often convert the fossil fuels for significantly less than world market conditions to electricity, but this is equal to subsidizing the local power sector.

In the case of gas power plants, PV power plants are lower in LCOE than gas power plants on total plant basis already in the early 2010s in nearly all sunny regions in the world (Figure 8). PV LCOE compared to fuel-only LCOE of gas fired power plants begin their breakeven in the first half of the 2010s in the very sunny regions, however the adequate economic reference is the total plant basis and the fuel-only level is the economically strictest reference. Consequence of lower natural gas prices, i.e. looser price coupling to crude oil, would be a delayed economic breakthrough of hybrid PV-Gas power plants. PV LCOE start to be lower than those of gas power plants on a total plant basis in the very sunny regions in the world in the year 2010 and reach the regions of moderate solar resources by the end of the decade.

Only in very sunny regions in the world, PV power plants are lower in LCOE than coal power plants on total plant basis in the second half of the 2010s (Figure 8). PV LCOE compared to fuel-only LCOE of coal fired power plants begin their breakeven after the year 2020 even in the very sunny regions, however the adequate economic reference is the total plant basis and the fuel-only level is the economically strictest reference. Consequence of lower hard coal prices, i.e. looser price coupling to crude oil, would be a delayed economic breakthrough of hybrid PV-Coal power plants. PV LCOE start to be lower than those of coal power plants on a total plant basis in the very sunny regions in the world in the very end of the 2010s.

The results for hybrid PV-Fossil power plant economics show several characteristics for a beneficial combination. Already existing oil power plants should be operated for at least 2,000 FLh during daytime. Fuel represents the by far highest fraction of power plant LCOE, e.g. about 80% (oil), about 75% (gas) and about 50% (coal) for a crude oil price of 80 USD/barrel, hence fossil power plant LCOE are highly influenced by the crude oil price. The solar resource quality at local sites of existing power plants is very important for PV LCOE and thus hybrid PV-Fossil power plant economics, but the crude oil price is more decisive. Fossil fuel producing countries have the identical fossil power plant LCOE due to the respective opportunity cost in case of burning fossil fuels priced lower than world market prices. However, these countries would have no problems in organising the financing of large scale PV power plant investments.

Summing up, results for hybrid PV-Fossil power plant economics give plenty of insights for excellent competitiveness of this approach for upgrading existing fossil fuel fired power plants. Financial upgrading benefit for resulting hybrid PV-Fossil power plants is quickly increasing as a consequence of fast PV LCOE reductions and higher than expected crude oil price escalation.

7 Hybrid PV-Fossil Power Plant Demand Curve

The approach of upgrading existing fossil fuel fired power plants by PV power plants is discussed in the previous sections. The PV cost reduction dynamics complemented by fossil fuel price scenario assumptions have major impact on the competitiveness of this approach.

When applying LCOE data for fossil fuel fired power plants and PV power plants for all coordinates in the world, a global demand curve for hybrid PV-Fossil power plants can be derived. All fossil fuel power plants are georeferenced, thus the year of financially beneficial hybridization for the different fuel types for all existing fossil fuel power plants can be derived and plotted in an integrated manner. The global hybrid PV-Fossil power plant demand curve based on fuel-parity is depicted in Figure 9 for the case of total plant and fuel-only LCOE parity for fossil power plants operated in countries of an average of at least 2,000 FLh and for plants firing coal of at least bituminous coal quality.

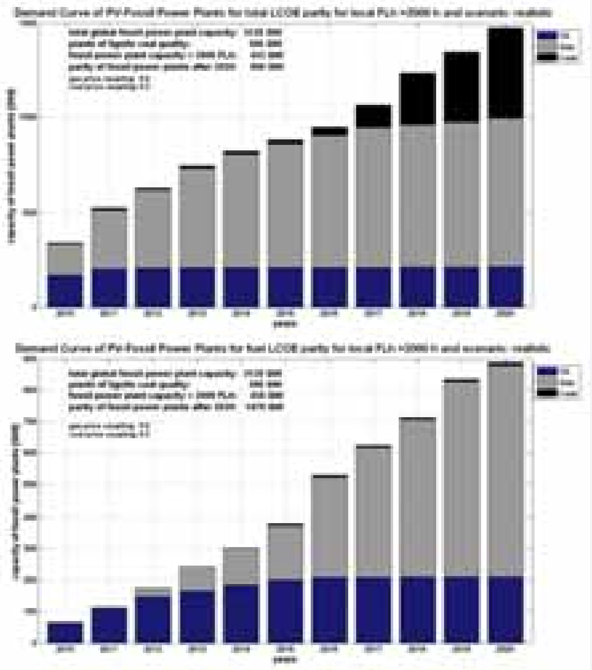


Figure 9: Global hybrid PV-Fossil power plant demand curve in the 2010s on total plant (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV power plants in the 2010s. Fossil power plant capacity, i.e. oil, natural gas and coal, is counted only in case of PV LCOE (plus higher fossil capital cost due to reduced FLh) lower than total plant and fuel-only fossil LCOE. Every coordinate of a 1°x1° mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the fuel categories. Power plant scenario assumptions are defined in sections 5 and 6. Countries operating respective fossil fuel power plants in average of at least 2,000 FLh and coal plants firing coal of at least bituminous coal are included in the analysis. Data for fossil fuel power plant capacity are taken from UDI World Electric Power Plants database [17].

The global hybrid PV-Fossil power plant market potential is structured as following: Total plant LCOE parity is already given for about 350 GW (oil and gas) in 2010, rising to 750 GW (oil, gas and begin of coal) in the middle of the 2010s and reaching about 1,500 GW (oil, gas and coal) by the end of the 2010s. Fuel-only LCOE parity is already given for about 60 GW (oil) in 2010, rising to about 380 GW (oil, gas and begin of coal) in the middle of the 2010s and reaching about 900 GW (oil, gas and very little coal) by the end of the 2010s. Global total fossil power plant capacity is about 3,130 GW by early 2009. About 460 GW of that capacity is identified as being operated less than 2,000 FLh and therefore excluded from the analysis. Further about 310 GW coal power capacity is excluded due to the use of low quality coal not tradable on the world market. The remaining about 2,370 GW fossil fuel power plant capacity can be economically upgraded by PV power plants by 2020 to approximately 63% and 38% for total plant and fuel-only LCOE parity, respectively.

In the year 2020, fuel-parity of PV power plants and conventional fossil fuel fired power plants might be in the order of 1,500 GW, whereas a capacity of approximately 900 GW fulfils the most aggressive criteria of PV LCOE parity to fuel-only LCOE of fossil power plants.

The two economic key drivers for the fast PV cost reduction are the high growth and learning rates of PV systems (Figures 1 and 2). The growth rate in the scenario is assumed to be significantly lower than on average over the last 15 years. However, the impact of the learning rate on the fast cost degression and the dependence of the global hybrid PV-Fossil power plant demand curve on the learning rate remains somehow unclear. For lowering this uncertainty a sensitivity analysis is performed by varying the learning rates within a range of 10% to 25% for modules and inverters and 5% to 20% for the other balance of system (BOS) components. The learning rates are lowered by 5% for the years 2013 to 2020. All the other assumptions are identical to the previous sections. The outcome of this parameter variation is displayed in Figure 10.

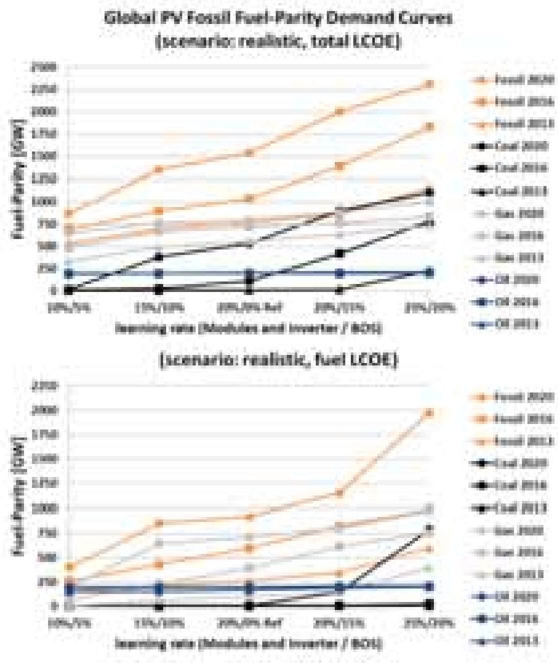


Figure 10: Global hybrid PV-Fossil power plant demand curve for total plant (top) and fuel-only LCOE parity (bottom) in dependence of learning rates for the 2010s.

No substantial consequence of varying learning rates on hybrid PV-Oil power plants can be expected, neither in the total plant nor in the fuel-only LCOE parity (Figure 10). The reason for that is the already achieved competitiveness of hybrid PV-Oil power plants. However, a faster cost reduction as result of higher learning rates would further increase the profit of upgrading existing oil fired power plants by PV power plants, thus resulting in a faster market diffusion of hybrid PV-Oil power plants.

The impact of declining learning rates on hybrid PV-Gas power plants is rather low on a total plant LCOE basis but more significant for fuel-only LCOE parity (Figure 10). Even in the case of very low learning rates of 15% (modules and inverters) and 10% (rest of BOS) for the years 2010 to 2012 and 10% and 5% for the years 2013 to 2020, the economic market potential of hybrid PV-Gas power plants on fuel-only LCOE parity basis would reach 70% of the size compared to the case of even higher learning rates than observed for the past decades.

The profitability of hybrid PV-Coal power plants is very sensitive to the learning rate of PV systems for both fuel-parity definitions (Figure 10). Nevertheless, the market diffusion of hybrid PV-Coal power plants can be expected in the second half of the 2010s and at latest by the end of the 2010s.

By comparing the results of different years in the 2010s, it can be estimated that even significantly lower learning rates of only 10% for modules and inverters and 5% for the additional BOS components would delay the respective economic market potential by a maximum of about 3 to 4 years.

A lower learning rate reduces the market growth but would be no show stopper at all. PV cost projections on basis of experience curve approach enable feasible estimates of a very high sustainable global PV market potential in this decade. Significantly lower learning rates would reduce this potential accessible in the 2010s, but PV market diffusion would be delayed only by a few years, typically below four years.

The PV learning rate and its impact on the total economic market potential of PV systems is discussed in more detail by Kersten et al. [12] and embedded into a broader perspective including the grid-parity approach for end-user PV systems and off-grid solutions by the first author of this paper [28].

Summing up, the total fossil fuel power plant capacity of 3,130 GW by early 2009 is by about 70% (2,170 GW) suitable for upgrading with PV power plants. By 2020, this PV power plant upgrading market potential is at least 25% to 40% of the suitable capacity due to very conservative scenario assumptions, i.e. dramatic decline in PV learning rates and fuel-only LCOE parity. A more realistic, maybe slightly optimistic, consideration is beyond 90% of suitable capacity. The fuel-parity market potential for hybrid PV-Fossil power plants can be expected to be in the range of at least 700 GW up to even more than 2,100 GW by 2020. These numbers are very likely to grow in parallel to new net installed fossil power plant capacity during the 2010s.

8 Outlook

Significant amounts of conventional power plant capacity in Figure 9 might not only be used for upgrading with PV power plants but also used for installations of hybrid Wind-Fossil power plants. Therefore it is of utmost relevance to understand the degree of competitiveness or complementarity of the two major and fast growing renewable power technologies.

A first global analysis of the complementary characteristics of PV and wind power plants gives plenty of indications that these two major renewable power technologies complement each other to a very high extent (Figure 11) and show nearly no competition due to the fundamental underlying solar and wind resources.[29] The degree of complementarity is measured by overlap FLh, i.e. the amount of power provided by PV and wind power plants adjacent to each other in the same time interval. However, typically the overlap FLh indicate a good complementarity due to part load conditions of the respective power plants. For extracting the amount of power being problematic, the critical overlap FLh are defined, i.e. the amount of power being above the rated capacity of PV or wind power per geographic unit and time interval. In these cases the renewable power might be lost due to limited power line, balancing power plant or storage capacities. The first insights for the analysis of the complementarity of PV and wind power is depicted in Figure 11.

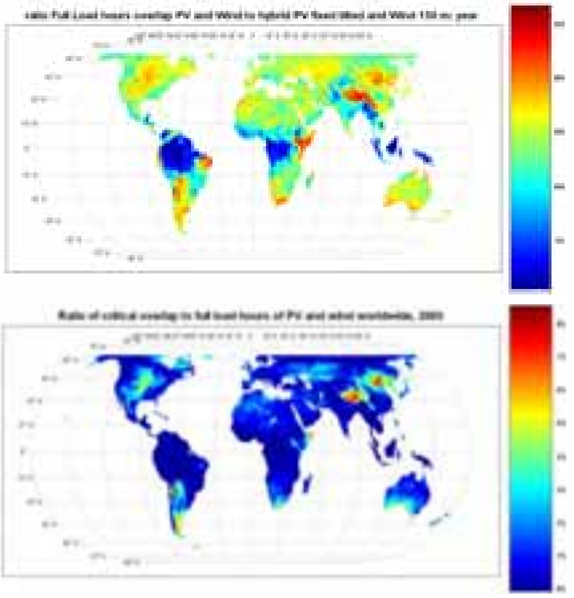


Figure 11: Ratio of annual total (top) and critical (bottom) overlap full load hours of PV and wind power to added up full load hours of both power technologies.[29] Assumed are PV fixed optimally tilted power plants and wind power plants at 150 m hub height. Calculations are performed on a mesh of 1°x1° latitude and longitude and a one hourly time interval for the year 2005. Power capacity of PV and wind power is set to an equal value.

Global average total overlap is about 15%, whereas the maximum overlap is 25%. Critical overlap is significantly lower, i.e. available power per coordinate higher than rated power capacity of one power technology. Critical overlap FLh are worldwide below 9% and at most places even below 3% to 4%. Consequently, PV and wind power plants are finally no competition to each other and the findings for the global hybrid PV-Fossil power plant demand curve need not to be lowered. However, it seems to be likely that hybrid PV-Wind-Fossil power plants can capture significant market share in the 2010s and further reduce the remaining FLh of the fossil fuel power plant component of the hybrid power plant.

For reaching a sustainable equilibrium in global power supply the remaining fossil fuel plants need to be substituted, since harmful greenhouse gas emissions, price escalating, diminishing and degrading fossil resources and supply disruptions induced by military and economic conflicts around remaining fossil fuel resources force the power plant operators to low risk investments.

A very promising option in the mid- to long-term arises by renewable power methane (RPM).[30] RPM would enable hybrid PV-Wind-RPM power plants to establish a fully dispatchable power supply based on fluctuating wind and solar resources. In the concept of RPM the excess power is converted in a first step by electrolysis into hydrogen and in a second step by methanation into methane. Besides electricity only water and carbon dioxide are needed. Major advantage of RPM is the step by step switch from current fossil methane (natural gas) to the future renewable power methane, since the entire downstream inftrastructure can be used, i.e. transmission pipelines, distribution networks and the methane (gas) power plants. A first economic analysis on the global impact potential of the RPM based on hybrid PV-Wind-RPM power plants finds indications that this approach becomes competitive in the early 2020s.[31]

9 Conclusions

The economic potential of hybrid PV-Fossil power plants is in the order 1,500 GW in the year 2020. This market potential for PV power plants is available without any subsidies for PV or fossil fuels. Due to the fast cost degression of PV in contrast to a cost escalation of fossil fuels as a consequence of diminishing resources the profitability of hybrid PV-Fossil power plants is increasing very fast. PV and wind power plants are complementary and not competitive, hence hybrid PV-Wind-Fossil power plants might become a major trend in global power business mainly driven by its highly competitive cost structure.

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