FUEL-PARITY: IMPACT OF PHOTOVOLTAICS ON GLOBAL FOSSIL FUEL FIRED POWER PLANT BUSINESS

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ABSTRACT

Over the last 15 years global photovoltaic (PV) installations have shown an average annual growth rate of 45%. Combined with a constant learning rate of about 20% this leads to an ongoing and fast reduction of PV installation costs. While PV has been highly competitive for decades in powering space satellites and off-grid applications for rural electrification, commercial on-grid PV markets for end-users are currently about to establish as reflected by first grid-parity events.

In parallel, the fast decrease in levelized cost of electricity (LCOE) of PV power plants creates an additional and sustainable large-scale market segment for PV, which is best described by the fuel-parity concept. LCOE of oil and natural gas fired 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 end of this decade in the order of at least 900 GWp installed capacity without any electricity grid constraints. PV electricity is very likely to become the least electricity cost option for most regions in the world.

Major PV Diffusion Phases - Consequence of High Learning Rates

Average annual growth rates of global photovoltaic (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).[1] 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.[2] 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.[3] By end of 2009 about 22.8 GWp of cumulated PV power capacity has been globally installed and most interestingly PV products found their markets in all countries in the world.[4] This paper intends to give some insights for the fourth diffusion phase: commercial utility-scale PV power plants.

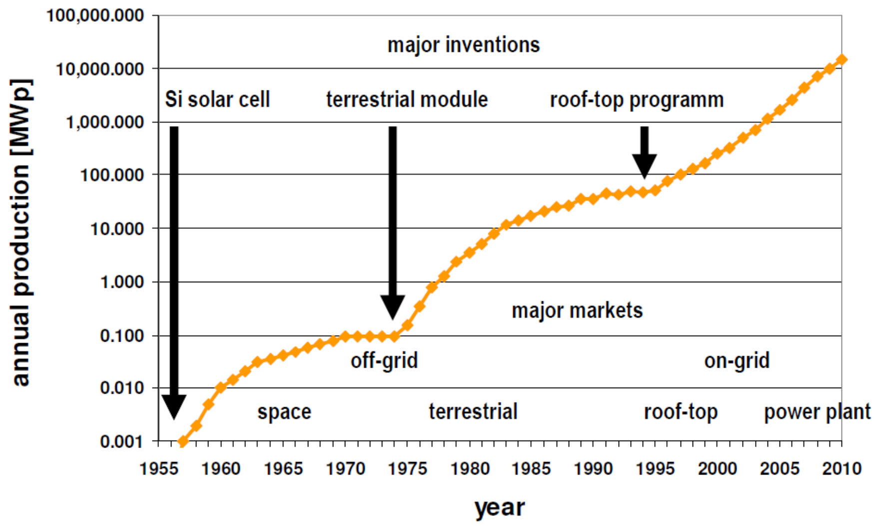

Figure 1: Historic PV production in dependence of major inventions and market segments.

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) [5,6], in the kilowatt size (e.g. residential roof-top systems) [3] up to the multi megawatt dimension (utility-scale power plants) [7]. 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.[8] 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 mid

1970s until 2010 (Figure 2). A broader discussion of the PV learning curve can be found elsewhere [1].

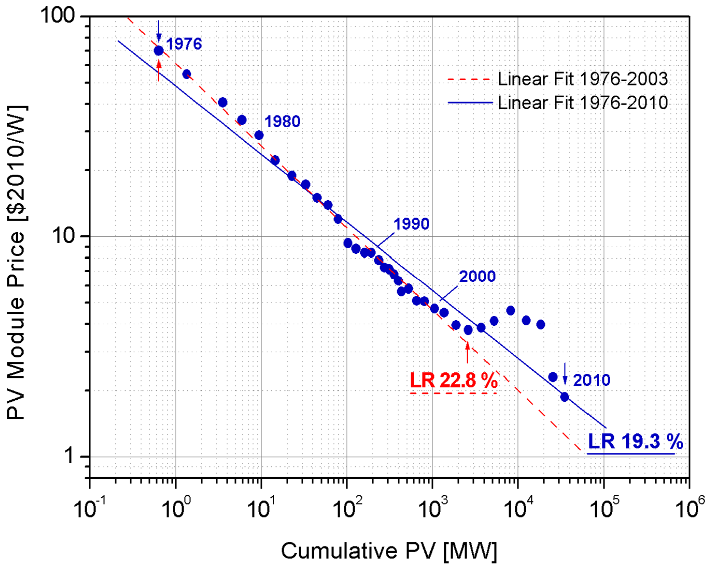

Figure 2: Learning curve for PV modules for the mid 1970s - 2010. Best approximation for the cost is the price curve as information rated in Wp. Oscillations around this trend are mainly caused by varying PV industry market dynamics and therefore profit margins, documented by applying different learning rates of 22.8% and 19.3% for the periods 1976 – 2003 and 1976 – 2010, respectively.[1]

Grid-Parity of Residential PV Systems

Residential grid-parity is defined by the parity of PV electricity generation cost and cost of electricity supply for end-users.[3] The most appropriate method for cost calculation is the levelized cost of electricity (LCOE) approach [9] summarized and adapted to PV in Equation 1:

$$LCOE = \frac{Capex}{Y_{ref} \cdot PerfR} \cdot \left(\frac{WACC \cdot (1+WACC)^N}{(1+WACC)^N - 1} + k \right) \quad \text{(Eq. 1a)}$$

$$WACC = \frac{E}{E+D} \cdot k_E + \frac{D}{E+D} \cdot k_D \qquad k = k_{ins} + k_{O\&M} \quad \text{(Eq. 1b,c)}$$

Equation 1: Levelized cost of electricity (*LCOE*) for PV systems. Abbreviations stand for: capital expenditures (*Capex*), reference yield for specific PV system at specific site (Y_{ref}), performance ratio (*PerfR*), weighted average cost of capital (*WACC*), lifetime of PV system (*N*), annual operation and maintenance expenditures (*Opex*), annual cost of Opex in percent of Capex (k), equity (E), debt (D), return on equity (k_E), cost of debt (k_D), annual insurance cost in percent of Capex (k_{ins}) and annual Opex in percent of Capex ($k_{O\&M}$).

The dynamics of grid-parity have been analysed for more than 150 countries representing more than 98% of world population and more than 99% of global gross domestic product (Figure 3).[3] First residential grid-parity events occur today in all regions in the world and continue throughout the entire decade. Cyprus, Italy, the Caribbean and West Africa are markets were grid-parity is reached first. At the end of this decade more than 80% of market segments in Europe, the Americas and Asia are beyond residential grid-parity. Due to energy subsidies in South Africa and Egypt, which represent more than 60% of African electricity generation, exception is given for Africa. Residential grid-parity is complemented by highly economic off-grid PV in rural regions of developing countries.[5,6] This is the case for about 1.5 billion people in the world, mostly living in Africa and South Asia. PV systems are in operation in all countries in the world.[4] Therefore sustainable markets might grow very fast after grid-parity, in particular in case of low technical and legal obstacles.

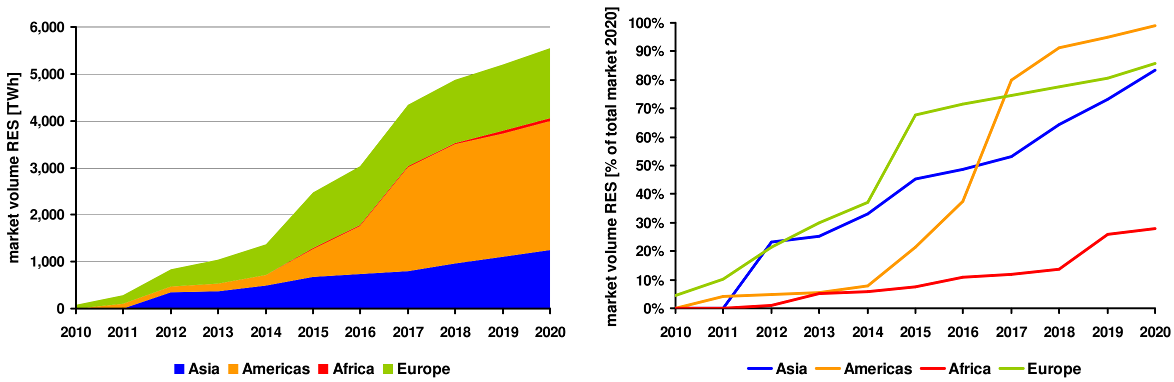

Figure 3: Grid-Parity market volume for residential segments in absolute (left) and relative (right) numbers for all regions in the world in the years 2010 to 2020.[3]

By conducting a global grid-parity analysis the market potential for on-grid residential PV electricity can be estimated to a maximum of about 5,500 TWh by 2020 (Figure 3). This market volume can be translated into a cumulated installed PV capacity potential by assuming a global electricity generation weighted average annual irradiation of 1,690 kWh/m² on fixed optimally tilted PV systems [10], a global performance ratio of 78%, a global residential PV self-supply fraction of 30% and a global market penetration of 50%. These assumptions lead to a fully economically sustainable installed residential PV capacity potential of about 630 GWp in 2020. Looking at the market potential for on-grid industrial PV electricity, which is estimated to be about 6,000 TWh by 2020, some parameters should be adjusted, at least the performance ratio to 82% and the industrial PV self-supply fraction to 50%. The industrial grid-parity events might generate another installed PV capacity potential of 1,080 GWp. The PV self-supply fraction might be significantly increased to about 80% for the case of available economic storage solutions. Finally, electricity market volume addressable by PV might enable an installed PV capacity potential of 1,710 GWp (630 GWp residential and 1,080 GWp industrial) without any storage solutions and up to 3,400 GW (1,670 GWp residential and 1,730 GWp industrial), if an advanced economic storage system for PV electricity is available.

The key question is who will own and operate the economically feasible PV systems of the residential and industrial end-users. In some markets the majority of the PV systems could be owned by the individual electricity end-users, but in other markets the most PV systems might be owned by utilities partly in decentralised applications and partly in centralised PV power plants.

Fuel-Parity of PV Power Plants

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 generating 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.[11] 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 of fossil power plants. Relative competitiveness of PV and oil power plants is depicted exemplarily in Figure 4 for typical conditions on the Arabian Peninsula.[7,12] 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 1% to 5% of specific GHG per kWh compared to fossil power plants on basis of total life cycle analysis.

Conditions for the LCOE comparison in Figure 4 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 PV power plants, the solar conditions are derived for all oil and natural gas fired power plants in the world (Figure 5).

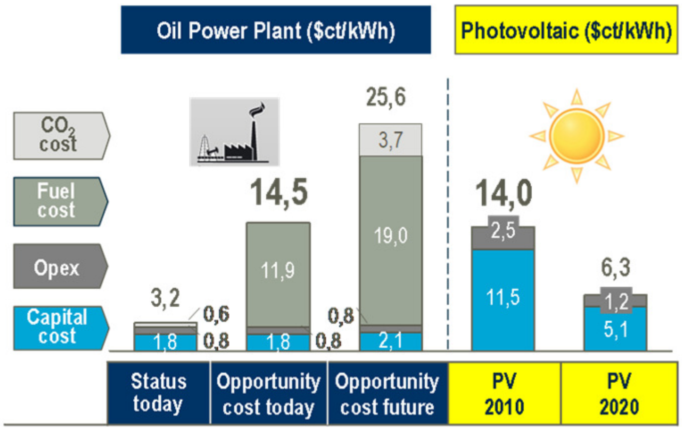

Figure 4: Cost structure of oil and solar PV power plants for very sunny and oil rich regions.[12] LCOE of oil power plants are largely dominated by fuel cost and relative low capital cost and operational expenses (Opex). LCOE of solar PV power plants are dominated by capital cost, whereas solar fuel 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.

Necessary input for the evaluation of the global market potential are globally distributed and georeferenced solar resource data for fixed optimally tilted PV systems [13] and the coordinates of all fossil fuel fired power plants in the world [14]. The georeferenced power plants are sorted by solar irradiation of fixed optimally tilted PV modules and depicted in Figure 5.

There are thousands of oil and gas fired power plants located in very sunny regions of more than 2,000 kWh/m²/y (Figure 5). Total oil and gas fired power plant capacity in the world is about 560 GW and 1,100 GW, respectively, of which more than 150 GW and 250 GW being located at very sunny sites of more than 2,000 kWh/m²/y. By combining PV power plants with oil and gas fired power plants to hybrid PV-Oil and hybrid PV-Gas 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. Thus, there is no fundamental problem in combining PV power plants with oil and gas power plants to hybrid power plants.

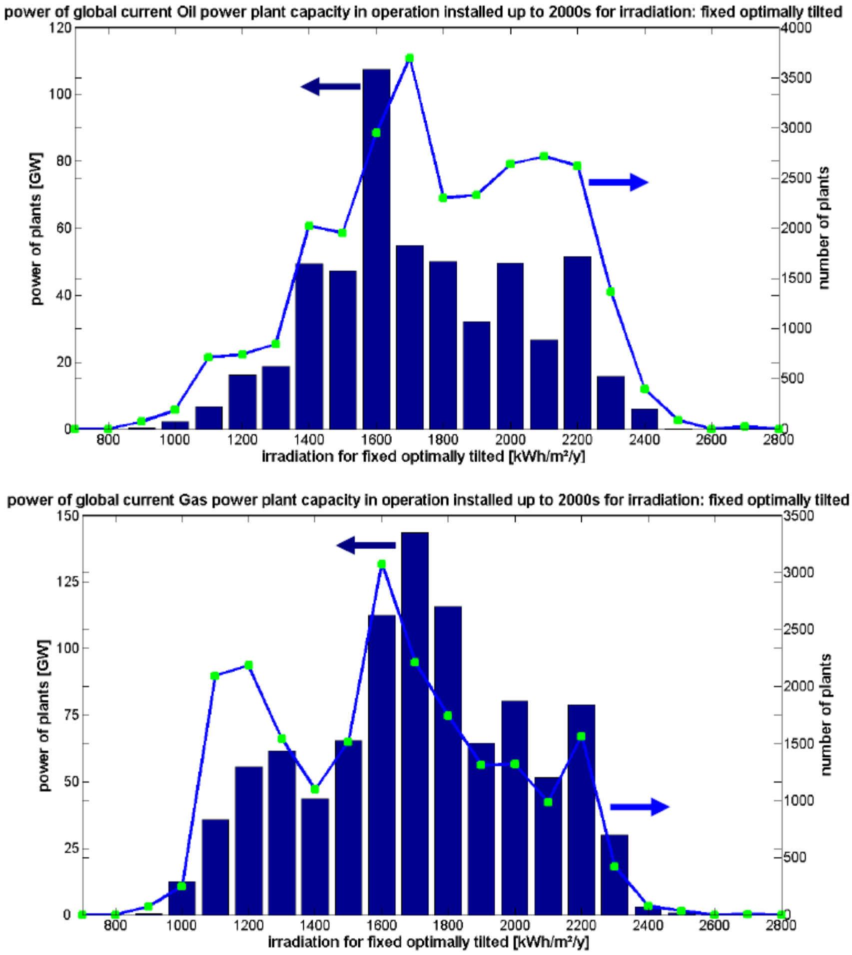

Figure 5: Solar location of oil (top) and natural gas (bottom) power plants as of end 2010s.[15] Power plants are georeferenced [14] and sorted by solar irradiation of fixed optimally tilted PV modules [13]. Total oil power plants are 560 GW, of which about 150 GW are located in very sunny regions of more than 2,000 kWh/m²/y of solar irradiation. Total gas power plants are 1,100 GW, of which about 250 GW are located in very sunny regions of more than 2,000 kWh/m²/y of solar irradiation.

Demand Curve for Hybrid PV-Fossil Power Plants

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 (Figure 6). 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, described elsewhere [3]. 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 in the last 15 years and a cost reduction according to the PV learning curve. Nevertheless, a few PV industry players in the market manage a faster cost reduction and hence a much faster individual company growth than the average, i.e. the scenario used is slightly conservative and reality might be more aggressive. Discussion on business-as-usual and aggressive cost reduction can be found in several other publications.[1,3,7,15]

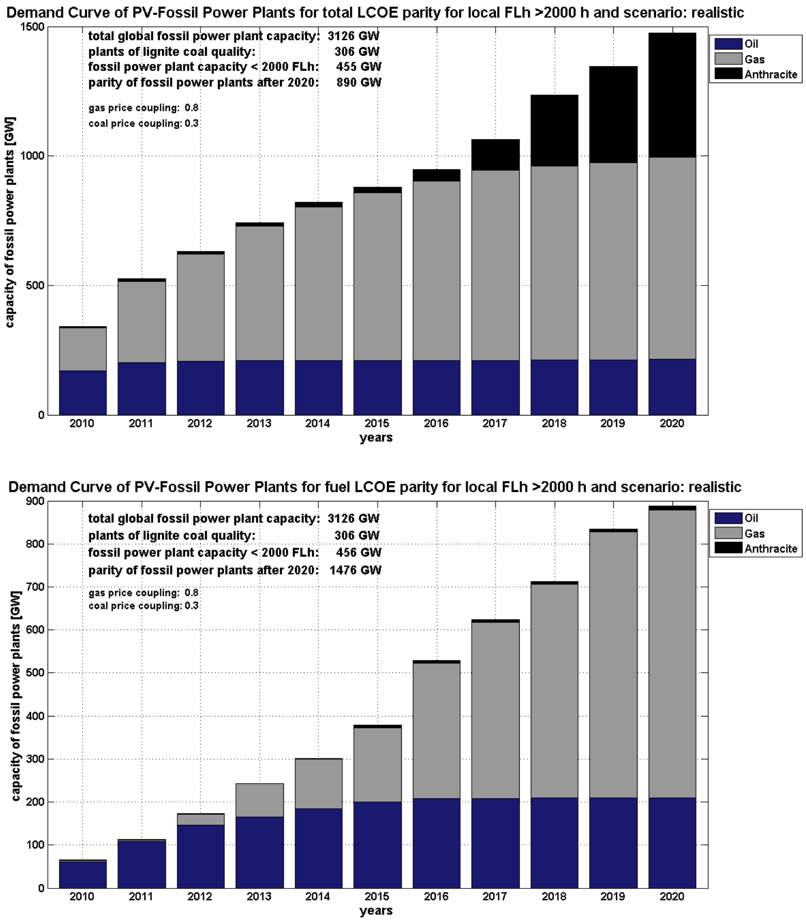

Figure 6: Demand curve of hybrid PV-Fossil power plants for total plant fuel-parity (top) and fuel-only fuel-parity (bottom) in the years 2010 - 2020. Fossil (oil, natural gas and anthracite coal) fired power plants are georeferenced [14] and their fuel LCOE are compared to LCOE of fixed optimally tilted PV power plants located at respective sites. Assumptions for fossil power plant LCOE are: fuel cost of 80 USD/barrel in 2010, annual price escalation of 3% and average full load hours of respective power plant type and country of location, no greenhouse gas emission cost are included. Capex and non fuel Opex are based on current

data.[16] Fuel cost of natural gas and coal power plants are coupled to crude oil price on thermal energy units.[7] PV power plant costs are based on current data and scenario projections mainly driven by PV growth rate (Figure 1) and learning curve concept (Figure 2). Bars at the bottom represent oil and bars on the top anthracite fuel.

Not only oil and gas fired fossil power plants but also anthracite (hard) coal fired power plants can be coupled with PV power plants to hybrid PV-Fossil power plants. Anthracite coal power plants are classical intermediate load plants typically switched on and off once a day, i.e. coupling to PV power plants on basis of state-of-the-art energy meteorology should be possible. This might not be the case for lignite coal fired power plants, therefore this class of coal power plants is excluded in the demand curve evaluation. Cost for fossil fuel fired power plants are based on current cost data [16] for all cost categories excluding fuel cost. Fuel cost taken for all calculations are based on the crude oil price, as both natural gas and coal are coupled to the crude oil price on basis of their primary energy. Coupling is discussed in more detail elsewhere [7]. Price coupling of natural gas and coal to crude oil is assumed to be 80% and 30% on primary energy units according to the global long-term average. Fossil power plants are only included in the calculations in countries where the respective class of power plants is in operation more than 2,000 full load hours (FLh) per year.

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 market potential for installed PV capacity in year 2020 based on the grid-parity analysis can be estimated to be about 1,700 GWp to 3,400 GWp, whereas the estimate based on fuel-parity analysis results in approximately about 1,500 GWp. However, there is an unknown overlap between both estimates. We assume that the number of disjunct capacity accounts for only some hundred GWp in both calculations, e.g. there are nearly no grid-parity events in oil producing countries as a consequence of high subsidies in the energy sector [3,7,12] but most of those countries have significant power capacities based on oil and natural gas and have also access to excellent solar resources [7,10,12]. Significant amounts of conventional power plant capacity in Figure 6 might also be used for installations of hybrid Wind-Fossil power plants, but preliminary insights of respective research activities indicate a maximum overlap of full load hours of PV and wind power plants of about 25% and an average value for most sites in the world of 15%. Hence, PV and wind power can be considered as complementary rather than competitive.

Impact of PV on Conventional Power Plant Business

As a consequence of PV economics, there will be at least two driving forces for the economic pressure of on-grid PV systems on conventional fossil fuel fired power plants. Firstly, grid-parity economics for end-users will generate highly attractive returns for PV investments for partly substituting high priced end-user electricity cost mainly dominated by conventional fossil fuel fired power plants. Secondly, in the beginning of the 2010s, the PV LCOE are expected to be below those of respective nearby conventional fossil fuel fired power plants at an increasing number of sites in the world, starting with oil, than natural gas and in the end also coal fired power plants. The question for all players active in the business of conventional fossil fuel fired power plants is how to manage this economic trend of fast decreasing PV LCOE being in contradiction to the trend for fossil fuel which dominates the cost structure of fossil power plants. For **utilities** the answer seems to be not too difficult, i.e. either investing in PV systems (decentralised and/ or centralised) or trying to hinder the market diffusion of PV systems. The last option might generate higher profits in the first years but lead to disruptive economic stress mid- to long-term. The option of investing in PV systems might be significantly more sustainable and in the end easier to control. For **power plant technology providers** the answer seems to be rather obvious. Overall investments in renewable power plants will be much higher than for conventional power plants, simply as an effect of capitalization of the fuel expenditures in the Capex and for the case of PV due to lower full load hours, which need to be managed by hybridization and in the mid- to long-term by storage solutions. Consequently, the market for renewable and PV power plants will grow much faster then for conventional power plants. For maximizing the individual benefit, the best strategy for power plant technology providers is to invest in the renewable power plant value chain. For **policy makers** the answer seems to be not too difficult, as well. PV LCOE trend generates benefits for end-users, but also for operators of conventional fossil fuel fired power plants, at least those being interested in least total LCOE of their power plant portfolio. Furthermore, social cost of PV are very low unlike fossil and nuclear power plants.[1,3] Policy makers interested in public welfare will tend to PV systems for sure, but lobbying pressure might create other decisions in the short- and mid-term, but the enormous economic benefit of PV systems will convince dependent policy makers long-term, either by own insight or by indirect economic forces as well. The stakeholder analysis for

fossil fuel producing and mining companies is more differentiated. The large national fossil fuel companies could enlarge and maximize public welfare by investing in renewable and PV systems. In particular this is the current reality for those companies near to their production maximum which is often coupled to a fast growing domestic fossil energy demand, but also existing long-term export supply contracts. They could reduce their stress by focussing on a domestic renewable and PV power strategy to free capacities to fulfil their export contracts. The financial perspective is quite different for public listed and privately held fossil fuel companies. Their profits will grow fast for the case of strong global demand growth and lower growth or stagnation of fossil fuel production. It is nearly impossible for this group to earn comparable margins by investments in the renewable and PV industry, hence their best strategy is to hinder the growth of renewable and PV industry. For **electricity end-users** the answer is not too difficult, as well. Mid- to long-term they benefit from massive global renewable and PV investments, due to the cost stabilizing effect indicated for the case of PV by grid-parity and fuel-parity analyses.

Summary

PV growth rates are high and lead in conjunction with high learning rates to a fast reduction of LCOE. Market potential for installed PV capacity in the year 2020 is estimated to range between 1,500 GWp and 3,400 GWp which is driven by highly attractive PV economics for both, electricity end-users (grid-parity analysis) and conventional fossil fuel fired power plant operators (fuel-parity analysis). The market potential might be even higher, as the beneficial economics for end-users and fossil power plant operators are disjunct in some regions in the world. A stakeholder analysis gives some indication that positive effects of strong PV economics are attractive for power plant technology providers, electricity end-users and utilities. Attractiveness remains somewhat unclear for some policy makers and some fossil fuel producing and mining companies, whereas attractiveness seems to be negative for most public listed and privately held fossil fuel companies and policy makers in close relation to those companies.

The impact of PV on the fossil fuel power plant business will be very beneficial for those being aware of the enormous dynamic of PV economics, as most of the players can increase their profits or lower their cost, but there will be also players that are not capable of generating benefits for their own businesses and interests.

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