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THE PHOTOVOLTAIC REALITY AHEAD: TERAWATT SCALE MARKET POTENTIAL POWERED BY PICO TO GIGAWATT PV SYSTEMS AND ENABLED BY HIGH LEARNING AND GROWTH RATES

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ABSTRACT
The photovoltaic (PV) energy technology has the potential to contribute to the global energy supply on a large scale. This potential can only be realised if sustainable and highly competitive PV economics are achieved. An integrated economic PV market potential assessment is presented consisting of grid-parity and fuel-parity analyses for the on-grid markets and an amortization analysis for rural off-grid PV markets. All analyses are mainly driven by cost projections based on the experience curve approach and growth rates for PV systems and electricity and fossil fuel prices for the currently used power supply. A total economic PV market potential of 2,800 GW to 4,300 GW is derived for the year 2020. 600 GW to 1,600 GW of cumulated installed PV capacity is estimated for the year 2020, depending on scenario assumptions. Even the low edge of the expected total installed PV capacity exceeds the scenario assumptions of leading energy organizations, such as IEA, by a factor of more than three to five. In conclusion, PV is on its way to become a highly competitive energy technology. Being complementary to wind power, PV together with wind power might become the backbone of the global energy supply in the coming decades.

Keywords
Grid-Parity, Fuel-Parity, off-grid PV, 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 and by electricity prices for end-users. The intersection of these two trends is commonly referred to as grid-parity and fuel-parity, respectively, whereas grid-parity allows for cost neural residential and commercial end-user PV installations and fuel-parity indicates cost neutral PV power plant investments. Moreover, small PV applications are very competitive for a large majority of the 1.4 billion people without access to electricity and are complemented by renewables-based mini-grids in rural regions of higher income.

The purpose of this study is, at first, a comprehensive analysis of the total economic PV market potential until the year 2020. To the knowledge of the author, this work is the first of its kind, which is based on the economic PV market potential including all major global PV market segments in an integrated manner. Secondly, the study aims at critically discussing the contribution of PV to the global energy supply which is assumed to be of minor relevance only in almost all important energy scenarios.

An overview on PV scenarios expected by various leading institutions is given (section 2) followed by and a subsequent detailed economic analysis mainly based on the levelized cost of electricity (LCOE) concept coupled to the experience curve approach (section 3). The methodology of deriving an economic PV market potential is based on the grid-parity (section 4), fuel-parity (section 5) and off-grid cost amortization approach (section 6). Results for the major PV market segments are consolidated in section 7 and discussed in comparison to the currently available energy scenarios (section 8).

This study 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 fuel-parity considerations, thereby covering the economic market potential of PV power plants which are most promising in very sunny but heavily subsidised markets. First fuel-parity insights have already been published [4-6] but the first comprehensive PV hybridization analysis for all major fossil fuel fired power technologies on a global scale is also published at this conference [7]. These major PV markets are complemented by highly profitable but comparably small PV off-grid markets being already covered on a fragmented view [5,8] but again in a more comprehensive and integrated manner in a separate publication [9,10]. All these mentioned topics are the major part of a more comprehensive work on the economics of hybrid PV power plants.[11]

2 Overview on PV Scenarios

Energy scenarios are a very helpful tool for guiding different stakeholder groups to what might happen in future in dependence of various policy options. Such scenarios show long-term consequences of potential policy decisions and enable an assessment whether respective developments would be acceptable in reference to relevant constraints, e.g. diminishing fuel resources, greenhouse gas emissions or social cost of energy supply. Gredler compared the recent development of PV production to forecasts of various institutions (Figure 1).[12,13]

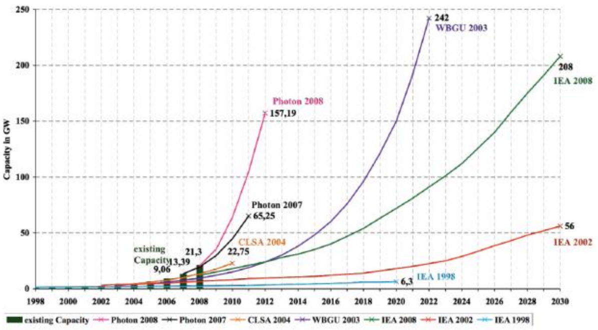
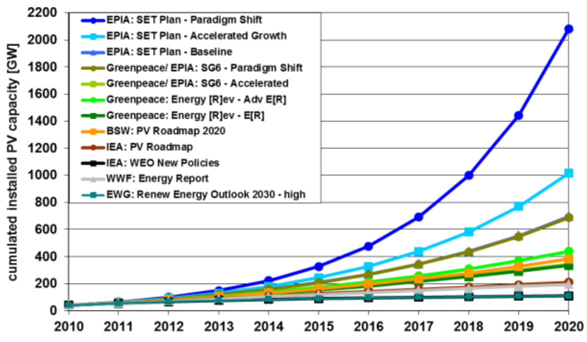


Figure 1: Forecasts of PV development and real cumulated installed PV capacity for the status of the year 2008. Please note that the production numbers for PV are shown in the graph and the cumulated installed PV capacity as of end of year would be 7.0 GW (2006), 9.5 GW (2007) and 15.7 GW (2008) according to EPIA.[1] The references for mentioned studies are: ‘Photon 2008’ [14], ‘Photon 2007’ [15], ‘CLSA 2004’ [16], ‘WBGU 2003’ [17] and ‘IEA 2008’ [18].

Results indicate, that projections of the International Energy Agency structurally underestimate the growth rate of PV and even the German Advisory Council on Global Change remains significantly below the real development. Market research performed with deep insights and a broad coverage of the PV industry, such as studies performed under the lead of Michael Rogol, show the necessity for upwards adaption, as well, but implying substantial higher growth rates.

In Figure 2, PV market projections of various sources are visualised in an integrated view in order to display the substantial variance in market expectations in the current decade until the year 2020 for the cumulated installed PV capacity and the annual installations. For being included in this integrated view, the studies need to cover at least the time span from the year 2010 to 2020, therefore all short-term reports have been excluded, i.e. PV industry research companies like Photon Consulting, EuPD Research and IHS Research but also the reports of all financial analysts.



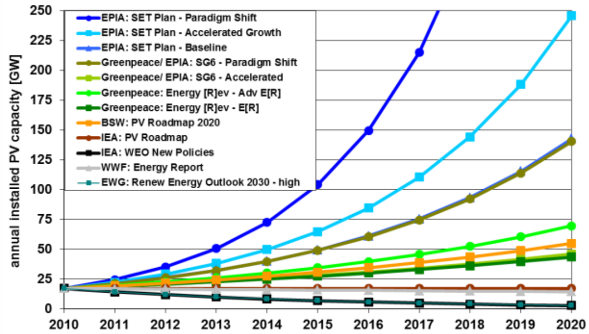


Figure 2: Projections of cumulated (top) and annual (bottom) installed PV capacity of various institutions. Numbers of EPIA are only provided for Europe and have been extended on a global basis according to total installed power plant capacity [19], since this is the only study representing the market potential of PV being in line with the outcome of this paper. Data are taken from EPIA [20], Greenpeace [21,22], BSW [23], IEA [24,25], WWF [27] and EWG [28].

The most obvious result of the integrated view on the relevant studies covering the PV market development in the 2010s is the enormous range of market projections. There are roughly three fundamental different projections: Firstly, PV will become a major source of global energy supply (EPIA and partly Greenpeace). Secondly, PV will grow but growth rate will decline on a fraction of the mean of the past 15 years (BSW and partly Greenpeace). Thirdly, growth rates of annual PV installations will become negative, i.e. decline in further market development is expected (IEA, WWF and EWG). The projected annual PV market growth rates for these three major groups amount to roughly 25% to 45% (EPIA and partly Greenpeace), 10% to 12% (BSW and partly Greenpeace) and 0% to -17% (IEA, WWF and EWG). The IEA assumes a cumulated installed PV capacity of 110 GW in the year 2020 in its most progressive ‘New Policies’ scenario in the latest World Energy Outlook.[25] This is in vast contrast to the average annual growth rate of PV for all major diffusion phases which has been never below 30% and for the last 15 years was about 45% (Figure 3).

The annual installations at the end of the 2010s show again three fundamental different expectations, as the very conservative group projects average installations at the end of the 2010s below the numbers of 2010, the moderate group expects annual installations between 40 GW and 70 GW and the progressive group takes into account that annual installations might be 140 GW and higher. This can be compared to overall power plant installation numbers having doubled from about 80 GW in the 1990s to about 160 GW in the 2000s [7]. Moreover, the power plants in the world are operated at about 4,300 annual full load hours in average, whereas PV power plants will range between 1,000 and 2,500 full load hours. Either PV complements another sources of electricity or PV plus storage solutions fulfil all requirements for full power supply. In any case new PV installations in the order of newly installed conventional power plant capacity are not technically limited at all.

Comparing the market projections with the realised growth in the past, the reasonable expectation might be the progressive assessment by EPIA and some Greenpeace scenarios. It remains unclear why some institutions assume a decline in market growth or even a decline in annual installations, i.e. negative growth rates, strongly violating the long-term growth trend of PV (Figure 3). No arguments have been found in these studies that could explain this sudden deviation from the trend being fully intact for more than five decades. This is very surprising, as nearly all of these institutions draw a drastic view on the business-as-usual scenario and some of them claim a reduction in greenhouse gas emissions as soon as possible, e.g. WWF and EWG.

3 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 about 45% for the last 15 years during on-grid diffusion (Figure 3).[29] 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 [2,7]. The fourth diffusion phase comprises commercial utility-scale PV power plants and is starting right now.

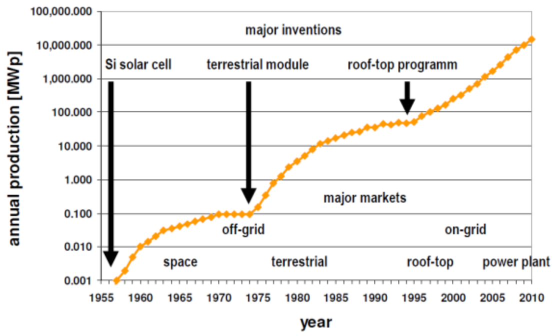


Figure 3: Historic PV production in dependence of major inventions and market segments.[29]

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 (Figure 4).[10] From the year 2009 to 2010, the cumulated installed PV capacities grew by more than 50% in the majority of the countries in the world, and still more than 50 countries achieved growth rates of more than 100%. The future PV market potential and growth ahead is illustrated by the ratio of already installed PV capacity to total installed power plant capacities per country (Figure 4). An important threshold of market saturation is the ratio of about 50% PV to total installed capacity, however still without significant storage capacities. Including storage this level would be substantial higher. Such high PV penetration ratios are possible due to relatively low full load hours of PV systems and the good match of PV power feed-in to the load curve as a consequence of daily sunshine characteristics.

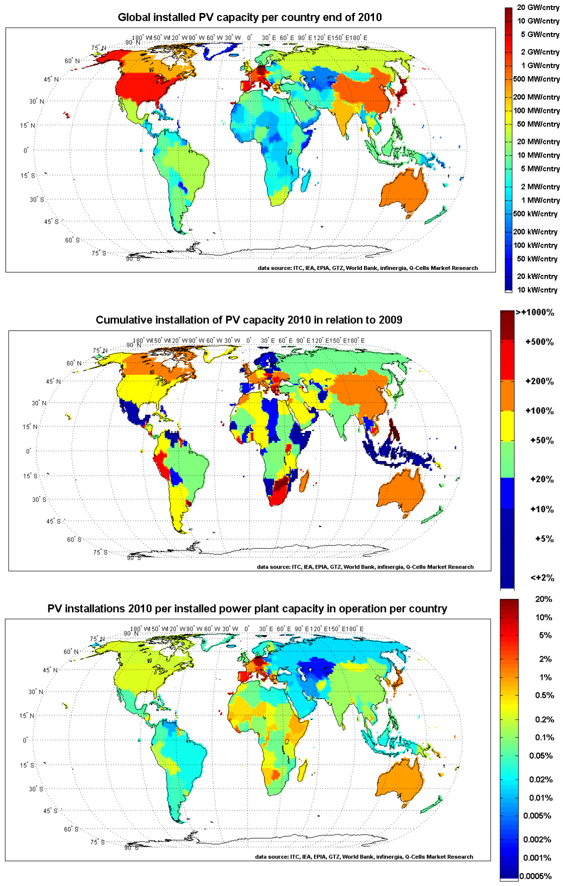


Figure 4: Total installed PV capacity (top), growth rate classification of cumulated installed PV capacity (center) and ratio of PV installations to total power plant capacity per country by end of 2010.[10] Some countries have already broken the 1% threshold. Data for total power plant capacity have been taken from Platts [19].

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) [9], in the kilowatt size (e.g. residential roof-top systems) [2] up to the multi megawatt dimension (utility-scale power plants) [5-7]. 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.[30]

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 5). Stable learning rates can be expected in the years to come due to fast increasing corporate PV R&D investments.[29] A broader discussion of the PV learning curve can be found elsewhere [29,31]. For a proper discussion the PV learning curve on the system level has to be taken into account, however no historical data are available.

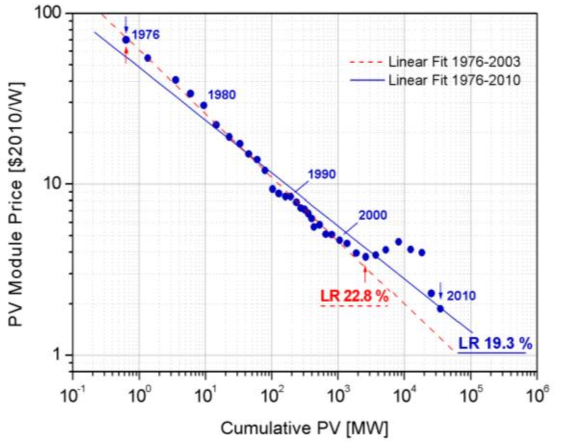


Figure 5: Learning curve for PV modules for the mid 1970s - 2010. Best approximation for the cost is the price curve as information rated in Wp. Oscillations around this trend are mainly caused by varying PV industry market dynamics and therefore profit margins, documented by applying different learning rates of 22.8% and 19.3% for the periods 1976 – 2003 and 1976 – 2010, respectively.[29]

4 Grid-Parity of PV Systems

Grid-parity for end-users is defined by the parity of PV electricity generation cost and cost of electricity supply.[2] The most appropriate method for cost calculation is the levelized cost of electricity (LCOE) approach [32] 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.[2] 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 ($k_{O\&M}$).

For analysing the grid-parity dynamics in time, the critical input parameters are the progress ratio of PV, the growth rate of the global PV industry, both key drivers of the experience curve, and the electricity price trends.

The experience curve approach is an empirical law of cost reduction in industries. It was observed that per each doubling of cumulated output the specific cost decreases by a nearly stable percentage (Equation 2). This stable cost reduction is defined as learning or experience rate. For use in calculations, the progress ratio is introduced, which is defined as unity minus learning rate.

$$c_x = c_0 \cdot \left(\frac{P_x}{P_0} \right)^{\frac{\log progress\,ratio}{\log 2}} \quad \text{(Eq. 2a)}$$

$$P_x = \sum_{t=0}^{T} P_t \quad \text{(Eq. 2b)}$$

$$P_t = P_{t-1} \cdot (1 + GR_t) \quad \text{for} \quad t \geq 1 \quad \text{(Eq. 2c)}$$

$$P_x = P_0 \cdot \prod_{t=0}^{T} (1 + GR_t) \quad \text{(Eq. 2d)}$$

Equation 2: Empirical law of experience curves.[2] Abbreviations stand for: cost at historically cumulated output level of P_x (c_x), cost at initial output level P_0 (c_0), historically cumulated output level (P_x), initial output level (P_0), unity minus learning rate defined as (*progress ratio*), annual production of a specific year (P_t), and growth rate of a specific year (GR_t). Eq. 2b and 2d are equivalent. In this work the variables *Capex* and c_x are identical and describe the specific investment cost in a PV system in cost/Wp. Combination of Eqs. 2a and 2d effectively transforms the cost function from production volume dependence to time dependence, which is often more convenient for scenario analyses.

The empirical law of experience curves (Eq. 2a) drives the levelized cost of electricity of PV systems (Eq. 1a) via the Capex parameter which has to compete against local electricity prices in respective markets.

The dynamics of grid-parity have been analysed for the residential and industrial market segment for more than 150 countries representing more than 98% of world population and more than 99% of global gross domestic product (Figure 6).[2]

The key parameters for the model are set to Capex for residential and industrial systems in 2010 of 2.70 €/Wp and 2.40 €/Wp, PV system learning rate of 20%, PV installation growth rate of 30%, WACC of 6.4% and Opex including insurance of 1.5% of Capex. The lifetime is assumed to steadily increase from 25 years in 2010 to 30 years in 2015 and stay constant afterwards. Solar irradiation on modules at optimal fixed-tilted angle for each location [33] is averaged by population distribution for respective countries and aggregated regions.[34] The PV system performance ratio is assumed to constantly increase for residential and industrial systems from 75% and 78% in 2010 to 80% and 82% in 2015, respectively, and remain constant afterwards. Electricity prices are assumed to increase in the same manner as in the last years by 5%, 3% and 1% per year for electricity price levels of 0 – 0.15 €kWh, 0.15 – 0.30 €/kWh and more than 0.30 €/kWh, respectively. Data and method is described in more detail elsewhere [2].

Based on this model, the 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, Africa is an exception in this point. Residential grid-parity is complemented by highly economic off-grid PV in rural regions of developing countries (section 6). This is the case for about 1.4 billion people in the world, mostly living in Africa and South Asia. PV systems are in operation in all countries in the world.[10] Therefore sustainable markets might grow very fast after grid-parity, in particular in case of low technical and legal obstacles.

Similarily, first industrial grid-parity events occur today in all regions in the world and often on islands. They continue throughout the entire decade (Figure 6). Very early market segments are Cyprus, West Africa, Seychelles, Caribbean, Cambodia and Fiji. Europe, the Americas and Asia-Pacific show quite similar characteristics of industrial grid-parity events throughout the entire decade. At the end of the decade more than 75% of market segments in Europe, the Americas and Asia are beyond industrial grid-parity. Again, Africa is an exception, due to extensive energy subsidies in South Africa and Egypt. Further exceptions are mainly oil producing countries used to substantially subsidizing their energy markets, e.g. Russia, Saudi Arabia, Libya, Venezuela, Iran, Iraq, Kuwait, Qatar, Oman and Angola. However, most of these countries can generate significant benefits by applying PV systems on the power plant level [7] analysed in section 5.

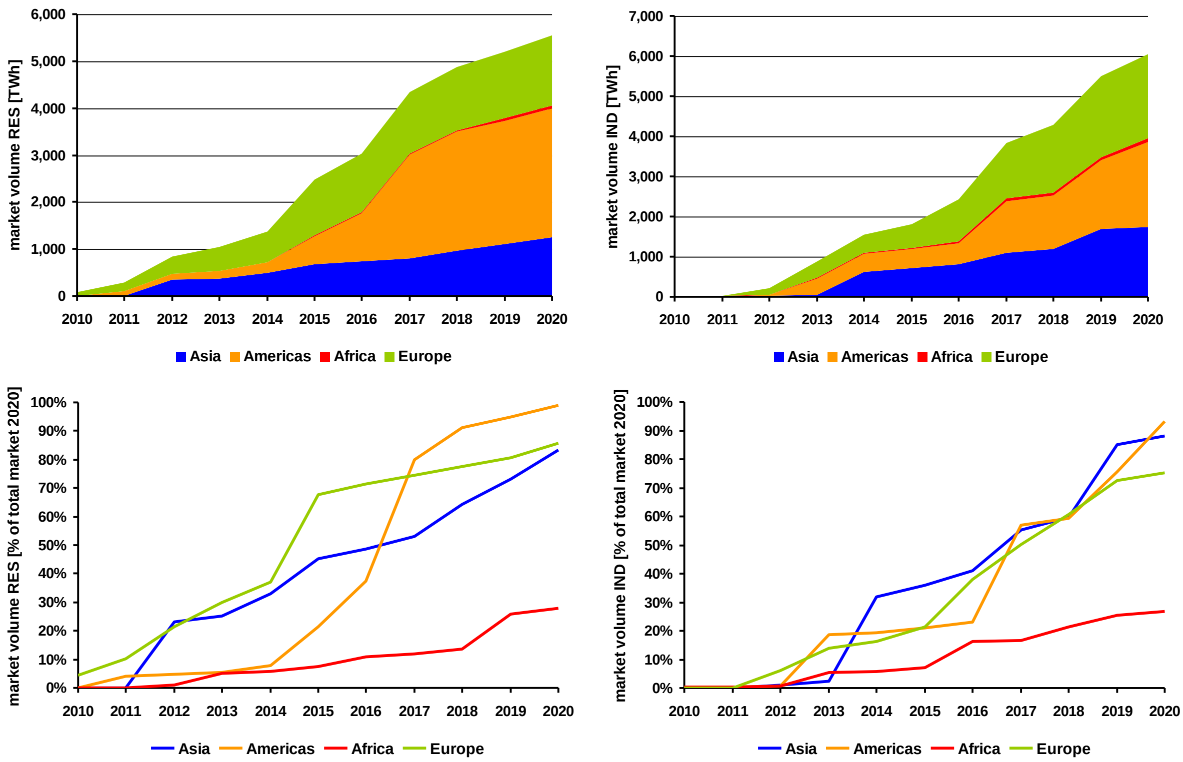


Figure 6: Grid-Parity market volume for residential (left) and industrial (right) segments in absolute (top) and relative (bottom) numbers for all regions in the world in the years 2010 to 2020.[2] Numbers for the market volume include a 1% - 4% growth rate in electricity depending on the market maturity.

Based on the global grid-parity analysis, the market potential for on-grid end-user PV electricity is estimated. On the 2010 electricity consumption basis the grid-parity market volume of the entire power market by end of the 2010s is about 13,000 TWh in total composed by about 3,900 TWh (residential), about 3,600 TWh (small medium enterprises) and about 5,500 TWh (industrial).

To translate the aforementioned market volume into a cumulated installed PV capacity potential, the following assumptions are made: a population weighted average annual irradiation on fixed optimally tilted PV systems on a per country level [34], a global performance ratio of 80% (residential) and 82% (industrial), a global maximum PV supply contribution between 10% (without storage) and 80% (including storage) and a global market penetration of this supply contribution of not more than 50%, i.e. maximum PV share is assumed to not exceed 40% of total power supply. The 10% PV supply contribution threshold requires a flexible power plant portfolio but enables the full utilization of the PV capacity even without storage. Based on these assumptions, an upper and a lower limit of the sustainable economic market potential for PV systems is estimated for the year 2020. The upper limit for the grid-parity economic market potential would be the net metering grid-parity, i.e. parity of PV LCOE and the electricity price for the end-users. A more appropriate upper limit would be the cost of PV plus storage solutions compared to the electricity price. First work in progress insights indicate roughly a PV plus storage grid-parity about four years after the net metering grid-parity [35]. The lowest limit for the economic grid-parity market potential assumes the case of no storage availability, thus an effective 10% energy contribution based on the maximal fully utilizable PV power in the grid.

In result, these assumptions lead to a total fully economically sustainable installed end-user PV capacity potential of about 980 GW without any storage solutions (lower limit) and up to 3,930 GW (upper limit) including storage in case of the financial net metering approach. However, the appropriate economic PV plus storage grid-parity comprises the storage cost resulting in 2,070 GW (upper limit) full economic market potential by 2020, if an advanced economic storage system for PV electricity is available.

5 Fuel-Parity of PV Power Plants

As a consequence of fast decreasing PV 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 to hybrid PV-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 (Equation 1) summarized and adapted to fossil fuel fired power plants in Equation 3:

$$LCOE_i = \frac{Capex_i \cdot crf + Opex_{i,fix}}{FLh_{i,el}} + Opex_{i,\mathrm{var}} + \frac{fuel_i}{PE_{th,i} \cdot \eta_{i,el}} + \frac{carbon \cdot GHG_i}{\eta_{i,el}} \quad \text{(Eq. 3a)}$$

$$crf = \frac{WACC \cdot (1+WACC)^N}{(1+WACC)^N - 1} \quad \text{(Eq. 3b)}$$

$$fuel_i = fuel_{crudeoil} \cdot cf_i \quad \text{(Eq. 3c)}$$

$$fuel_{crudeoil} = fuel_{crudeoil,2010} \cdot (1 + r_{crudeoil})^{y-2010} \quad \text{(Eq. 3d)}$$

Equation 3: Levelized cost of electricity (LCOE) for PV and fossil fuel fired power plants.[7] Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), oil/ natural gas and coal fossil plants as index (*i*), annual fixed 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*) defined in Eq. 1b, lifetime of plants (*N*), 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 for PV by operating several large scale multi 10-100 MW power plants. PV power plants can be built in the 10 MW scale but also for a power capacity of more than 1 GW.[26] 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. Fuel-parity is therefore defined by the parity of PV LCOE to the LCOE of respective fossil fuel fired power plants at the respective geographical location plus the cost of reduced full load hours (FLh) of fossil power plants. 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.[36]

The first fuel-parity events have already started in very sunny regions supplied by oil fired power plants, like on the Arabian Peninsula.[5-7]

The total global installed fossil fuel power plant capacity amounts to about 3,180 GW, being about 67% of total global installed power plant capacity, and by end of 2008 it consists of 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 capacicity and the generated electricity makes it possible to characterize the power technologies by their FLh, being 2,520 FLh (oil), 3,500 FLh (gas) and 5,460 FLh (coal).[3]

Several requirements need to be fulfilled for a successful hybridization of PV and fossil fuel fired power plants, in particular applicability of the hybridization concept, flexible fossil power plant operation modes and sophisticated energy meteorology. These prerequisites are fulfilled for hybrid PV-Fossil power plants and discussed in more detail elsewhere [7].

Necessary input for the evaluation of the global market potential of hybrid PV-Fossil power plants are globally distributed and georeferenced solar resource data for fixed optimally tilted PV systems [33] and the coordinates and capacities of all fossil fuel fired power plants in the world [19]. The georeferenced power plants are sorted by the respective local solar irradiation of fixed optimally tilted PV modules.

There are thousands of oil, gas and coal fired power plants located in very sunny regions of more than 2,000 kWh/m²/y. Total fossil fuel fired power plant capacity in the world being located at very sunny sites of more than 2,000 kWh/m²/y is about 150 GW (oil), 250 GW (gas) and 290 GW (coal).[7] 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, because otherwise new to be built plants will have to be realised such as integrated gasification combined cycle (IGCC) coal plants, since they are as flexible as oil and gas fired power plants.

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. 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.[7]

For a simplified economic description a price coupling of natural gas and coal to the crude oil price is used in this study. 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.[7] 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 last decades. The fossil fuel prices can be compared on basis of harmonized thermal energy units, like USD per barrel (of oil equivalent), showing a long-term price ratio of natural gas to crude oil of 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 the International Energy Agency to be about 0.9 for the US and 0.8 for Europe and Japan [37].

The applied economic scenario for fossil fuel power plants is defined as follows: Capex of 800 €/kW (oil)/ 750 €/kW (gas) and 1,500 €/kW (coal), annual fixed Opex of 17 €/kW (oil)/ 15 €/kW (gas) and 20 €/kW (coal), annual variable Opex of 1 €/MWh_{el} for all fossil power plants, power plant lifetime of 30 years (oil and gas) and 40 years (coal), average power plant efficiency in the year 2010 of 40% (oil)/ 50% (gas) and 35% (coal), annual increase of the absolute average power plant efficiency of 1% (oil and coal) and 0.5% (gas), coupling factor of 0.8 (gas) and 0.3 (coal), WACC 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 of the entire scenario period and a thermal energy conversion of 1.6806 MWh_{th}/barrel. In general the scenario covers a business-as-usual approach and reflects 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 the rate of the 2000s, the real price could be twice as high at the end of 2010s as assumed in the applied scenario. Numbers mentioned are for fossil fuel power plants of multi-100 MW. Data are taken from various sources described elsewhere [7,11].

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 [33], 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, but maybe slightly too conservative. The PV growth rates have been higher for the last 15 years (Figure 3), 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 [38] being in line with the realistic scenario assumptions. Most competitive PV industry leaders achieve an even better cost level. True cost 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. Accordingly, 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.[38]

Comprehensive hybridization economics of PV and fossil fuel power plants can be derived on basis of the scenario assumptions for PV power plants and fossil fuel power plants, the LCOE modelling (Equations 1 and 3), the experience curve approach (Equation 2 and Figure 5) 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 constraints 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 3a and has to be generated additionally by the PV component, thus lowers the PV LCOE of the hybrid PV-Fossil power plant. All breakeven analyses, i.e. fuel-parity analyses in this paper take this effect into account. 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 costs 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.

When applying LCOE data for fossil fuel fired power plants and PV power plants for all coordinates in the world, a detailed world map of local fuel-parity events dynamics can be derived [7] and based thereupon a global demand curve for hybrid PV-Fossil power plants. Since all fossil fuel power plants are georeferenced, 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 7 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.

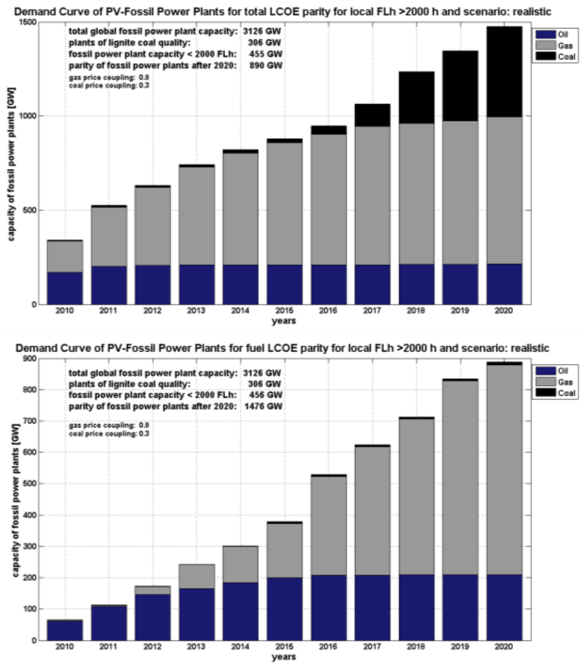


Figure 7: Global hybrid PV-Fossil power plant demand curve in the 2010s on total plant (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV power plants in the 2010s.[7] Fossil power plant capacity, i.e. oil, natural gas and coal, is counted only in case of PV LCOE (plus higher fossil capital cost due to reduced FLh) lower than total and fuel-only fossil LCOE. All coordinates are aggregated to the fuel categories. Power plant scenario assumptions are applied as defined in this section. 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.

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 (upper limit), whereas a capacity of approximately 900 GW fulfils the most aggressive criteria of PV LCOE parity to fuel-only LCOE of fossil power plants (lower limit).

6 Rural Off-Grid Market Potential of PV Systems

In the world 1.4 billion people have no access to electricity.[3] Small PV applications, like solar home systems (SHS) and PV pico systems (PS) [39], enormously improve local standards of living. More than 80% of people without access to electricity live in rural areas of developing countries [3] typically showing high solar irradiation.[9] Thus attractive priced SHS and PS enable a fast financial amortization compared to conventional energy costs. Increasing demand for small PV applications and constant reduction of financial amortization create large market potentials in countries with low electrification rates. The off-grid economic market potential of PV cannot be estimated by the grid-parity or fuel-parity approach, but by an amortization calculation discussed in this section.

People without access to electricity mainly live in sub-Saharan Africa, South Asia and in some countries of the Pacific Rim. A large majority of them lives in India, Bangladesh, Indonesia, Nigeria, Pakistan and Ethiopia.[9] Georeferenced analysis of solar irradiation of those regions where the 1.4 billion people without access to electricity live confirms that a majority of them has access to very good up to excellent solar resources of about 1,800 – 2,200 kWh/m²/y irradiation on module surfaces of fixed optimally tilted PV systems. Most people without access to electricity live in developing countries of gross domestic product (GDP) per capita of less than 2,500 USD. Only few of those countries show PV installations on a promising level (Figure 4).[9]

People without access to electricity spend money on kerosene for lamps, dry cell batteries for radios and tape recorders and charging mobile phones. All those basic energy needs are able to be substituted by SHS and PS. The conventional energy costs are paid week by week, or month by month, whereas PV systems have to be bought in total but can be used for years. Attractiveness of PV applications is distinguished by their financial amortization period. For calculating the financial amortization of SHS and PS their specific cost including replacement cost of key components need to be taken into account and compared to the substituted energy cost, mainly driven by expenditures for kerosene and dry cell batteries. Details on the assumptions for the amortization calculation are given elsewhere [9].

Amortization of complete PV systems ranges between 6 - 18 months (PS) and 12 – 36 months (SHS) but strongly depending on energy consumption patterns (Figure 8). Thus, small PV applications are the least energy cost option for people without access to electricity in rural areas. Analysis shows that upfront investment seems to be less of a financial burden than anticipated. The capitalized value of the various small PV systems range between 10 – 45 (PS) and 5 – 20 (SHS) times the original capital expenditures in most countries.[9]

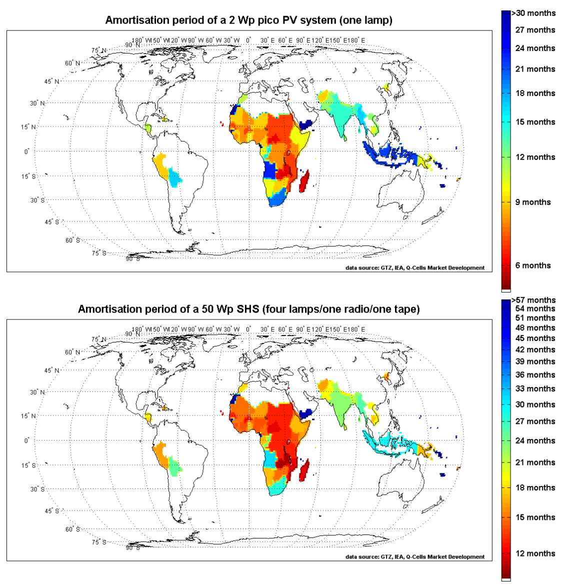


Figure 8: Amortization period for 2 Wp PS (top) and 50 Wp SHS (bottom).[9] Coloured countries show electrification rates of less than 80%. Economics are based on the assumptions: system cost between 8 €/Wp (SHS) and 23 €/Wp (PS), monthly kerosene consumption between 5 l (PS) and 20 l (SHS), monthly cost of batteries of 5.2 € (SHS), local diesel prices, inflation of 10% plus a real interest rate of 3%.[9]

Attractive prices for PS and SHS lead to short financial amortization periods and enable people without access to electricity to cover their energy needs in a sustainable manner. Moreover, small PV applications are the least cost energy option and fast growing global on-grid PV markets and scaling effects in local distribution channels will further reduce system cost. Excellent economics of small PV applications might significantly accelerate the growth rate of off-grid PV markets in the years to come.

A local market evaluation for Ethiopia, one of the poorest countries in the world, has led to a total market potential of about 280 MWp for roughly 70 million people without electricity access.[8] These numbers correspond to about 30 Wp per small PV system. The market for the 1.4 billion people without access to electricity might be evenly addressed by small PV systems of the average size of 30 Wp for very poor regions, larger scale small PV systems of an average size of about 100 Wp for less poor regions and mini-grid applications providing annually about 300 kWh/user. The such derived global market potential for PS and SHS in very poor rural regions for residential purposes might be about 2 GWp, whereas the market potential for less poor rural regions might represent about 6 GWp. The market potential for residential electricity in rural PV based mini-grids might be in the order of 16 GW.[9] PV based mini-grids are higher in LCOE than on-grid power solutions, but lower in LCOE than comparable diesel powered mini-grids as a result of fast decreasing PV LCOE.[5,8,11]

However, advanced commercial applications and public services lead to an even higher market potential. Most well emerging and developed countries in the world show a residential fraction of total final electricity consumption of roughly one third [9], i.e. commercial, industrial and public consumption is two times higher than the residential one. Therefore, the commercial and public (schools, health centres, lanterns, water pumping, telecommunication, etc.) small PV off-grid market might be two times larger than the market for residential applications.

The total addressable economic market potential for rural off-grid PV systems can be estimated to roughly 70 GW being composed by about 24 GW residential and about 46 GW commercial and public demand or about 24 GW PS and SHS (residential, commercial and public) and about 46 GW mini-grids. Roughly two third of the off-grid PV market potential is due to mini-grid applications, but two third of the not electrified people will get access to electricity by small PV solutions like PV pico systems or solar home systems.

7 Total Sustainable Economic PV Market Potential

As presented in sections 4 to 6 there are three major classes of PV markets and hence two different parity concepts for deriving the sustainable on-grid economic market potential and an additional amortization approach for the off-grid segment. Some countries reach grid-parity first, e.g. Spain, Germany and Japan, and others initially achieve fuel-parity, e.g. Saudi Arabia, UAE, India and Mexico [2,6]. In the mid- to long-term all countries reach grid-parity and fuel-parity, therefore the overlap capacity of the two approaches needs to be quantified on a per country basis in order to avoid double counting. The highly profitable PV off-grid markets (section 6) are characterized by no overlap with the grid-parity and fuel-parity approach, thus they are not included in the following overlap considerations.

Based on the grid-parity and fuel-parity concept, an upper and a lower limit of the sustainable economic market potential for PV systems can be estimated. The upper limit for the grid-parity would be the net metering grid-parity, i.e. parity of PV LCOE and the electricity price for the end-users. The lower and more appropriate limit would be the cost of PV plus storage solutions compared to the electricity price. The upper limit for the fuel-parity would be the comparison to the total plant LCOE of fossil fuel fired power plants reduced by increasing capital cost due to lower FLh as a consequence of hybridization with PV systems. The lower limit for the fuel-parity refers to the marginal cost of fossil fuel fired power plants, i.e. the fuel-only LCOE. For avoiding double counting of capacities the overlap of grid-parity and fuel-parity has to be quantified. Therefore, in case of reaching grid-parity and fuel-parity the smaller accessible market potential for PV systems has been counted as overlap and excluded from the integrated total parity capacity. This consideration has been applied on an annual and per country basis and aggregated afterwards on a worldwide scale. This implies not whether it is more favourable to install the PV systems in a more decentralised end-user structure or a more centralised utility-scale manner. The global economic market potential for PV systems analyzed in this work is based on a global grid-parity analysis for more than 99% of global electricity consumption (section 4) and a comparable global fuel-parity analysis for all fossil fuel fired power plants in the world on a per power plant basis (section 5). The outcome is depicted in Figure 9 for the first integrated sustainable economic market potential estimate for PV systems on basis of a learning rate of 20% for modules and inverter and 15% for the other balance of system (BOS) components. The total economic market potential can be estimated to about 2,700 GW to 4,200 GW for the year 2020.

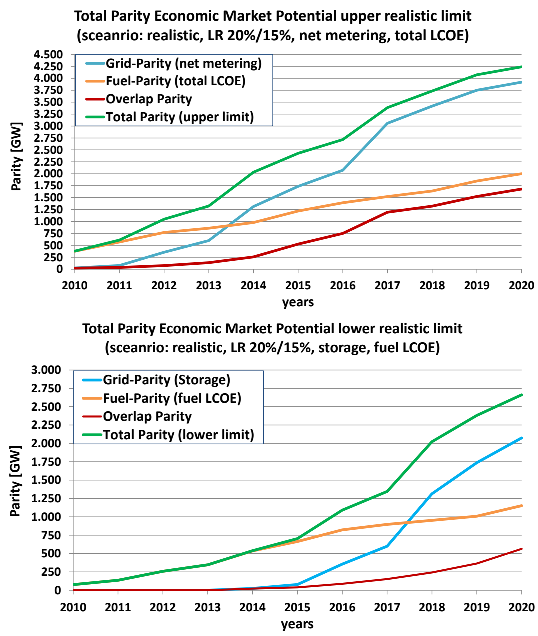


Figure 9: Total economic market potential for PV systems in the 2010s in the upper (top) and lower limit (bottom). The key assumptions are: grid-parity and fuel-parity approach, learning rate of 20% for modules and inverter and 15% for other BOS components, growth rate of 30% in 2010s, substitution of 80% of the single end-users power demand and 50% maximal addressable market potential in case of grid-parity and hybrid PV-Fossil power plants without any storage capacities in case of fuel-parity.

The economic market potential for PV systems is comparably low in the very early 2010s but growing fast during the entire decade particularly for the lower limit of PV plus storage grid-parity and marginal cost fuel-parity. In the beginning, the majority of the global economic market potential is driven by fuel-parity (typically PV power plants) and later by grid-parity (typically decentralized roof-top applications).

A lower learning rate reduces the market growth but would be no show stopper at all. Significantly lower learning rates of 10% for modules and inverters and 5% for the additional balance-of-system components would reduce this potential accessible in the 2010s, but PV market diffusion would be delayed only by a few years, typically below four years. A more detailed sensitivity analysis on the impact of learning rates on the economic PV market potential is discussed elsewhere [7,31].

In result, the economic market potential for total installed on-grid PV capacity in year 2020 can be estimated to about 2,700 GW to 4,200 GW based on grid-parity and fuel-parity analyses. The additional market potential for rural off-grid PV applications, however, is by at least one order of magnitude smaller and estimated to be about 70 GW (section 6). Nevertheless, this capacity would be equivalent to a quantum jump for the 1.4 billion people currently without access to electricity. The total overall economic PV market potential can be, thus estimated to roughly 2,800 GW to 4,300 GW based on grid-parity, fuel-parity and off-grid amortization analyses.

8 Discussion of the Economic PV Market Potential and Expectations by PV Scenarios

The fully economic market potential for installed PV capacity in year 2020 based on grid-parity, fuel-parity and rural off-grid economic analyses can be estimated to about 2,800 GWp to 4,300 GWp on a global scale (section 7).

It is obvious that only a fraction of the economic market potential derived in section 7 will be realised in the same time. In this study, a realization of 20% (pessimistic), 35% (realistic) and 50% (optimistic) of the full PV market potential is assumed. When applying these scenario assumptions one can expect a cumulated installed PV capacity in the year 2020 for a pessimistic case of about 560 – 860 GW, for a realistic case about 980 – 1,500 GW and for an optimistic case about 1,400 – 2,150 GW. To be more on the save side the final expectation is about 600 GW (pessimistic), 1,000 GW (realistic) and about 1,600 GW (optimistic) and summarized in Table 1. These three cases are roughly equivalent to average annual growth rates of new installations of 20%, 30% and 40%, i.e. fully in line to the long-term growth of global PV installations (Figure 3). Technological restrictions for these installation numbers need not to be feared, since the fuel-parity approach requires only grid access of PV power plants nearby to existing power plants, many grid-parity market segments become profitable even including local storage options and small PV applications are already highly profitable including storage.

scenario	cumulative global installed PV capacity by end of the year 2020	average annual market growth rate
pessimistic	600 GWp	20%
realistic	1,000 GWp	30%
optimistic	1,600 GWp	40%

Table 1: Cumulative global installed PV capacity by end of the year 2020 depending on scenario assumptions and resulting average annual growth rates of new installations.

These PV market expectations are in drastic contrast to market projections of major institutions in the field of PV scenarios, since only the progressive group (section 2) fulfils the pessimistic case derived in this section, i.e. only EPIA and partly Greenpeace can really imagine that PV can show such a fast progress towards the long-term target of becoming a major source of energy supply. The 'SET FOR 2020' study from EPIA [20] is the only publication expecting a cumulated installed PV capacity in the order of the realistic case derived in this work.

It is not surprising that the two global leading organizations in the fields of PV association (EPIA) and the campaigning for protecting and conserving the environment (Greenpeace) possess the know-how and visionary leadership for a realistic energy scenarios in the field of PV.[20-22]

On the contrary, is has to be stated that the global leading organizations in the fields of energy (IEA) and conservation of the environment (WWF) assume a substantial lower diffusion of PV, and thus, cannot imagine the true potential of PV as a near term game changer in the global energy business.[24-27] Even an organization like the EWG does not recognize the true near term potential of PV despite of being focussed on the short-term shortage in conventional energy fuels and strategies for a long-term secure energy supply based on cost competitive renewable energy sources.[28] The three organizations expect a cumulated installed PV capacity in the year 2020 of 110 GW (IEA in its most progressive 'New Policies' scenario), 111 GW (EWG in the 'High' scenario) and 194 GW (WWF in the '100% RE by 2050' scenario). Even the result of 600 GW cumulated installed capacity for the pessimistic case assumptions derived in this work are more than three (WWF) and five (IEA and EWG) times higher than the most progressive assumptions of these organizations, despite of taking into account in this work only the fully economic sustainable PV market potential in the decade of the 2010s.

One of the most prominent characteristics of PV is the faster than expected progress mainly based on the long-term stable high learning rate and growth rate. The learning rate is driven by modular, highly scalable but not very complex production processes and still retaining enormous room for further progress. The growth rate is driven by the highly modular character of the PV technology ranging from 2 Wp PV pico systems to 1 GW very large scale PV power plants generating sustainable economic benefits in outer space and on earth, off-grid and on-grid, in residential and power plant applications. Additionally, the PV power technology is the only established energy technology based on the fundamental cost structure of semiconductor based electronics without any moving parts and the potential for a further substantial increase in lifetime, decrease in energy pay back time and hence increase in energy return on energy invested.[40] In every market segment captured by PV during the major diffusion phases in the past decades, the PV applications set standards in establishing a least cost energy option: firstly in powering space applications, secondly in the off-grid field and currently in parallel for on-grid decentralised residential roof-top and on-grid more centralised power plants.

In consequence, it has to be considered as highly probable that the technological basis of PV coupled to the economic characteristics drive sustainable and high PV market growth rates in the decade of the 2010s which will result in a structural change of the global energy system in the following one to two decades due to a historically very fast increase in market share.

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.

In a broader perspective, the three major future power technologies in relation to minimised fully loaded social cost must be considered solar PV, wind power and hydro power. But only solar PV and wind power have access to nearly abundant resources, whereas the solar resource is the most homogeneously distributed energy source in the world. It is a godsend that the two least cost energy options for the 21st century are fully complementary to each other.[41]

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 due to the fundamental underlying solar and wind resources.[41] 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 (section 5) need not be lowered. However, it seems to be likely that hybrid PV-Wind-Fossil power plants can capture a significant market share in the 2010s and further reduce the remaining full load hours of the fossil fuel power plant component of the hybrid power plant.

A very promising option in the mid- to long-term arises by renewable power methane (RPM).[42] RPM would enable hybrid PV-Wind-RPM power plants establishing 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 the RPM is the step by step switch from current fossil methane (natural gas) to the future renewable power methane, since the entire downstream infrastructure 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.[43]

The complementarity of PV and wind power enormously reduces further investments in the energy system and will enable the power sector to offer highly competitive solutions for the heat and transportation sector and maybe even for the chemical industry via renewable power generated methane.[43]

9 Summary

In this study an integrated approach has been presented for estimating the sustainable economic PV market potential in the 2010s up to the year 2020. The results for a global grid-parity analysis, a global fuel-parity analysis and PV off-grid economics have been taken into account. These analyses are mainly based on PV cost projections including experience curves and PV growth rates. Finally the outcome of the such derived economic PV market potential has been transformed to a pessimistic, realistic and optimistic estimate of a cumulated installed PV capacity by the end of 2020. These installed capacity estimates have been compared to PV scenarios published by leading organizations in the field of energy and PV scenarios.

The economic PV market potential derived by the grid-parity approach is estimated to about 980 GW up to 3,930 GW and in the most likely case to about 2,070 GW by the year 2020, if an advanced economic storage system for PV electricity is available. The market estimate according to the fuel-parity approach leads to about 900 GW up to 1,500 GW fully economic potential for PV power plants in the year 2020. The total addressable economic market potential for rural off-grid PV applications is estimated to about 70 GW. An integrated economic PV market potential has been performed for avoiding double counting. The integrated assessment leads to an overall sustainable economic PV market potential of about 2,800 GW to 4,300 GW in the year 2020.

Only a fraction of the market potential will be realised in time, thus PV market expectations have been derived resulting in a pessimistic (600 GW installed capacity in 2020 and an annual growth rate of 20%), realistic (1,000 GW in 2020 and growth rate of 30%) and optimistic market view (1,600 GW in 2020 and growth rate of 40%). Only EPIA and Greenpeace can imagine such a fast progress in PV development. Other leading organizations like the IEA, WWF and EWG expect about one third or even less compared to the pessimistic market expectation derived in this work.

Due to the complementarity of solar PV and wind power, market expectations for PV need not to be lowered. However, hybrid PV-Wind systems are very likely to start to strongly influence the global power system in the next decade by sophisticated hybrid concepts, like the renewable power methane technology.

The fast progress of sustainable energy technologies seems not to be included in current energy scenarios of leading international organisations. This work gives plenty of indications that in the field of PV several organizations would make no mistake in revising their scenarios in the field of PV.

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