GLOBAL OVERVIEW ON GRID-PARITY EVENT DYNAMICS

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ABSTRACT
Grid-parity is a very important milestone for further photovoltaic (PV) diffusion. A grid-parity model is presented, which is based on levelized cost of electricity (LCOE) coupled with the experience curve approach. Relevant assumptions for the model are given and its key driving forces are discussed in detail. Results of the analysis are shown for more than 150 countries and a total of 305 market segments all over the world. High PV industry growth rates enable a fast reduction of LCOE. Depletion of fossil fuel resources and climate change mitigation forces societies to internalize these effects and pave the way for sustainable energy technologies. First grid-parity events occur right now. The 2010s are characterized by ongoing grid-parity events throughout the most regions in the world, reaching an addressable market of about 75% up to 90% of total global electricity market. In consequence, new political frameworks for maximizing social benefits will be required. In parallel, PV industry tackle its next milestone, fuel-parity. In conclusion, PV is on the pathway to become a highly competitive energy technology.

Keywords
Grid-parity, Fuel-parity, Economic Analysis, Energy Options, PV Markets, Modelling, Sustainable, Strategy

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 electricity prices for end-users. The intersection of these two trends is defined as grid-parity and indicates cost neutral PV installations. The purpose of the presented study is a detailed analysis of global grid-parity event dynamics for nearly all countries in the world and respective residential and industrial market segments in the years to come. Key motivation of this work was to learn more about the geographic and temporal distribution in the occurrence of grid-parity in the world.

This paper presents a detailed analysis of grid-parity dynamics based on the levelized cost of electricity (LCOE) concept coupled with the experience curve approach (section 2) including a broad discussion of the key driving forces of the model (section 3). Results of the analysis are shown for Europe, the Americas, Africa and the Asia-Pacific region (section 4). Finally, consequences of these results are discussed (section 4 and 5).

This conference contribution presents results of Q-Cells research. First results for Europe had been a cornerstone that led to the 12% supply target of European electricity demand by 2020 of the European Photovoltaic Industry Association (EPIA) as announced on the 23rd PVSEC in Valencia in 2008.[2,3] Results for the US had been published first in the US [4] and together with all European Union (EU) member states on the 24th PVSEC in Hamburg in 2009.[5] Results for Japan, India, Middle East and North Africa (MENA) and Asia had been presented at respective regional conferences.[6-9] In this study we present results for 151 countries plus some regional aggregations of the US, India and China. We now cover 98.0% of world population and 99.7% of global gross domestic product (GDP), therefore we have now finalised our work of the last years focussed on understanding global grid-parity event dynamics.

2 GRID-PARITY MODEL

In history of PV three major inventions led to sustainable markets for PV systems (Figure 1). The first PV market diffusion phase started after introducing PV power supply in space as least cost option, which was achieved only a few years after pioneering results in silicon based solar cell research by Darryl Chapin, Calvin Fuller and Gerald Pearson in 1954.[10] As a consequence of the oil-price crises in 1970s PV applications started the second PV diffusion phase. Off-grid applications have been growing after former space technology was brought to earth by Elliot Berman due to his invention of the terrestrial PV module concept.[11] PV has become the least cost option for off-grid rural electrification, in particular in developing countries.[12] The third PV market diffusion phase has been enabled by the political invention of roof-top programmes and feed-in tariff (FiT) laws.[13,14] Right now, the third PV diffusion phase can be observed: grid-parity in residential markets throughout the world. This paper gives some insights for the third PV market diffusion. On the horizon one can already recognize the fourth diffusion phase: commercial utility-scale PV power plants.[8,15,16] A good overview on PV diffusion patterns is given by Andersson and Jacobsson.[17]

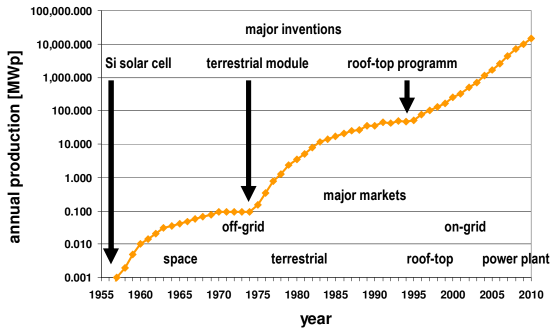

Figure 1: Historic PV production in dependence of major inventions and market segments. Notably, annual growth rates increased from about 33% in space age and during off-grid diffusion to 45% for the last 15 years during on-grid diffusion. Figure and underlying trends are discussed in more detail elsewhere.[18]

For analysing the third PV market diffusion phase a dynamic grid-parity model has been designed.[19] The outcome is a time and geography dependent investigation method for sustainable market potentials of PV for the considered countries. Each country is represented by the two major market segments of residential and industrial customers (users). PV generation costs are calculated by the LCOE method [20] and compared to the electricity prices of market segments in respective countries. It has to be mentioned, that no subsidies for PV are taken into account, i.e. real PV costs are regarded. It was neither possible nor intended to exclude various subsidies in the global electricity markets. These direct financial subsidies for fossil fuels are estimated to about 310 and 20 – 30 bnUSD per year for non-OECD and OECD countries, respectively.[21,22]

Using the **LCOE method** (Equation 1) one can easily transform the cost/Wp numbers usually used in PV industry into the more decisive cost/kWh category of the power industry. All cost categories, i.e. investment and capital expenditures (Capex), operation and maintenance expenditures (Opex), have to be put on an annual basis. LCOE are obtained by dividing annual costs by annual electricity generation. LCOE enables a direct comparison of alternative energy technologies in terms of cost per energy, in this paper €/kWh.

$$LCOE = \frac{Capex \cdot crf + Opex}{E_{net}} \qquad \text{(Eq. 1.1)}$$

$$crf = \frac{WACC \cdot (1+WACC)^N}{(1+WACC)^N - 1} + k_{ins} \qquad \text{(Eq. 1.2)}$$

$$WACC = \frac{E}{E+D} \cdot k_E + \frac{D}{E+D} \cdot k_D \qquad \text{(Eq. 1.3)}$$

Equation 1: Levelized cost of electricity (LCOE). Abbreviations stand for: capital expenditures (*Capex*), annual operation and maintenance expenditures (*Opex*), net electrical energy yield (E_{net}), annuity factor (*crf*), weighted average cost of capital, (*WACC*), lifetime of PV system, (*N*), annual insurance cost in percent of Capex (k_{ins}), equity (*E*), dept (*D*), return of equity (k_E), and cost of dept (k_D).

The input parameters for LCOE formula are mainly dependent on circumstances regarding geography, time, energy and financial markets. Net generated energy is a function of local solar irradiance, which is given by latitude and average annual weather conditions of a specific site.[23] Capital expenditures for PV systems are derived from the empirical experience curve for PV (Equation 2 and Figure 3) further described below, which depends on the growth rate of global PV markets (Figure 1) and hence, on time and the general energy markets. The interdependencies of these key driving forces are discussed in detail in section 3.

For analysing the grid-parity dynamics in time (section 4) 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[24] and was first discovered in aviation and shipbuilding industry in the 1930s to 1950s.[25,26] It was observed that per each doubling of cumulated output the specific cost decrease 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.

$$c_x = c_0 \cdot \left(\frac{P_x}{P_0}\right)^{\frac{\log \, progress\ ratio}{\log 2}} \qquad \text{(Eq. 2.1)}$$

$$P_x = \sum_{t=0}^{T} P_t \qquad \text{(Eq. 2.2)}$$

$$P_t = P_{t-1} \cdot (1 + GR_t) \quad \text{for} \quad t \geq 1 \qquad \text{(Eq. 2.3)}$$

$$P_x = P_0 \cdot \prod_{t=0}^{T} (1 + GR_t) \qquad \text{(Eq. 2.4)}$$

Equation 2: Empirical law of experience curves. 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. 2.2 and 2.4 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. 2.1 and 2.4 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. 2.1) drives the levelized cost of electricity of PV systems (Eq. 1.1) which has to compete against local electricity prices in respective markets. Electricity prices differ strongly in different markets and even for different players in the same market segment as a consequence of market forces.

Nevertheless, average electricity prices can be derived for market segments. In general, electricity prices are a function of fuel cost, capital cost, labour cost, grid cost, energy taxes, energy subsidies, greenhouse gas (GHG) emission cost and profit margins of generation, transmission and distribution companies. PV grid-parity is defined as the intersection of LCOE of PV and local electricity price in time.

The model is based on the effective average PV system price in Germany in 2010 of 2.70 €/Wp and 2.40 €/Wp for residential roof-top systems and industrial large-scale roof and accordingly PV power plants, respectively. These market segments take over a global price setting function due to the sheer size of the German market.[1] System price assumptions are based on consensus view of several financial PV industry analysts all published in 2010.[27-33] The empirical observed experience curve (Eq. 2.1 and Figure 3) correctly describes the cost reduction of PV systems for the last 30 to 40 years. Over the last three decades the learning rate of PV has been on a stable 20% level. Mature industries show a flattening of experience curves, therefore the decrease of LOCE for PV was calculated by a progress ratio of 0.80 and 0.85 as well, i.e. a learning rate of 20% and 15%, respectively. Cost reductions are indirectly driven by PV industry growth, which was set to 30% for the entire scenario period from 2010 to 2020. The annual growth rate was in average 45% for the last 15 years (Figure 1) but consensus expectation of PV installation growth rate is about 30% (section 3.2). We might underestimate the cost reduction in time in case of continued growth at the rate of the last 15 years.

Concerning electricity prices, initial market sizes for the year 2010 and average annual market growth rates of the market segments in the different regions are taken from various sources [34-40] and 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.

Further assumptions for important parameters are taken into account. 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. Weighted average cost of capital is set to 6.4%, as in several markets PV investments start at about 5% average cost of capital. Annual PV operation and maintenance expenditures (Opex) are estimated to be 1.5% of initial PV system investments (Capex). PV system 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 (Figure 2) [23] is averaged by population distribution for respective countries and aggregated regions. Data and method is described in detail elsewhere.[41]

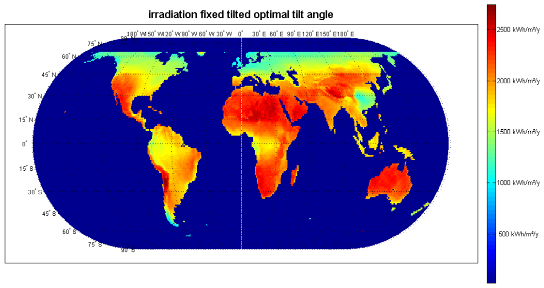

Figure 2: Annual irradiation on module surface of fixed tilted PV systems at optimal tilt angle for optimised irradiation. Every coordinate of a 1°x1° mesh within 65°S and 65°N is separately optimised for maximum annual irradiation on module surface. Hay-Davies-Klucher-Reindl model is applied by calculating each month of the year and selecting the tilt angle of maximum annual irradiation.[23]

The dynamic grid-parity model enables estimates where and when sustainable market segments are created by implementing PV electricity generation. Scenario assessment has been applied for the years 2010 to 2020.

Major assumptions and respective key driving forces of the dynamic grid-parity model are the experience curve approach, PV industry growth, PV system cost and electricity prices. Due to their enormous impact on the analysis these key driving forces are discussed in detail in section 3.

3 KEY DRIVING FORCES OF GRID-PARITY ANALYSIS

In the following subsections the five key driving forces of grid-parity analysis are discussed in detail to give a more founded basis for the assumptions applied. The intention of the authors is to give more transparency to the applied scenario and its conservative parameter setting.

3.1 EXPERIENCE CURVE APPROACH AND PV SYSTEM COST

Analyses of technological change have identified patterns in the ways that technologies are invented, improved and diffuse into society. Studies have described the complex nature of the innovation process in which uncertainty is inherent, knowledge flows across sectors are important, and lags can be long. Perhaps because of characteristics such as these, theoretical work on innovation provides only a limited set of methods with which to predict changes in technology. The learning or experience curve model offers an exception.[24]

The learning curve originates from observations that workers in manufacturing plants become more efficient as they produce more units. In its original conception, the learning curve referred to the changes in the productivity of labour which were enabled by the experience of cumulative production within a manufacturing plant. The experience curve approach was further developed to provide a more general formulation of the concept, including not just labour but all manufacturing costs and aggregating entire industries rather than single plants.[24] A good overview on experience curves in general and PV in particular is given by Nemet [24] and Swanson [42]. Consensus results of different studies on learning rates in PV industry led to a well accepted learning rate of 20% (Figure 3), hence a progress ratio of 0.80.[43-]

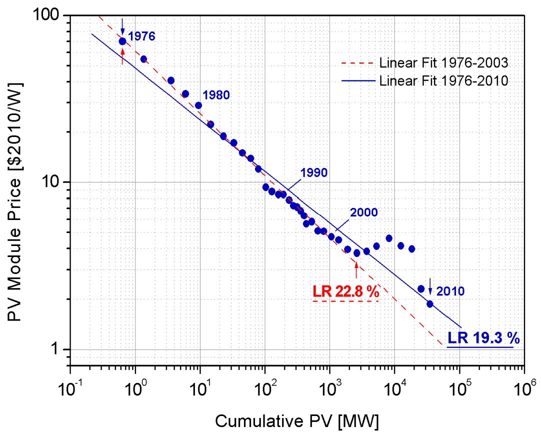

Figure 3: Learning curve for PV modules for the years 1976 - 2010. Long-term cost trend of reducing PV module cost by 20% per doubling of cumulated historic production has been stable for the entire period. Oscillations around this trend are mainly caused by varying PV industry market dynamics and therefore profit margins, documented by applying different learning rates of 22.8 and 19.3% for the periods 1976 – 2003 and 1976 – 2010, respectively. Figure and underlying trends are discussed in more detail elsewhere.[18]

Historically, no energy technology showed such a high learning rate over such a long period of time.[43,44] Renewable energy technologies typically exhibit learning rates of about 10%, e.g. wind power and solar thermal power plants (STEGs).[43,45]

PV learning curve characteristics are well documented for all value chain steps from metallurgical silicon (Si) or other semiconductor ores to PV modules. A few works also describe inverters, systems and the most relevant metric cost per generated energy [43,46,47,24]. They confirm for entire PV systems a learning rate of 20% and an even higher learning rate for cost per energy, induced by increasing overall system efficiency. Even higher learning rates have been recorded for similar technologies: as a long-term trend for DRAM memory chips and flat panel displays learning rates of 40 and 35%, respectively.[48] Comparison to solar PV is quite interesting due to the fact that both technologies are semiconductor based, just as PV is, but DRAMs getting lower in cost by increasing integration density of transistors while displays reduce cost by increasing production area. Former cost reduction strategy is not possible for PV, except for high concentrating PV, whereas generating scaling effects by increasing area might also be a valuable pathway for further cost reductions and have already been applied in last decades [24]. Fundamental differences in cost structures of displays and PV systems should be better analysed due to a twofold higher learning rate for displays than for PV.

In many industries it was observed that as a function of cumulated production the learning rates declined and showed a more flattening characteristic which is a consequence of ultimate floor cost of a fully optimized product.[49] Nevertheless, until now this has not been observed in PV industry. Authors not fully aware of current and future potentials of PV cost structure usually assume much too high PV floor cost, i.e. lowest future possible cost for PV technology, e.g. recently published PV system floor cost assumption of 2.1 €/Wp for the year 2100.[50] Even today reality has already reached lower levels and cost might decline drastically in the decades to come. Leading PV experts estimate the achievable long-term cost potential for PV module technology and respective industry below 0.30 USD/Wp[51] and Pietzcker et al expect PV system floor cost, i.e. long-term cost level, of 0.60 USD/Wp[[52] Currently, lowest manufacturing cost of PV modules are 0.74 USD/Wp and are achieved by cadmium telluride (CdTe) PV company First Solar.[53] Lowest possible today's PV power plant system costs are about 1.5 – 1.6 €/Wp, including all manufacturing, sales, general administration and research cost, excluding cost for debt, equity and value chain inefficiencies, which can be achieved for both CdTe PV and crystalline silicon PV technology.[54]

3.2 GROWTH RATE OF PV INDUSTRY

Growth rates of worldwide PV installations have been on a constant high level of 45% in the last 15 years (Figure 1). Compared to industries of similar preconditions growth rates of worldwide PV installations are outstanding. Benchmarking industries are for example wind power, mobile phones and crude oil. In the end all these three industries offer commodity like products, due to its standardization and modularity. In particular, wind power and mobile phones show this modular characteristic. Modularity and scalability might be one of the greatest advantages of PV, as solar cells can be used for both a 10 Wp solar home system and a multi hundred MWp PV power plant. Growth rates for PV sales have been outstandingly high for more than one decade. This phenomenon is discussed in more detail elsewhere.[5]

There are tremendous needs to establish a sustainable energy industry as 80% of global energy market is structural not sustainable, either due to diminishing resources (crude oil, natural gas, uranium), climate change restrictions (coal, crude oil, natural gas) or severe lasting security problems (nuclear power).[21,55-61]. Need for a sustainable energy supply is greater than ever in human history.

Structural characteristics of renewable energy technologies fit well to fundamental requirements of energy technologies in the 21st century: low greenhouse gas (GHG) emissions, high energy yield factors for a fast substitution of today's not sustainable technologies, i.e. short energy payback times (EPBT), and pathways to reach a sustainable low cost level. PV well fulfils these requirements: GHG emissions are between 15 – 45 gCO_{2eq}/kWh [62-65], energy yield factors are between 10 – 30 due to a EPBT of 0.8 to 2.5 years [62-65] and fast declining LCOE (section 3.1 and 4).

Remarkably, fundamental growth limits are still outstandingly far away for PV embedded in respective local and global electricity systems. For PV it will take a long time to reach these limits which are estimated to be at least between 1,500 and 12,000 GWp total installed capacity within the next four decades and depending on economically available storage solutions and global wealth convergence.[18] There are several studies outlining technologically and economically feasible pathways for a PV share in local, nationwide, continental and even global electricity systems of 25 up to 100%.[66-72] One of the authors of this paper was involved in an estimate of overall energy supply potential of solar power [72], which was calculated for solar thermal electricity power generation (STEG), but due to nearly identical overall land use efficiencies it can be transferred to PV and by applying the storage assumptions of Denholm and Margolis [68] and Zweibel et al. [66] it would be possible to entirely transfer the outcome to PV.

Growth rates of PV seem not to be limited for at least the next one to two decades. The assumption in this paper of an average annual 30% growth rate of PV industry in the scenario period of 2010 to 2020 is considered to be very conservative. Annual growth trend for the last 15 years has been 45% (Figure 1). Nevertheless, consensus of scientific researchers and financial analysts is a growth rate of about 30%.[1,73,28,29,31,74-76] However, it has been very common to underestimate both near and long-term growth rates of PV.[77]

3.3 PV SYSTEM PERFORMANCE

The key performance index of PV is LCOE and therefore improvements in lifetime, performance ratio and yield (kWh/kWp), e.g. better temperature coefficients and better low light performance, will increase the yield and therefore decrease the LCOE. There are indications that PV module lifetime is longer than the assumed 25 years [78] which will further improve LCOE. Better performance and longer lifetimes of key components will improve the performance ratio and lower operation and maintenance, hence improve LCOE.

3.4 ELECTRICITY PRICES

Real electricity price escalation for residential market segments has been on average 4.3% p.a. in the years 2000 to 2007 in the EU [34] and on average 3.6% p.a. in the years 2000 to 2006 in the US [35]. Cost trends in other regions in the world are dependent on local electricity subsidies or taxes, vulnerability to oil and natural gas price volatility, increase in environmental standards and stranded power plant investments.

In liberalized electricity markets, like in the EU and the US, electricity prices are coupled to respective electricity wholesale prices. These wholesale prices are typically a function of available supply and demand and are dependent on the last class of power plants which is needed to cover supply (merit-order). Therefore, the cost structure of natural gas (NG) power plants strongly influences wholesale prices. The cost structure of NG power plants itself is dominated by NG fuel cost. It has been observed for the last three decades that NG prices are strongly correlated to crude oil prices [21], thus in the end the global crude oil price determines end-users electricity prices in liberalized electricity markets. Probability is high that historical peak-oil occurs in the years till 2015 which will be accompanied by high crude oil prices [55-57] and consequently high electricity prices. Regulated markets in the world also face increasing electricity cost due to rising fuel prices.

Global electricity supply is dominated by coal, NG, hydro-electric, nuclear and oil power plants, which generate 40.9, 20.1, 16.4, 14.7 and 5.7% of electricity.[86] All other sources, in particular renewable energy sources, still contribute to a minor fraction.

Social cost of climate change mitigation will have to be internalized in energy cost for having real price signals of energy use.[59] Conservative estimates clearly show that social cost of climate change are in the order of 70 €/tCO_2.[59] Electricity prices outside the EU reflect no CO_2 cost and respective prices in the EU started to internalize GHG emissions in the mid 2000s, but on a subcritical low level of 10 – 25 €/tCO_2. Maybe marginal cost of GHG emissions to tackle climate change will be even higher than 70 €/tCO_2. Regions dependent on fossil fuel fired power plants, in particular coal, will be affected by high escalation rates of true electricity cost.

Other social cost of electricity supply are also not internalised in electricity prices, but have to be paid. Such cost are for instance: higher mortality and multiple illnesses due to heavy metal emissions of coal and oil power plants, military conflicts due to diminishing energy resources, reduced ecological value of destroyed ecosystems by use and exploitation of conventional energy and insecurity due to nuclear proliferation, nuclear terrorism and unclear nuclear waste disposal.

Summing up, the assumption of future electricity price escalation rates is very likely to be conservative.

3.5 ACCESS TO ELECTRICITY

Prerequisite for grid-parity analysis is access to an electricity grid. This is not the case for about 1.5 billion people in the world.[79] Most of them live in rural areas in Sub-Sahara Africa (about 590 million), South Asia (about 610 million) and East Asia (about 195 million). Overview on global access to electricity is depicted in Figure 4.

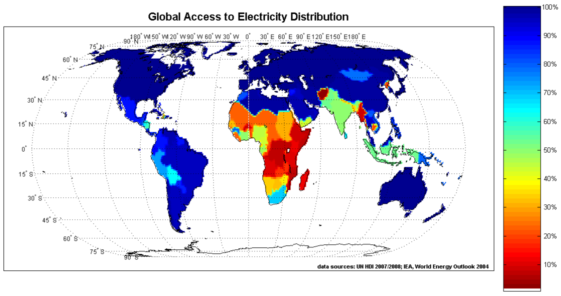

Figure 4: Global access to electricity in percent of local population. Dark blue colour coding represents up to 100% electricity access of local population, whereas dark red is an indication for very low electrification rate of local population of 10% or even less. Data is taken from United Nations Development Programme [80] and International Energy Agency [81].

By far the most people having no access to modern forms of energy live in sunny regions (Figures 2 and 4). Detailed analysis of georeferenced location of world population [82], location of people without access to electricity (Figure 4) and local irradiation on module surface of fixed optimally tilted PV systems (Figure 2) [23] clearly shows excellent solar conditions for most of the 1.5 billion people having no access to electricity (Figure 5).

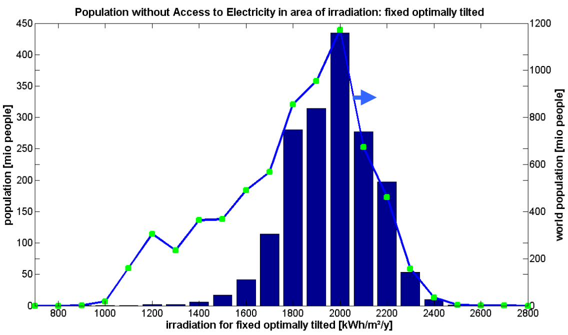

Figure 5: Population without access to electricity in dependence of respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents distribution of world population. The bars are referred to the left axis and represent population without access to electricity.

However grid-parity concept makes no sense for people without access to electricity, but most of them live in areas of excellent solar conditions, hence highly economic off-grid PV systems are a best adapted and the least cost solution for their energy needs.[12]

4 RESULTS OF GRID-PARITY ANALYSIS

Main result of dynamic grid-parity analysis is a constant market diffusion potential of PV all around the world (Figures 6 – 11).

Starting between 2010 and 2012, the share of all addressable residential electricity market segments increases towards the end of the decade to 86, 99, 28 and 83% in Europe, the Americas, Africa and Asia (Figure 10), corresponding to 1,490, 2,750, 60 and 1,250 TWh, respectively. The same addressable share for all industrial electricity market segments reaches at the end of the decade to 75, 93, 27 and 88% in Europe, the Americas, Africa and Asia at the end of the decade (Figure 11), corresponding to 2,100, 2,110, 90 and 1,750 TWh, respectively.

In Europe grid-parity events of large residential market segments occur first, quickly followed by Asia-Pacific and succeeded by the Americas in the mid of the decade (Figure 10). Most segments in Africa reach grid-parity early in the 2010s, but the largest markets, South Africa and Egypt, heavily subsidize their electricity markets and therefore reach grid-parity only beyond 2020. Grid-parity events of large industrial market segments start between 2011 and 2013 and are synchronous in Europe, the Americas and Asia to a large extent of the entire decade (Figure 8). The characteristics of the industrial segments in Africa are quite similar to the residential ones. As an important remark, it should be pointed out that a flattening of the progress ratio from 0.80 to 0.85 and significantly higher profit margins of PV industry would slow down grid-parity events by one to two years in maximum, as already shown in previews work.[5]

Regions with high solar irradiation and high electricity prices reach grid-parity first, whereas regions with high electricity prices and moderate solar irradiance will quickly follow. LCOE of PV electricity generation in regions of high solar irradiance will decrease from 16 to 6 €ct/kWh in the years 2010 to 2020, respectively.

4.1 EUROPE

Figure 6 depicts grid-parity dynamics in the 2010s for 75 market segments in Europe. First grid-parity market segments are the residential segment in Italy and the residential and industrial segments in Cyprus. This market segments combine best combination for early grid-parity: good solar conditions and high electricity prices. Generally, islands show early grid-parity events all over the world, for which Cyprus is an excellent example. Fundamental reason for this are high electricity generation costs on islands as a consequence of usually oil (diesel) fired power plants, suffering high fuel prices.

Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for residential market segments in Portugal and Denmark, respectively. By the mid 2010s about 70% of residential and 30% of industrial market segments in Europe will be beyond grid-parity (Figures 6, 10 and 11). By the end of the 2010s the great majority of all electricity market segments (80% for residential and 75% for industrial) in Europe will be beyond grid-parity. In year 2010 total electricity consumption is about 4,400 TWh. As a consequence of PV capacity factors in Europe and grid restrictions, an overall share of PV electricity in Europe of 6 to 12% in 2020 can be achieved.

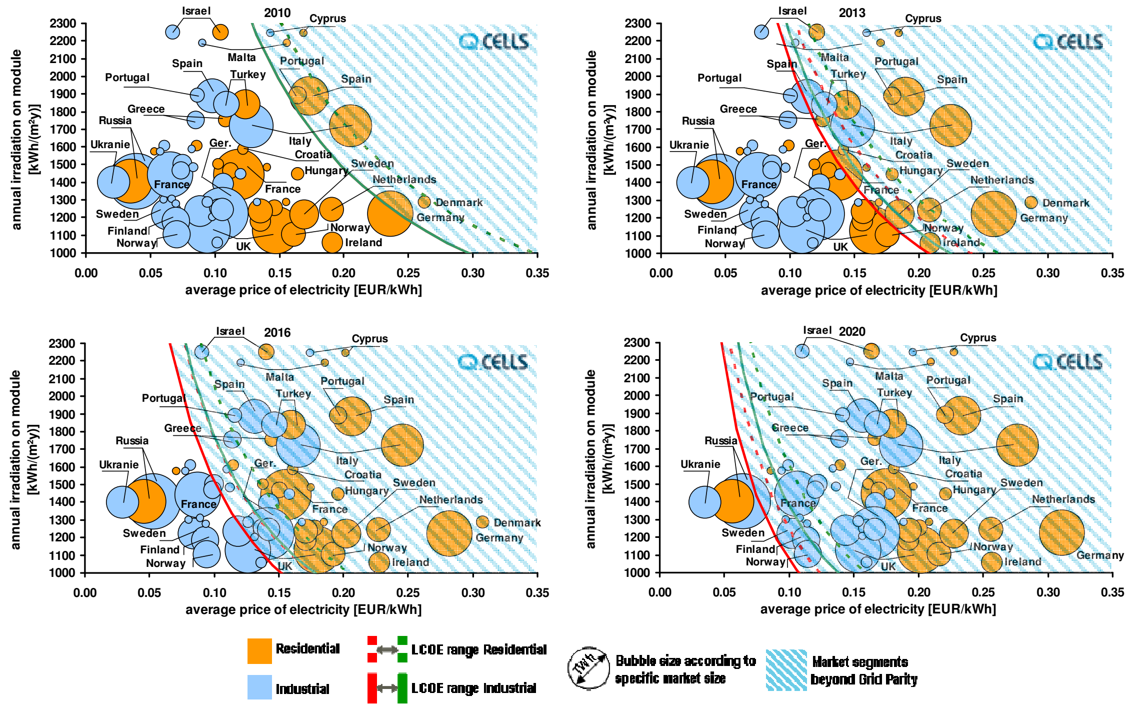

Figure 6: Grid-parity analysis for Europe in 2010 (top left), 2013 (top right), 2016 (bottom left) and 2020 (bottom right). European countries are rated by their population weighted solar irradiation [41] and electricity prices of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries is given in Appendix Tables 1 – 3.

Clear outcome of grid-parity analysis for Europe is a fast reduction in LCOE of PV and therefore market introduction cost will decline as a consequence. Market deployment of PV is essential for a fast reduction of PV LCOE and hence large contribution of PV to European electricity supply. A significant electricity supply in the EU by PV will help to lower social cost of diminishing fossil fuel resources and GHG emission as discussed in detail in section 3.

4.2 THE AMERICAS

Figure 7 plots grid-parity dynamics in the 2010s for 64 market segments in the Americas. The characteristics of commercial and industrial market segments can be regarded as very similar to those of Europe (section 4.1). First grid-parity market segments are in the Caribbean, consequence of excellent solar conditions and costly oil (diesel) fuel for power supply on islands. Such market segments show best combinations for early grid-parity, as good solar conditions and high electricity prices are given. Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for residential market segments in El Salvador and Guyana, respectively. Further examples for last finding would be California and Massachusetts for states of the US.[5]

By the mid 2010s about 30% of residential and 22% of industrial market segments will be beyond grid-parity (Figures 7, 10 and 11). By the end of the 2010s the great majority of all electricity market segments (99% for residential and 93% for industrial) in the Americas will be beyond grid-parity. In 2010 total electricity consumption is about 8,900 TWh. As a consequence of PV capacity factors in the Americas and grid restrictions, an overall share of PV electricity in the Americas of 8 to 16% in 2020 can be achieved.

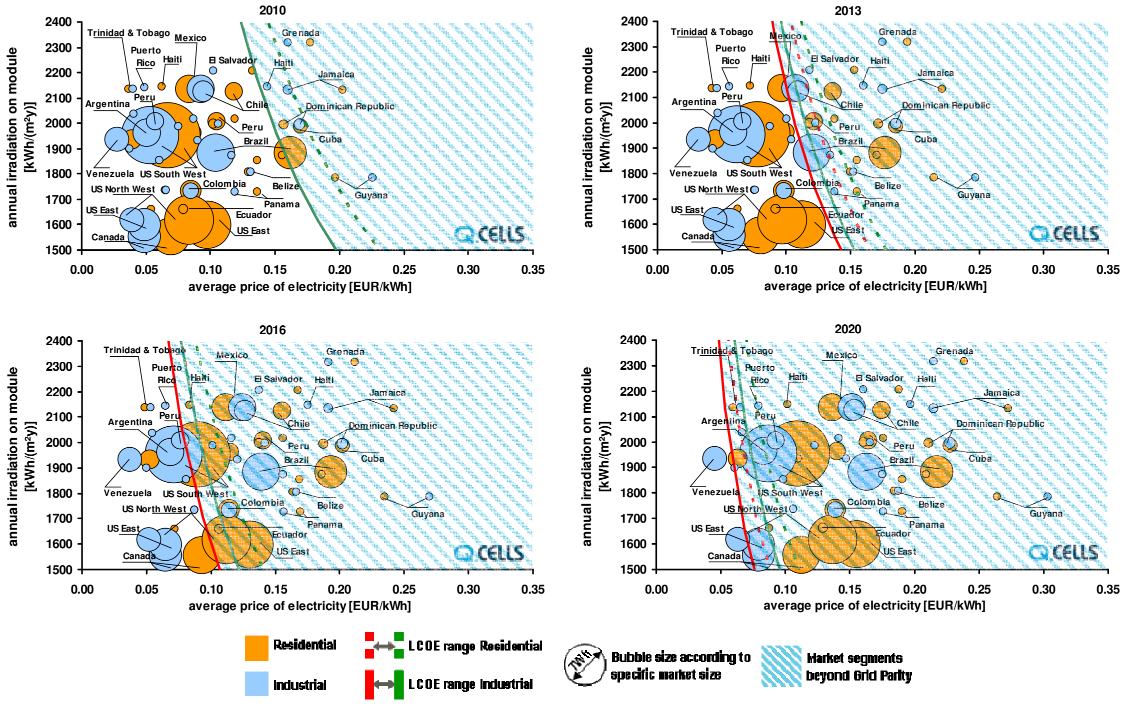

Figure 7: Grid-parity analysis for the Americas in 2010 (top left), 2013 (top right), 2016 (bottom left) and 2020 (bottom right). American countries are rated by their population weighted solar irradiation [41] and electricity prices of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries is given in Appendix Tables 1 – 3.

An assessment of the outcome for the Americas is quite similar to that of Europe (section 4.1). PV will be also a highly important energy technology for the Americas to tackle depletion of fossil fuel resources and climate change. The faster a broad market introduction of PV is started the faster the highly positive effects of significant PV electricity supply can be realized in the Americas.

4.3 AFRICA

Figure 8 depicts grid-parity dynamics in the 2010s for 81 market segments in Africa. First grid-parity market segments are the residential and mostly industrial segments on the Seychelles and Madagascar and in The Gambia, Burkina Faso, Senegal, Mali and Chad. These market segments show the best combination for early grid-parity: excellent solar conditions and high electricity prices. Similar to Europe and the Americas (section 4.1 and 4.2), islands are among the first grid-parity regions. Several West African countries reach grid-parity early. However, grid-parity should not be overestimated for Sub-Sahara countries, as most people living there do not have access to electricity, particularly in rural areas (section 3.5).[79-81]

Most residential and industrial market segments reach grid-parity in this decade, except South Africa and Egypt (both account together for 64% of total African electricity generation) which heavily subsidize their energy markets with 9 and 15 bnUSD in 2007, respectively.[21] Countries allocate enormous public spending to energy subsidies, e.g. Iran, China, Russia, Saudi-Arabia, India, Venezuela, Indonesia and Ukraine, might enter a vicious circle. In a world faced with rising energy prices (section 3.4) rapidly increasing subsidies are needed for stabilising local prices, whereas only very limited resources are left for investments for inexpensive and price stabilizing renewable energy technologies, like solar PV (section 3.2) and wind power. Energy subsidy induced destabilized national budgets might become an enormous burden for further economic development of those countries.

By the mid 2010s about 8% of residential and 7% of industrial market segments will be beyond grid-parity (Figures 8, 10 and 11). By the end of the 2010s the majority of all electricity market segments (which only account for 28% for residential and 27% for industrial electricity consumption) in Africa will be beyond grid-parity. In 2010 total electricity consumption is about 500 TWh, whereas about 320 TWh are generated in South Africa and Egypt. As a consequence of PV capacity factors in Africa and grid restrictions, an overall share of PV electricity in Africa of 16 to 32% could be achieved by 2020.

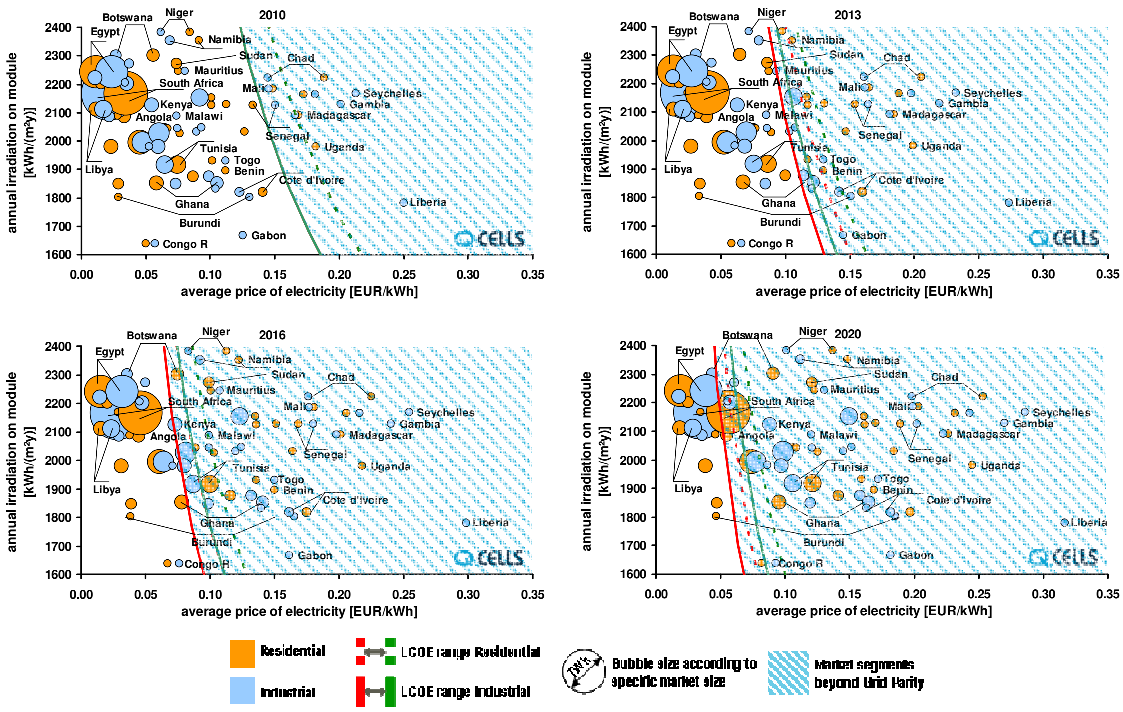

Figure 8: Grid-parity analysis for Africa in 2010 (top left), 2013 (top right), 2016 (bottom left) and 2020 (bottom right). African countries are rated by their population weighted solar irradiation [41] and electricity prices of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries is given in Appendix Tables 1 – 3.

About 1.5 billion people do not have access to electricity of whom a large fraction live in Africa. The grid-parity concept is not applicable to those people. However, off-grid PV is a very economic option for them due to very low financial amortization periods of two to three years in most rural areas.[12]

4.4 ASIA-PACIFIC

Figure 9 depicts grid-parity dynamics in the 2010s for 85 market segments in Asia-Pacific. First grid-parity market segments are the residential segment in Cambodia, Fiji, Japan and the Philippines and industrial segments in Western China and the Philippines. These market segments show the best combination for early grid-parity: good solar conditions and high electricity prices. Similar to other world regions islands show early grid-parity events.

Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for industrial and residential market segments in Western China and Japan, respectively. By the mid 2010s about 45% of residential and 36% of industrial market segments will be beyond grid-parity (Figures 9 - 11). By the end of the 2010s the great majority of all electricity market segments (83% for residential and 88% for industrial) in Asia-Pacific will be beyond grid-parity. In 2010 total electricity consumption is about 8,180 TWh. As a consequence of PV capacity factors in Asia-Pacific and grid restrictions, an overall share of PV electricity in Asia-Pacific of 11 to 22% in 2020 can be achieved.

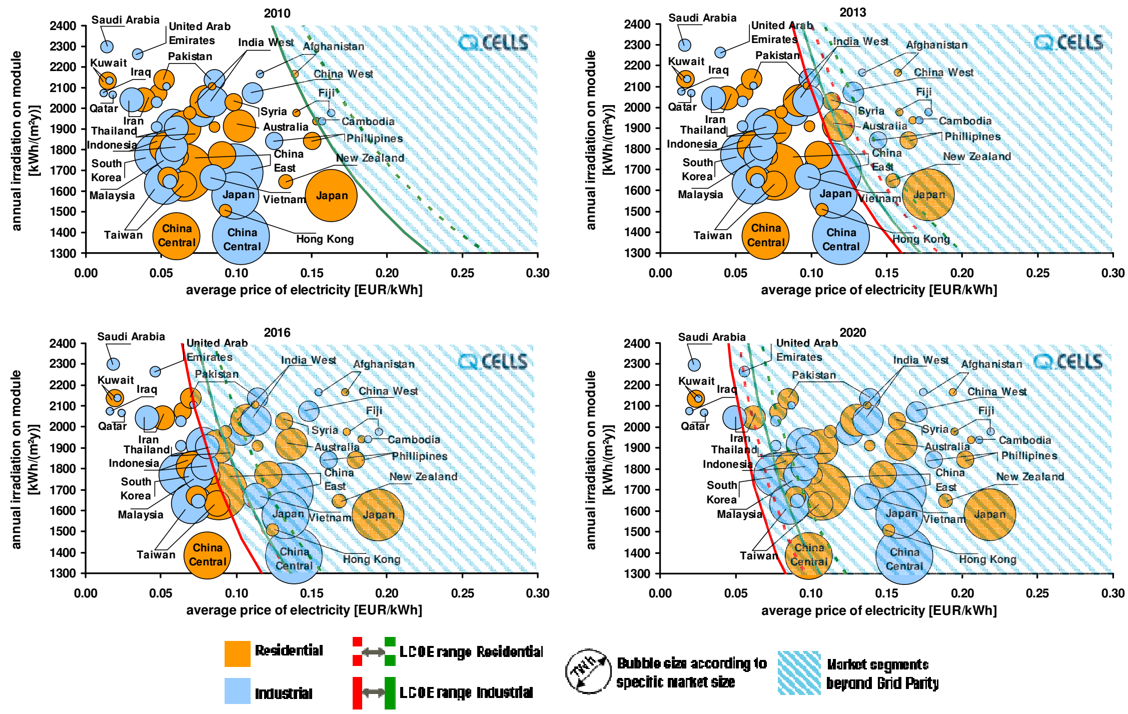

Figure 9: Grid-parity analysis for Asia in 2010 (top left), 2013 (top right), 2016 (bottom left) and 2020 (bottom right). Asian countries are rated by their population weighted solar irradiation [41] and electricity prices of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries is given in Appendix Tables 1 – 3.

Clear outcome of grid-parity analysis for Asia-Pacific is a fast reduction in LCOE of PV and therefore market introduction cost will decline as a consequence. A significant PV electricity supply in Asia-Pacific will help to lower social cost of current electricity supply, e.g. increasing health cost due to coal related emissions, increasing political insecurity as a consequence of diminishing fossil fuel resources or destabilizing of fragile ecosystems induced by GHG emissions.

Oil producing Asian countries reach grid-parity at the end of the 2010s or even later, which is directly related to very high energy subsidies in these countries.[21] However, high social costs have to be paid, due to very high opportunity cost. For these countries, a much better economic outcome could be realised by shifting opportunity costs into renewable investments, like large-scale solar PV power plants. Currently, historic first fuel-parity events can be observed in Middle East, i.e. generating electricity by burning oil in oil power plants is higher in LCOE than the same amount of electricity in solar PV power plants.[8,15,16] Consequently, enormous local economic benefits could be created by switching from one domestic energy source, fossil fuels, to another: solar photovoltaic energy.

4.5 DEVELOPMENT OVER TIME OF TOTAL ADDRESSABLE GRID-PARITY MARKET SEGMENTS

As shown in the last four subsections a fast market diffusion of PV can be expected all around the world. These fast growing market potentials for PV due to grid-parity events are complemented by highly economic off-grid PV markets in rural areas of developing countries [12] and fuel-parity events which will create highly profitable utility-scale solar PV markets, in particular in sunny oil producing countries and best analysed for MENA region.[8,15,16] In 2008 global electricity generation has been about 19,800 TWh [83] and is expected to increase to about 27,000 TWh by the end of the 2010s. Population weighted mean irradiation on fixed optimally tilted module surface for Europe, the Americas, Africa and Asia is 1,450, 1,890, 2,070 and 1,830, kWh/m²/y, respectively.[41]

Total electricity consumption is about 4,390, 8,940, 500 and 8,180 TWh in Europe, the Americas, Africa and Asia-Pacific in 2010 and might grow to a global total of about 27,200 TWh in 2020.[83]

The development over time for absolute and relative grid-parity market segments in the world is depicted for residential (Figure 10) and industrial (Figure 11) market segments. Detailed data can be found in Appendix Tables

1 – 3.

First residential grid-parity events occur today in all regions in the world and continue throughout the entire decade (Figure 10). Very early grid-parity showing market segments are Cyprus, Italy, the Caribbean and West Africa. At the end of this decade more than 80% of market segments in Europe, the Americas and Asia are beyond residential grid-parity. Exception is given for Africa, due to energy subsidies in South Africa and Egypt, which represent more than 60% of electricity generation in Africa. Residential grid-parity is complemented by highly economic off-grid PV in rural regions of developing countries. This is the case for about 1.5 billion people in the world, mostly living in Africa and South Asia.

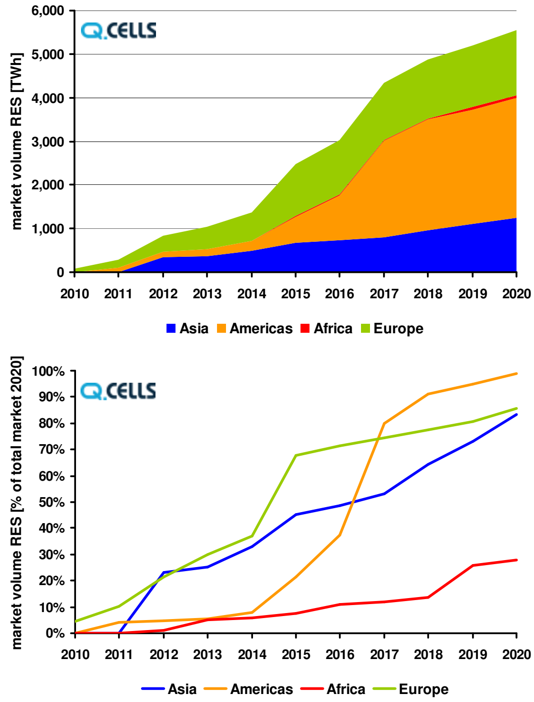

Figure 10: Grid-Parity market volume for residential segments in absolute (top) and relative (bottom) numbers for all regions in the world in the years 2010 to 2020. Detailed data is given in Appendix Tables 1 – 3.

Residential grid-parity analysis (Figures 6 – 10) is performed for 154 countries in the world. These countries account for 98.0% of world population [84], 99.7% of global gross domestic product [85], 99.5% of global electricity consumption [86] and 99.2% of global greenhouse gas emissions [87]. Detailed data is given in Appendix Tables 1 – 3.

First industrial grid-parity events occur today in all regions in the world and often on islands. They continue throughout the entire decade (Figure 11). 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 end of decade more than 75% of market segments in Europe, the Americas and Asia are beyond industrial grid-parity. Exception is given for Africa, due to energy subsidies in South Africa and Egypt. Further exception 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.

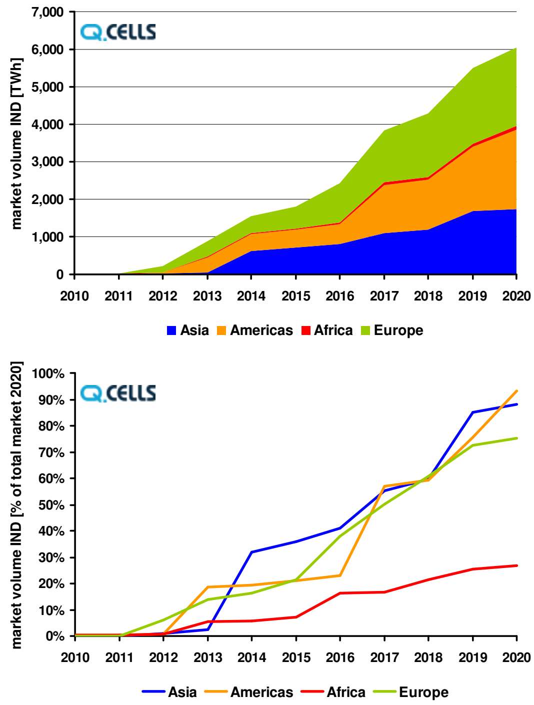

Figure 11: Grid-Parity market volume for industrial segments in absolute (top) and relative (bottom) numbers for all regions in the world in the years 2010 to 2020. Detailed data is given in Appendix Tables 1 – 3.

Nevertheless, significant opportunity cost might become a pressing burden for these countries, as most could substitute substantial amounts of currently burnt oil and natural gas resources by renewable energy sources like solar PV. As consequence of fuel-parity in these countries fast growing utility-scale solar PV power plant markets are very likely. PV power plants can be used as fuel saving technology. Usually, solar PV sceptics claim that PV would be one of the most expensive options for reducing greenhouse gas (GHG) emissions.[88-91] After fuel-parity, PV LCOE are lower in cost than LCOE of oil fired power plants, used as baseload power plants in several countries in the world. As a consequence, reducing GHG emissions by combining oil power plants and PV power plants generates economic GHG reduction benefits. The authors of this publication encourage all readers to be aware of this new fact that might be surprising, in particular for conventional energy economists.

Industrial grid-parity analysis (Figures 6 – 9 and 11) is performed for 151 countries in the world. These countries account for 97.7% of world population [84], 99.3% of global gross domestic product [85], 99.6% of global electricity consumption [86] and 99.1% of global greenhouse gas emissions [87]. Detailed data is given in Appendix Tables 1 – 3.

assumption.

Key driving force of PV LCOE and therefore for all results presented in this section is system cost. Consensus expectation of financial analysts is 2.70 and 2.40 €/Wp for residential and commercial/ industrial PV systems in Germany in 2010.[27-33] Most parts of PV systems are globally traded and produced to similar world market cost. Furthermore, all PV markets in the world comprising several hundred MWp installations per year will show similar distribution cost. Hence a global average sales price is applicable reflecting similar global PV cost. The most competitive and by far largest PV market is Germany. Therefore German PV prices are used as price benchmark in the world (Figure 12). Experience curve of PV and market growth rates are key factors of ongoing cost reductions of PV systems (section 3.1 and 3.2).

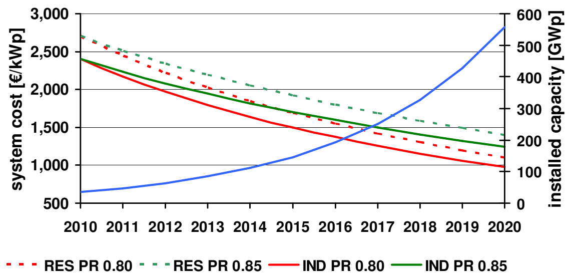

Figure 12: PV system prices in the 2010s assumed for grid-parity analysis. PV system price includes module, inverter, land and all necessary balance of system components. PV system price of 2.70 €/Wp is indicated for smaller residential systems by dashed lines and for larger commercial systems of 2.40 €/Wp by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Growth rate of global PV markets is assumed to be 30% p.a. PV system price is the major contributor to levelized cost of electricity (LCOE). Further assumptions for LCOE are weighted average cost of capital of 6.4%, lifetime of 25 up to 30 years, operation and maintenance cost of 1.5% of PV system price and performance ratio of 75 up to 82%.

Assumptions for underlying PV system cost might be too conservative. Growth rates of global PV installations have been 45% for the past 15 years, which is much higher than expected 30%. Lower future cost potential is also indicated by today's best practice cost for large PV power plants of about 1.5 – 1.6 €/Wp, including all manufacturing, sales, general administration and research cost, excluding cost for debt and equity and value chain inefficiencies, which can be achieved for both CdTe PV and crystalline silicon PV technology.[54] First PV industry players plan to reach fully-loaded PV power plant cost of about 1.20 – 1.35 €/Wp in 2014 [92] (numbers include 0.20 €/Wp additional cost before excluded and an USD/€ exchange rate of 1.4), which is far below expectations in Figure 12 used in this model and provides a further indication of conservative assumption.

For further analysis several parameter combinations of the grid-parity model are given for residential (Table 1) and industrial (Table 2) conditions. Applying all parameter settings, given in section 2, time dependent decrease of capital expenditures (Capex) for new PV installations and respective LCOE can be easily combined. Impact of variations in net PV electricity yield and progress ratio is significant but does not exceed a multiple of 2.5 in the outcome.

year	Capex		E_{net} = 1000 kWh/kWp		E_{net} = 1400 kWh/kWp		E_{net} = 1700 kWh/kWp	
	0.80	0.85	0.80	0.85	0.80	0.85	0.80	0.85
	[€/Wp]		[€/kWh]		[€/kWh]		[€/kWh]	
2010	2.70	2.70	0.277	0.277	0.185	0.185	0.159	0.159
2012	2.22	2.34	0.216	0.228	0.144	0.152	0.124	0.131
2014	1.85	2.05	0.172	0.190	0.115	0.127	0.099	0.109
2016	1.55	1.80	0.141	0.163	0.094	0.109	0.081	0.094
2018	1.30	1.59	0.118	0.143	0.079	0.096	0.068	0.082
2020	1.09	1.40	0.099	0.127	0.066	0.085	0.057	0.073

Table 1: Levelized cost of electricity of residential PV systems in dependence of Capex of PV systems, net PV electricity yield and progress ratio. Calculations are performed according to the assumptions of section 2. PV electricity yield is assumed for the year 2010 and further increase in performance ratio is applied to status of 2010. Net PV electricity yield of 1,000, 1,400 and 1,700 kWh/kWp can be expected in e.g. Czech Republic, Korea and Nepal, respectively. Progress ratio is assumed to be between 0.80 and 0.85.

year	Capex		E_{net} = 1000 kWh/kWp		E_{net} = 1400 kWh/kWp		E_{net} = 1700 kWh/kWp	
	0.80	0.85	0.80	0.85	0.80	0.85	0.80	0.85
	[€/Wp]		[€/kWh]		[€/kWh]		[€/kWh]	
2010	2.40	2.40	0.230	0.230	0.185	0.185	0.136	0.136
2012	1.97	2.08	0.180	0.190	0.129	0.136	0.106	0.112
2014	1.64	1.82	0.144	0.160	0.103	0.114	0.085	0.094
2016	1.37	1.60	0.118	0.138	0.085	0.099	0.069	0.081
2018	1.16	1.41	0.099	0.121	0.071	0.087	0.058	0.072
2020	0.97	1.24	0.083	0.107	0.060	0.076	0.049	0.063

Table 2: Levelized cost of electricity of industrial PV systems in dependence of Capex of PV systems, net PV electricity yield and progress ratio. Calculations are performed according to the assumptions of section 2. PV electricity yield is assumed for the year 2010 and further increase in performance ratio is applied to status of 2010. Net PV electricity yield of 1,000, 1,400 and 1,700 kWh/kWp can be expected in e.g. Germany, Italy and Arizona, respectively. Progress ratio is assumed to be between 0.80 and 0.85.

In regions reaching grid-parity in the early 2010s, e.g. Spain, PV installations will generate a significant benefit for system owners in the following years (Figure 13). New PV solutions, like decentralised storage of PV electricity, might arise due to an enormous financial scope. It might be possible, that the very successful feed-in tariffs in Europe will have to be supplemented by new legal frameworks to further enable a fast diffusion of PV and respective social benefits.

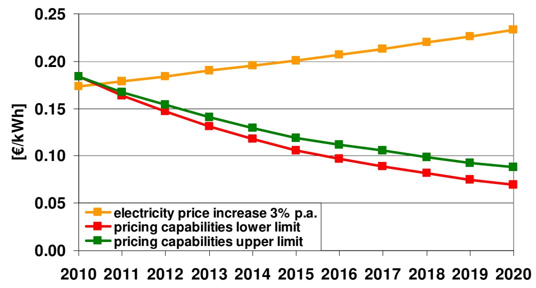

Figure 13: Grid-parity dynamics in Spain – residential segment. Large difference in expected levelized PV cost and electricity supplied by grid may result in stand-alone PV solutions.

Results presented in this section clearly show the enormous potential of PV to become a major source of electricity in the next two decades. Solar energy is available all over the world and distributed more or less homogenously. Based on rapidly improving economics, low technological complexity and excellent resource accessibility solar PV has the potential to become the most democratic source of energy with various beneficial social impacts all over the world.

4.4 OUTLOOK

First of all, it should be noted, that there are already highly economic and therefore sustainable PV markets which will accelerate their growth rates, in particular off-grid PV markets in rural areas in developing countries.[12]

Grid-parity as the third major PV diffusion phase will be observed in the next years in several countries around the world. It poses a question: what will occur beyond grid-parity? Grid-parity events will trigger development of new business models, like PV-storage applications, and will induce progress in electric grid management, like PV induced locally temporarily reversed power flows.

Next parity for PV applications might happen in parallel to grid-parity. As a consequence of high crude oil prices large-scale PV power plants will become a very fast growing market segment due to fuel-parity events occurring right now.[8,15,16] These large PV power plants substitute high priced fossil fuels for fuel saving reasons, hence they will stabilize electricity supply cost in on-grid markets on utility level.

In the years to come, an intensified research, development and demonstration for all fields of PV grid-integration is essential. Systematic R&D is needed on symbiotic relations among renewable energy sources and respective technologies. This might lead for example to hybrid PV-Wind power plants [71] hybrid PV-STEG power plants or PV-Hydro power plants [93]. Key objective should be to achieve the ability to dispatch decentralized PV installations and utility-scale PV power plants on demand, which could include bio methane or even solar methane [94] powered combined cycle power plants, peaking geothermal power plants, hydro-electric pumped storage or other kinds of storage technologies, in particular with regard to arising electric vehicles.

5 CONCLUSIONS

We have presented a model for analyzing grid-parity patterns of PV. A detailed discussion on the key driving forces of grid-parity dynamics, i.e. experience curve approach, PV system cost, growth rate of PV industry, PV system performance, electricity prices and access to electricity, has strongly indicated a more or less conservative parameter setting in the assumptions of the applied scenario for grid-parity in the 2010s. The model has been applied to more than 150 countries in the world accounting for 98.0% of world population and 99.7% of global GDP. Grid-parity events will occur throughout the next decade in the majority of all market segments in the world, starting on islands and regions of good solar conditions and high electricity prices. Cost of PV electricity generation in regions of high solar irradiance will decrease from 16 to 6 €ct/kWh in the years 2010 to 2020.

Besides grid-parity, large commercially addressable PV markets are already available for off-grid PV systems in rural areas in developing countries. True fuel-parity for utility-scale PV power plants starts right now and is very likely to create very large and fast growing commercial PV power plant markets.

Low PV electricity generation cost beyond grid-parity may establish new business models for the PV industry. Furthermore, reaching grid-parity will require new political frameworks for maximizing social benefits.

Finally, it can be stated that PV electricity generation will achieve grid-parity in most market segments in the world and will become a very competitive source of energy.

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APPENDIX

Three Tables are added here:

Appendix Table 1: Residential grid-parity events by year and world region.
Appendix Table 2: Industrial grid-parity events by year and world region.
Appendix Table 3: List of about 161 countries and respective data for grid-parity events, electricity prices, irradiation on fixed optimally tilted module surface, population, gross domestic product, greenhouse gas emissions, electricity generation and electrification rate.

year	Europe	The Americas	Africa	Asia-Pacific
2010	Cyprus, Italy	Grenada, Guyana, Jamaica	Burkina Faso, Chad, Liberia, Madagascar, Uganda	
2011	Denmark, Malta, Portugal, Spain	Brazil, Cuba, Dominican Republic	Mali	Afghanistan, Cambodia
2012	Austria, Germany	Chile, Suriname, Uruguay	Central African Republic, Cote d'Ivoire, Senegal	Fiji, Japan, Palestine (W.Bank/Gaza), Philippines
2013	Belgium, Hungary, Israel, Luxembourg, Netherlands, Turkey	Belize, El Salvador, Nicaragua, Panama, Peru, Puerto Rico	Benin, Gambia, Kenya, Morocco, Namibia	New Zealand
2014	Croatia, Greece, Ireland, Slovakia, Slovenia, Sweden	Guatemala, Mexico	Niger, Rwanda, Togo	Australia, Jordan, Lebanon, Syria
2015	Czech Republic, Finland, France, Norway, Poland, Romania, Switzerland, United Kingdom	Argentina, United States East	Cameroon, Mauritius, Mozambique, Sudan	Bangladesh, Brunei Darussalam, Burma (Myanmar), India West, South Korea
2016	Bulgaria, Latvia	Colombia, Ecuador, Haiti, United States, United States North West	Gabon, Guinea, Tanzania, Tunisia	Hong Kong (China), India East
2017	Estonia, Lithuania	Bolivia, Honduras, United States South West	Botswana	India, Thailand
2018		Canada, Costa Rica, Paraguay	Ghana	China, China East, Malaysia, Pakistan, Sri Lanka, Taiwan
2019	Armenia		Algeria	China West, Indonesia, Vietnam
2020	Belarus, Serbia	Trinidad and Tobago	Congo R, Ethiopia	China Central, Iran, United Arab Emirates
2020+	Moldova, Russian Federation, Ukranie	Venezuela	Angola, Burundi, Congo DR, Egypt, Libya, Malawi, Nigeria, Seychelles, South Africa, Zambia, Zimbabwe	Azerbaijan, Iraq, Kazakhstan, Kuwait, Kyrgyzstan, Lao PDR, Qatar, Saudi Arabia, Tajikistan, Turkmenistan

Appendix Table 1: Residential grid-parity events by year and world region.

year	Europe	The Americas	Africa	Asia-Pacific
2010	Cyprus	Dominican Republic, Grenada, Guyana, Haiti, Jamaica	Burkina Faso, Chad, Gambia, Liberia, Madagascar, Mali, Senegal, Seychelles	Cambodia, Fiji
2011				Afghanistan, Palestine (W.Bank/Gaza)
2012	Italy	Belize, El Salvador, Guatemala, Suriname	Burundi, Cote d'Ivoire, Togo	China West, Philippines
2013	Malta, Turkey	Brazil, Chile, Mexico, Panama	Cameroon, Central African Republic, Gabon, Ghana, Guinea, Mauritius, Morocco, Rwanda	Pakistan
2014	Hungary, Portugal, Spain	Honduras, Nicaragua	Malawi, Namibia	Burma (Myanmar), China, China East, India, India West, Japan, Sri Lanka
2015	Austria, Greece, Israel, Netherlands, Slovakia	Colombia, Cuba	Congo DR, Niger, Tanzania	Brunei Darussalam, China Central, India East, Vietnam

2016	Belgium, Croatia, Czech Republic, Denmark, Germany, Luxembourg, Slovenia	Costa Rica, Peru	Kenya, Mozambique, Nigeria, Tunisia	Thailand
2017	Ireland, Poland, Romania, Switzerland, United Kingdom	Argentina, Puerto Rico, United States South West, Uruguay	Uganda	Australia, Indonesia, Jordan, Lao PDR, Malaysia
2018	Bulgaria, France, Latvia, Lithuania, Serbia	Ecuador	Algeria	Bangladesh, New Zealand, Syria
2019	Estonia, Finland, Norway, Sweden	Bolivia, Trinidad and Tobago, United States East	Congo R, Sudan, Zambia	Azerbaijan, South Korea, Taiwan, United Arab Emirates
2020		Canada, Paraguay, United States	Ethiopia	
2020+	Belarus, Moldova, Russian Federation, Ukranie	United States North West, Venezuela	Angola, Botswana, Egypt, Libya, South Africa, Zimbabwe	Iran, Iraq, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Qatar, Saudi Arabia, Tajikistan, Turkmenistan, Uzbekistan

Appendix Table 2: Industrial grid-parity events by year and world region.

	Grid-Parity		**Electricity prices 2010**		**Irradiation fixed optimally tilted**							**Electricity total Generation**	**Electrification rate**	
Country	**RES**	**IND**	**RES**	**IND**	**Pop weigh**	**Area weigh**	**max**	**min**	**Popula-tion**	**GDP**	**GHG**			
Data source	section 4		[34–40]		[23]				[84]	[85]	[87]	[86]	[80]	[81]
	[year]		[€/kWh]		[kWh/m²/y]				[mio pop]	[bn USD]	[mio t CO_2]	[GWh]	[% of pop]	
Afghanistan	2011	2011	0.139	0.116	2164	2165	2298	1966	29.1	10.2	0.7	n/a	n/a	0.020
Albania			0.000	0.000	1923	1959	2069	1791	3.2	12.3	4.3	5094	n/a	0.995
Algeria	2019	2018	0.046	0.048	1993	2260	2488	1856	35.4	173.9	132.7	35226	n/a	0.985
Angola	2020+	2020+	0.034	0.022	2084	2128	2398	1677	19.0	83.4	10.6	2959	0.150	0.050
Argentina	2015	2017	0.086	0.051	1962	1947	2681	974	40.7	328.4	173.5	115197	0.950	0.950
Armenia	2019		0.056	0.000	1830	1789	1856	1723	3.1	11.9	4.4	5941	n/a	0.995
Australia	2014	2017	0.102	0.058	1914	2215	2570	1429	21.5	1015.2	372.0	251659	1.000	1.000
Austria	2012	2015	0.197	0.106	1389	1395	1476	1324	8.4	416.4	71.8	63505	1.000	1.000
Azerbaijan	2020+	2019	0.020	0.050	1685	1695	1968	1482	8.9	46.3	35.1	23611	n/a	0.995
Bangladesh	2015	2018	0.086	0.047	1908	1907	2022	1820	164.4	79.0	41.6	24334	0.320	0.263
Belarus	2020	2020+	0.067	0.061	1264	1269	1320	1229	9.6	60.3	68.8	31811	n/a	0.995
Belgium	2013	2016	0.194	0.103	1203	1243	1364	1200	10.7	497.6	107.2	85617	1.000	1.000
Belize	2013	2012	0.130	0.132	1807	1893	2094	1757	0.3	1.4	0.8	n/a	n/a	0.870
Benin	2013		0.112	0.000	1895	2008	2135	1809	9.2	6.7	3.1	127	0.220	0.248
Bolivia	2017	2019	0.058	0.041	2037	1983	2690	1625	10.0	16.7	7.0	5293	0.640	0.651
Bosnia			0.000	0.000	1548	1696	2025	1447	3.8	18.5	27.4	13346	n/a	0.995
Botswana	2017	2020+	0.056	0.027	2302	2315	2363	2237	2.0	13.0	4.8	1042	0.390	0.264
Brazil	2011	2013	0.162	0.104	1883	1881	2353	1545	195.4	1612.5	352.5	419337	0.970	0.946
Brunei Darussalam	2015	2015	0.087	0.072	1915	1915	1915	1915	0.4	11.5	5.9	3298	0.990	0.992
Bulgaria	2016	2018	0.086	0.061	1606	1607	1703	1569	7.5	49.9	48.1	45843	n/a	0.995
Burkina Faso	2010	2010	0.172	0.181	2164	2166	2352	2081	16.3	7.9	0.8	n/a	0.070	0.100
Burma (Myanmar)	2015	2014	0.088	0.088	1939	1917	2047	1625	50.5	n/a	10.0	6164	0.110	0.050
Burundi	2020+	2012	0.029	0.131	1803	1803	1803	1803	8.5	1.2	0.2	n/a	n/a	0.235
Cambodia	2011	2010	0.153	0.157	1937	1933	2006	1757	15.1	9.6	4.1	1235	0.200	0.183
Cameroon	2015	2013	0.087	0.099	1875	1889	2157	1580	20.0	23.4	3.6	3954	0.470	0.407
Canada	2018	2020	0.069	0.049	1554	1095	1702	1102	33.9	1400.1	544.7	612594	1.000	1.000
Central African Republic	2012	2013	0.127	0.089	2031	2080	2237	1840	4.5	2.0	0.2	n/a	n/a	0.235
Chad	2010	2010	0.188	0.145	2222	2366	2592	2107	11.5	8.4	0.4	n/a	n/a	0.235
Chile	2012	2013	0.118	0.094	2124	1775	2769	916	17.1	169.5	60.1	57555	0.990	0.970
China	2018	2014	0.064	0.102	1631	1911	2615	1087	1354.7	4344.8	6105.7	2864204	0.990	0.990
China Central	2020	2015	0.061	0.103	1381				315.3					
China East	2018	2014	0.066	0.099	1689				950.7					

China West	2019	2012	0.048	0.111	2071				88.8					
Colombia	2016	2015	0.085	0.085	1732	1725	2454	1375	46.3	242.3	63.4	54301	0.860	0.902
Congo DR	2020+	2015	0.029	0.074	1848	1872	2216	1571	67.8	11.6	2.2	7886	0.060	0.083
Congo R	2020	2019	0.050	0.057	1638	1724	1897	1517	3.8	10.7	1.5	453	0.200	0.196
Costa Rica	2018	2016	0.065	0.065	1735	1899	2222	1537	4.6	29.8	7.9	8698	0.990	0.970
Cote d'Ivoire	2012	2012	0.141	0.123	1818	1891	2100	1708	21.6	23.4	6.9	5530	0.500	0.507
Croatia	2014	2016	0.122	0.082	1586	1652	1906	1490	4.4	69.3	23.7	12430	n/a	0.995
Cuba	2011	2015	0.170	0.076	1987	2198	2386	1950	11.2	n/a	29.6	16469	0.960	0.958
Cyprus	2010	2010	0.169	0.143	2244	2248	2259	2237	0.9	21.3	7.8	4651	n/a	1.000
Czech Republic	2015	2016	0.146	0.103	1251	1259	1293	1197	10.4	216.5	117.0	84361	n/a	0.995
Denmark	2011	2016	0.263	0.095	1287	1240	1378	975	5.5	342.7	54.6	45716	1.000	1.000
Djibouti			0.000	0.000	2318	2318	2318	2318	0.9	0.9	0.5	n/a	n/a	0.235
Dominican Republic	2011	2010	0.157	0.169	1995	2115	2393	1930	10.2	45.8	20.4	14150	0.930	0.923
Ecuador	2016	2018	0.079	0.054	1660	1807	2384	1368	13.8	52.6	31.3	15406	0.900	0.897
Egypt	2020+	2020+	0.012	0.024	2242	2374	2589	1964	84.5	162.8	166.8	115407	0.980	0.977
El Salvador	2013	2012	0.132	0.103	2206	2206	2206	2206	6.2	22.1	6.5	5597	0.800	0.769
Eritrea			0.000	0.000	2215	2239	2389	2049	5.2	1.7	0.6	269	0.200	0.184
Estonia	2017	2019	0.097	0.060	1298	1318	1414	1262	1.3	23.1	17.5	9731	n/a	0.995
Ethiopia	2020	2020	0.038	0.034	2205	2183	2365	1927	85.0	26.5	6.0	3269	0.150	0.026
Fiji	2012	2010	0.140	0.163	1976	2030	2131	1803	0.9	3.5	1.6	n/a	n/a	0.800
Finland	2015	2019	0.135	0.070	1181	849	1394	1167	5.3	271.3	66.7	82304	1.000	1.000
France	2015	2018	0.119	0.065	1441	1521	2065	1239	63.1	2853.1	384.0	574473	1.000	1.000
Gabon	2016	2013	0.086	0.125	1667	1657	1880	1531	1.5	14.4	2.1	1726	0.480	0.479
Gambia	2013	2010	0.113	0.201	2129	2118	2159	2081	1.8	0.8	0.3	n/a	n/a	0.235
Georgia			0.000	0.000	1678	1684	1840	1605	4.2	12.8	5.5	7287	n/a	0.995
Germany	2012	2016	0.236	0.106	1222	1223	1475	1140	82.1	3652.8	805.1	636761	1.000	1.000
Ghana	2018	2013	0.059	0.105	1852	1921	2087	1709	24.3	16.1	9.2	8429	0.490	0.485
Greece	2014	2015	0.108	0.085	1753	1983	2330	1680	11.2	356.8	96.4	60789	1.000	0.995
Grenada	2010	2010	0.178	0.160	2317	2317	2317	2317	0.1	0.6	0.2	n/a	n/a	0.995
Guatemala	2014	2012	0.102	0.106	1997	2061	2355	1778	14.4	39.0	11.8	7916	0.790	0.844
Guinea	2016	2013	0.065	0.093	2046	2063	2139	1953	10.3	4.3	1.4	n/a	n/a	0.800
Guyana	2010	2010	0.197	0.226	1784	1844	1948	1749	0.8	1.2	1.5	n/a	n/a	0.870
Haiti	2016	2010	0.063	0.144	2146	2276	2435	2062	10.2	7.0	1.8	570	0.360	0.335
Honduras	2017	2014	0.068	0.090	1932	1959	2181	1789	7.6	14.1	7.2	5982	0.620	0.601
Hong Kong (China)	2016		0.093	0.000	1506	1605	1703	1506	7.1	215.4	39.0	38616	n/a	1.000
Hungary	2013	2014	0.164	0.120	1445	1448	1500	1339	10.0	154.7	57.6	35859	n/a	0.995
India	2017	2014	0.064	0.079	2032	2027	2446	1615	1214.4	1217.5	1510.4	744078	0.560	0.444
India East	2016	2015	0.069	0.077	1975				338.6					
India West	2015	2014	0.080	0.085	2051				875.8					
Indonesia	2019	2017	0.053	0.059	1809	1916	2415	1616	233.7	514.9	333.7	133108	0.540	0.525
Iran	2020	2020+	0.038	0.031	2041	2121	2459	1569	75.1	385.1	467.0	201029	0.970	0.992
Iraq	2020+	2020+	0.012	0.012	2073	2096	2190	2022	31.5	n/a	92.6	31869	n/a	0.954
Ireland	2014	2017	0.191	0.102	1055	1151	1331	1032	4.6	281.8	43.8	28046	1.000	1.000
Israel	2013	2015	0.105	0.068	2247	2258	2320	2205	7.3	199.5	70.4	51811	0.970	1.000
Italy	2010	2012	0.206	0.129	1720	1855	2186	1568	60.1	2294.7	474.1	314121	1.000	1.000
Jamaica	2010	2010	0.203	0.160	2132	2257	2353	2132	2.7	15.1	12.2	7473	0.870	0.870
Japan	2012	2014	0.163	0.099	1578	1603	1999	1362	127.0	4909.3	1293.4	1100364	1.000	1.000
Jordan	2014	2017	0.084	0.054	2103	2194	2298	2084	6.5	20.0	20.7	11560	1.000	0.955
Kazakhstan	2020+	2020+	0.036	0.024	1709	1704	1954	1508	15.8	132.2	193.5	71653	n/a	0.995
Kenya	2013	2016	0.101	0.054	2124	2117	2313	1929	40.9	34.5	12.2	6477	0.140	0.091
Korea, North (DR)			0.000	0.000	1874	1892	2001	1780	24.0	n/a	79.1	22436	n/a	0.200
Kuwait	2020+	2020+	0.015	0.016	2134	2134	2134	2134	3.1	112.1	86.6	47607	1.000	1.000
Kyrgyzstan	2020+	2020+	0.016	0.016	1840	1880	2007	1698	5.6	4.4	5.6	17082	n/a	0.995
Lao PDR	2020+	2017	0.036	0.057	1829	1827	1949	1656	6.4	5.4	1.4	n/a	n/a	0.800
Latvia	2016	2018	0.105	0.067	1307	1331	1418	1259	2.2	33.8	7.5	4891	n/a	0.995
Lebanon	2014	2020+	0.088	0.022	2159	2262	2334	2159	4.3	28.7	15.3	9287	1.000	0.960

Liberia	2010	2010	0.250	0.250	1781	1788	1915	1696	4.1	0.9	0.8	n/a	n/a	0.235
Libya	2020+	2020+	0.011	0.018	2110	2341	2575	1899	6.6	99.9	55.5	23992	0.970	0.998
Lithuania	2017	2018	0.097	0.070	1277	1286	1381	1218	3.3	47.3	14.2	12482	n/a	0.995
Luxembourg	2013	2016	0.194	0.098					0.5	54.3	11.3	4333	1.000	1.000
Macedonia			0.000	0.000	1718	1713	1774	1636	2.0	9.5	10.9	7006	n/a	0.995
Madagascar	2010	2010	0.169	0.166	2091	2168	2531	1654	20.1	9.0	2.8	n/a	0.150	0.083
Malawi	2020+	2014	0.028	0.074	2088	2103	2176	2041	15.7	4.3	1.0	n/a	0.070	0.058
Malaysia	2018	2017	0.063	0.056	1766	1844	2148	1636	27.9	194.9	187.9	91563	0.980	0.971
Mali	2011	2010	0.148	0.145	2185	2270	2497	2106	13.3	8.7	0.6	n/a	n/a	0.235
Malta	2011	2013	0.156	0.090	2188	2188	2188	2188	0.4	7.4	2.5	2296	n/a	1.000
Mauretania			0.000	0.000	2202	2267	2443	2098	3.4	2.9	1.7	n/a	n/a	0.235
Mauritius	2015	2013	0.075	0.080	2244	2248	2273	2222	1.3	8.7	3.9	n/a	0.940	1.000
Mexico	2014	2013	0.083	0.093	2136	2194	2530	1696	110.6	1086.0	436.2	249648	n/a	0.870
Moldova	2020+	2020+	0.037	0.037	1492	1497	1577	1445	3.6	6.0	7.8	3829	n/a	0.995
Mongolia			0.000	0.000	1910	1996	2333	1701	2.7	5.3	9.4	3649	0.650	0.900
Morocco	2013	2013	0.101	0.092	2153	2194	2410	1938	32.4	86.3	45.3	23192	0.850	0.774
Mozambique	2015	2016	0.077	0.061	2026	2053	2339	1943	23.4	9.7	2.0	14737	0.060	0.087
Namibia	2013	2014	0.091	0.069	2352	2355	2521	1952	2.2	8.6	2.8	1606	0.340	0.347
Nepal			0.000	0.000	2176	2191	2276	2082	29.9	12.6	3.2	2684	0.330	0.259
Netherlands	2013	2015	0.191	0.106	1242	1259	1325	1153	17.0	860.3	175.1	99664	1.000	1.000
New Zealand	2013	2018	0.133	0.056	1644	1644	2017	1309	4.3	130.7	30.5	43519	1.000	1.000
Nicaragua	2013	2014	0.119	0.087	2016	1907	2387	1621	5.8	6.6	4.3	2958	0.690	0.466
Niger	2014	2015	0.084	0.062	2382	2450	2599	2170	15.9	5.4	0.9	n/a	n/a	0.235
Nigeria	2020+	2016	0.023	0.060	1978	2037	2370	1523	158.3	212.1	97.3	23110	0.460	0.449
Norway	2015	2019	0.161	0.071	1103	575	1378	994	4.9	450.0	40.2	121663	1.000	1.000
Oman			0.000	0.000	2239	2336	2511	2167	2.9	35.7	41.4	13585	0.960	0.946
Pakistan	2018	2013	0.052	0.086	2135	2137	2468	1863	184.8	168.3	142.7	98350	0.540	0.530
Palestine	2012	2011	0.125	0.125	2056	2056	2056	2056	4.4	n/a	3.0	n/a	n/a	n/a
Panama	2013	2013	0.136	0.119	1728	1758	1921	1523	3.5	23.1	6.4	5989	0.850	0.851
Paraguay	2018	2020	0.055	0.037	1898	1891	1930	1850	6.5	16.0	4.0	53784	0.860	0.853
Peru	2013	2016	0.105	0.057	2006	1868	2422	1448	29.5	127.4	38.6	27358	0.720	0.757
Philippines	2012	2012	0.151	0.125	1842	1977	2219	1689	93.6	166.9	68.3	56730	0.810	0.891
Poland	2015	2017	0.136	0.088	1235	1236	1326	1173	38.0	527.0	318.2	161742	n/a	0.995
Portugal	2011	2014	0.164	0.087	1891	1947	2222	1769	10.7	242.7	60.0	49041	1.000	1.000
Puerto Rico	2013	2017	0.097	0.049	2142	2295	2367	2142	4.0	n/a	n/a	n/a	n/a	0.995
Qatar	2020+	2020+	0.018	0.018	2065	2223	2381	2065	1.5	52.7	46.2	15325	0.710	0.956
Romania	2015	2017	0.103	0.075	1500	1492	1625	1364	21.2	200.1	98.5	62697	n/a	0.995
Russian Federation	2020+	2020+	0.034	0.039	1403	993	1998	1012	140.4	1607.8	1564.7	995794	n/a	0.995
Rwanda	2014	2013	0.104	0.104	1831	1819	1854	1783	10.3	4.5	0.8	n/a	n/a	0.235
Saudi Arabia	2020+	2020+	0.014	0.014	2296	2327	2621	2149	26.2	467.6	381.6	179782	0.970	0.984
Senegal	2012	2010	0.133	0.151	2126	2160	2329	2039	12.9	13.2	4.3	2439	0.330	0.314
Serbia	2020	2018	0.053	0.058	1573	1585	1820	1512	10.5	54.6	53.3	36481	n/a	0.995
Seychelles	2020+	2010	0.021	0.213	2168	2168	2168	2168	0.1	0.8	0.7	n/a	n/a	0.800
Sierra Leone			0.000	0.000	1861	1888	1994	1757	5.8	2.0	1.0	n/a	n/a	0.235
Slovakia	2014	2014	0.155	0.133	1286	1296	1363	1240	5.4	95.0	37.5	31418	n/a	1.000
Slovenia	2014	2016	0.141	0.084	1483	1484	1485	1482	2.0	54.6	15.2	15115	n/a	1.000
Somalia			0.000	0.000	2100	2188	2538	1970	9.4	n/a	0.2	n/a	n/a	0.070
South Africa	2020+	2020+	0.035	0.021	2166	2238	2455	1784	50.5	276.8	414.6	253798	0.700	0.671
South Korea	2015	2019	0.091	0.047	1770	1779	1912	1672	48.5	929.1	475.2	404021	1.000	1.000
Spain	2011	2013	0.173	0.098	1886	1967	2479	1450	45.3	1604.2	352.2	303051	1.000	1.000
Sri Lanka	2018	2014	0.057	0.085	1813	1944	2146	1765	20.4	40.7	11.9	9389	0.660	0.655
Sudan	2015	2019	0.074	0.037	2271	2294	2574	1938	43.2	58.4	10.8	4209	0.300	0.310
Suriname	2012	2012	0.156	0.116	1872	1934	2270	1856	0.5	2.9	2.4	n/a	n/a	0.870
Swaziland			0.000	0.000	1982	1982	1982	1982	1.2	2.6	1.0	n/a	n/a	0.235
Sweden	2014	2019	0.170	0.063	1218	927	1458	1045	9.3	480.0	50.9	143299	1.000	1.000
Switzerland	2015	2017	0.112	0.074	1467	1482	1511	1423	7.6	488.5	41.8	64038	1.000	1.000

Syria	2014	2018	0.098	0.047	2026	2068	2269	1991	22.5	55.2	68.5	37283	0.900	0.866
Taiwan	2018	2019	0.065	0.053	1632	1628	1920	1407	n/a	n/a	n/a	235371	n/a	0.988
Tajikistan	2020+	2020+	0.007	0.007	1996	1987	2238	1777	7.1	5.1	6.4	16924	n/a	0.995
Tanzania	2016	2015	0.067	0.074	2043	2049	2284	1805	45.0	20.5	5.4	2776	0.110	0.092
Thailand	2017	2016	0.066	0.060	1903	1899	2007	1728	68.1	260.7	272.5	138742	0.990	0.911
Togo	2014	2012	0.102	0.112	1931	1991	2079	1849	6.8	2.8	1.2	221	0.170	0.170
Trinidad and Tobago	2020	2019	0.036	0.040	2136	2242	2320	2136	1.3	23.9	33.6	7045	0.990	0.990
Tunisia	2016	2016	0.075	0.065	1916	2062	2306	1819	10.4	40.2	23.1	14122	0.990	0.950
Turkey	2013	2013	0.124	0.109	1839	1883	2274	1520	75.7	794.2	269.5	176299	n/a	0.995
Turkmenistan	2020+	2020+	0.025	0.025	1894	1888	2033	1712	5.2	18.3	44.1	13650	n/a	0.995
Uganda	2010	2017	0.182	0.053	1980	2015	2179	1815	33.8	14.5	2.7	n/a	0.090	0.040
Ukranie	2020+	2020+	0.022	0.022	1398	1424	1697	1259	45.4	180.4	319.2	193381	n/a	0.995
United Arab Emirates	2020	2019	0.035	0.035	2261	2311	2453	2191	4.7	163.3	139.6	66768	0.920	0.974
United Kingdom	2015	2017	0.148	0.095	1128	1153	1456	984	62.3	2660.5	569.0	398478	1.000	1.000
United States	2016	2020+	0.083	0.034	1796	1657	2442	1067	317.8	14204.7	5752.9	4300100	1.000	1.000
United States East	2015	2019	0.097	0.049	1598				176.9					
United States North West	2016	2020+	0.084	0.039	1618				55.9					
United States South West	2017	2017	0.067	0.053	1953				88.0					
Uruguay	2012	2017	0.136	0.060	1853	1860	1915	1778	3.4	32.2	6.9	5619	0.950	0.990
Uzbekistan	2020+	2020+	0.015	0.015	1976	1907	2080	1787	27.8	27.9	115.7	49299	n/a	0.995
Venezuela	2020+	2020+	0.039	0.028	1934	1951	2463	1582	29.0	313.8	171.6	110357	0.990	0.940
Vietnam	2019	2015	0.055	0.084	1665	1744	2054	1387	89.0	90.7	106.1	56494	0.840	0.796
Yemen			0.000	0.000	2295	2375	2525	2162	24.3	26.6	21.2	5337	0.360	0.503
Zambia	2020+	2019	0.015	0.035	2201	2214	2315	2114	13.3	14.3	2.5	9385	0.190	0.184
Zimbabwe	2020+	2020+	0.011	0.011	2221	2220	2331	2072	12.6	3.4	11.1	9776	0.340	0.409
World					1846	1776	2769	772	6883.1	59557	28313	18913638		

Appendix Table 3: List of 161 countries and respective data for grid-parity events, electricity prices, irradiation on fixed optimally tilted module surface, population, gross domestic product, greenhouse gas emissions, electricity generation and electrification rate.