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Outlook of solar energy in Europe based on economic growth characteristics

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ABSTRACT

Solar power production in Europe has raised from about 130 MW to 110 GW of installed capacity (corresponding to 90 GWh to 120 TWh in annual electricity generation) during the present century. Together with wind power, it constitutes the largest growth within renewable energy sources in the last decades. At present however, clear signs of saturation can be observed in the leading areas of solar power in Europe. Here, the development of solar power in Europe is analysed and, for the three leading countries (Germany, Italy, Spain) a logistic growth path at the national level and a proportionality between saturation level of the growth curve of each country and its gross domestic product (GDP) is found. The sum of the next three countries (France, UK, Belgium) is well described by a logistic path with a time offset relative to the first group of three, and the sum of the two logistic paths, representing in total about 85% of European solar power production, describes the growth pattern in the corresponding area very well. Based on this, an estimate of a future saturation level for solar power in Europe is obtained by extrapolation. Finally, a model based on logistic growth patterns and learning curves that links solar power production data to investment data, is proposed. The proposed model is validated and calibrated on historical European data and extrapolated into the future. In a future scenario where European investments continue to decrease, a saturation level that is fully in line with our GDP based 200 TWh/y estimate is found and the application of the findings is discussed in a global context.

1. Introduction

As early as in 1974 it was realized that solar energy carries the potential to cover the energy needs for the entire global population practically without climate emissions [1]. Here it was concluded that "present prospects are far behind the expectations aroused by popular writers". More than four decades later, this statement is still valid, as solar energy contributes below 1% of the global primary energy supply [2,3]. At present, solar heat technologies have seen a decreasing growth rate for half a decade and was recently passed by solar photovoltaics (PV), which now contributes about 2% of the global electricity generation.

Primary energy sources have undergone several long term substitution transitions during the last centuries. This has brought us to the current energy use where 80% of the current energy supply is fluid fossil fuel based [4,5]. Now, with a fast diminishing remaining carbon budget to spend, an energy transition on a completely different and more rapid timescale than the previous transitions is requested. The IPCC special report Global Warming of 1.5 °C (2018) [6] quantifies this in terms of a demand of a 45% reduction in CO_2 emissions relative to the 2010 level by 2030 and reaching a net-zero situation by 2050 to stay on a 1.5° target pathway with limited temperature overshoot on the way. Yet, the dependence of fossil fuels does not seem to decrease [7].

On the other hand, the growth rate of solar power generation since the turn of the century has been remarkable, with an average growth rate of almost 50% per year from 2006 to 2016, and a 32% growth rate in 2017 [2], suggesting that solar power can play an important role in the requested energy transition. The asymptotic contribution of solar power to the future energy mix is in this respect a key question. However, due to the urgency of the situation, the time aspect of this transition is a question of equal importance: How will the growth rate develop over time?

The future role of solar power depends on many factors, mainly related to policies, technology development and cost of competing technologies [8]. So far, near future growth projections have often turned out to be too pessimistic [9]. The long-term lesson of this experience is frequently used as an argument for predictions of PV solar power taking fractions of up to 30% of the electricity consumption as early as 2035 and 30–50% in 2050. However, the majority of scenarios predict PV contributions much below this level [9–13]. At a regional European level, related predictions suggest PV solar power fractions of

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up to 27% of the electricity consumption by 2030 [10].

Recently, early signs of decelerated global growth of solar power was discussed [14]. This picture becomes clearer at a regional level since start-up times of large-scale deployment defer with several years between e.g. Asia and Europe. In China the growth rate since 2015 has been significant (in average 66% per year), while in a number of European countries the growth rate peaked around 2010–2012. In these European countries (e.g. Germany and Italy), the solar power production as function of time can be well described by a logistic curve [15,16].

In this paper the development of solar power in Europe, a region that has had a leading position in the deployment of this energy resource, is analysed. The global logistic growth model proposed in Ref. [14] is here applied on a national and European level. From the three leading countries (Germany, Italy and Spain) which amounts to about two thirds of European solar power production, common features of the growth pattern is identified. First, it is shown that the development follows a logistic path saturating at a level approximately proportional to the GDP of the individual countries. Second, the relation between solar investments and produced solar power is modelled, combining investment data with learning rates in order to quantify the resources required to reach and maintain a given level of solar power. A narrow range of model parameters gives an excellent agreement with historic produced power. Based on this, an extrapolation into the future is performed based on various investment scenarios.

2. Methods

In spite of annual fluctuations, produced solar power offers several advantages as a measure for deployment of solar power, being independent of technical details and varying definitions of nominal power, and allowing for treating fundamentally different technologies, like PV and CSP (concentrated solar power), together. Based on time-series data [12] for produced solar power for each European country, the realized growth rates are calculated. The calculated rates show that, for the last decade, Europe as a whole and all major individual European “solar” countries demonstrate a clear general declining tendency in the realized growth rate, a characteristic feature for a logistic growth pattern.

Growth processes characterized by resistance free initial evolution towards an upper biological, physical or economic bound are well described by so-called logistic evolution. The governing equation dates back to Verhulst [17] in 1838 and its solution contains an initial exponential growth phase followed by a declining period of growth towards zero. This was recently proposed as an underlying equation describing the production pattern from various energy sources in terms of an instantaneous produced amount of power from a particular energy source since the onset [14]. The differential form of the logistic function can be written as

$$\frac{dP}{dt} = a\left(1 - \frac{P}{P_{max}}\right)P$$

where P is produced solar power, P_{max} is a saturation level, t is time, and a is the initial specific growth rate in produced power. As P increases the realized growth rate, $a\,(1 - P/P_{max})$ is seen to decrease towards zero, leaving $P = P_{max}$. Integration of the logistic differential equation gives

$$P(t) = P_{max}/\left(1 + e^{-a(t-t_p)}\right)$$

where t_p is the time where the growth dP/dt peaks.

Several phenomena may affect the accuracy of the logistic model when applied to growth of solar power. With a sufficiently long time horizon, e.g. the remaining part of the present century, effects of population growth, economic growth and advances in energy effectivization may change the picture significantly. Even disruptive energy technologies may lead to a completely new displacement path of existing energy sources. However, considering the single region Europe, within a timespan of 20–30 years, neither of these potential modifying factors appear to change the model assumption dramatically. For example, the population of Europe is today 739 billion and is projected to be 723 in 2040 [18].

In a first step, the logistic function was fitted to solar power production time-series data [2] for each of the three European countries with highest solar power production (Germany, Italy and Spain) to estimate P_{max}, a and t_p for each country. To compare the development in the three countries the fitted functions were also normalised with respect to GDP, showing very similar saturation levels relative to GDP. Next, the three countries were considered as one region and the sum of production in the three countries were fitted using a GDP-based scaling. Further, the sum of the six European countries with highest solar power production was considered by adding the next three countries as a second region. A crude estimate for the future solar power production in Europe was then obtained by scaling based on the total European GDP.

In the second step, a model, which is based on the logistic growth pattern, and correlates investment and learning curve data to produced solar power a year later, is proposed. The model is validated by fitting to historical solar power production data, using growth parameters extracted by a logistic fit to the global data and learning curve data from literature [17,18] as input, in addition to historical investment time series data. Since the time scale of the expansion of the solar power production is short relative to the lifetime of PV panels and also rather short relative to BOS lifetime (balance of system; converters etc.), these are negligible on a short time scale but must be included on a longer timescale, e.g. in future scenarios [19].

The annual produced power during the year t is expressed as $P_{prod}(t) = c_1(t)\cdot Capacity(t)$ where $Capacity(t)$ is the accumulated installed capacity at time t and $c_1(t)$ is a time dependent proportionality factor. Time-series data for produced power and installed capacity reveal that $c_1(t)$ has historically fluctuated somewhat but has stabilised during the last half a decade (with a slight regional dependence, e.g. a somewhat higher value is seen for Italy than for Germany). The time dependence of c_1 is therefore disregarded.

As a technology matures the unit cost decreases. Technological learning curves track unit cost versus total number of produced units and often follow an exponentially declining curve that approaches some lower limit asymptotically [17,20]. The installed capacity can be written as a sum of investments in a given period (where the n'th unit is produced) divided by the price per unit in that period (Y_n). The latter can be expressed by the Crawford learning curve expression $Y_n = Y_1\cdot n^{-b}$, where Y_1 is the price of the first unit, Y_n is the price of the n'th unit and n is the number of units. The constant b is positive and relates to the learning rate by $-b = \log(learning\ rate)/\log 2$. This gives, expressed as a function of n,

$$P_{prod}(n) = \frac{c_1}{Y_1}\cdot \sum_{n=1}^{N} new\_investment(n)\cdot n^b$$

Based on the observations during the first step, a logistic growth pattern is assumed when establishing the correlation between the unit number n and the time t:

Inserting this in the previous expression for P_{prod} gives

$$P_{prod}(t) = c_2\cdot \sum_{t=1}^{t'} new\_investment(t)\cdot\left(1 + c_4 e^{c_5 t}\right)^{-b}$$

where $new\_investment(t)$ is new investments during the year t. The constant c_5 is $-a$ and c_4 is e^{at_p}, where a and t_p refer to the global development [14], as the learning curve is driven forward globally. (The constant c_2 is $(c_1/Y_1)\cdot c_3^b$ where c_3 is P_{max}). Several estimates of the constant b is available in the literature [17,18].

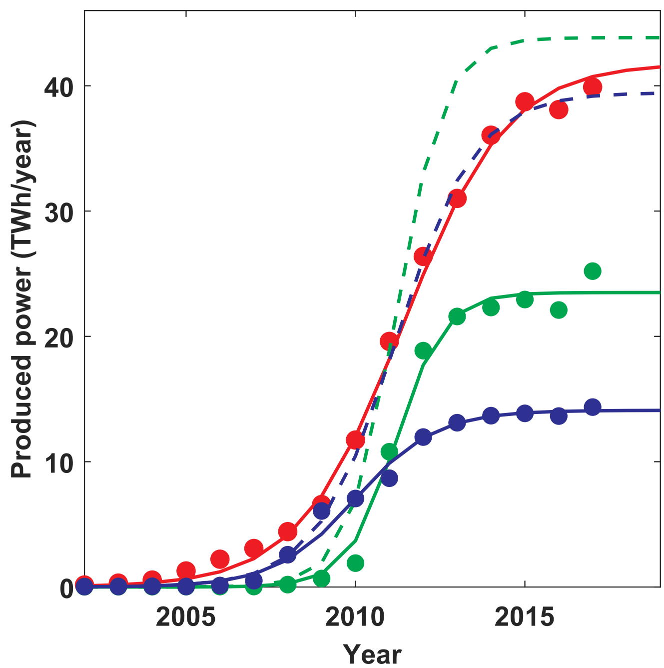

Fig. 1. caption: Solar power production in TWh/y (circles) versus time, and fits of the logistic function to the data (solid lines) for Germany (red), Italy (green) and Spain (blue). The green dashed line is the aforementioned fitting curve for Italy scaled by the ratio between the German and the Italian GDP. The dashed blue line is the fitting curve for Spain scaled by the German/Spanish GDP ratio. Data from Refs. [2,21]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

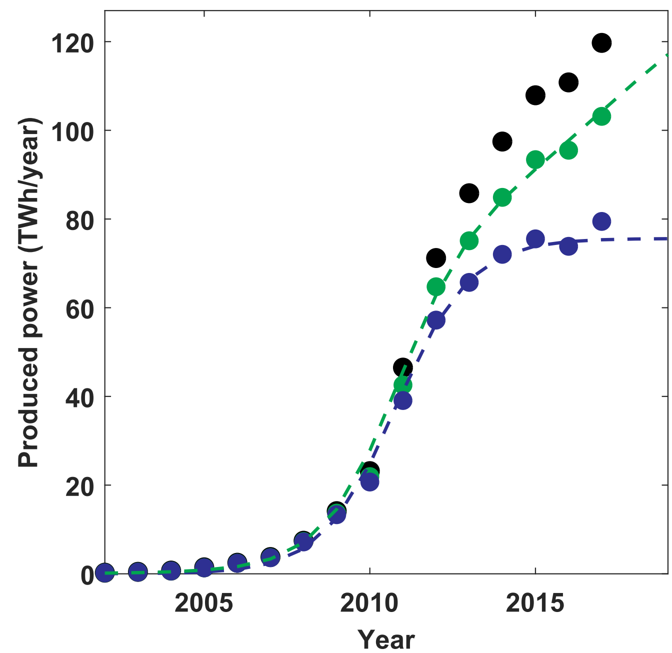

Fig. 2. caption: Solar production in TWh/y (circles) versus time, and fits of the logistic function to the data (solid lines). Blue markers: Region 1 (Germany, Italy and Spain), scaled by the total GDP of the region, with Germany as reference (S = 1.6 TWh/y). Green markers: Sum of region 1 and region 2 (France, UK and Belgium), equally scaled by GDP (S = 1.7 TWh/y). Black dots: Total European solar power production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results

Solar power production time-series data for each of the three dominating European solar power producing nations, Germany, Italy and Spain, are shown in Fig. 1 together with fits of the logistic function to the data for each of the countries. The logistic function is seen to describe the development well. For all three countries the growth at the end of the period is very limited and the development appear to be close to plateauing (i.e. approaching a P_{max}). Estimated fitting parameters (P_{max}, a, t_p) are (41.8 TWh/y, 0.65 y^{-1}, 2011.4 y), (23.5 TWh/y, 1.4 y^{-1}, 2011.2 y) and (14.1 TWh/y, 0.85 y^{-1}, 2010.0 y) for Germany, Italy and Spain, respectively (with standard error of estimates (S) 0.7 TWh/y, 0.7 TWh/y and 0.5 TWh/y, respectively). To compare the development in the three countries, the fitting curves of Italy and Spain are scaled by the size of the economies relative to the German economy, i.e. by the ratio of the German to the Italian GDP and the German to the Spanish GDP, respectively (green and blue dashed lines). With Germany as a benchmark, Italy has a faster development (larger a-value), while Spain has a somewhat slower development (smaller a-value), but the increase in production peaked at approximately the same time (t_p). Evidently, the three countries have close to identical P_{max}/GDP ratios, levelling off at approximately the same level when scaled relative to the GDP of the country.

In Fig. 2, the sum of the three dominating European solar power nations is treated as one region (blue markers), accounting for 40% of the European economy and 66% of the European solar power production. The fit for this region is scaled by the sum of the GDPs of the included countries, with Germany as reference, and fitting parameters are a = 0.9 and t_p = 2010.8. The fit describes the development in the region well, in spite of the national differences.

Next, the sum of the six European countries contributing most to the solar power production (accounting for 75% of the European economy and 85% of the solar power production) is considered (green circles (data) and dashed line (fit)). The model is seen to describe the data quite well. The additional tree countries (France, UK and Belgium) are treated as one region. The logistic function is fitted to the data (scaled by GDP relative to Germany), and then added to the dominating region (Germany, Italy and Spain). The dominating countries in this second region are characterised by a smaller but significantly expanding solar power production. Estimated fitting parameters are a = 0.4 and t_p = 2017.4 corresponding to a slower, and later, development as compared to region 1. Finally, the total European solar power production is indicated (black circles). The rest of Europe account for 14% of the solar power production and 25% of the economy. By simple scaling of the P_{max} values estimated for the region consisting of the three dominating countries with respect to the size of the economies, a crude estimate for the future solar power production in Europe of about 200 TWh a year is obtained. For comparison, the current annual electric power consumption in Europe is well above 3000 TWh [2].

In the next step, the relation between solar power investment and annual produced power is modelled. Fig. 3 displays solar power production data for Europe (blue circles) and Germany (black circles) together with the expected output based on our model. The delay between investment and production is set to 1 year. The only free fitting parameter in the model is the scaling on the y-axis. All other constants entering the model are well defined: a and t_p for the global development of solar power (a = 0.42 and t_p = 2017), an offset set by the production level in the data-set starting year, and the technology learning rate (set to 24% cost decrease for each doubling of experience for the system [18]. Since the BOS learning rate is significantly less than the PV module learning rate and accounts for about half of the system cost, a total learning rate of 24% for the system is an optimistic estimate. Investment data (nominal value) from Ref. [22] are inflation corrected to 2017 US$ [23]. The model describes the relation between investments and produced solar power very well for the historical data, allowing us to model future solar power production based on different investment scenarios. Due to the rather short time scale of the historical

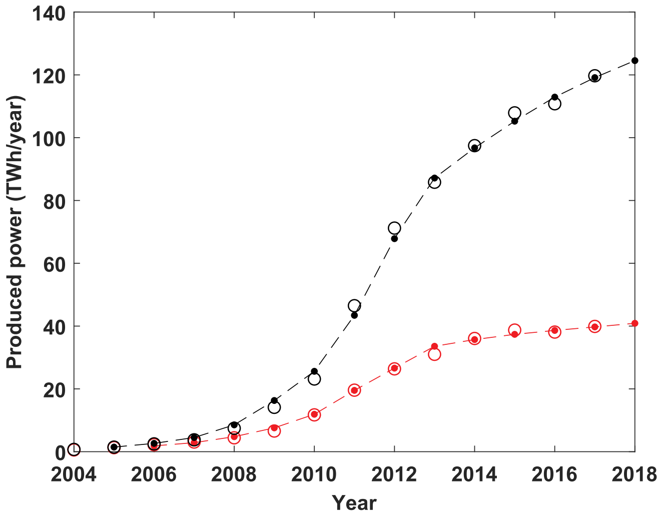

Fig. 3. caption: Historical data for solar power production in TWh/y (circles) versus time, and model output (dots with dashed lines), for Europe (black, S = 1.9 TWh/y) and Germany (red, S = 0.9 TWh/y). Model input is investment data for Europe and Germany [22], parameters a and $t_p$for global solar power deployment [14 (updated data)] and learning rate for PV systems [18]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

development relative to the expected lifetime of the installed capacity and minimal performance decrease over time [19], decommissioning has no significance with respect to the historic data. However, on longer timescales, when modelling future production, decommissioning becomes important, in particular for low levels of investment. For simplicity, a total system lifetime of 30 years is included.

Future European solar power production was estimated for a range of different investment scenarios (Fig. 4). Around 2040 the capacity that was build out during the recent years reaches the expected lifetime, and for the scenarios with modest future investments this results in a

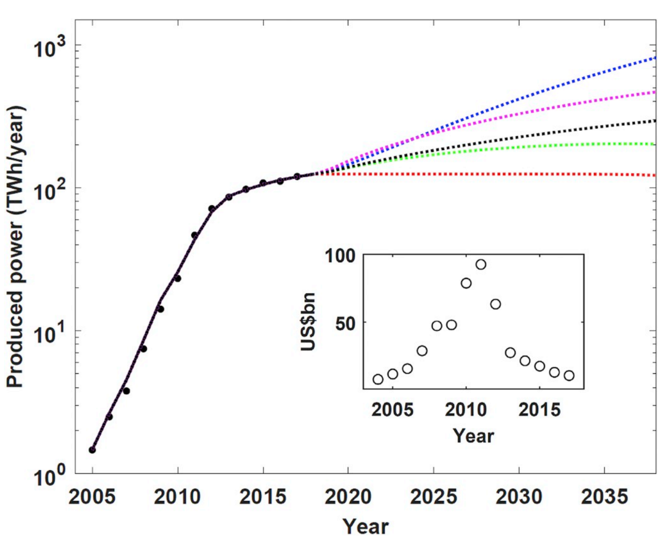

Fig. 4. caption: Future European solar power production estimated for different future investment scenarios: Black: Continued investment at the current level. Magenta: constant investment at the double of the current level. Blue: Annual investment increase of 3 US$bn (2017)). Green: Linear investment decrease from current level to zero over 20 years. Red: No future investments. The development in the rest of the world is assumed to follow a logistic path estimated from the current global development and, on top of this, follow the European development scenarios. The insert shows the historical annual investments in Europe (nominal value (2017)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dip in the estimated production, as the investments in those scenarios are smaller than what the replacement of decommissioned capacity requires. The possibility for such future pulsing production behavior arising from fast energy system transitions has been described for wind [24]. In our model the effect is enhanced by the simplified treatment of lifetime. In reality, the replacement costs will be distributed over a larger timespan due to different lifetimes of PV modules and the various BOS elements, reducing the production over time, rather than giving a significant dip in production.

4. Discussion

The early signs of restrictions of growth in the fast expanding deployment of solar power emerging a few years ago has become clear indications that the growth of solar power is plateauing for all the leading European solar power nations, at a level corresponding to a common fraction of their GDP. For Germany the energy supply is now heavily based on imported fluid fossil fuels and coal [25]. The German *Energiewende* started in the early 1990's and includes targets for as far as 2050, including reduction of carbon footprint, abandoning of nuclear power (before 2022), and improvement of energy security [26]. Renewables, in particularly wind and solar, are foreseen to be the backbone of the future German energy regime. In this program, feed-in tariffs (FIT) has been a powerful political tool to enhance the deployment of solar power, and regulations of the FIT appear to have a strong impact on new investments. Italy and Spain have very limited traditional primary energy resources, and are strongly dependent on net energy import. However, both countries have very good conditions for solar PV, and regions in the most southern parts of the countries have conditions suitable for CSP [27]. In Italy and Spain solar power deployment has also been driven by feed-in tariff policies (FIT), with different weight on PV and CSP. Spain has a significant share of CSP (deviating from the other European countries), while Italy has mainly PV installations. The FITs attract also foreign investors. With increasing solar power production, the costs of the FIT schemes rises. The negative regulations of the national feed in tariffs to a lower level that have been introduced gradually during the last several years for all three countries are seen to coincide with the very strong reductions in new investments [28,29].

This strong connection between plateauing of solar power production growth and down-regulations of FIT schemes with rising scheme cost etc, correlates well with our observation that the growth of solar power production for a country is limited to a certain share of the GDP. The evolution of the Italian *Conto Energia* clearly reflects that the decrease in FIT is related to reaching an upper limit of allocation of economic resources to the enhancement of the deployment of solar power [30,31], - *Conto Energia* was set to end when the annual cost reached a certain limit (6.7 million euro) rather than reaching a certain technological maturity level.

Kramer and Haigh proposed, based on historical data, some "fundamental laws" of new energy technology deployment describing a few phases of growth [32]. When a new technology has become "available" it will first undergo a few decades of exponential growth to reach "materiality". In the next phase it will enter a linear growth pattern which brings it to the final market share of the technology. "Available" and "material" were quantified as 1000 TJ/y and 1% of global TPES (currently corresponding to about 5 EJ/y). Solar power passed the defined level for availability around 1990 and is (globally) still below the "material" level.

From Fig. 2, displaying the annual solar power production in Europe versus time, it appears that the deployment of solar power in the full European region shows similar features, with an exponential growth period followed by an apparently linear period. It is noteworthy that the sum of a number of logistic growth patterns, with different offsets in time (e.g. a number of regions each undergoing a logistic growth pattern at different point in times) can generate such a pattern, starting exponentially, and transferring into a (prolonged) near-linear phase as some regions saturate while new regions start their development, and finally saturating when all regions are saturated. E.g. the green curve in Fig. 2 is the sum of logistic descriptions of our defined regions 1 (Germany, Spain and Italy) and 2 (France, UK and Belgium).

The crude estimate of future European solar power production of about 200 TWh/y based on simple scaling of economies, aligns well with the maximum of the green curve in Fig. 4, i.e. the scenario where new investments are decreasing linearly to zero over 20 years. Considering the declining current trend of new investments in Europe, this is not an unrealistic scenario. In the World Energy Scenarios suggested by World Energy Council [11], two different scenarios are rolled out, with focus on energy equity (scenario 1) and environmental sustainability (scenario 2), respectively. The two scenarios foresee an annual global solar-based electricity generation in the years 2030, 2040, and 2050 of 462 TWh/y, 732 TWh/y, and 2979 TWh/y in scenario 1 and 2054 TWh/y, 5752 TWh/y, and 7741 TWh/y in scenario 2, respectively. The difference between the scenarios reflects that the implementation of solar PV is in general foreseen to be strongly dependent on governmental intervention. Europe is one of the regions that is foreseen to be very sensitive to the intervention level and European generations in the years 2030, 2040, and 2050 are forecasted to be 118 TWh/y, 85 TWh/y, and 82 TWh/y in scenario 1 and 306 TWh/y, 468 TWh/y, and 554 TWh/y in scenario 2, respectively. Currently, with about 120 TWh/y in 2017, the European development is well within the range of the two scenarios.

Crudely estimating the future global solar power production based on our model and the size of the global economy relative to the European, gives about 1000 TWh/y. In 2017 the global production was about 443 TWh/y. Taking technological learning and the resulting technology price reductions into account gives a future global production in the 1200 TWh/y range. This is significantly higher than the forecasted solar PV production in 2040 in the World Energy Scenario 1, but far below the 2030 level in scenario 2. In the IEA Tracking of Clean Energy Progress (2018) a global level of 2732 TWh/y is forecasted in 2030, passing the 1200 TWh/y level around 2023.

Clearly, a near future global deployment that is much stronger than the current European trend suggests, is necessary if solar PV is to fulfil the significant role in the requested energy transition it is foreseen to play. It is argued that solar PV (in combination with batteries) has become a disruptive technology, which is now competitive or close to competitive in regions with favourable geological conditions [8]. To improve competitiveness of the technology in Europe the European Union minimum import price measures on PV cells and modules from China introduced in 2013 was ended in September 2018 to reach a price level closer to the world-market level. It remains to see if this has an effect in Europe. Still, the modest levels of investment in solar PV in Europe are also argued to be a result of an inherent mismatch between the solar PV technology and the European geological conditions, giving highest energy demand during dark and cold winters [12]. In this view, China is expected to dominate the global solar PV power production. Investments in solar PV in China is growing again after a dip in 2016, showing a positive trend [22]. However, China has not yet reached the ratio of PV power production to GDP seen in Germany, Italy and Spain. Grubler et al. found in their studies of innovation diffusion patterns that deployment of a technology tends to be slower, but more pervasive, in the technology core area (the area where the technology is first deployed) than in the subsequent deployment in rim and periphery areas, where the growth tend to be faster, but also to saturate at lower levels [33,34]. Following this framework, the faster growth in China does not necessarily forecast a higher saturation level in this region.

5. Conclusion

In this work the development of solar power in Europe has been analysed. For the three leading countries, producing two thirds of the European solar power, a logistic growth pattern with national saturation levels proportional to the GDP of the country was found. The sum of the next three countries were found to be well described by a logistic growth path with inflection point later in time, so the sum of the logistic paths for the two regions reproduce the power production in these regions (covering 85% of the European production) very well. It was noticed that the total growth path that arises from the sum of these time-shifted logistic functions conforms with the energy-technology deployment patterns suggested by Kramer et al. with an initial exponential growth phase followed by a linear growth phase [32]. Based on the observed ratio of saturation level to GDP, and by scaling of economies, crude estimates of European and global saturation levels of 200 TWh/y and 1200 TWh/y were found, where estimated technology price reductions due to technological learning is taken into account. Clearly, these deployment levels do not induce any strong price reduction in the near future.

Finally,a model for the relation between solar investments and produced solar power, was proposed, combining investment data with learning rate and the indicated logistic growth in time. The model was seen to reproduce historical data very well, and allowedfor estimating future solar power production levels for a given future investment scenario. The crude estimate of future European solar power production of about 200 TWh/y based on simple scaling of economies, aligns well with the level obtained in the scenario where new investments are decreasing linearly from the current level to zero over 20 years. With the current European investment trends, the results indicate that solar power will contribute a rather limited fraction in the 2030–2040 energy mix without a drastic increase of investments.

In the IPCC special report Global Warming of 1.5 °C (2018) scenarios which stay on a 1.5° target pathway with limited temperature overshoot on the way show median values for the role of solar energy of about 14 EJ/y (~4000 TWh/y) in 2030 and 56 EJ/y (~16000 TWh/y) in 2050 of which solar power is to contribute about 9 EJ/y (~2500 TWh/y) in 2030 and 36 EJ/y (~10000 TWh/y) in 2050 [6]. For solar power, the levels in the IPCC report are somewhat higher than the levels in the environmental sustainability focussed scenario 2 of Scenarios by World Energy Council, and the 2030 IPCC value is approximately a factor of 2 higher than our crude global estimate (based on the assumption that the ratio of saturation level to GDP that was found in Europe is globally applicable). Solar heat technologies have seen a clear decreasing growth rate during the last half a decade and will at best, if entering a linear growth path rather than plateauing, reach a level at the order of 600 TWh/y by 2030. Clearly, more aggressive investments and incentives schemes are needed for solar energy to fill out the foreseen role. Further, the time aspect is demanding as it requires growth rates over time that are very high compared to historical experience [35].

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