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Renewable Resources of Energy for Electricity Generation – Development Trends and Necessities Within the Overall Energy System

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Abstract

Global primary energy demand will most likely increase in the coming decades as a result of a growing world population and generally increasing prosperity. Historically, increasing energy demand has usually been associated with increases in greenhouse gas (GHG) emissions as the additional energy needs are met by the utilization of fossil fuels. However, in order to meet the efforts to curb climate change, both existing and emerging energy demands (and therefore energy supply systems) must be sustainably covered using renewable energy resources. In this context, two different development scenarios are presented in this paper: First, based on historical developments in recent years, the given expansion pathway of renewable energies is extrapolated until the year 2050 (bottom-up perspective). However, as this expansion does not meet the climate goals set to meet the 1.5 °C target, additionally a development pathway, which meets the GHG reduction goals in 2050 is developed (top-down perspective). Given the very high levels of energy delivered from (fluctuating) renewable energy sources needed for such a sustainable development path, comprehensive decarbonization (concerning fossil carbon) requires a much better interconnection of the different energy sectors (electricity, heat, mobility) compared to today; some of these necessities are also presented because they influence the further development of the energy system and thus the role of renewables considerably. All over, the paper shows that the already ongoing efforts to achieve the 1.5 °C target must be intensified dramatically; the already significant developments related to the installation of new systems to use renewable sources of energy are not enough to achieve the defined targets.

Keywords: Renewable energies, primary energy demand, greenhouse gas emissions, system-transformation;

1. Introduction

Global primary energy demand amounted to roughly 547 EJ (152 PWh) in 2017 ([1, 2] and own calculations). This energy demand is expected to grow significantly in the coming decades summing up to an overall energy consumption of roughly 670 EJ/a (187 PWh/a) [3] until the year 2040. Around 88 % of this demand is covered by using fossil fuel energy (namely coal, natural gas and crude oil), whose energy-related use leads to a release of additional (anthropogenic) carbon dioxide as well as other greenhouse gases (GHG), which together in turn affect global climate [3]. Especially the combustion of such fossil fuels in a variety of consumption sectors constitutes the main contribution to manmade greenhouse gas emissions and therefore the so-called anthropogenic greenhouse effect. Thus, Fig. 1 shows the specific GHG emissions in relation to the specific energy demand of different countries related to the year 2014. A clear interrelationship between high-income and high GHG emissions is apparent. Higher income is related to an increased consumption of energy and thus (based on current energy supply structures) higher GHG emissions. To address the increasing riskiness of global climate change, the overarching goal should be to drastically reduce such emissions. Stopping or hindering global development towards increasing energy use (due to prosperity reasons) cannot be a widely acceptable solution. Therefore – in order to limit global GHG-emissions – the establishment of global low-GHG emission or GHG emission-free energy supply structures should be the overarching goal of energy and environmental politics within the various governments throughout the world. Consequently, energy supply systems in countries with already high or even very high GHG emissions must be transformed in a way, that a high energy demand can increasingly be met without releasing (significant amounts of) GHG emissions (dark grey arrow in Fig. 1). Likewise, countries with low GHG-emissions – and this usually means so far low-income countries (light grey circles) – must be able to increase the amount of supplied energy – and thus welfare and standard of living – while also slightly reducing (or at least without increasing) GHG emissions (light grey arrow).

To achieve such a development goal contributing towards a more sustainable development, energy supply

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must become increasingly less dependent on fossil carbon-based energy carriers (i.e. coal, crude oil, natural gas). The only way to do this in a sustainable manner (without producing nuclear waste) and based on acceptable costs lies in a strongly expanded use of renewable energies – and this means for the time being a clearly increased utilization of wind energy and solar radiation.

Energy conversion technologies and systems using renewable energies mostly provide electrical energy. Due to the almost arbitrarily realizable transformation of electricity to other forms of energy (e.g. heat, mechanical energy), electrical energy from renewables can be used to substitute carbon-based fossil fuels in basically all sectors of the overall energy system, enabling (on the longer term) a basically climate-neutral energy supply. Nevertheless, such fundamental transformations will imply additional changes within the overall energy system. An appropriate and improved coupling of different energy sectors (e.g., electricity sector, heat sector, mobility sector) is needed to integrate lager shares of electricity in formerly un-electrified energy sectors (e.g., mobility). Also, some additional applications are needed to sustain a secure system operation especially of the electricity supply system even with high shares of wind and solar power production characterized by strong fluctuations and clear regional supply differences.

As a result of the Kyoto process, the need for the significant reduction of GHG emissions has been recognized by more and more countries (90 % of the warmest years since the start of temperature records in 1880 occurred within the past decade [6], which is becoming more and more evident globally). The consequences of this slow process of cognition have been a multitude of multilateral and international agreements aiming to reduce GHG emissions in the coming years. Even though global GHG emissions continue to rise significantly due to over-proportional rising welfare, such agreements – even if certain states have temporarily stepped out for primarily domestic political reasons – support a rethinking process within the global energy industry. Thus, on a global scale, in recent years, most capacity additions within the electricity sector have been in systems using renewable energies – and here in particular photovoltaic and wind powered plants. For example, in 2017 157 GW of renewable power production capacity was installed, by far exceeding the 70 GW for conventional power plants [7].

Against this background, first the most important drivers for the development of global energy demand are elucidated. Then, based on the current energy supply system structure, the global energy demand for the year 2050 is estimated (the forecast for 2040 from [3] is extrapolated till 2050 by assuming an overall growth rate that is 50 % of the growth rate between today and 2040). This global energy demand implicitly states the population's demand for usable energy (considering conversion efficiencies). Based on this demand, two development pathways until the year 2050 are shown – on the one hand based on currently visible and already ongoing worldwide developments especially for renewable energies (bottom-up) and on the other hand based on the necessary reductions of GHG emissions to achieve the so called 1.5 °C-goal (top-down), assuming the same demand for usable energy in all cases. Finally, some conclusions are drawn and discussed. The approach is schematically depicted in Fig. 2.

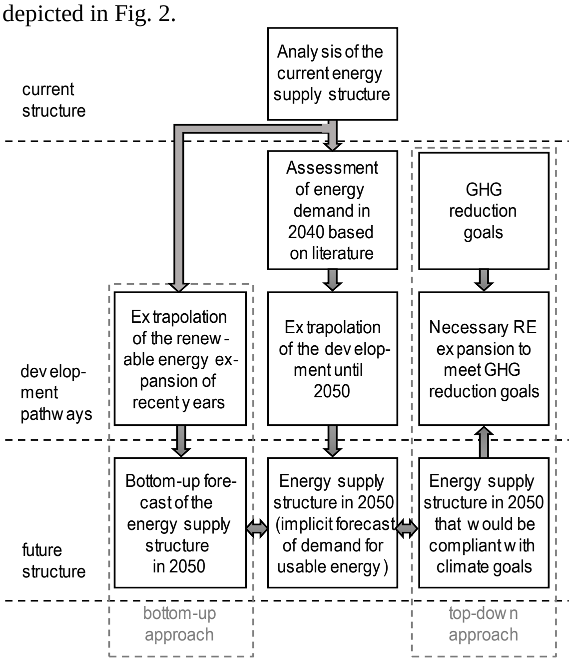

Figure 2. Schematic illustration of the approach

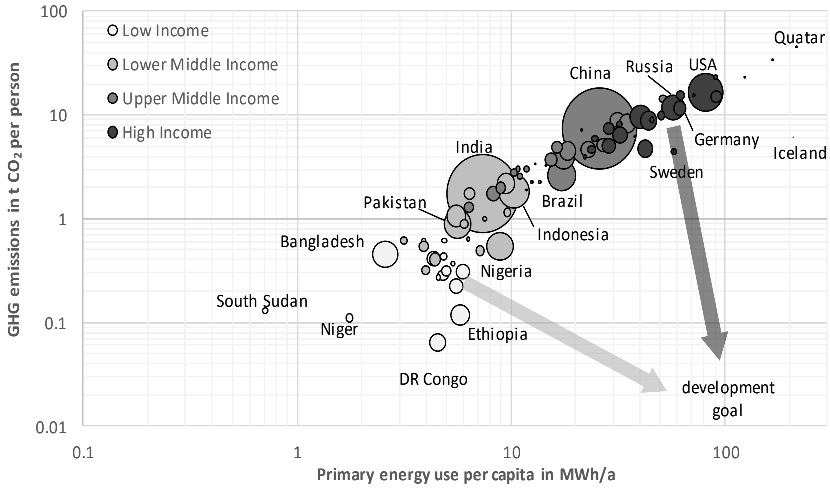

Figure 1. Overview of GHG emissions and energy consumption in 2014 for different countries (size of bubbles represents the population of each country) [4, 5]

There are multiple different forecasts for the development of the global energy supply for the year 2040 / 2050 (e.g. [3, 8–10]). Additionally, there are different elaborations on development pathways for reaching an energy supply structure that is compliant with climate goals (e.g. [11, 12]). The following elaboration serves as a connection between both types of forecasts by explicitly pointing out the gap between the system development that is currently taking place and one that would be needed in order to evade the threat of a global climate crisis.

2. Global Trends and key drivers

The further development of the energy demand and thus of the global energy supply system are fundamentally determined and driven by only very few main key drivers. These globally visible trends have significant and profound implications on the worldwide development of the various energy systems; they are described hereinafter.

2.1. Growing energy demand

Certain ongoing and irreversible trends inevitably lead to a strong increase in global energy demand. The main driving developments (world population and prosperity) are discussed below.

World population. The current world population of around 7.5 billion people demands on average around 20.1 MWh/a or 72.5 GJ/a of primary energy per person ([13, 14]). By the year 2100, about 10 to 11 billion people will populate our planet (Fig. 3) [13]. Due to the still increasing life expectancy in connection with birth rates, which are decreasing but still amount to roughly 2.5 babies per woman on average [15], there will be a significant increase in world population in the coming decades. Especially in highly populated countries such as China or India, the sharply increasing life expectancy in recent decades is particularly apparent. Under the assumption, that the global energy demand (without consideration of the individual energy demand) is at least proportional to the population, this alone will inevitably lead to a (strong) increase in energy demand in the future.

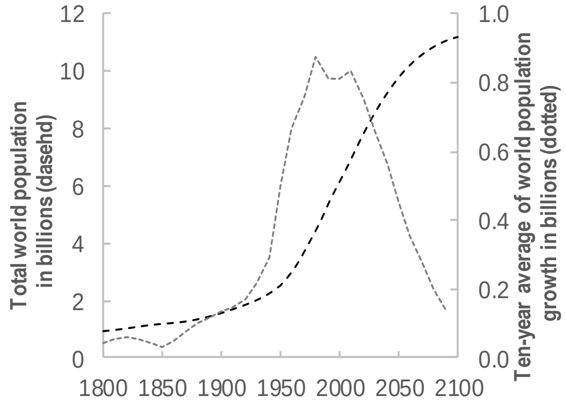

Figure 3. Development of the world population (dashed line: left axis; dotted line; right axis) [13]

Prosperity. In addition to population growth, the average prosperity of the overall society respectively of each average citizen is increasing on a global scale. In recent decades, there has been a clear trend towards significantly higher incomes of larger and larger population groups in an increasing number of countries with a former low-income level; i.e., the so-called middle class is growing very fast worldwide in absolute and relative terms. Consequently, growing prosperity leads to an over-proportionally rising energy demand (Fig. 4). The average global income increased by a factor of 2.5 between 1965 and 2014 with an even higher growth in energy consumption by a factor of 3.5. The decade with the highest growth was from 2000 to 2010, where emerging countries like China entered a phase of rapid economic development paired with a significant growth in energy demand. The growing incomes and the associated additional financial opportunities within more and more emerging countries lead to more and new needs, typically associated with (increasing) energy consumption (e.g., mobility, consumption of high-quality and energy-intensive food and consumer goods, air conditioning or communication).

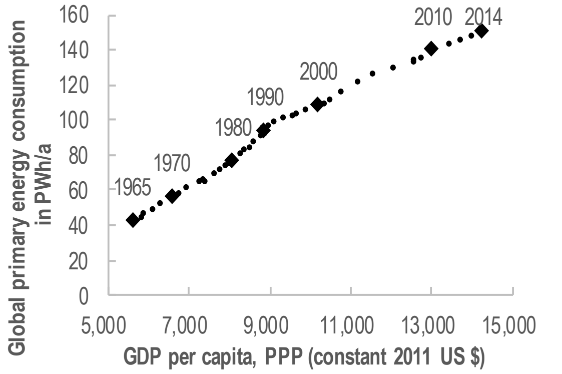

Figure 4. Yearly global average of energy consumption in relation to the yearly average global income (purchasing power parity, PPP) [5, 16]

In the medium to longer term, it is likely that the rise in energy demand due to increasing prosperity in many developing and emerging countries will approach the level of the industrialized OECD countries characterized today by a significantly higher demand of energy (Fig. 1). Even if the energy efficiency efforts should be more successful in the future than in the past in the industrialized countries (and in many developing and emerging countries), this development will most likely lead to a significant increase in global energy demand in the future.

The historical increase of global energy demand caused a steady increase in global GHG emissions over the past decades and centuries. As shown in Fig. 5, there is a strong correlation between increasing energy consumption and global GHG emissions due to the strong utilization of mostly carbon-based fossil fuels. This is due the fact that apart from hydropower (and nuclear power based on public subsidies) typically the use of fossil fuels has been the economically most promising (and most easily realizable) option for energy provision in the last century. For this reason, existing energy systems are largely based on fossil fuels, since these were (and are) available in large quantities and at low cost.

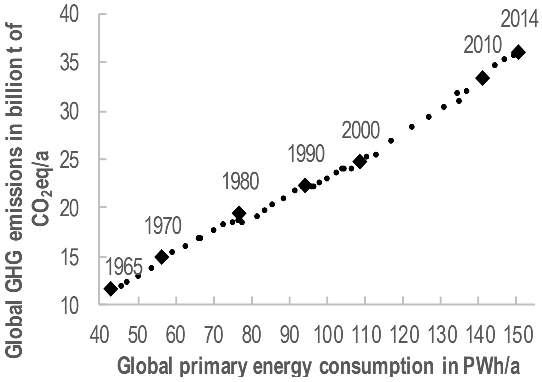

Figure 5. Yearly global average of GHG emissions in relation to energy consumption [15, 17]

2.2. Environmentally friendly energy

The strong economic growth in recent years and the corresponding sharp rise in energy consumption (due to rising population as well as growing prosperity) have led to massive consequences for the global energy supply system. Most of the power plants, which were built in the past, are based on the conversion of fossil fuels and therefore are responsible for emitting carbon dioxide and other substances like Sulphur dioxide and nitrogen oxide influencing the local as well as the global environment. Furthermore, the exploration, extraction and use of fossil fuels as well as the use of nuclear power is strongly linked with the risk of significant anthropogenic environmental catastrophes with a global impact (e.g., the Chernobyl and Fukushima Daiichi nuclear disaster, the Deepwater Horizon explosion and the resulting oil spill in the Gulf of Mexico or the disaster of the crude oil super tanker Exxon Valdez). Such significant impacts on local and global environment resulting in the loss of single species and even complete operating eco systems lead to a growing awareness related to environmental aspects within people of various countries on this globe. Additionally, an increasing sensitivity for a (more) sustainable development emerges globally from such environmental disasters, which are presented by media globally.

Consequently, research and technological development of the recent decades has focused primarily on a more efficient use of wind and solar power, as these represent options to address the described challenges and can enable an emission-free and sustainable provision of electricity respectively energy. Additionally, they can contribute to a rural electricity supply, which does only exist rudimentary (or not at all) in some developing and emerging countries. These technological trends towards more efficient and less expensive technologies for energy supply from renewable energy resources characterized by a modular installation have contributed significantly to the recent unexpected expansion of renewable energies on a global scale. And this development will continue in the years to come due to the reasons outlined above.

2.3. Interim conclusion

As explained in Chapter 2.1, global energy demand will most likely continue to rise sharply. In order to secure a climate and environmentally friendly energy provision, this mandatory rising energy demand has to be met mostly based on renewable energies. This necessity demands for the two different transformation pathways for energy systems in countries around the globe outlined below.

- Already developed energy systems, which predominantly exist in high-income and highly industrializes countries, have to be transformed by replacing conventional (fossil) energy provision with an increasing amount of renewable power plants (dark grey arrow in Fig. 1). These countries would have to follow a path of growth-neutral (or growth-unaffected) decarbonization concerning the carbon of fossil origin.
- Emerging energy supply systems, which predominantly exist in lower income countries (i.e., developing and emerging countries), will undoubtedly be characterized by growing energy systems coupled with growing prosperity. Nevertheless, these countries would have to manage a path of (fossil) carbon-neutral growth to allow compliance with global climate goals (light grey arrow in Fig. 1).

Hybrid paths (combinations of both paths) are also possible for countries in the medium income region (i.e., emerging and partly industrialized countries). Nonetheless, all these transformation paths are connected to a massive expansion of the utilization of renewable energies globally. Therefore, the following chapters analyze global expansion trends for renewable energies. Additionally, based on a bottom-up perspective, global shares of renewable energies are forecasted based on current development trends. Beside this, from a top-down perspective, based on the globally agreed GHG-emission limitations the necessary development of a use of renewable energies to be compliant with climate goals in the year 2050 is assessed.

3. Global energy supply – status and developments

Analyzing the current global energy supply system, a clear dominance of fossil fuels in terms of total primary energy supply is apparent (Fig. 6). In 2016, fossil fuels accounted for roughly 88 % of the world's primary energy supply (hydro and nuclear are treated directly as electrical energy); that means coal (hard coal and lignite), crude oil and natural gas are currently the most commonly used energy carriers worldwide. Renewable energies play only a minor role with a total contribution of roughly 9.1 % ([1, 2] and own calculation). The share of primary energy used for the provision of electricity is roughly 30 % globally (accounting for transformation losses for fossil fuels); i.e., about 70 % of worlds primary energy demand is used for heating, mobility and other purposes (e.g., used as a raw material for the chemical industry) [1]. The largest share of electricity generation is provided based on coal-fired power plants; crude oil respectively its derivate are mostly used for mobility and natural gas is flexibly divided between different sectors.

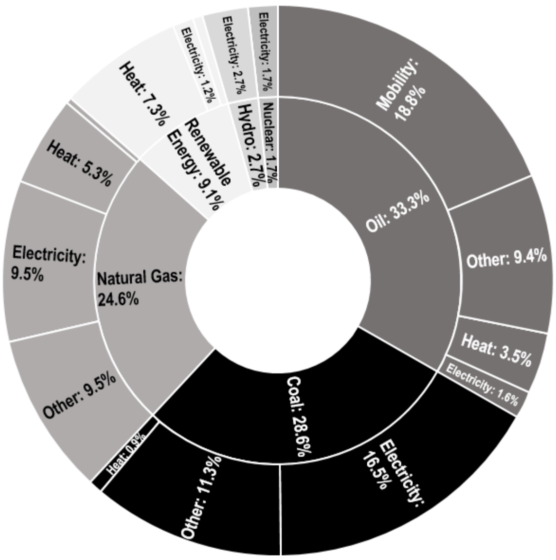

Figure 6. Share of the total global primary energy consumption (151 PWh) by fuel in 2016 and sector of use [1, 2].

The shares of the energy sources by sector indicate, which parts of energy supply will be easily substituted by electricity from power plants based on the use of renewable sources of energy (e.g. electricity from all other sources) and which parts ask for additional technology. For example, roughly 20 % of global primary energy demand is attributable to mobility (almost completely met using oil). To substitute this primary energy component through renewable energies (which predominantly provide electrical energy), formerly separated energy sectors existing within the overall energy system must be increasingly interconnected (e.g. meeting mobility demand through e-mobility). Such sector coupling normally requires further integration technologies like new charging infrastructures or battery storage in cars.

Fig. 7 shows the development of global primary energy demand until the year 2050 (based on [17] and own calculations). Following this analysis, the total energy demand will rise considerably (driven by the factors described above). Most likely, this clearly increasing energy demand will be covered by electricity to a much higher share compared to today (this development tendency is already apparent).

The shown demand for 2050 is treated as a basis for the global population's demand for usable energy (considering conversion efficiencies), that must be met by the energy supply system for each development pathway. While electricity from renewable energies (as well as from nuclear power) is directly treated as primary energy in this paper, this increasing share of electricity consumption within the overall global energy system reduces overall conversion losses from primary to usable energy which in turn reduces overall primary energy demand. This is a reason why the prospected energy demand does not increase as strong as expected based on the currently visible developments also discussed in chapter 2. Another reason for this rather moderate increase of energy demand is the fact that improvements of energy efficiency measures are implied to become more effective. To be compliant with climate goals, overall GHG emissions must be reduced drastically. In 2017 they amounted to roughly 36 Gt/a [18], which would have to be reduced as close to zero as possible until 2050.

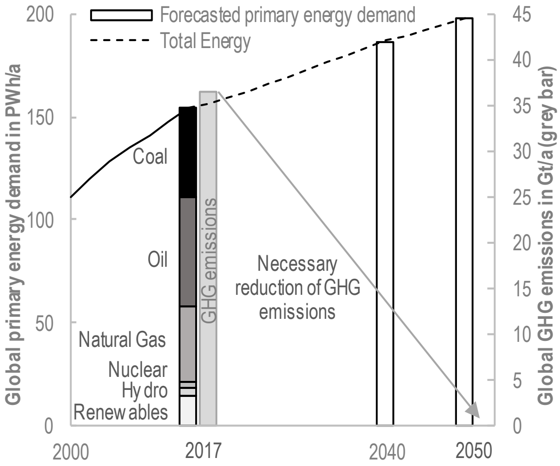

Figure 7. Development of primary energy demand until 2050 (based on [17] and own calculations) and necessary reductions of GHG emissions

4. Energy from renewables – status and developments

The described drivers (chapter 2.1 and 2.2) will significantly impact the expansion of renewable power production capacities in the coming decades. In addition, there will most likely be some further technological development as it has been realized in the past. Hereinafter, a bottom-up discussion about the advancement of the most relevant options to use renewable sources of energy for electricity provision is presented from today's point of view. Already emerging tendencies are carried on and developed for the following years under the assumption that the expansion of renewable power plants is mostly based on economic and not predominantly on environmental and/or political respectively legally controlled decisions.

4.1. Photovoltaics

Economic and technological development of photovoltaics (concerning solar cells / modules as well as system components) has been unexpectedly rapid in the past decade. Photovoltaics systems are becoming increasingly durable, robust, efficient and especially cheaper. Additionally, it is most likely that this development will continue in the coming years.

By the end of 2017, around 385 GW of photovoltaic capacity had been installed worldwide, with more than 90 GW newly added in 2017 alone. For the past four years, photovoltaic has been the world's fastest-growing technology for power generation from renewable energies with a potential electricity generation of around 435 to 635 TWh in 2017 [19, 20]. This development is shown in Fig. 8.

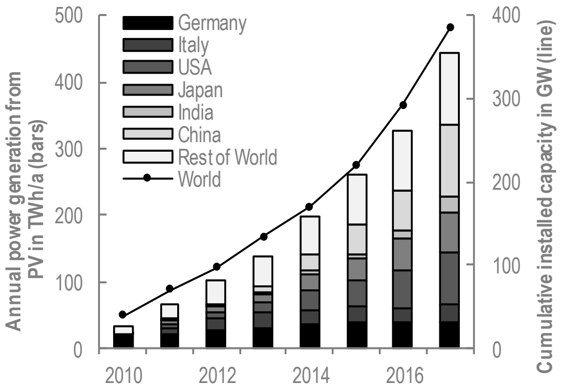

Figure 8. Annual power generation and cumulative installed photovoltaic capacity worldwide [17, 19]

This overall development has led to a significant global expansion of the installed photovoltaic capacity as well as power production. Additionally, the globally available potential for further photovoltaic development does not seem to be limited for the years to come; i.e., a further fast development of a photovoltaic electricity generation is expected with a high probability.

Under consideration of the known development goals for the main active markets till 2022 (adding remaining nations with average past growth rates) a global installed capacity of at least 835 GW is likely. Electricity production would than amount to 900 till 1,300 TWh/a. With an ongoing decline of cost and thus accelerated expansion, installed capacities would rise to roughly 1,600 GW until the year 2030 with a power production between 1,700 and 2,800 TWh/a (the upper value assumes that a rise in global mean capacity factor takes place). In 2050 an installed capacity of over 8,000 GW is quite likely, which would provide roughly 10,800 to 14,800 TWh/a. From today’s perspective, it is rather probable, that photovoltaic will become the most important power generation technology based on renewable energies in the future [20].

4.2. Wind Energy

Strong cost reduction for wind power plants has driven a global increase of on- and offshore wind power production in the past years paired with increasingly more robust and reliable wind mills. This is true for onshore application anyway and in recent years more and more valid also for offshore wind parks.

By the end of 2017, around 539 GW of installed capacity of wind turbines were operating worldwide (new capacity in 2017 of around 52 GW) [21], which generated around 1,060 TWh of electricity (Fig. 9). The majority is installed onshore, only about 4 % are installed offshore [20].

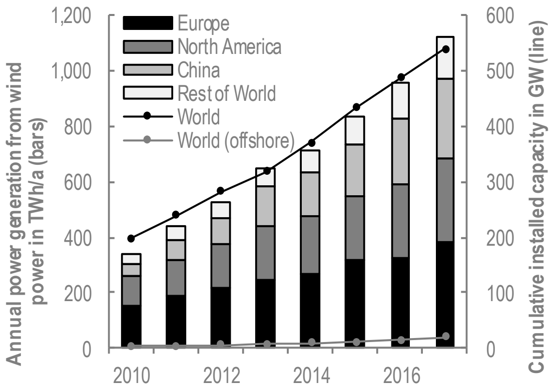

Figure 9. Annual power generation and cumulative installed wind turbines capacity worldwide [17, 20]

Globally there are still many undeveloped sites (onshore as well as offshore) with high average wind speeds, allowing the assumption, that wind power will be further developed in der future. This development goes hand in hand with reduced specific prices. On a global scale there is no real limitation to wind power expansion from today’s point of view. Existing national expansion goals add up to around 50 to 60 GW of additional capacity in the next years mostly in Asia, followed by Europe and North America. Until the year 2022, globally installed capacity could potentially amount to 840 GW, providing roughly 1,700 TWh/a of electricity. Offshore wind will only make up a small share of this (about 50 GW). Under the assumption of a continuously progressive expansion, the worldwide installed capacity will amount to 1,400 GW (electricity provision of 3,000 TWh/a) in 2030. Until the year 2050 this capacity can amount to roughly 5,000 GW – implying an ongoing stable expansion. The power production will than sum up to 10,000 to 12,500 TWh/a. In the long run, wind power together with photovoltaic will most likely show the largest market shares of renewable energies [20].

4.3. Hydro power

Hydroelectric power plants are an established technology. Thus, there has not been any major technological development in the recent years and is not foreseeable that there will be any major improvement in the future (the overall efficiency lies between 80 and 90 % and is therefore already quite high). Main disadvantages of hydro power are its dependency on suitable locations and high specific investments. Many suitable locations are already exploited; therefore, the focus will increasingly lie on small hydroelectric power stations – and even there, the potential is foreseeably limited.

In 2017, approximately 1,267 GW of electrical power was installed in hydropower plants (including an addition of 22 GW in 2017), including approximately 153 GW of capacity installed in pumped storage power plants. In total, about 4,185 TWh of electricity were generated in 2017 by hydro power (Fig. 10).

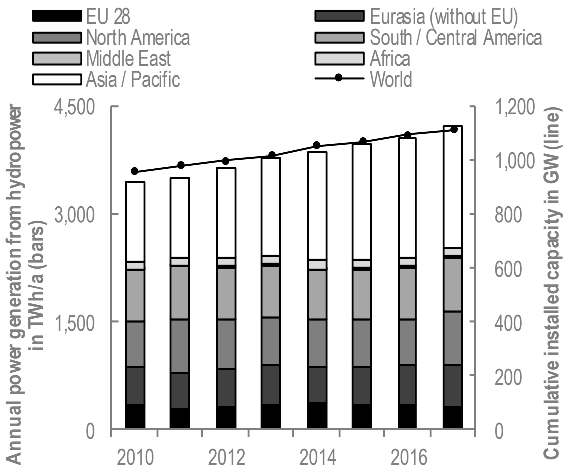

Figure 10. Annual power generation and cumulative installed hydro power capacity worldwide [20]

Nonetheless, multiple hydro power plants are currently planned or constructed, which will lead to an increase of the overall installed capacity in the following years, resulting in a global installed capacity of around 1,400 GW providing roughly 4,600 TWh/a of electricity in 2022. By the year 2030 this capacity will potentially increase to between 1,500 to 1,600 GW (roughly 5,000 TWh/a) [20] and until 2050 global installed hydroelectric power capacity might amount to 2,200 GW with an electricity production of roughly 7,300 TWh/a. The high cost of exploitation of further, more inaccessible sites will be the main obstruction for a stronger advancement of hydro power.

4.4. Biomass

Another renewable energy option is the utilization of biomass. Nowadays, biomass constitutes the largest renewable energy source, mainly due to the use of biomass for cooking and heating in less developed energy systems as well as in industrialized countries especially in the country side. Additionally, modern biomass utilization has increased globally for heat and electricity production in the last decades, as a result of improved and more reliable conversion technologies. An increased use of organic waste materials (e.g. organic waste fraction, organic waste from the food processing industry) adds up to this development. The sustainably usable amount of biomass will nevertheless be a limiting factor for biomass related energy provision.

At the end of 2017, around 112 GW of power plants using solid biofuels were operating, generating a total of 555 TWh of electricity; the largest existing capacities are in the USA (17 GW) [22]. In 2017, about 330 million t of organic waste have been thermally utilized providing between 82 and 110 TWh of electricity. For 2017, it can be assumed that the installed capacity for biogas lies between 19 to 23 GW. With this capacity, a potential power generation of 114 to 137 TWh is possible globally ([20, 23]).

Concerning solid biomass for electricity generation with a continuously increasing global capacity until 2022, roughly 112 GW will be installed with an energy provision of around 460 TWh. Global capacity might rise to 130 GW in 2030 (600 TWh/a) and to 190 GW in 2050 (850 to 950 TWh/a). Biogas production is also increasing, leading to roughly 25 GW of installed capacity in 2022, providing 162 TWh/a of electricity. This capacity will potentially rise to 30 GW till 2030 [20] and 40 GW until 2050 with an electricity production of 230 TWh/a and 300 TWh/a respectively. A possibly larger potential for biomass energy lies in the use for thermal energy supply, which is already partly exploited today and will most likely be an integrative part of future energy systems.

4.5. Other renewables

Geothermal energy and concentrated solar power (CSP) will most likely only play a minor role in renewable power production in the future.

In the year 2017 the global electric capacity of geothermal energy amounted to roughly 13 GW, providing around 73 TWh/a of electricity. Strongly limited high-enthalpy resources make the electricity provision from geothermal energy a niche technology with no major influence on global electricity production in the future. Nevertheless, geothermal energy might be of larger importance concerning heat energy supply (in district heating systems as well as small applications like single family household heat pumps). CSP is even less developed globally. Merely 5 GW of power are installed today. Due to the high cost compared to photovoltaics, the expansion will be drastically limited.

4.6. Summary – current development trends

A bottom-up approach from today's point of view (assuming a commercially driven expansion of renewable energies based on the current frame conditions and price relations) forecasts a quite fast expansion of power production from renewable sources of energy. Fig. 11 shows this expected development of the electricity provision namely for wind power, photovoltaics, hydro power and others for the coming decades (Fig. 11 does only include electricity from renewables).

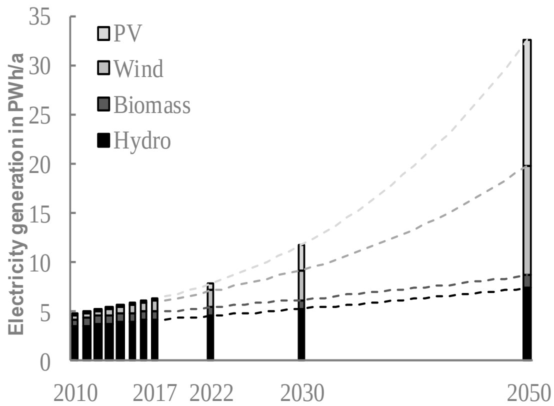

Figure 11. Forecast of global renewable electricity production [17]

4.7. Comparison

Even though this development constitutes a strong increase compared to the development in recent years, renewable energies for electricity provision will only contribute with a rather small part of overall electricity provision according to the development scenario outlined above.

As another consequence of a raising share of electricity generation especially from renewable sources of energy, also other energy sectors (e.g., heat sector, mobility sector) will be increasingly electrified. In this context electricity will most likely also be used in combination with other energy sources (like low enthalpy heat for heat pumps) to over-proportionately increase the share of renewables within the overall energy supply system; but for technological reasons this option is limited to certain markets. This development is very much powered and pushed by GHG reduction efforts in some countries and/or regions.

Based on the forecasted energy demand by fuel for the year 2040 according to [3] including the bottom-up forecast of renewable energies realized above, the overall composition of global energy supply for the year 2050 can be roughly estimated. For this assessment, the following assumptions are made.

- Growth rates by fuel between 2040 and 2050 are roughly half of those between 2016 and 2040 as assumed in [3].
- Often in such assessments, electricity from nuclear, hydro and other renewable sources of energy are converted back to primary energy by calculating the primary energy equivalent of an average thermal power plant (with an efficiency of 38 %) needed to supply the same amount of electricity; this is for example also realized in [3]. In contrast to that, here, electricity from those technologies using e.g. renewable sources of energy is directly treated as primary energy (which does in fact lead to an underrepresentation of renewable energies compared to the approach realized in [3]).
- Differences between the assumed development for hydro power and renewables based on [3] and those described in this chapter (i.e., the development shown in Fig. 11) are included in the overall energy supply forecast for the year 2050 (i.e. here, the amount of energy from renewable sources is roughly 25 % higher in comparison to [3]). The amount of energy by which the forecasts of Fig. 11 exceeds the forecasts in [3] is accounted for by reducing the share of fossil fuel (compared to [3]). The reduction is determined by calculating the primary energy a thermal power plant with an efficiency of 38 % would need to supply the same amount of electricity. This amount is than subtracted from the fossil primary energy components.
- An increasing electricity provision from renewable sources will primarily substitute electricity production formerly accomplished by conventional power plants (i.e., driven by fossil fuel energy). In this context primarily oil and coal fired power plants are replaced. Power production from hydroelectric power plants is assumed to directly substitute electricity provided by conventional power plants. For other renewable power provision, which supposedly mostly relies on fluctuating production from wind energy and solar power, an increasing need for energy storage will reduce its capability to replace demand-driven conventional power production. To account for this reduction, renewable electricity is assumed to replace fossil-based electricity production by a factor of 0.75 (e.g., to replace 0.75 MWh of electricity from demand-driven power plants 1 MWh of electricity from fluctuating renewable energies must be provided).

This calculation results in the shares shown in Fig. 12. Overall energy demand amounts to roughly 189 PWh/a (considering an overall tendency towards increasing electrification). Out of these around 42.2 PWh/a are provided based on renewable sources of energy including hydro power. The main source of primary energy is now natural gas with 59 PWh/a, because of the massive build-up of the use of renewable energy, both less oil and coal are used; thus, their shares within the overall electricity provision system are declining.

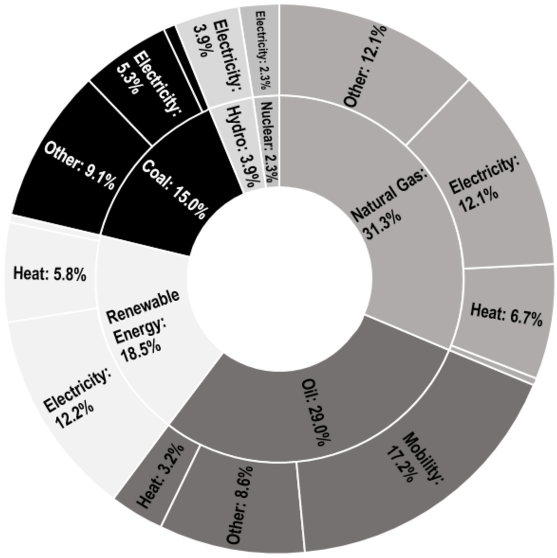

Figure 12. Forecasted shares of total global primary energy consumption (189 PWh) in 2050 (bottom up)

Against this background, based on such a bottom-up perspective the total primary energy demand estimated by 2050 (chapter 3) can be covered by roughly 22 % by the described utilization of renewable sources of energy.

Even though this development assumes a quite strong increase of renewable power production, there is still a large deficit between the resulting energy supply and an energy provision system that is conform with the globally accepted 1.5 °C-goal. If the use of energy sources is structured as shown in Fig. 12, there will be energy related GHG-emissions of roughly 36 Gt/a in 2050 emitted, which is roughly the amount of today's global emissions [18]. This is again shown in Fig. 13. The increased energy supply from renewable energy sources is almost compensated by growth, leading to mostly constant GHG emissions. Overall, primary energy consumption is slightly lower than the forecasted amount, due to a higher degree of electrification.

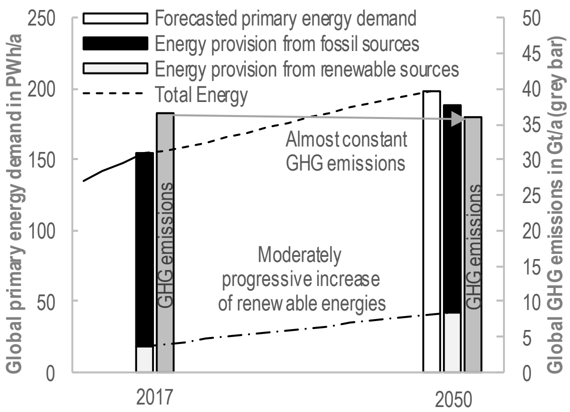

Figure 13. Bottom-up development of renewable energies and the overall energy supply system

The amount of GHG-emissions in that scenario will quite clearly exceed the emissions for the year 2050 according to the latest GHG abatement agreement (e.g. Paris climate agreement); i.e., this scenario is not compliant with global climate goals. Despite the assumed strong development of the use of renewable energies, countries will clearly fail to follow the necessary reduction paths depicted in Fig. 1. To achieve those goals, a much more rapid expansion would be needed.

5. Necessary global expansion of renewable energies

In order to be compliant with the Paris climate agreement, it is necessary, to significantly reduce GHG emissions in the years to come. The Intergovernmental Panel on Climate Change (IPCC) stated in 2018, that according to limit the rise of mean global temperature to 1.5 °C with a probability of 66 %, the overall global GHG emissions yet to be made should not exceed 420 billion t [24]. If the goal is to limit the increase to 2 °C, the amount of allowed GHG emissions slightly increases. But nevertheless, a net zero emission status has to be reached rather early than late. Thus, numerous GHG-reduction pathways have been developed. One of these pathways assumes halving the CO_2 emissions every decade from 2020 to 2050 [25]. For 2050 this results in an allowed amount of 5 Gt/a of GHG to be emitted. Assuming that all emissions not related to fossil fuels are either reduced through a change of process or captured (carbon capture and storage, CSS), these 5 Gt/a would be the absolute limit for emissions from the use of fossil fuels in the year 2050.

5.1. Necessary development

The trends described in the previous chapter assume a mostly cost-driven (commercially viable) expansion of an increased use of renewable energies based on current frame conditions and the relative cost differences valid now. In opposite to this approach in the following, a top-down discussion about the necessary global expansion of the use of renewable sources of energy is given based on the climate goals described above. Therefore, this chapter presents a development of the increased use of renewable energies under the precondition that the development fulfils the valid reduction goals and thus the advancements are mostly driven by environmental aspects. Additionally, it is assumed that such a development is possible without additionally reducing the overall energy demand (i.e., the economic development is assumed to be the same as already defined in chapters 3 and 4).

To reach an energy supply compliant with global climate goals, the use of fossil fuels as an energy source would have to be drastically reduced. To estimate a necessary global energy supply structure, that would fulfil this strong reduction of fossil fuels, a broad variety of assumptions must be made (the following elaboration, therefore, must be explicitly understood as a rough estimation).

- The still allowed GHG-emissions of 5 Gt/a in 2050 are divided equally between natural gas (equal shares for electricity, heat and other) and crude oil (equal shares for mobility and other).
- The use of coal is out-phased and substituted by electricity provided by renewables sources of energy.
- Nuclear power production stays constant in comparison to the previous scenario.
- Hydroelectric power generation additionally increases by 25 % compared to the forecast in Fig. 11. Additional hydroelectric power generation is used to directly substitute electricity from fossil fuel-based power plants.
- Including higher shares of renewables demands for more frequent use of energy storage. This use again is assumed to have an efficiency of 75 % (estimated average across all storage technologies available and under operation in 2050). Electricity from renewables other than hydro power therefore substitutes electricity from fossil-based power plants by a factor of 0.75.
- Using renewables to meet mobility demand relates to a shift of mobility structures. The still usable oil can be utilized in aviation, shipping and heavy-duty vehicles. The demand (for these types of transport) which goes beyond that, is met through the generation of synthetic fuels. It is assumed, that 20 % of the remaining mobility demand is met by such fuels with an efficiency for the conversion of electrical energy to chemical energy of 35 %. The additional 80 % are met by electro-mobility. Direct electric mobility needs less primary energy as conventional engine driven mobility, because in combustion engines large shares of the used primary energy (mostly oil) are lost due to the engine's efficiency (which is assumed to be 33 %).
- Including renewable sources of energy within the heating sector leads to additional implications. It is assumed that 60 % of the heat demand will be met by using heat pump technology (with an overall coefficient of power of 4), 25 % is met by generating and using synthetic gas (with a process efficiency for gas production of 50 %) and 15 % of the overall heat demand is met by using electricity directly.
- Meeting the demand for "Other" (Fig. 6 and Fig. 12) through electricity from renewable power plants is assumed to be one-to-one. Due to the lack of a definable efficiency for conversion, this constitutes the best guess.

These assumptions result in an overall renewable power production (mostly wind and photovoltaics) of nearly 126 PWh/a (including renewable heat and mobility shares) related to the year 2050. Due to the fact, that

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renewable power would than mostly rely on producing electricity, the global share of electrical energy as an energy carrier would increase to roughly 82 % of which nearly 88 % would be based on renewable energies (other than hydroelectric power generation). Fig. 14 shows the overall shares of primary energy by fuel and sector.

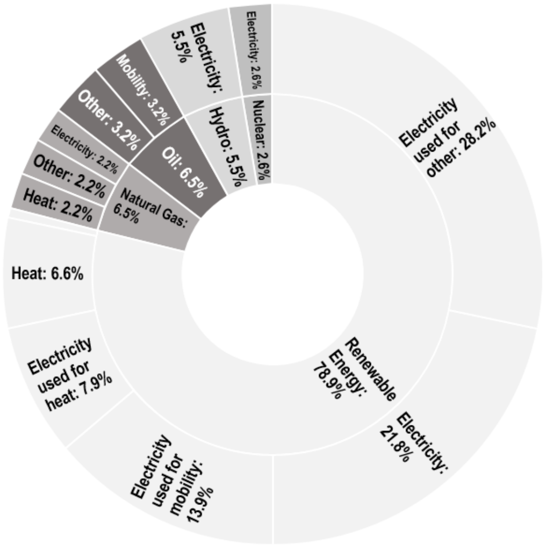

Figure 14. Shares of total global primary energy consumption (167 PWh) in 2050 needed to be compliant with global climate goals (top-down)

To supply such a massive amount of energy from renewable power plants, global installed capacities would have to amount to roughly 33 TW of photovoltaic systems (providing 66 PWh/a), 19.2 TW of wind power plants (providing 48 PWh/a) and 1.2 TW of other renewable electricity generation facilities providing 6 PWh/a (assuming global mean full load hours of 2 000 h/a for photovoltaics, 2 500 h/a for wind power and 5 000 h/a for power provision from other renewable sources of energy). These capacity calculations assume that photovoltaic power production exceeds that of wind power plants so that renewable electricity generation is divided upon photovoltaics, wind power and others in shares of 55 %, 40 % and 5 %.

The necessary development is shown in Fig. 15. Electricity production from power plants based on renewable energies must be drastically increased to reach the described shares of roughly 81 %. Consequential, the GHG emissions drop substantially, and reach 5 Gt/a.

Such a massive expansion of the use of renewable sources of energy would only be possible, if in the near future a kind of collective global realization of climate change threats leads to far-reaching political decisions, additionally boosting the expansion of the use of renewable energies and also the expansion of technologies that would enable the amount of sector coupling necessary to allow renewable based electricity to replace fossil fuels in different sectors (the additional expansion of nuclear power is not considered here, due to its high cost, high riskiness and unresolved issues concerning nuclear waste repositories; additionally, possible technological leaps – e.g. getting nuclear fusion to work – are also not considered as a realistic option for those time horizons). Additionally, the legal frame condition must support such a development.

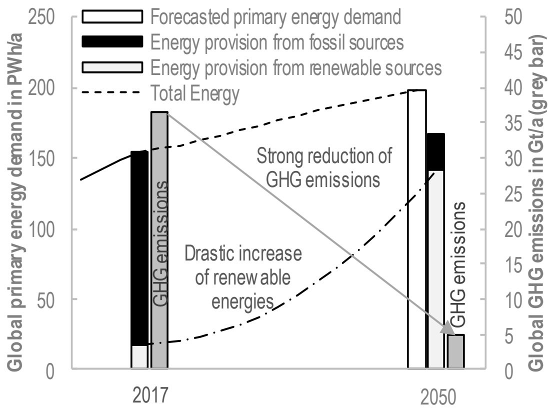

Figure 15. Top-down development of renewable energies and the overall energy supply system

5.2. Consequences

Even though, it is not the scope of this paper to decide, how realistic such a development is, such an advanced expansion would lead to extensive implications for global energy supply system structures. Therefore, below an overview to different challenges arising from such strongly increasing shares of renewable power production are discussed.

Electricity system. The expansion of renewable power plants will increasingly challenge electricity supply systems globally. Thereby it is mostly irrelevant, whether the specific energy system is developing (i.e. energy demand is rising and there is a net increase of power production) or transforming (i.e. there is no considerable change in overall energy demand, but the used energy sources are switched from fossil to renewable). Anyway, the resulting system will have to include several aspects, to cope with increasing shares of (fluctuating) renewable energies.

The power production of photovoltaic and wind power plants is characterized by strong fluctuations and additionally relies strongly on the availability of solar radiation and high wind speeds, respectively. Therefore, it will become increasingly important for electricity systems to flexibly react upon those increasingly prevailing fluctuations and availability uncertainties. This leads to several implications, that will make future electricity systems differ from today's. Some of them are discussed below.

- The overall power supply system needs to become increasingly flexible. For example, the thermal power plants must operate with higher load gradients and a wider range of operational states. Such an improvement of the flexibility of the overall power production can be reached by different approaches. Concerning renewable power production, among others it is very important to increase forecast quality even further to secure the highest possible plannability of renewable power output. Additionally, power plants providing the residual load (i.e. the load not covered by fluctuation sources like wind and solar) must be upgraded and new-built plants have to be prepared for flexible power production implicitly. This will most likely result in operation with higher load gradients and fewer full load hours [26]. Due the fact that these thermal power plants are not operated by fossil fuel energy any more this is true for conversion units using e.g. demolition and residual wood, organic waste fractions from the food processing industry, domestic waste and other similar fuels.

- Fluctuations must be spatially and temporally balanced by either increased transmission capability (i.e., expansion of electricity grids related to capacity and covering) and/or large-scale storage systems (i.e., expansion of system wide storage capacity). Spatial balancing / compensation can be achieved through strong electricity grids with high transmission capabilities and a high degree of crosslinking. Those structures allow for energy harnessing in high potential regions (e.g., coastal areas for high wind power production) independent of the location of high demand regions; but the installation of such an infrastructure is very costly. For energy supply systems in countries with developing demand structures, it might also be possible, to locate high consumption facilities close to high yield areas, but all in all, enough transmission capabilities seem indispensable; this is basically a precondition to close the gap between areas most promising for energy provision and the huge demand centers. Temporal balancing is another important issue. Diurnal patterns of solar power production as well as the stochastic behavior of wind energy supply demands for the possibility to store energy for a timely shifted use. Several storage technologies are already state of the art like pumped-storage power plants and electrochemical battery storages; beside this, these concepts are under ongoing improvement and additional approaches are researched in depth (e.g., compressed air storages). The main focus is to find cost efficient concepts with the ability to store sufficient amounts of energy for a certain period of time. Thus, storage systems – either "real" storage like pumped hydropower stations or battery systems or "virtual" storage concepts like virtual power plants or sector coupling with e.g. the heat sector – are needed necessarily. Such storage systems can be realized on the small scale in clearly decentralized structures as well as within large scale systems helping to stabilize the overall supply system; most likely both approaches are needed within a fully integrated system expected in the years to come. Strong grid structures reduce the need for energy storage, because weather effects partly compensate over larger areas. Therefore, spatial and temporal compensation of fluctuation should be considered in combination.
- The demand side must become increasingly flexible; a key measure to achieve this goal is that the customer can benefit from the strongly volatile prices to be expected due to this development. The overarching goal is to make the demand increasingly more flexible and controllable. There are numerous options. For example, the operation of selected time-flexible industrial processes could follow the power production from renewable sources (i.e. increasing electricity demand while electricity provision from renewable energies is high and reducing it, while production is low). Additionally, some energy consuming applications show intrinsic storage effects (e.g., electro thermal applications with large thermal masses like houses with large surface area heating or cooling devices), which also enable demand flexibility. Thus, to completely reduce GHG emissions using mainly wind and photovoltaic systems, the rest of the energy system will have to be considered too.

Overall energy system. In addition to the implications for the electricity system, there will be some major implications for the overall energy system. Because most conversion systems using renewable sources of energy provide electrical energy as an output, it will be increasingly important to couple the power production system to other energy systems respectively other energy sectors (i.e. sector coupling). If for GHG-reduction reasons large amounts of oil and gas are substituted by electrical energy from renewable sources in the years to come, the demand that was formerly met by those fossil fuels must be met by electricity in the future (this was the basis of the system adaptation for high renewable shares in Fig. 14). One example for this kind of sector coupling is power-to-heat – the transformation of electrical energy to thermal energy in order to fulfil heat demand especially during winter time. This can be achieved by utilizing heat-pumps, which use the energy of low temperature sources (e.g., air, soil, groundwater) and increase its temperature to a technically useable level with the help of electrical energy. Heat pumps can supply thermal energy several factors larger than the input electricity amount and thus constitute a highly efficient way of sector coupling. Due to thermal storage effects of buildings such heat pump systems additionally help to flexibly react to renewable power production fluctuations. Power-to-heat can additionally be implemented as highly flexible direct electric heating, to solely use electricity for heating purposes, when a surplus of renewable energy would otherwise be prevailing.

Another way of sector coupling, which directly substitutes fossil fuels, lies in the power-to-gas and power-to-liquid technology. Both processes start with using electricity and water to produce hydrogen by electrolysis. This hydrogen can either be used directly or transformed to other forms of energy carriers. A direct use (instantaneously or after storage) would constitute the most efficient way, but there are practical issues (storability, existing non hydrogen-based infrastructure in many parts of the world) that hinder the implementation of a pure hydrogen infrastructure (regions with still developing energy demand might be able to directly implement a more hydrogen-based energy supply, provided reasonable costs of implementation and therefore reduced overall system cost). To evade these problems, additional processes are used to turn hydrogen into e.g. methane (power-to-gas) or a liquid energy carrier (power-to-liquid) by adding CO_2. After such a further treatment they can be used in already existing infrastructure and with existing technology. The liquid fuels can fulfil all specifications of currently used fuels and are therefore able to directly substitute those fossil-based fuels and be used in e.g. aviation. Both – power-to-gas and the power-to-liquid – processes show rather low overall efficiencies. Therefore, a direct use of electricity should be the preferred solution. E-mobility offers that kind of solution.

By either being directly grid connected (rail-based transport) or by using mobile batteries (electricity-based individual mobility) that feed an electric motor, electricity can directly power the engine of vehicles and therefore help to reduce the demand for fossil fuels within the transport sector. For global scale implementation, a reliable and sustainable battery technology would therefore be needed. Nevertheless, there might always be some cases, in which liquid fuels with a high energy density are needed, which might not be possible for battery systems (e.g. aviation). Therefore, it is most likely that no single technology will help to master the stated challenges but rather a mixture of different approaches and technologies.

6. Conclusion

Trends in global population and prosperity development will most likely lead to a significant further increase of global primary energy demand in the years to come. Having in mind the increasingly drastic effects of global climate change, it is necessary, that this rising primary energy demand will be met by the utilization of basically GHG-emission free renewable energies. In this context, two different scenarios for the development of the global primary energy supply system – especially focusing on renewable energies – have been elaborated and discussed.

As a basis for these development scenarios, the current status of primary energy demand (2016) was discussed in chapter 3 and a forecast for the year 2050 has been developed. Based on this, first, a bottom-up approach was presented in chapter 4, progressively extrapolating the current trends and developments on providing useable energy based on renewable sources of energy until 2050. Due to falling prices, photovoltaics and wind power will be the dominant technologies of renewable energies in the decades to come. However, the main energy carriers will be natural gas and crude oil in this scenario (providing roughly 60 % of the global primary energy); i.e. most of the the world’s energy demand will be served by fossil fuels (roughly 75 % in total). Thus, as a matter of fact, based on the currently ongoing developments the challenging GHG reduction goals cannot be met by the year 2050.

In contrast to the bottom-up approach presented in chapter 4, a top-down scenario has been developed and discussed in chapter 5. To be compliant with the overall goals of the Paris climate agreement a total of roughly 5 Gt/a of GHG emissions are still allowed in the year 2050; this overarching goal must be achieved within this scenario. This goal in view, a new share of renewable energy carriers has been calculated, summing up to roughly 84 % of total primary energy by 2050. Although, the global population’s demand for usable energy was kept constant, this scenario implied a reduction of the global primary energy demand due to the direct use of electricity from renewable energy sources (and thus a reduction of overall energy conversion losses; i.e., electricity from e.g. wind power and solar radiation is treated directly as primary energy).

Both pathways (bottom-up as well as the top-down approach) are again shown in Fig 16. Clearly recognizable are the different developments for the expansion of energy provision from renewable sources (dashed/dotted lines). There it becomes obvious that the top-down approach enforced basically by the Paris agreement would require a very strong expansion of power plants based on renewable energies within the next decades. And to achieve such a development much stronger political measures need to be implemented as already in force today – and such a development needs to be implemented by basically all countries globally.

Even though, these development and expansion paths are merely estimations of possible (and necessary) developments for the future and do not necessarily have to turn out exactly as described, they show that on the one hand it is quite obvious that some major transformations are about to occur in global energy systems; on the other hand, the estimations suggest, that a substantial increase in efforts from politics and industry – as well as from the customers – concerning the expansion of renewable energies would be needed globally, to be able to meet global climate goals.

High income countries with already high energy demand will have to successively replace power plants operating with fossil fuels by power supply technologies based on renewable energies. Simultaneously, transmission capabilities must be strengthened, storage systems must be installed, demand must become more flexible and energy sectors must become increasingly intertwined. Low income countries will have to align growth of their energy system with being climate-neutral and must incorporate mostly (or only) technology based on renewable energies in their growing energy supply structures.

With an increasing share of fluctuating electricity related to the overall electricity provision more and more technical and organizational measures need to be implemented to allow for a stable electricity and thus also energy supply system. Fig. 17 illustrates the necessary and partly already ongoing transformation processes. The historical structure of electricity supply from the large power plants down to consumers will increasingly develop into a more and more integrated energy provision structure. Industry and private end consumers are increasingly interacting with the distribution structures and the conventional power plants based on fossil fuels are being successively reduced while more and more power plants based on renewable energies are installed. In addition to that, due to more and more volatile renewable energy infeed, the historical load following operation is not further suitable, a flexibilization of electricity demand and integration of further flexibility measures to respond to increasingly fluctuating power generation is needed.

The historically independent view of electricity, heating and mobility markets must transform into an integrative optimization of all (sub-) energy markets in the entire energy system, taking advantage of possible cross-sector synergy effects. If the perspective of optimizing the energy system, sets in the short to medium term – and a practical alternative to this is not recognizable – solutions for the resulting challenges need to be found as part of this paradigm shift; first ideas and approaches are already visible. Thus, decisions to be taken today about the further development of the electricity system should take care about this development and the resulting necessities to maximize the exploitation of possible synergy effects in the future.

From a global perspective, about 80 % of the primary energy demand must be met by renewable energies in 2050 (which will primarily be supplied as electricity) to be compliant with the climate goals agreed on within the Paris agreement. In addition to being used as such, this electricity must be integrated across the various energy sectors for heating, mobility and other uses, to allow for widespread decarbonization (concerning fossil carbon) in order to achieve the set climate goals. For these paths to be followed accordingly a coordinated global effort from both politics and industry would be necessary; this has to be supported by the customers. Mastering these overall tasks is truly challenging but nevertheless not impossible.

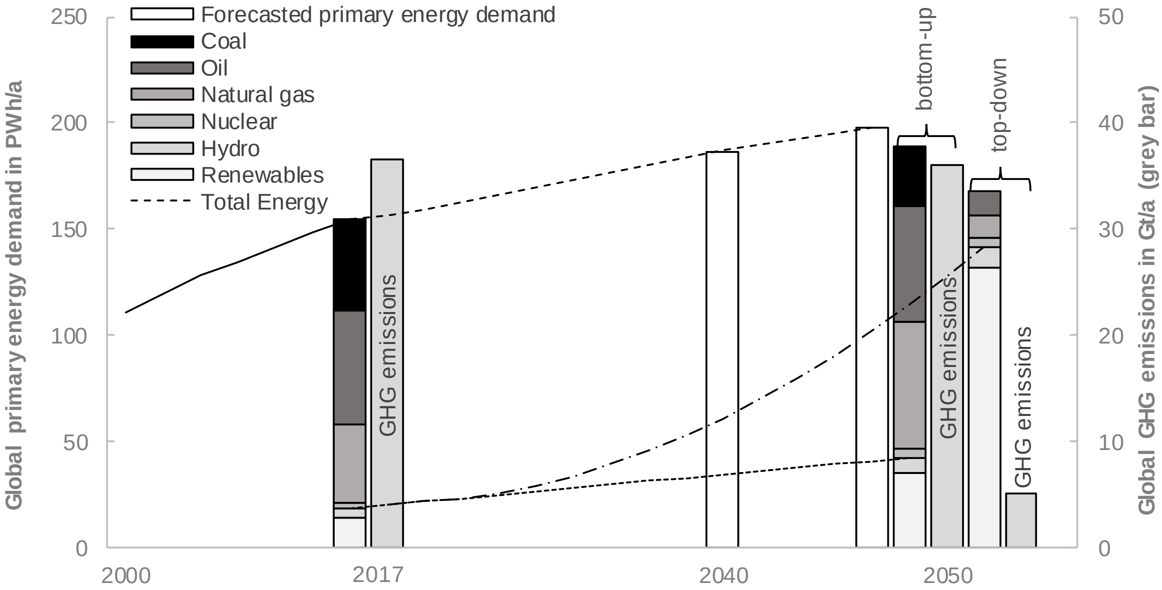

Figure 16. Possible development of primary energy demand until 2050 for bottom-up and top-down scenarios for renewable energy expansion ([17] and own calculation)

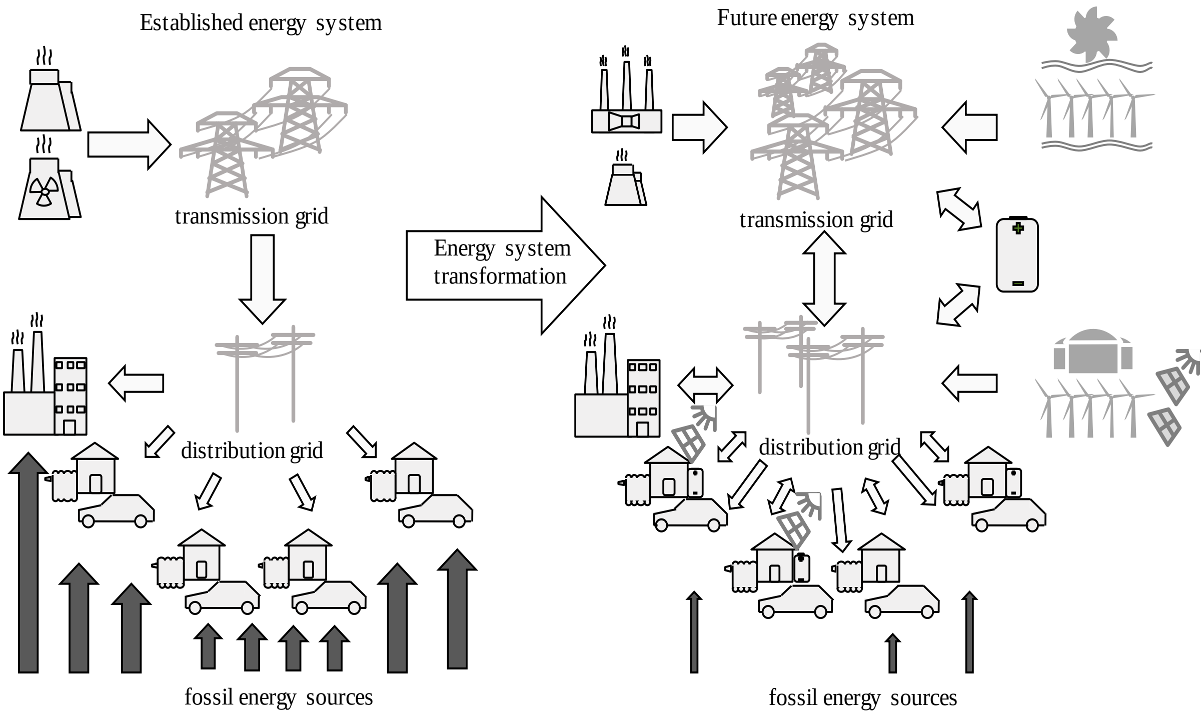

Figure 17. Energy system transformation (light arrows: flow of electricity, dark arrows: flow of fossil fuels, based on [27])

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