The projections for the future and quality in the past of the World Energy Outlook for solar PV and other renewable energy technologies

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ABSTRACT
Global energy demand has grown steadily since the industrial revolution. During the two decades from 1991 to 2012, total primary energy demand (TPED) grew from 91,200 to 155,400 TWh_{th}, or by 70%, and projections expect this number to increase by a further 40% by 2040. Although greenhouse gas emissions in the energy sector have to be reduced to zero by mid-century or earlier to avoid an ecologic disaster, less than 15% of this energy demand is supplied by renewable resources nowadays. The International Energy Agency (IEA) has a significant impact on both political and economic decisions of governments and stakeholders regarding energy. The World Energy Outlook (WEO) report published annually by the IEA projects for the decades to come how TPED and electricity generation, amongst others, will evolve for all major technologies. Since the WEO is often used as a basis for policy making on renewable and conventional energy, a comprehensive analysis of past WEO projections is crucial. Such analysis will ensure well-grounded and realistic energy policy making and can contribute to efforts to fight climate change and to achieve energy security.
In this article, the deviation between the real figures documented in the latest WEO reports and the projections of earlier ones is analysed, as well as the different projections of all reports from 1994 to 2014. The results obtained so far show that projections for solar technologies and wind energy have been strongly underestimated, whereas projections for nuclear energy are contradictory from one year to the next. A key reason for the high deviations of solar PV and wind capacities in the projections and the historic data is an incorrectly applied growth pattern. The WEO reports assume linear growth, whereas history shows an exponential growth for the new renewable energy (RE) technologies. The current exponential growth is part of long-term logistic growth of new RE technologies. Furthermore, a model proposed regarding RE technologies shows that to satisfy the world's needs with sustainable technologies in the decades to come, the approach of the WEO reports needs to be substantially reworked.
Due to continuously falling prices of renewable energy technology, one can expect a fast deployment of renewables and a replacement of conventional energy. In its latest projections the WEOs did not take into account recent developments, including measures on climate protection and divestment of finance from the conventional energy sector. Therefore, policy-makers are advised to consider the expansion of renewables well beyond the WEO projections in their energy policies in order to avoid stranded investments in future.

Keywords
PV market projection, renewable market projection, electricity demand projection, World Energy Outlook, International Energy Agency, policy-making

1. Motivation

The reckless overexploitation of fossil fuels over the last decades has led to the situation we know presently: climate change is inducing effects which shall have dramatic consequences on humankind. The Intergovernmental Panel on Climate Change (IPCC) expects an average temperature increase of 6 to 7 degrees by the end of the 21th century if no action is taken, whereas a limit of 2 degrees must not be overstepped [1].

Twenty-five years after the explosion of the nuclear reactor in Chernobyl, Japan's nuclear disaster at Fukushima in 2011 confirmed again the fact that nuclear energy is not a sustainable resource at all and that the technology is far from being under control. Four years after the catastrophe, the site has still not been decontaminated and wastewater full of hazardous elements is still being released into the sea. Repercussions will affect us directly and indirectly for decades as the Chernobyl's event did, and even still does. Furthermore, the threat of nuclear weapons proliferation is very high and leads to tensions between countries and sanctions such as in the case of Iran. Furthermore, the risk of terrorist attacks against nuclear plants is highly underestimated.

Reasons that explain a slow expansion of renewable energy (RE) technologies are numerous as varied. From a social point of view, a total carelessness regarding the impacts of fossil fuel exploitation discouraged expansion. In the past, lower yields and production capacities of RE technologies combined with low prices for fossil fuels to incite decision-makers to invest in fossil fuel based production technologies in order to meet rapidly growing global energy demand. In addition, a key reason for a slower than possible growth of RE technologies is the huge subsidies for fossil fuels, accounting for about 5300 bnUSD annually [2].

Electricity did not play as important a role in our daily lives 100 years ago as it does today, and it is the fastest-growing end-use energy. Yet all non-sustainable technologies work the same way: combustion, through which a lot of energy is wasted as it is needed to evaporate a liquid, usually water, which passes through a turbine producing electricity. Concentrating solar thermal power (CSP), solar PV, geothermal energy, wind energy or ocean energy directly convert natural heat, radiant or mechanical energy into electricity (heat can also be generated in some cases) shortening processes and reducing significantly losses and emissions.

However, today, all these reasons have found their limits. People's consciences have awaken and all over the world campaigns against industrial companies emitting harmful substances can be observed at various levels, such as international NGOs, governments or at the local level. For example, in the current year, the Obama administration rallied against the Keystone project that planned to extract oil from tar sands, an unconventional fossil fuel, in Alberta, Canada. In addition to being an extremely polluting and highly energy intensive process, its energy return on energy invested is low. The low energy efficiency of tar sands, but also shale oil, are expressed in the EROI, which is only 1:4 (tar sands) and 1:7 (shale oil) [103]. In addition, a giant pipeline has to be built from the exploitation site in Canada to the US Gulf Coast where oil refineries are located, thereby crossing the USA in its entirety from north to south. A further example is that several countries such as Scotland, France, Wales, even the state of New York, have forbidden fracking technology. In the region of In Salah, Algeria, inhabitants have protested since the beginning of 2015 against this technique, known to pollute the surrounding groundwater. Unlike fossil fuels, there is no place on Earth where the sun is not shining and many places have abundant access to wind energy, hydropower and geothermal energy. Even if all the RE resources are not equally distributed worldwide, there is always at least one of them that can be harvested. Most countries have the potential to achieve a self-sufficient energy supply based on RE.

The lack of investment is, according a recent declaration of the International Energy Agency (IEA) [77], what is assumed to prevent RE technologies from exponential growth, whereas their potential is close to infinite. The IEA is seen as a benchmark reference by stakeholders, and influences the decisions in different energy-related sectors (markets, investment, etc.). Yet, what if the IEA's projections were not reliable? Should decision-makers keep basing their decisions on IEA results? The projections of the IEA in the flagship report, the World Energy Outlook (WEO) [3-23] have never shown substantially high projections for RE, which would be needed to act upon the climate change, nor have they fully accounted fossil-nuclear energy subsidies, nuclear security and depleting fossil-nuclear energy resources [24, 25].

Stranded investments in coal and gas companies in the past, based on misjudgement of future growth rates and cost reductions in the renewable energy sector, have led to substantial financial losses in Germany. This has been obvious from the latest balance sheets of RWE, Vattenfall and E.ON [85, 86, 87].

Since OECD participating states and other countries base their national energy policies on the WEO projections, their significance cannot be understated. The WEO often provides a basis for political decisions on the expansion of renewable energies and on the availability of conventional energy resources. Climate protection can succeed only if a steep expansion of renewable energy is ensured, whereas some claim that energy security is feasible only with conventional energy, at least in the short- to mid-term. Since these two energy strategies conflict with each other, reliable projections are even more important. If a steep expansion of renewable energies is predicted, it will be easier for the governments to engage in climate protection with renewable energy, and ensure energy security. For an adequate and reliable basis for future political decisions on energy, a comprehensive analysis of the past WEO projections is crucial. Future energy policy decisions can be well grounded only when it is known that earlier WEO projections coincide with reality.

The objective of this article is to compare the past projections on the future development of solar PV, other RE technologies, nuclear energy, total primary energy demand (TPED), and electricity demand to real numbers. This can help to assess the value of the current projections of the WEO for the respective categories.

2. Methodology and data

Data have been gathered from all the WEO reports available (1994 – 2014) [3-23] regarding total primary energy demand (TPED), electricity generation and power capacity in a database and classified per category for coal, oil, gas, nuclear, hydro power, biomass, geothermal, wind, solar photovoltaics (PV), concentrating solar thermal power (CSP) and ocean energy. Each report provides actual measured data for the year ended two years prior to the respective report published after 2000 and three years prior for the ones published before 2000. This means that actual measured data are available for the years 1991 - 2012. In addition to that, projections are given up to three decades ahead. Thus, projections extend to 2040. For some reports data are missing, not given for the whole world, or are only given for specific regions, thus making it impossible to exploit these reports. The ones concerned are WEO 1997, 1998, 1999, 2001 and 2005. Therefore, they have been excluded from the analysis. WEO 2003 and 2007 present figures for electrical capacity and electricity generation. From WEO 2010 and onwards, three scenarios exist and projections differ in some scenarios widely. For these WEO reports analysis was focused on the scenario called "New Policies Scenario". The main difference with the two others is that this scenario takes into account proposals that have been made public over the past year but not yet officially adopted. Based on these data, diagrams are created for TPED, total electricity generation and key technologies comprised of historic data and future projections of all exploitable WEO reports. An additional chart has been created for the full load hours of the electricity technologies. Each half-decade in these diagrams is visualised by a colour graduation.

The past projections are compared to the real numbers as far as possible. The deviations of projections and real numbers are documented and discussed as well as structural trends and some changes of the projections.

A model based on logistic growth has been added to renewable electricity generation for better estimating real growth (section 4).

3. Results and Discussion

In the following section, the projections and the real data are visualised in figures and discussed. The sub-sections are comprised of TPED (3.1), electricity generation in total (3.2), solar PV (3.3), CSP (3.4), solar technologies (3.5), wind energy (3.6), hydro power (3.7), bioenergy (3.8), geothermal energy (3.9), ocean energy (3.10), renewables in total (3.11), coal (3.12), oil (3.13), gas (3.14), and nuclear energy (3.15).

3.1. Total Primary Energy Demand (TPED)

TPED represents the entire energy consumed and by consequence gathers together all the following sectors: industry, transport, building and end-use energy. TPED is shown in Figure 1, revealing three major points. First of all, the growth in TPED in the late 1990s and 2000s had not been anticipated in the early WEOs of the mid-1990s. Since 2000, all projections show the same trend with an average difference inferior at 10% between them. This trend is aligned with the historical data although the latter does not increase linearly yet in steps. A small drop in 2009 in the historical data needs to be highlighted. However, this had been a short-term reaction to the financial crisis after the Lehman bankruptcy and the trend became stable again soon after. There can be observed a non-negligible difference between the three curves representing the reports before 2000 and the real numbers, where projections have been underestimated. On the contrary, WEO 2007's projections have been lightly overestimated.
Summing up, the deviations in the TPED projections compared to the historical data seem to be in line with an acceptable projection error.

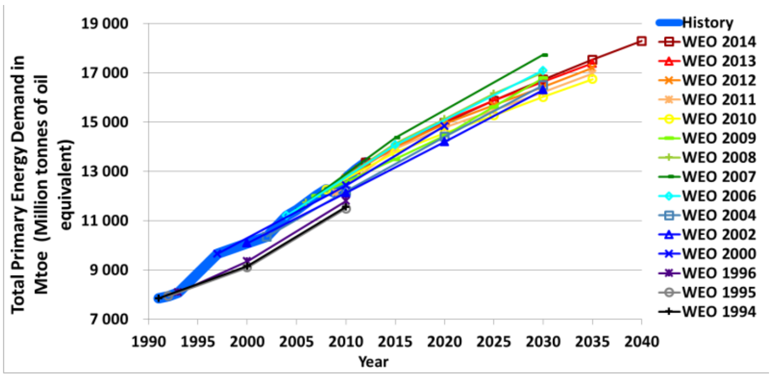


Fig. 1: Total primary energy demand (TPED) for the years 1991 to 2040. The historical data are given for the years 1991 to 2012. The projections range from 2000 to 2040. Data are based on WEO 1994 to WEO 2014 [9-23].

3.2. Electricity generation

The development of global electricity generation is visualised in Figure 2 and shown for power generation capacity, generated electricity and full load hours as an average of all generation capacities. The figures show the data for total electricity generation, which represents an average of 15% of TPED (12% for the earliest figures and up to 19% for the year 2040 projection). As shown earlier for TPED (Fig. 1), projections are well matched with the historic data for both capacities and generation, even if real figures seem to follow a slightly higher slope regarding the capacities. It can be also noticed that projections have been revised upwards year by year, even though all different curves keep the same slope. The first half-decade projections for the year 2010 have been 15% below the real figures in WEO 2012. The difference between these reports and WEO 2014, that seems to be the closest to the real data, reaches up to 20% for the projections in 2020 and 2030.

On the generation figure it can be seen that the disparity regarding projections is considerably smaller compared to the capacity. The full load diagram gives another view, and represents a combination of the first two. The global trend of full load hours is in decline except in 2009 and 2012, when two significant peaks are present. Projections are similar in form to capacity projections except they are now upside-down. In the first case, future projections are increasing over time. With full load hours, it is the opposite. This diagram reveals that for three reports (WEO 2000, 2008 and 2009) an increase of full load hours had been expected in the future. The difference between the expectations of the WEOs of the first half-decade of the 2000s and reality is 10% in 2010. This perspective also shows that the WEO 2002 does not start with historical data. Real figures for this report are not given for the same year. We will find this particularity for each sub-section.

Summing up, interestingly there is no large deviation of electricity generation but of the installed capacities and the average full load hours. This can be easily explained by the fact that the WEOs systematically underestimated the installation growth of solar PV and wind energy. Both technologies show average full load hours of about 1400 - 1500 and 1900, respectively, which is substantially lower than the approximately 4300 of thermal power plants. Therefore, the generated electricity is well projected but not the installed capacities and the average full load hours. Interestingly, the latest WEO 2014 still assumes a relative stagnation of solar PV and wind energy installation in the years 2020 and onwards, since they expect a stabilization of the full load hours at about 3700 – 3800, which is still far higher than the average of PV and wind plants, respectively.

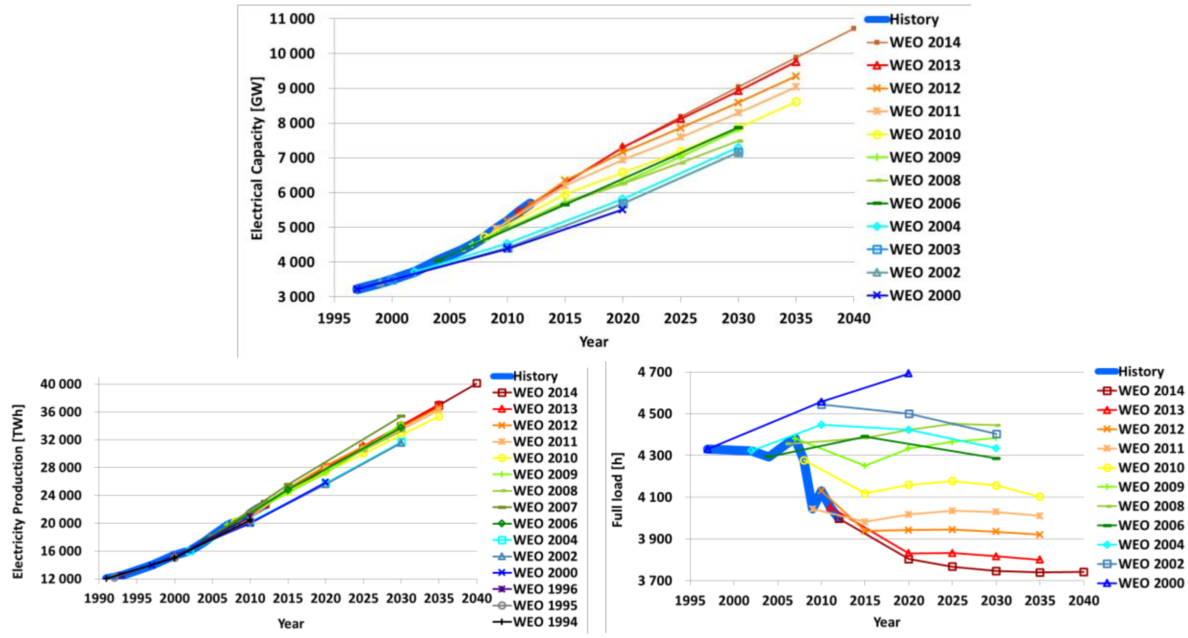


Fig. 2: Electricity generation globally in generation capacity (top), generated electricity (bottom, left) and full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2012 for both electrical capacity and full load hours and from 1991 to 2012 for generated electricity. The projections range from 2010 to 2040 for both generation capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [9-23].

3.3 Solar Photovoltaics

Distinction between solar technologies, solar PV and solar CSP, began from WEO 2010 onwards. Therefore, historical data range from 2008 to 2012 [19-23] plus additional numbers are added for the years 2013 and 2014 in capacity diagrams [26]. It is too early to compare projections with these numbers, yet these graphs show interesting facts. As shown for total electricity generation and capacity (Fig. 2), year by year projections are revised upwards. The projection for 2020 reported by WEO 2010 had been already achieved in 2012, eight years in advance and two years after the publication, which clearly documents the projection inefficiency of the WEO in the early 2010s. At that time PV had already become a major source for new power capacity investments. Real figures for 2013 and 2014 already show that the most recent WEO report (2014) needs to be adjusted in the near future in a similar manner to the previous ones. The full load hours diagram (Fig. 3, bottom, right) shows a V-shaped evolution of the historical data curve with a minimum in 2010, which contrasts with the projections showing an immediate growth. This may be mainly attributed to the substantial growth and market dominance of the German PV market, which accounted for the majority of global PV installations in these years [26] and where the full load hours are typically not higher than 1000 [27]. A further effect is due to the very high growth rates of up to 80% on an annual basis which lead to a recorded capacity by the end of a respective year, but no full generation of the capacity, since up to 44% of the total global cumulated installed capacity had been installed in the respective year. As a consequence, the recorded full load hours are artificially low [26].

Already in the year 2010 the PV installations represented more than 6% of total global power plant capacities and more than five times more than the new nuclear capacities of that year [26, 28]. Therefore, it had been more than overdue to include solar PV as its own category and a further indication that the WEO had been very slow in accepting the real role of PV.

The expected full load hours in the long-term make much sense, since they are close to the expected value of about 1500. This can be easily calculated based on the global population weighted mean irradiation on a module surface for optimally fixed tilted modules of about 1850 kWh/(m^2·a) [27] translating to about 1475 full load hours with a performance ratio of about 80%.

Quite interesting is the rate of adjustment of the expected PV capacities year by year. Focusing on the year 2030, from WEO 2010 to WEO 2014 the 2030 installed capacity numbers had been adjusted by 40%, 33%, 13% and 16%, respectively. Assuming a constant 14.5% adjustment of the expected cumulated PV capacity numbers, it might take some years, but for WEO 2019 or WEO 2020 one can then expect that the WEO will have reached the recent level of insight of the leading institutions in the world when it comes to solar PV market numbers: the most recent numbers for 2030 are 1764 GW (Greenpeace) [29], and 1840 GW (Bloomberg) [30]. Most interestingly the renewable energy experts of the IEA, who seem to have a rather small influence on their own WEO colleagues, project 1721 GW [31]. However, there are also market expectations for cumulated installed PV capacity of 2100 to 2300 GW [32].

It remains unclear why all WEOs since 2010 assume only linear growth for solar PV, although it is known that solar PV capacities have grown exponentially since the 1950s [33] and it is expected that exponential growth will continue in the decades to come [29, 30, 31,34, 32]. Complaints about poor projection quality related to PV are documented for the past [79], again most recently [80] and can be expected for the future [29, 30, 81, 82].

Summing up, since the introduction of solar PV as an individual technology in WEO 2010, projections have been updated year by year substantially but still lag by a factor of three for the reference year 2030 behind global leading organizations in the projection of solar PV capacities. One reason is that the WEO assumes only linear growth. However solar PV has been growing exponentially for decades. Why the WEOs do not reflect such relevant differences in structural growth patterns remains unclear. There are only a few years to compare the prognosis quality of the WEO with real development. However the achieved capacity of about 177.6 GW of PV at the end of 2014 [26] plus the installations of January 2015 had been projected in the WEO 2010 for the year 2024. The real installed PV capacity in 2014 has exceeded threefold the 2010 WEO projections for that year.

Finally, the WEO seems to be no reliable source for solar PV projections.

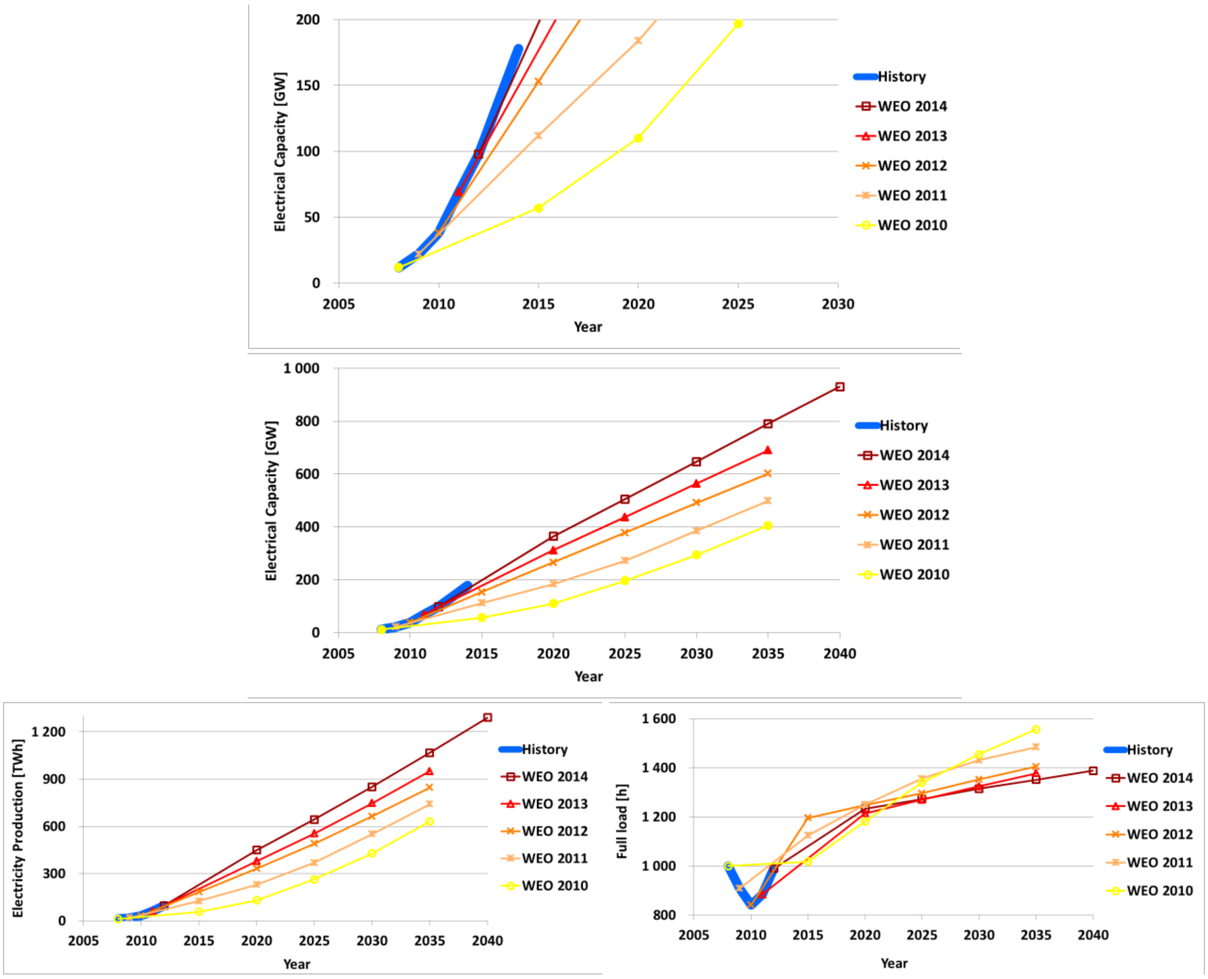


Fig. 3: Solar photovoltaic capacities (top and center), generated electricity (bottom, left) and solar PV full load hours (bottom, right) for the years 2008 to 2040. The historical data are given for the years 2008 to 2014 for electrical capacity and from 2008 to 2012 for both electricity production and full load hours. The projections range from 2010 to 2040. Data are based on WEO 2010 to WEO 2014 [19-23] and Werner et al. [26].

3.4 Concentrating Solar Power

The evolution of solar CSP (Fig. 4) is expected to be different than solar PV. First, the shape of the curves follows an exponential growth instead of a linear one for PV. Conversely, CSP projections are revised downwards over years. Thus in 2030, WEO 2010 envisaged an electricity production reaching 185 TWh against only 140 in the most recent report (2014) - a decrease of 24%. The WEOs of recent years project rather constantly about 40 GW of installed CSP capacities by 2030. The future potential of CSP is highly debated, as the projections for the year 2030 range from 20 GW (Bloomberg) [30], 261 GW (RE experts of the IEA) [35] and up to 714 GW (Greenpeace) [29]. The projection of Bloomberg is significant, since they have an impressive track record in the past and their analyses are strictly based on the current status and dynamics of the fundamental economics. About ten years ago the levelized cost of electricity (LCOE) of CSP had been half of solar PV. Early in 2015 the PV LCOE has been half that of CSP [36, 37]. However, it needs to be stated that CSP is significantly more valuable than solar PV from the technical point of view, since the solar energy can be easily and for low cost stored in thermal energy storage and the steam turbine leads to a secured power availability if backed-up by hydrocarbons [38]. Recent results indicate that this functionality of CSP can be by-passed by PV-battery-(power-to-gas)-gas turbine alternatives, as shown for the first time in an energy system analyses of Israel [39].

Summing up, the prospects of CSP are strongly debated and the WEO projects comparable numbers to Bloomberg, the leading market researcher in the field of RE.

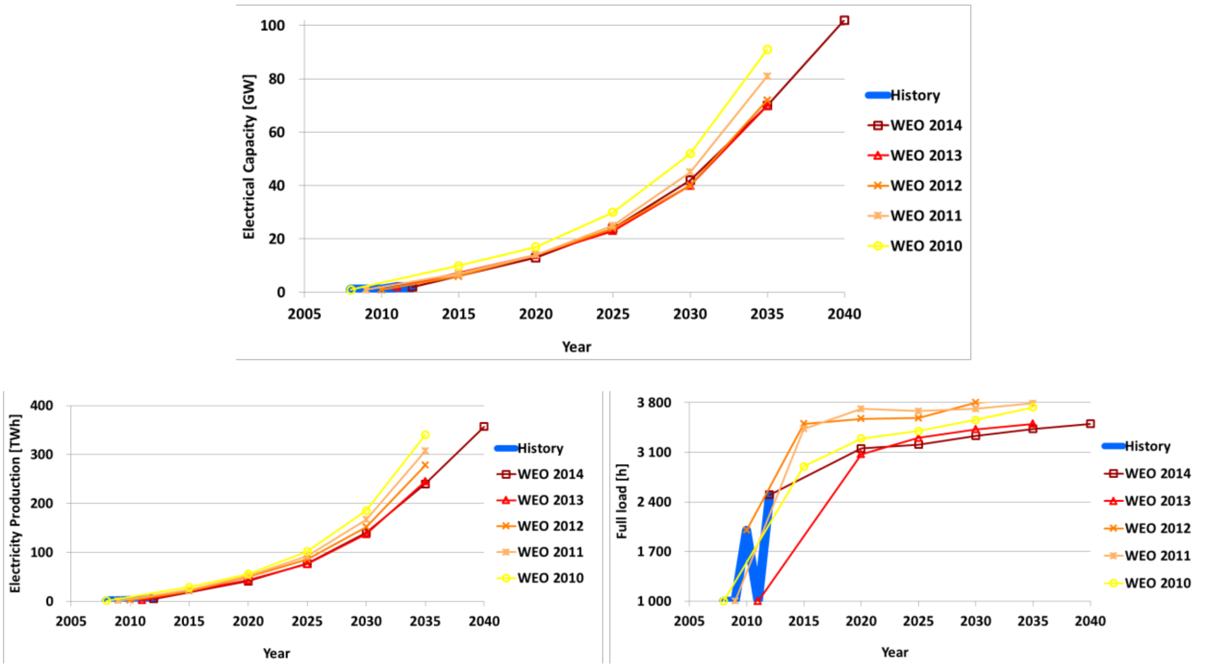


Fig. 4: Solar CSP capacity (top), electricity generation (bottom, left) and solar CSP full load hours (bottom, right) for the years 2008 to 2040. The historical data are given for the years 2008 to 2012. The projections range from 2015 to 2040. Data are based on WEO 2010 to WEO 2014 [19-23].

3.5 Solar

From WEO 2010 onwards, the solar category does not exist anymore, but is split into PV and CSP categories. Below, diagrams (Fig. 5) have been reconstructed as follows: the WEO 2010 to 2014 data presenting solar PV and solar CSP have been added and combined with existing data from WEO 2002 to 2009 presenting only solar, representing the two technologies. Solar technology first appears in WEO 2002, which means that the first data give information for the year 1999. A database has been created from this first occurrence in 1999 up to projections for 2040. Data from Werner et al. [26] REN21 [78] complete the historical data with numbers for 2013 and 2014 for capacity. Electrical capacity and electricity production figures have roughly the same shape: However, the vertical axis of the electrical capacity diagram has been adapted in order to highlight the historical curve (top). On this very diagram, it can be seen that figures of WEO 2002, 2004 and 2006 are complete underestimates, since projections for 2030 were reached more than 20 years before. Even the three following WEOs (2008, 2009 and 2010) had been wrong by about 10 years in their projections. WEO 2010 is a good example of the low level of the real solar market insights of the WEO, since the historic 2011 installed capacity numbers had been already higher than the 2015 projections of WEO 2010. Development of solar technology took off around the year 2007 when it grew from 9 GW to 100 GW in 2012 after it took eight years to reach 9 GW laboriously. The WEO did not expect such a growth and the electricity production diagram proves it. The two most recent numbers confirm the trend observed and described above, extending the historical curve with a slope more progressive than the WEO 2014 curve. The highest difference between two projections concerns the year 2030 whereas WEO 2002 and 2012 forecast 56 GW and 689 GW respectively, thus a gap of an impressive 1230%. The figure showing full load hours is rather unstable, alternating peaks downwards and upwards. However, projections seem to support an overall increase of full load hours.

There seems to be three domains of awareness on solar technologies. The first is the early mentioning in WEO (2002 to 2007), which assumes only a very limited role in global power supply till 2030 of less than 100 GW. Then there is a transition period of the WEO (2008, 2009) in which the role of solar had been increased but not so substantially. Finally there is a third period of the WEO (2010 to 2014) in which the linear projections for 2030 to 2040 had been increased year by year. It is unclear what it will take to adjust the WEO projections to the insight level of the leading organisations in the world, since for the year 2030 they project 2478 GW (Greenpeace) [29], 1860 GW (Bloomberg) [30] and 1982 GW (RE experts of the IEA) [31, 35]; numbers about three times higher.

The constant linear growth assumption, i.e. no annual market increase, reveals to be the key assumption which needs to be adjusted to the real development. It seems that the solar market insight of the WEO has been very limited in the past and is still in the present. This does not reflect the dynamics of the solar markets around the world.

It is recommended to examine in another scientific study what the reasons for these false projections of the WEO in the solar sector are: systematic scientific assumption errors or additional institutional limitations. Since solar PV plays a central role in the fight against climate change, a wide civil societal discussion of the causes of the structural failure in the WEO projections is needed in order to avoid these failures in future.

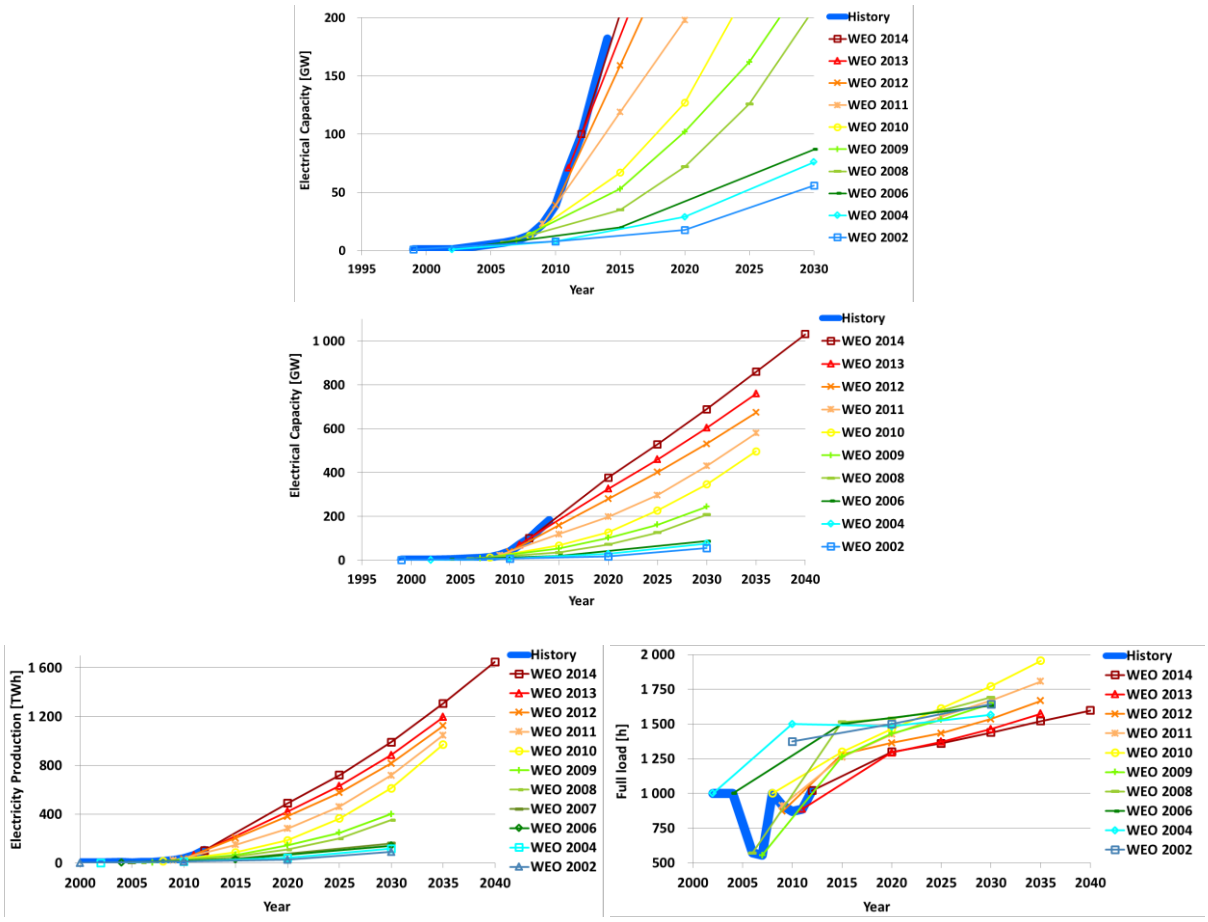


Fig. 5: Solar capacity (top and center), electricity generation (bottom, left) and solar full load hours (bottom, right) for the years 1999 to 2040. The historical data are given for the years 1999 to 2014 for electrical capacity, from 2000 to 2012 for electricity generation and from 2002 to 2012 for the full load hours. The projections range from 2010 to 2040. Data are based on WEO 2002 to WEO 2014 [13-23], Werner et al. [26] and REN21 [78].

3.6 Wind

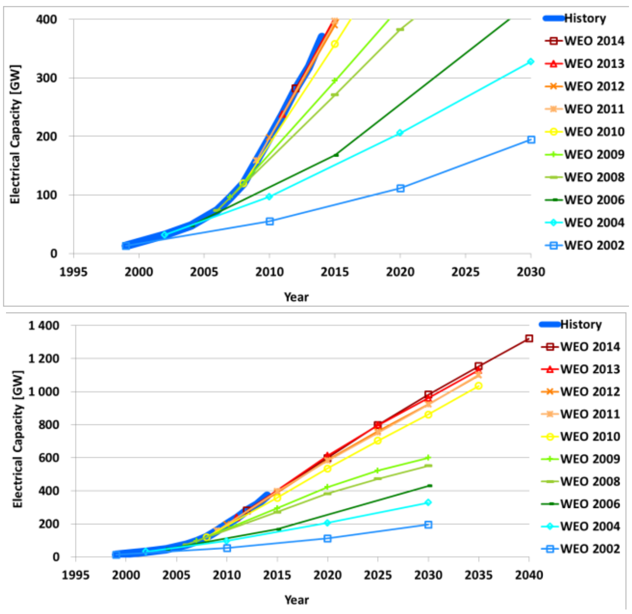
As with solar energy, wind energy was published for the first time in WEO 2002, which means that the historical curve starts from 1999 (Fig. 6). Wind energy presents the same particularities as solar energy, and a similar presentation can be found. The electrical capacity figure (Fig. 6) is focused on the historical curve (top), but also on future projections (center), while the electricity production figure gives an overall view of the situation. It can be seen that WEO 2002 projections are wrong from the very beginning, since the 2030 projections had been historically achieved in the year 2010, 20 years earlier and only eight years after publishing. The key reason for the misleading projections is the assumed linear growth, i.e. no annual market growth, instead of real exponential growth, i.e. annual market growth This is quite similar to the key projection error for solar PV. Real wind capacity in 2010 is respectively higher, i.e. 260% and 104%, than WEO 2002 and 2004 projections for the same year. Historic data for the years 2013 and 2014 coming from the REN21 report [78] for wind energy do not show a deviation of the historic data to the latest projections. It can be noticed that there is an inflexion point around 2009, where the annual growth before was 24 GW (or less) and 39 GW (and more) after, mainly accelerated by installations in China. On the diagram showing the generated electricity, the three trends observed previously for solar energy can be seen. But this time WEO 2002 forms a group itself. The second group spans the reports from 2004 to 2009 and the third the ones from 2010 to 2014. Despite a decrease in the full load hours in 2009, the trend is clearly upward as well as for historical data and for projections. Historic numbers show that the full load hours of wind energy are about two times higher than for solar PV, and projections assume roughly 80% higher full load hours, which is mainly driven by the fact that wind plants can harvest energy 24 hours per day and PV systems only during the daylight.

The leading international institutions on RE projections expect for the year 2030 wind energy capacities of 2908 GW (Greenpeace) [29], 1318 GW (Bloomberg) [30] and 960 GW (RE experts of the IEA) [40], which is in line with the WEO expectations. Bloomberg projects about 30% higher numbers, but the Greenpeace numbers appear unrealistically high, in particular in relation to their own projections for solar PV of 1764 GW, since the growth rates of solar PV are typically higher than those of wind energy. The relative growth ratio of solar PV and wind energy appears in line with the historic records for the projections of Bloomberg and RE experts of the IEA.

As far as the future WEO wind energy projections are concerned, we may assume that they will be significantly below the real growth rates. In the past, incorrect WEO projections already caused big problems for energy companies. Most companies want to achieve usual return rates of 10-20%. Yet, investments in renewable energy often allow only 5-10% return rates, which due to a significantly lower risk profile are accepted by many investors as sufficient. However, many energy companies showed a very limited propensity to invest in renewable energy and continued investing in conventional power plants. Since the WEO projections were wrong, the companies were not warned in time**.**

As a result, there were stranded investments in new nuclear power plants (on the side of state-influenced or state-owned enterprises, such as Flamanville in France or Olkiluoto in Finland) and many more in the fossil sector (both public and private companies), with significant economic dislocation and unnecessarily high CO_2 emissions.

Summing up, the WEO projections of the early 2000s had been as comparably wrong for wind energy as those for solar PV. The same linear growth assumption, instead of the real exponential growth such as that witnessed for solar PV, leads to rather low projections for the decades to come. The projections of leading international institutions do not show a consolidated picture and are partly rather close to the recent WEO projections.



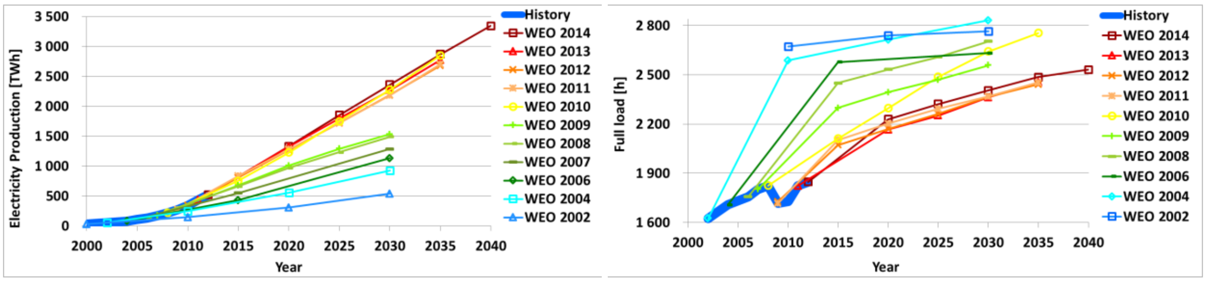


Fig. 6: Wind capacity (top and center), electricity generation (bottom, left) and wind full load hours (bottom, right) for the years 1999 to 2040. The historical data are given for the years 1999 to 2014 for the capacity, from 2000 to 2012 for the electricity generation and from 2002 to 2012 for the full load hours. The projections range from 2010 to 2040. Data are based on WEO 2002 to WEO 2014 [13-23] and REN21 [78].

3.7 Hydro power

Hydro power is the most used renewable electricity source, contributing to around 20% of total installed electrical capacity. However, its relative share is slightly decreasing due to faster growth of other power technologies. In 1997, hydropower represented 23% of the total global installed capacity, whereas the last WEO report shows that this share has been decreased to 19%. Nevertheless, as it can be seen on the diagrams below that both electrical capacity and generated electricity have continued growing (Fig. 7). The capacity has even been increased by 50% in 15 years, equivalent to about 350 GW, mainly driven by massive investments in China. Unlike wind or solar energy, hydro power developed linearly, i.e. more or less stable annual capacity additions and projections reflect this continuity. Projections are rather well matched by historical data proving that this technology is stably growing and well known. A light difference is observable in each figure for the oldest report (first half decade after 2000 for capacity and the report published before 2000 for generated electricity) that has been either overestimated or underestimated.

The full load hours show a rather stable historic development, which is assumed to stay within a range of natural fluctuations for the decades to come.

Summing up, hydro power showed a stable growth for the reported years of the WEO, while the relative share is shrinking. No significant deviations from historic development and projections can be recorded. The full load hours have been rather stable and are expected to stay stable in the decades to come.

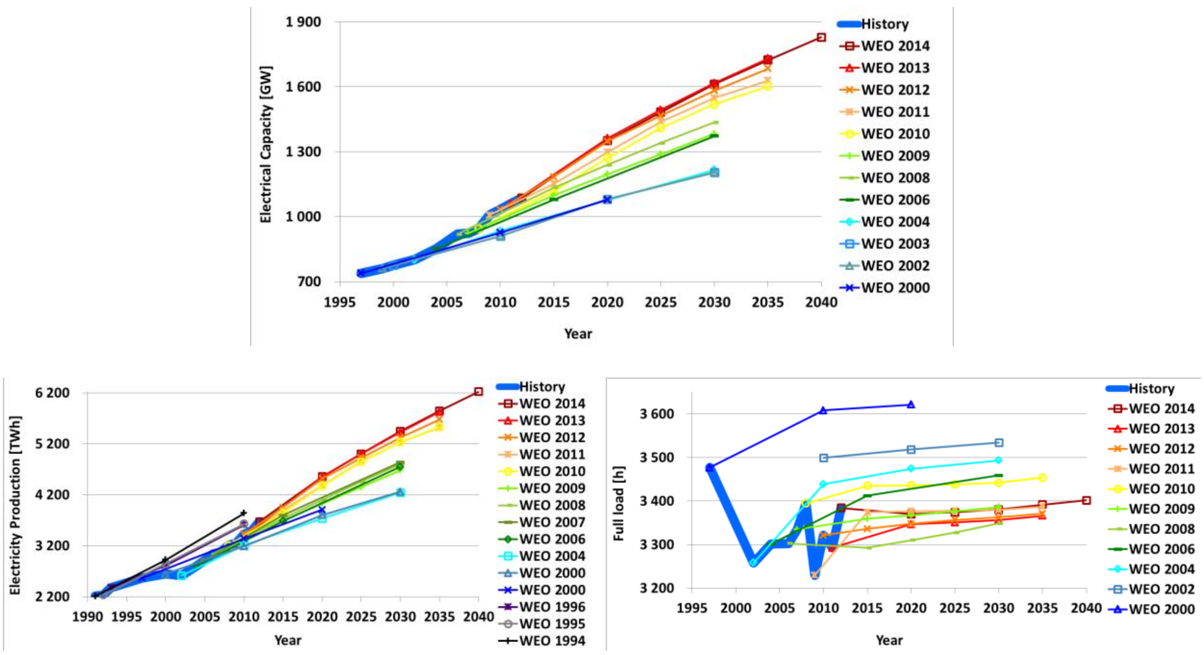


Fig. 7: Hydro capacity (top), electricity generation (bottom, left) and hydro full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1991 to 2012. The projections range from 2000 to 2040. Data are based on WEO 1994 to WEO 2014 [3-23].

3.8 Bioenergy

The historical curve's shape is extremely similar for both electrical capacity and electricity production (Fig. 8): figures increase slowly until 2009, going from 35 GW to 53 GW in 10 years, from 167 TWh to 288 TWh in 9 years, and are respectively multiplied by a factor 2 and 1.5 in the following 3 years. In both cases, projections for 2010 are a bit below the real numbers but remain realistic. This contrasts with further projections (2015 and 2020), which have already been reached. Whereas the projections for electrical capacity follow a regular increase year after year, the ones regarding electricity production are more diversified. Four trends can be distinguished, the first formed by WEO 2000 and 2004, the second by WEO 2006 to 2009, the third by reports from 2010 to 2012 and the last by WEO 2013 and 2014. The two first trends evolved linearly with a bigger slope for the second while curves for the third trend follow a parabolic profile. But in the two most recent WEO reports the projections were changed again and are now reduced again to the previous projections of about 250 GW for the year 2035, now assuming a linear growth. As a consequence, until 2030 WEO 2010 to 2012 projections are above those for WEO 2013 and 2014. For the same year a factor of two separates the highest and the lowest projections regarding electricity production. The leading institutions for RE projections have a very consolidated view for 2030, since they project capacities of 265 GW (Greenpeace) [29], 260 GW (Bloomberg) [30] and 270 GW (RE experts of the IEA) [41].

A drastic decline has happened in full load hours from about 6100 to about 4400 within the ten years from 2002 to 2012. This decrease may be mainly caused by the investments in combined heat and power (CHP) plants in some countries, which are mainly operated in a seasonal manner, hence reducing the average full load hours drastically. Thus, biomass is increasingly complementing solar and wind power, due to its ability to satisfy power demand during weather-related slump times.

Summing up, bioenergy witnessed stable growth in new installations from 1999 to 2009 and significantly higher new installations in the years after. Again, it appears that the WEO underestimated actual growth trends in the field of renewable energy. As in the case of solar and wind industries, the WEO possibly lacks sufficient monitoring instruments in the biomass sector or sensitivity to new sudden developments in the renewable energy sector. In any case, the WEO projections in 2009 did not foresee that the installed capacity of biomass-based generation would double by 2012, compared with 2009. Given the usually long processes of planning and construction, which should allow for reliable mid-term projections, miscalculations of the WEO are difficult to understand.

Leading international RE market organizations expect for the year 2030 capacities of around 260 GW, which are projected by the WEO for approximately five years later. WEO projections are still lagging considerably behind leading international RE market organizations. Due to a more seasonal operation of bioenergy plants, the full load hours have reduced by about 30% in the last 10 – 15 years.

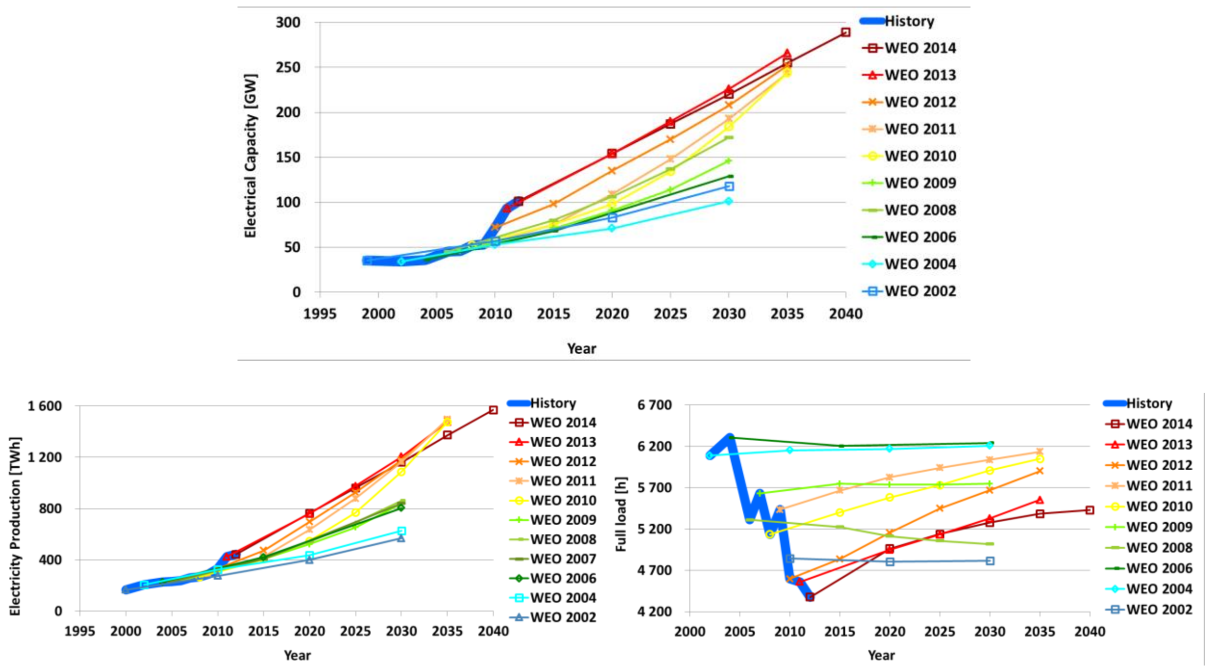


Fig. 8: Bioenergy capacity (top), electricity generation (bottom, left) and bioenergy full load hours (bottom, right) for the years 1999 to 2040. The historical data are given for the years 1999 to 2012 for electrical capacity, from 2000 to 2012 for electricity

production and from 2002 to 2012 for full load hours. The projections range from 2010 to 2040. Data are based on WEO 2002 to WEO 2014 [11-23].

3.9 Geothermal

Geothermal energy has barely evolved over the last decades (Fig. 9). Since 1999, 3 GW have been installed in addition to the 8 GW already existing, which brings the total capacity to 11 GW. A similar progress is visible for the electricity production figure. Estimations of the WEO have significantly changed since 2010. Two different trends can be observed in both figures. Reports before 2010 projected a slow and linear increase of the capacity and the production while reports from 2010 till 2014 forecast a higher expansion of the capacities. The projected installed capacity for the year 2030 had been increased by about 30% from WEO 2009 to WEO 2010 and has remained stable since then. Nevertheless, all projections in both groups are rather close to one another.

The leading institutions for RE projections do not have a consolidated view for 2030, since they project capacities of 219 GW (Greenpeace) [29], 40 GW (Bloomberg) [30] and 45 GW (RE experts of the IEA) [42].

The historic data showed a significant variation in full load hours, however future expectations converge at about 6600 to 6800 full load hours.

Summing up, geothermal plants show a rather negligible contribution to the current power supply and there seems to be a rather consolidated view on that to remain, except from Greenpeace, which projects an acceleration in new installed capacities in the decades to come.

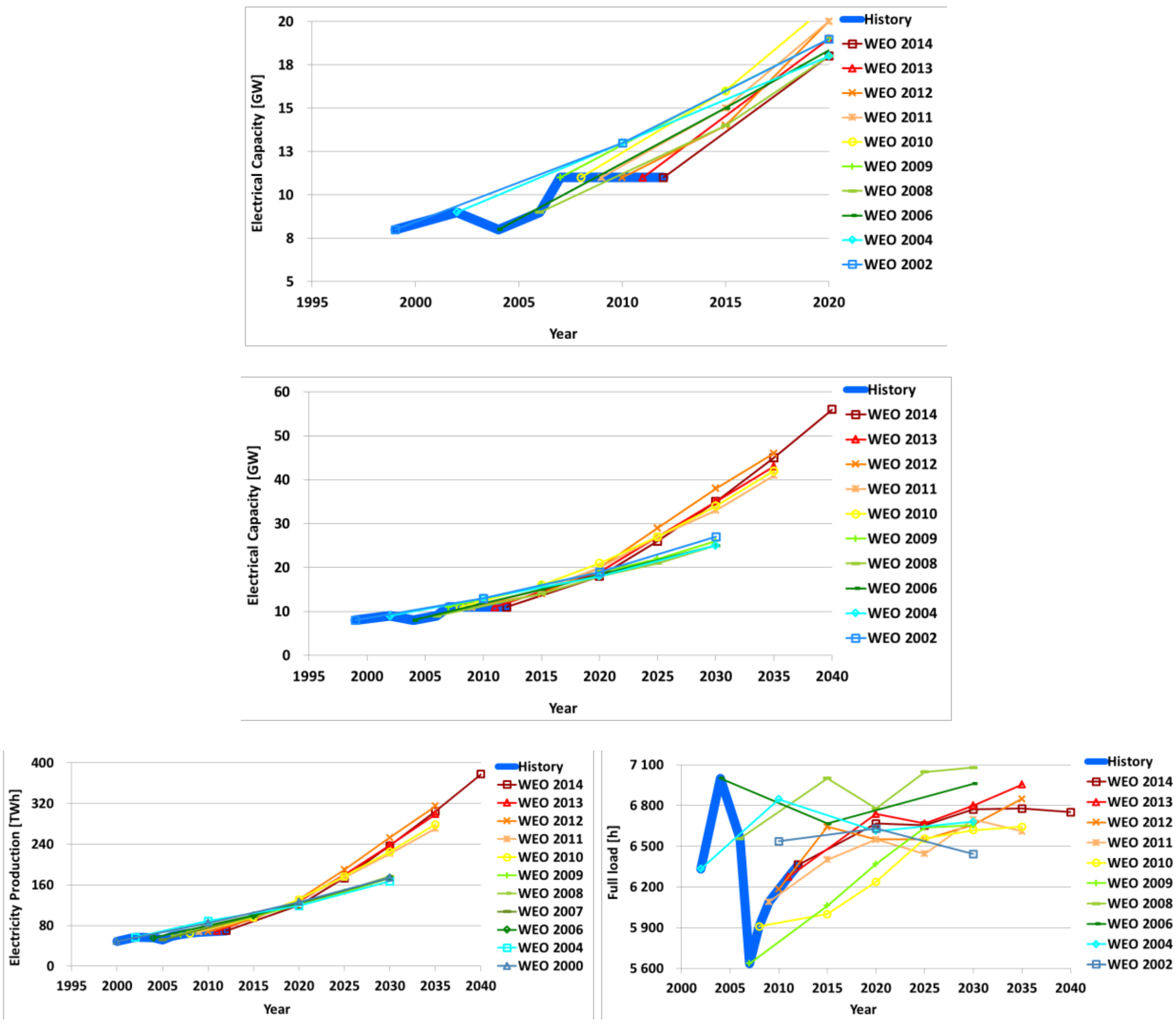


Fig. 9: Geothermal capacity (top and center), electricity generation (bottom, left) and geothermal full load hours (bottom, right) for the years 1999 to 2040. The historical data are given for the years 1999 to 2012 for electrical capacity, from 2000 to 2012

for electricity production and from 2002 to 2012 for full load hours. The projections range from 2010 to 2040. Data are based on WEO 2002 to WEO 2014 [11-23].

3.10 Marine/ Ocean energy

Marine energy, also called ocean energy, has a very large untapped resource base. However, the technology is at its early stage of maturity. This is why the global installed capacity is low (Fig. 10). Until WEO 2013, the reported electrical capacity was equal to 0 GW, even if the real installed capacity reached some hundred MW, as the generated electricity diagram shows it (1 TWh is produced each year since 1999). Due to the low level of installed power plants, the historical curve does not bring much information, yet projections show an exponential growth in the years to come. Why the WEO shows exponential growth for ocean energy, but not for exponentially growing technologies, such as solar PV and wind energy, remains unclear. The capacity figure (top) shows that the reports are rather in agreement for the whole period. Figures regarding electricity production are a bit more divergent. While capacity projections for the year 2035 (this concerns only WEOs from 2010 onwards) vary between 13 GW for WEO 2014 to 17 GW for WEO 2010, so a difference of 30%, the ones regarding the electricity production go from 36 TWh for WEO 2014 to 63 TWh for WEO 2010, so a variation of 75%.

From the leading institutions for RE projections only Greenpeace reports ocean energy capacities, expecting 176 GW [29] by 2030.

The future expectations for the full load hours vary between about 3000 to 4000 full load hours in WEO 2010 to 2014.

Summing up, ocean energy is an emerging power technology with substantial potential. Future projections on the role of ocean energy differ strongly between the WEO reports and Greenpeace.

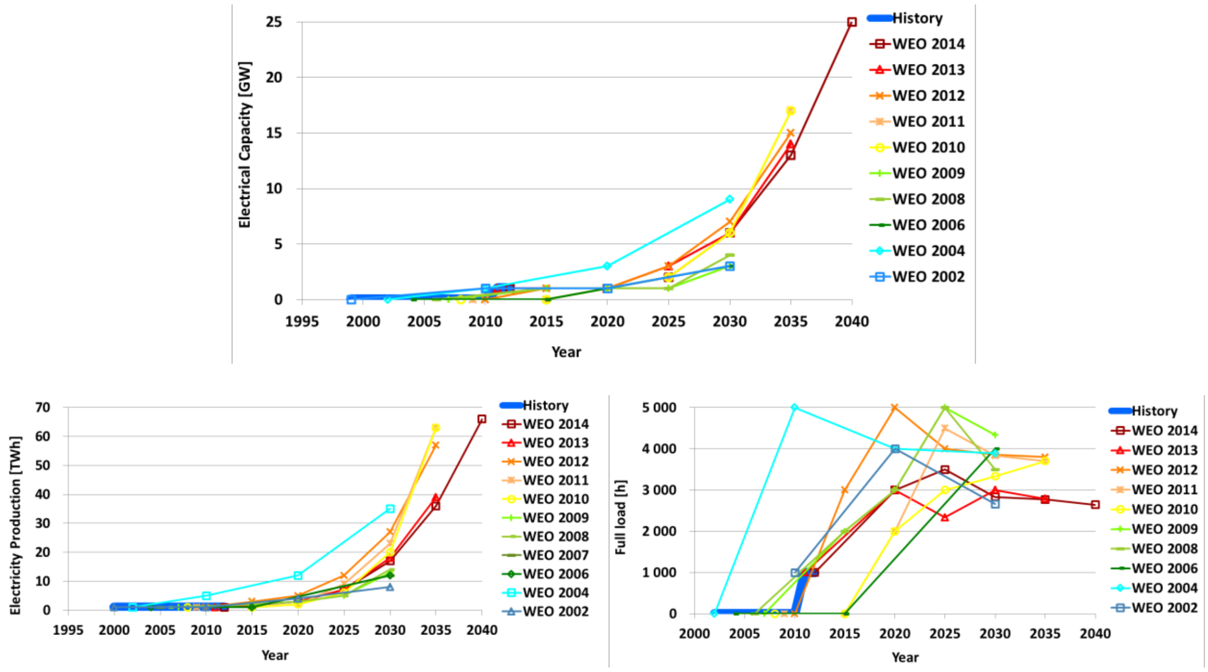


Fig. 10: Marine capacity (top), electricity generation (bottom, left) and marine full load hours (bottom, right) for the years 1999 to 2040. The historical data are given for the years 1999 to 2012 for electrical capacity, from 2000 to 2012 for electricity production and from 2002 to 2012 for full load hours. The projections range from 2010 to 2040. Data are based on WEO 2002 to WEO 2014 [11-23].

3.11 New Renewable Energy (excluding hydro power)

Until WEO 2004, renewable energy was a category by itself, excluding hydro. Thus from WEO 2006 (WEO 2005 does not give figures for the world) onwards, hydro power, wind energy, solar technologies, geothermal, bioenergy and marine energy have been summed to create the category of new renewables excluding hydro power, as it had been before. The first data for electrical capacity are from 1999 whereas the ones regarding electricity generation are known since 1991 (Fig. 11). Solar and wind constitute more than 90% of the capacity.

The electricity generation figure (bottom, left) clearly reveals three phases of the WEO in taking new renewable energy options into account:

- In the first phase (WEO 1994 to 1999) RE did not play any relevant role, since projections for 2010 had been for about 160 – 190 TWh (in reality 776 TWh had been achieved, four to five times more). Comparison of projection and reality clear show that in the mid-1990s the WEO assumed no relevant market progress of any new RE technology. This is indeed surprising, since at least wind energy had been already installed at stable growth rates, as annual installations grew from about 2 GW (1991) to about 6 GW (1996) and the three largest markets had been the US, Germany and Denmark.
- In the second phase (WEO 2000 to 2009) RE had been accepted as an energy option but only in a very limited amount. The 2010 projection of WEO 2000 had been exceeded already in the year 2005 and the 2020 projection had been exceeded in mid-2009, more than ten years earlier. The 2020 (1802 TWh) and 2030 (2962 TWh) projections of WEO 2009 are expected by Bloomberg [30] already in the year 2015 and 2019, respectively, and their projections for the year 2030 is 6829 TWh, which is 130% more. It is really surprising that all WEOs in the 2000s did not really reflect the enormous potential and growth rates of new RE, since in that decade both major new RE technologies, solar PV and wind energy, had very high growth rates, driven by many countries focussing on RE. For the case of wind energy the first countries realised it as their least cost electricity source. China started large scale wind energy installations in the 2000s and huge PV manufacturing capacities had been established in the second phase of the 2000s. Moreover, climate change had been finally recognised as the major threat for the human civilization [43]. Last but not least, more and more evidence had been gathered that peak-oil, peak-gas, peak-coal and peak-uranium may be real issues [24, 25]. Still, all this did not change the fundamental view of the WEO towards a substantial reassessment of the real low cost options, the new RE technologies.
- In the third phase (WEO 2010 to 2014) the new RE projections have been adjusted to higher numbers but still not accepting the fact of exponential growth, i.e. it is still not assumed that the annual markets for the new RE technologies would grow, completely ignoring the facts of the previous 25 years, in which the new RE electricity generation grew on a cumulated average growth rate (CAGR) of 17.1% for the years 1991 – 2012. In addition, for the same period on a year over year (YoY) basis in most of the year the growth rate had been between 10-20% and for two years had been higher and for four years lower. The CAGR for the years 2006 – 2012 shows a value of 17.4%, i.e. slightly higher than for the years 1991 – 2012, which means that in the recent years the exponential growth rate stayed fully stable, as for the last 20 years. Assuming a stable CAGR till the year 2030 would lead to an annual new RE electricity generation of 19,600 TWh, which is four times higher than the projected 4,768 TWh of WEO 2014 and still 2.9 times higher than the Bloomberg expectation [30]. However, it is still not more than 58% of the projected total electricity generation and only 10% of TPED. To solve the climate change threat the power sector needs to be shifted to RE as soon as possible and TPED needs also to be decarbonised as soon as possible, in particular in the mobility sector, where electric vehicles may play a substantially more relevant role, but also in the heat sector, where electric heat pumps may offer very good solutions, and last but not least in the industrial sector, where hydrocarbons from currently emerging power-to-gas/power-to-X technology can fully and in a sustainable way substitute for fossil fuels. All this is no wishful thinking, since more and more research articles are published which state that a 100% RE supply costs roughly the same or even less than the current fossil-nuclear based energy system [44, 45, 46, 47]. In summary, the difference in the WEO-assumed linear growth to the exponential growth being based on the facts of the last 20 years leads to projections of 14% (linear) and 58% (exponential, based on 20 years average) generation shares of new RE technologies in the year 2030. Most interestingly, in the latest WEO 2015 Special Report on Energy and Climate Change [77] it is stated that the CAGR for the new capacity additions of the new RE technologies (without hydro power) had been 17.4% from 2001 to 2014 and including hydro power still 15.1%. In other words, it is known within the WEO quite well how the growth pattern looks, and how stable it is, but still no adjustment of the future projections to the correct growth pattern has been made.
- Obviously, a fourth phase is still missing, in which the WEO would start to accept that the least (societal) cost source of electricity, new RE technologies, grows exponentially and that it need to become the key source to fix all the main energy-related problems we are facing currently.

This analysis cannot answer the question of why the IEA repeatedly ignores the exponential, or erratic growth of renewable energies: solar, wind and biomass. It is evident that the WEO does not learn from its past mistakes. This is all the more astonishing considering that many independent analysts were more correct in their projections of the successful expansion of renewable energies than the WEO. Only analyses of the companies in the conventional energy industry (BP, Shell, Exxon Mobil, ConocoPhillips, nuclear industry) were as similarly low as the forecasts of the IEA [88, 89, 90, 91, 92, 98, 99].

Forecasts influence investment decisions. The projected low growth of renewable energy for decades is used to justify the need for investments in conventional energy sources, because otherwise power supply cannot be guaranteed.

Incorrect WEO projections might be explained not by scientifically deficient assumptions, analyses and methodologies but by the institutional constraints of the IEA [93, 94]. The WEO reports have to be approved by the OECD governments. Government revenues of many large OECD countries depend fundamentally on the business development of the conventional energy industry. It would be therefore a worthwhile task not only for the scientific community but also for civil society to investigate potential political and business dependencies of the IEA publications.

If this hypothesis was confirmed, then the IEA with its WEO would have contributed significantly to a dramatic increase in recent decades in investments, particularly in coal, but also in oil and gas. That would mean that the IEA shares the responsibility for a substantial and rapid rise in greenhouse gas emissions in recent decades.

Summing up, the IEA keeps ignoring the exponential, growth of new RE, such as solar and wind, and does not learn from its past mistakes. Most independent analyses are more correct in their projections of the expansion of new RE than the WEO. Only analyses of the companies in the conventional energy industry were similarly low as the projections of the WEO. The WEOs since 1994 can be grouped into three phases, which could be called: New RE? - Never heard (phase one), New RE? – Exists but not relevant (phase two) and New RE? – Relevant but not the key to fix energy (security) problems (phase three). Still missing is the phase four: New RE? What other options are available for a sustainable energy supply?

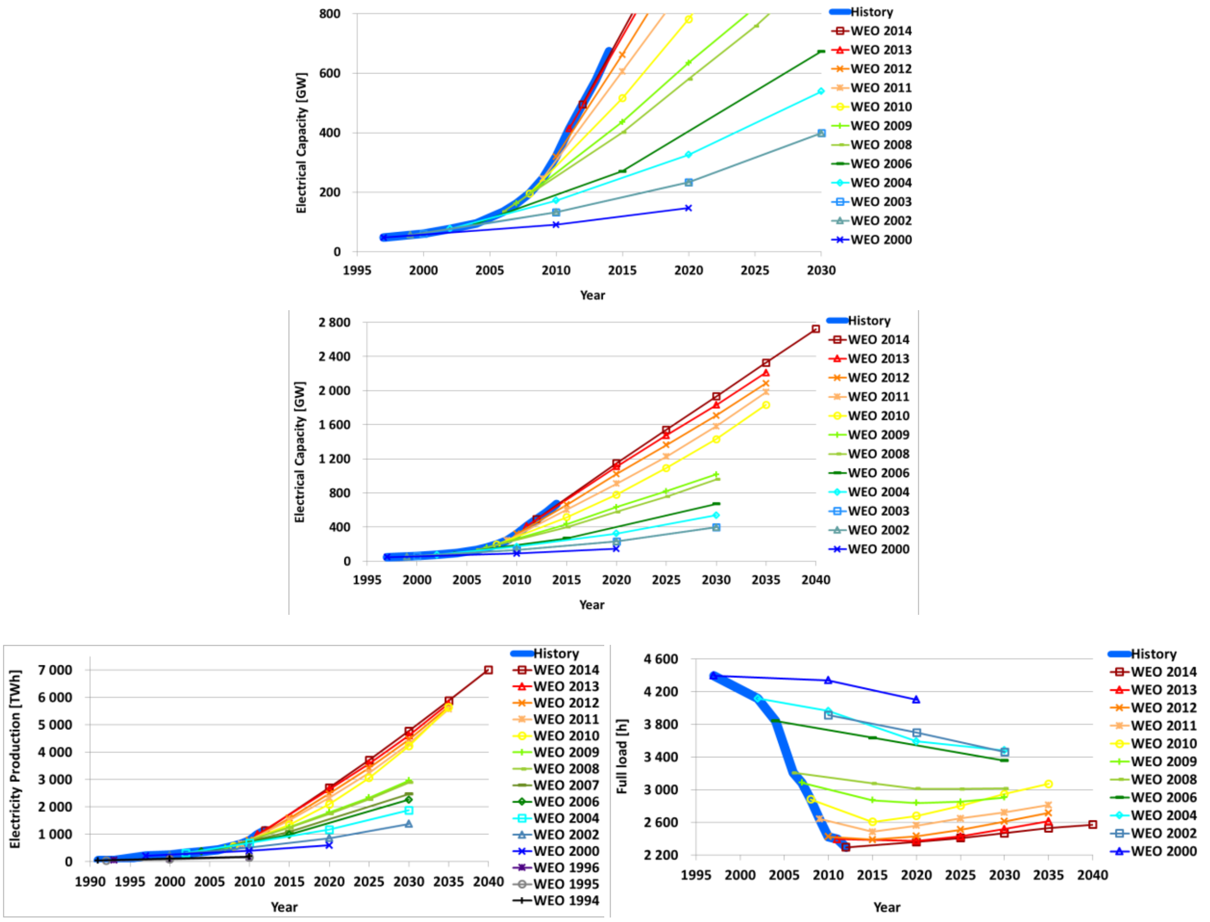


Fig. 11: New renewable capacity excluding hydro power (top and center), electricity generation (bottom, left) and renewable full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2014 for electrical capacity, from 1991 to 2012 for electricity generation and from 1997 to 2012 for full load hours. The projections range from 2010 to 2040 for both electrical capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [3-23], Werner et al. [26] and REN21 [78].

3.12 Coal

Coal-based generation keeps proving its importance in our actual energy system, representing up to a third of overall electrical capacity. Between 1997 and 2012, the capacity went from 1030 GW to almost 1805 GW, i.e. an increase of 80% in 15 years. Yet, its percent regarding global capacity for electricity production remained stable. With reference to the electrical capacity figure (Fig. 12), three trends can be observed. The first one concerns WEOs of the first half decade of the 2000s, since they predicted a growing relevance of coal while the other trends show a less and less steep increase. However, no stabilization or revised trend of coal capacities is projected, which seems to be very odd in the reality of climate change. Projections of the first trend for the year 2010 had been far below reality with an average error of 350 GW, so 21%, below the historical figure. The second and third trends are composed of the second half decade of the 2000s (green gradation) and by the WEOs published in 2010 and onwards (red gradation). The second group foretells a linear growth whereas the slope of the third group is lower in its linear growth. It can be noticed even if the difference between the first group and the second/ third is significant until 2020, all the projections for 2030 are rather close. The electricity production diagram is similar to that for electrical capacity. Main differences are a flatness among historical figures from 2007 to 2009 before a new significant increase of the production and contrasts between groups described above. The first and third group are closer while the second is distinct. Projections of the first and third groups for 2030 become even mixed up.

The full load hours show an increase from the mid-1990s to the mid-2000s from about 5200 to 5700. However, since the mid-2000s the full load hours declined to about 5100 and are expected to decline further to a level of about 4600.

An impact of the climate change debate on the projected coal capacities can be observed, but still not at a substantial level, since this would lead to a decline in coal capacities. Other relevant factors intensify need for a decline. The first key factor is that coal is a major source of greenhouse gas emissions and carbon capture and storage (CCS) technology is no real help as it will be not available in the market before 2030 [48] and its efficiency is too low for a zero carbon emission requirement [1]. Secondly, coal caused tremendous social costs due to heavy metal emissions, which is very likely to cause the phase-out of coal due to too high social costs of pollution and health hazards [2,83,95,104,105,106,107]. Thirdly, the total level of subsidies of coal is very high [2], higher than the full cost of new renewables. Fourthly, investors are starting to terminate their investments in coal assets due to the previously mentioned reasons for avoiding stranded assets [49, 50]. Fifthly, the two dominating coal investors in the world, China and India, are currently shifting their electricity portfolio towards new RE technologies by pushing the largest solar PV and wind energy investment programs in the world. These major trends are not reflected in the WEO coal projections.

Even today, the WEO projections apparently ignore the economic development of coal despite increasing warnings and divestment of finance from the coal industry in the last years [2, 49, 50]. The recent examples include the Norwegian Government Pension Fund Global, The World Bank and the Bank of England [100, 101, 102]. China attempts to counter air pollution with reductions in coal consumption in Beijing [95], just like Ontario did before [83]. Despite all these examples, the WEO keeps projecting high growth in the coal industry. It remains to be seen whether the current warnings from the investors will be reflected in future WEO projections.

A strong indication that global coal demand will decline and will not continue to rise as the WEO predicts, was provided by recent extrapolations of the coal consumption of the year 2015. According to a recent UBS report [96] global traded thermal coal demand declined to an annualized 900 million tons per annum in 2015 after peaking at an annualized 1,000 million tons. For the years 2013 and 2014 a decline in 0.7% of global coal production has been reported [97].

In 2000 and 2002, the WEO had massively underestimated investments in the coal industry. This might have been a result of the above-mentioned disregard of the growth potential of renewable energies and their contribution to energy security. The example of China supports this assumption. The massive investments in renewable energy in China in recent years [78] prove that the past WEO misjudgement should be quickly and significantly corrected. The WEO did not consider enough the start of China's coal exit [95] and the country's rapid deployment of renewable energy technologies, which demonstrate the structural inadequacies of the latest WEO projections.

Summing up, slightly downward grading of the coal projections can be observed, but the major trends against a substantial increase in coal capacities in the decades to come are not reflected in the WEO projections. The WEO ignores the recent trend of increasing measures to fight climate change and divestment of finance from the coal industry. The latest WEO projections also appear not to consider enough the recent developments in China, including its coming coal exit and rapid development of renewables in the last years.

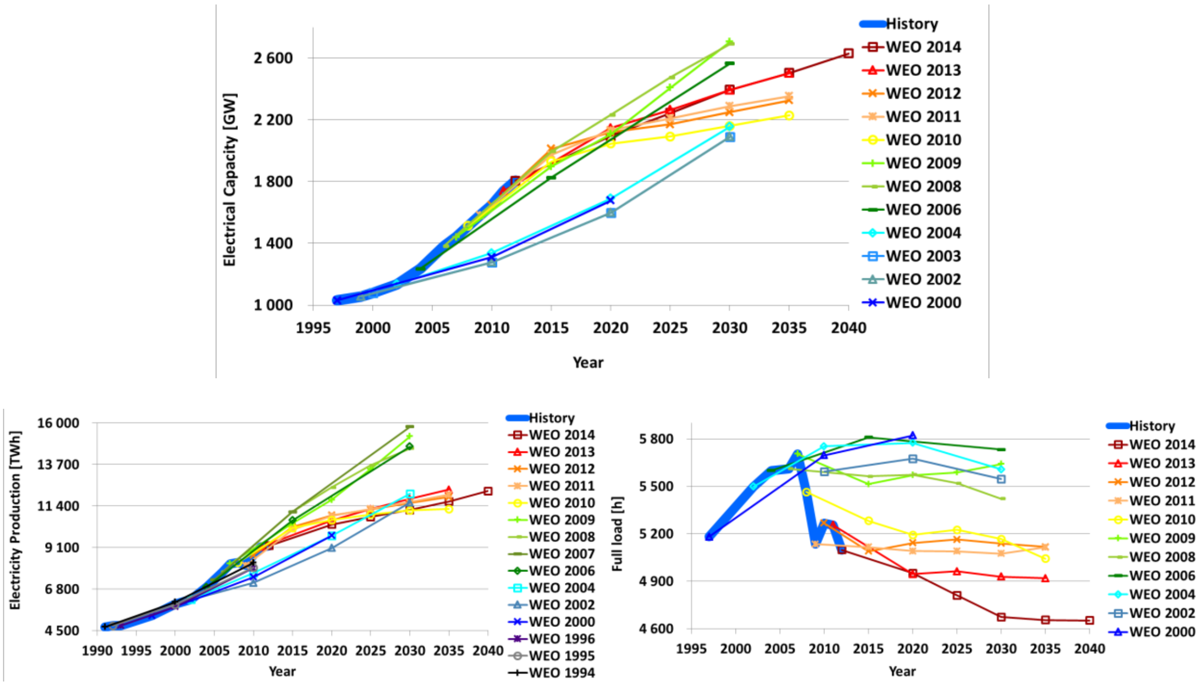


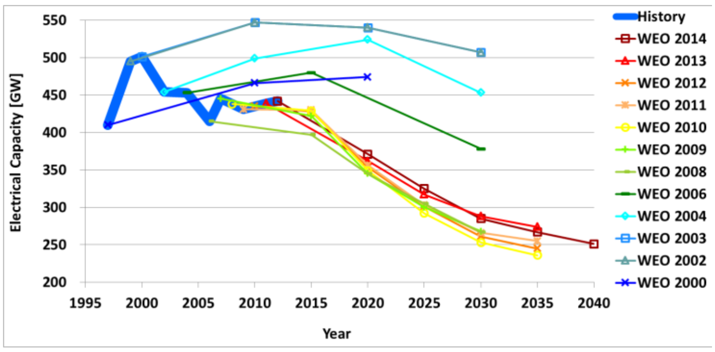
Fig. 12: Coal power (top), electricity generation (bottom, left) and coal full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2012 for both electrical capacity and full load hours and from 1991 to 2012 for electricity production. The projections range from 2010 to 2040 for both electrical capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [3-23].

3.13 Oil

Since 1991 oil-based electricity generation has been in decline, except the years after the Fukushima nuclear melt-down, which led to a temporary increase in oil-based power generation in Japan (Fig. 13). Oil-based power generation capacities had been expanded by nearly 25 % in three years, from 1997 to 2000, reaching a maximum capacity of 501 GW. Then followed a decrease during six years leading nearly to the same level as in 1997 (415 GW) before stabilizing at 435 GW. On the other hand, most recent WEOs predict a significant decrease for 2040 down to the half of the actual capacity. The highest difference between historical figures and projections for the year 2010 reaches 112 GW, or 25% more than the real number. Conversely, the electricity production diagram shows a different shape with a decrease from the years since 1991, even in the late 1990s during the peak of the electrical capacity. Earliest WEO reports foretold a rather constant evolution of generated electricity to around 1300 TWh, whereas the latest WEO reports foretell a decrease down to 500 TWh in spite of the recent increase in 2011 and 2012 due to the Fukushima melt-down. The consequences are a significant decrease of the full load hours, which have been reduced by approximately 30% since 1991.

However, there were big overestimations of oil-based electricity in the WEO from 2000 to 2006. Perhaps these misperceptions are the result of the general overestimation of the IEA of the availability of (conventional) crude oil [25].

Summing up, the role of oil-based power supply is projected to be reduced at a comparable low level. The decreasing and low level of full load hours qualify oil plants as balancing and back-up plants.



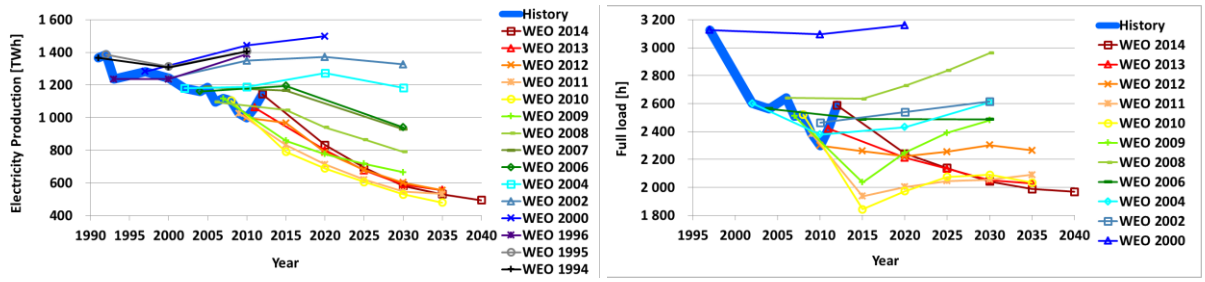


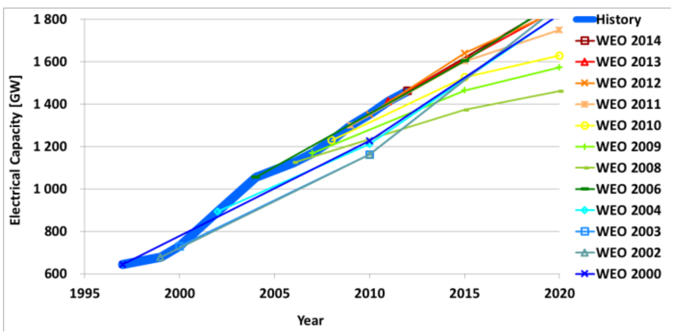
Fig. 13: Oil power (top), electricity generation (bottom, left) and oil full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2012 for both electrical capacity and full load hours and from 1991 to 2012 for electricity production. The projections range from 2010 to 2040 for both electrical capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [3-23].

3.14 Gas

Presently, gas represents, at 25%, the second most used resource for electricity production in terms of installed capacity. This share increased from 19% to 25% since 1991. The following diagrams (Fig. 14) prove that according to the WEO, gas will still have a strong role for the next decades. Although the overall capacity is planned to keep increasing roughly linearly, its contribution should remain around 25%. On both capacity and production diagrams it can be seen that all the projections are rather well matched in the past and for the future, as they are expected to extend the historical curve linearly. A slight deviation can be observed for WEO 2008, 2009, 2010 and 2011 for electrical capacity and WEO 2002, 2004 and 2006 for generated electricity, which moved lightly away from the general trend. The comparison respectively between the projections for both years 2000 and 2010 and the historical data given by WEO 2002 and 2012 shows that the evolution of the technology has been well managed until now and projections can be accounted as reliable for the past.

Gas power plant investments are not likely to end as stranded assets, unlike coal, since the burnt fuel shows less problems than coal. However, the CO_2 emissions still remain high, in particular for shale gas, and the zero carbon emission requirement is heavily violated. CCS is no help either, for the same reasons as for coal. But, for natural gas fired power plants, it is possible to shift the combusted fuel evolution from a fossil basis to a new, fully RE-based basis due to power-to-gas technology [51, 52] and biogas. All 100% RE energy scenarios take this emerging bridging technology into account [44, 45, 46, 47].

Summing up, gas power plants are on a stable growth trend for decades which is projected to be continued. The gas infrastructure is valuable due to the expected evolutionary shift from fossil to new RE-based fuel. This is not yet the view of the WEO, but of the research community focused on 100% RE supply scenarios.



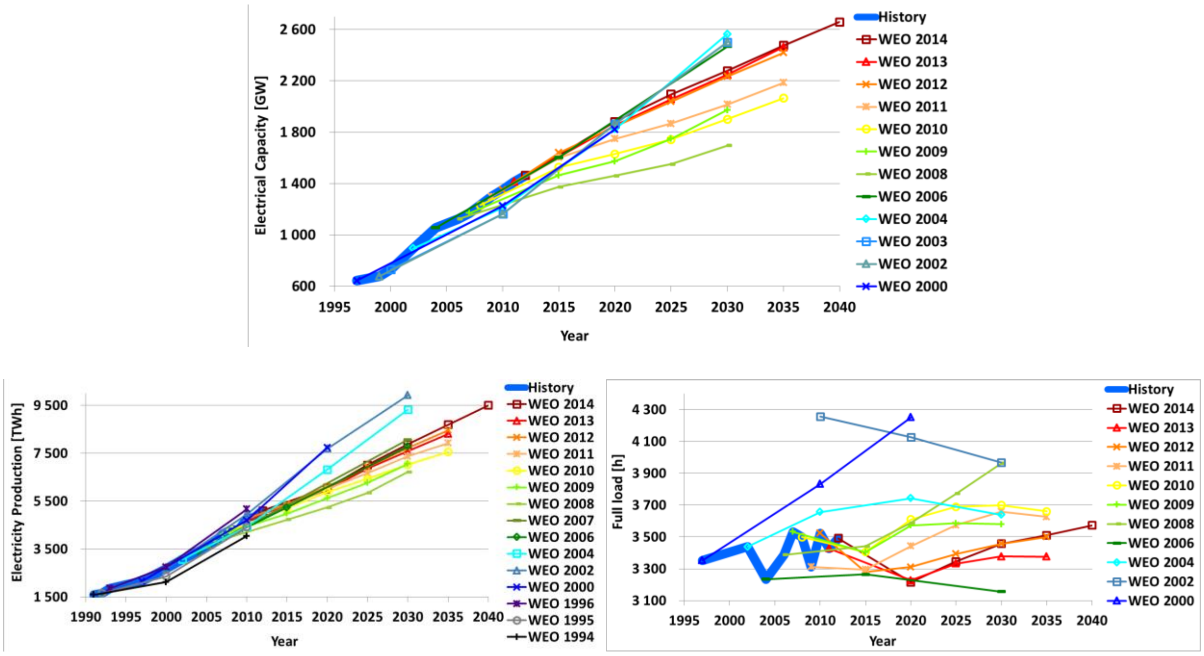


Fig. 14: Gas power (top and center), electricity generation (bottom, left) and gas full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2012 for both electrical capacity and full load hours and from 1991 to 2012 for electricity production. The projections range from 2010 to 2040 for both electrical capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [3-23].

3.15 Nuclear

Nuclear energy had been a dream in the 1970s to overcome fossil fuel dependence. This dream became a nightmare, in 1979 for scientists (Three Mile Island accident in Harrisburg), in 1986 for the broad public (Chernobyl), and for the remaining nuclear industry in 2011 (Fukushima meld-down). This development of the technology is partly reflected in WEO figures. In 1991 nuclear power plants represented 11% of global capacity producing electricity, compared to 7% currently. The generated electricity (Fig. 15) peaked in the relative contribution share in the year 1996, in absolute generation in the year 2006, and has been in decline since then. Nuclear capacity evolved over the years in three phases (top). The first one that ranges from 1997 to 2007 is characterised by a very moderate slope (plus 19 GW). The second phase that lasts a single year sees the capacity increase by 20 GW, reaching 391 GW, and the third phase remains constant (394 GW in 2012).

Three trends can also be observed regarding projections. The first concerns WEO reports published during the first part of the 2000s (blue gradation) that foretell a progressive decrease from 2010. The second trend, made up of the second part of the 2000s (green gradation) expects capacity to increase a bit. The last one made up of the 2010s foresees a considerable increase (plus 50% for 2035 compared to 2012 is expected by WEO 2010 and 2011). Thus, in spite of a stagnant capacity and production on the wrong slope, reports of the 2010s expect an astonishing increase, almost double for 2040 compared to 2012. This contrasts with all other power technologies in the WEO reports that were aligned with its historical curve. Although WEO reports from the 2000s were more or less far from reality regarding most of the others technologies, this time, WEO of the 1990s and 2000 have the best shot in projecting a decline.

Nothing fundamental has been changed since the 1990s on the technology, except growing evidence that sustainability cannot be achieved with this technology. Comprehensive analyses for the past decades show budget and time overruns of more than 100% are the usual outcome for nuclear [53]. Also, due to a negative learning rate of nuclear, the latest projects are higher in cost than previous ones [54]. The negligibly small liability insurance for nuclear power projects represents a major subsidy [55] and is difficult to argue for in a post-Fukushima world. Recent research on nuclear disaster risk concluded that there is a 50% chance of a Chernobyl-type event occurring in the next 27 years [56]. This results in very challenging economics for nuclear energy being competitive in the future with solar and wind energy in Europe [57, 58]. Solar PV and wind energy have been taken much more seriously for a zero carbon and low cost electricity supply in the previous 15 years, as documented well by the world and in particular China, and the same pattern can be now expected for India [59].

The recent WEO projections suggest an expansion of about 10 nuclear reactors a year with the capacity of 1 GW each in the next decade. In what way this expansion is to come, is a mystery, given a few commissioned and financed construction projects in Europe and the Americas [59] and especially given the 100-200% budget overruns over the planning costs and delays in the commissioning plans [84]. There are signals that the only two new European nuclear projects of this decade (Olkiluoto, Finland and Flamanville, France), will be connected to the grid 10 years later than planned [59]. Whether the major expansion plans in Asia are realistic given the considerable problems in Europe, the Americas and Japan, needs to be analysed [59]. In any case, the optimistic WEO projections need to be questioned in light of the developments in Europe, the Americas and Japan.

Summing up, nuclear energy has been in decline in relative and absolute numbers for at least 10 years, further pushed by the Fukushima melt-down. The technology's inherent risk is a burden and the steady cost increase worsens its already poor economic status. The major economic areas in the world and the two largest emerging countries do not bet on nuclear, but on solar PV and wind energy. On that basis, why the WEO projects a substantial increase of existing capacities by more than 50% in the decades to come remains a well-kept secret, in particular since WEO 2000 to 2003 had already described well and correctly the decline of nuclear energy.

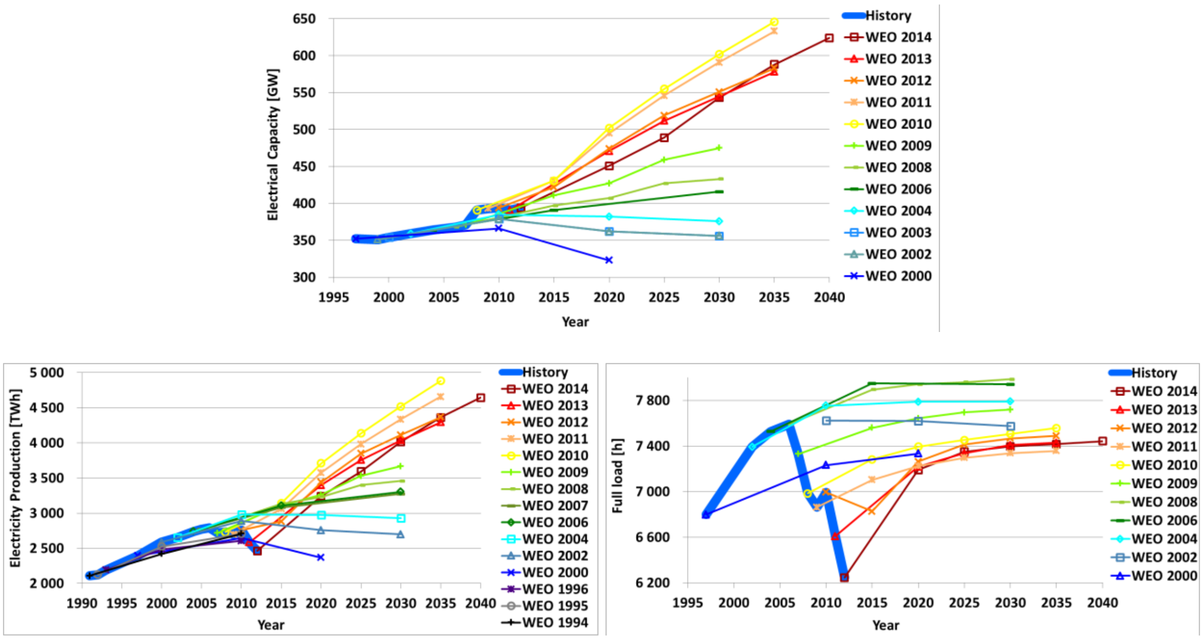


Fig. 15: Nuclear power (top), electricity generation (bottom, left) and nuclear full load hours (bottom, right) for the years 1991 to 2040. The historical data are given for the years 1997 to 2012 for both electrical capacity and full load hours and from 1991 to 2012 for electricity production. The projections range from 2010 to 2040 for both electrical capacity and full load hours and from 2000 to 2040 for generated electricity. Data are based on WEO 1994 to WEO 2014 [3-23].

4. Logistic growth for Renewable Electricity

This section is based on the discussion of long-term solar PV capacity demand in a world based on sustainable energy resources [60].

Further development of human welfare is at crossroads. For several decades humankind has needed the capacity of more than one planet Earth [61], whereas 50% is due to resource exploitation and emissions of the energy system. Diminishing energy fuels [25] have caused in the past and will cause in the future dramatic economic, social, political and military shocks. Poverty in the world needs to be tackled [62] not only for humanistic reasons but also for rebalancing the births and deaths annually in order to stabilize the world population. The world population is the key driver for global resource demand of humankind [63, 64], and experience of the last decades has shown that growing standards of living reduce population growth most effectively [65] and goes hand in hand with a fast increase in energy demand [66]. The only pathway to manage all these different major problems is a fully sustainable energy system which is able to cover an accelerated long-term demand for energy. The two key resources for very large-scale renewable energy (RE) harvesting is the wind resource and the direct solar resource. However, these resources will be complemented by hydro power, bioenergy, geothermal energy and ocean energy – each of these sources may account for about 5-

10% of the TPED for a world of 10 billion people living at today's energetic wealth level of Europe [67, 68, 69].

The Kaya identity [63, 64] describes well the demand for energy based on wealth (gross domestic product) and energy intensity, driven by the population. Assuming a good development of access to modern forms of energy, health services and education, the world population is assumed to stabilize at about 10 billion people [65]. An upper limit for energy demand by the year 2100 may be the per capita primary energy (PE) demand of today's European Union for all people in a population stabilized world. More and more researchers conclude that an efficient and least (societal) cost energy system will be based mainly on electricity, but the PE demand per capita may be stabilized at current levels of the well developed world [70-74]. A such derived long-term RE demand needs to be better understood in its temporal growth pattern, which can be done well by applying a logistic growth function (Eq. 1).

$$f(t) = A + \frac{K-A}{\left(1+Qe^{-B\cdot(t-M)}\right)^{1/v}} \qquad (1)$$

Eq. 1: Logistic growth function in generalized form. Abbreviations: time (*t*), lower asymptote (*A*), upper asymptote (*K*), growth rate (*B*), parameter affecting near which asymptote maximum growth occurs (*v*), scaling parameter depending on f(0) (*Q*) and time of maximum growth (*M*).

Estimates for a stabilized world population are in the median at about 10 billion people [65]. The primary energy (PE) demand per capita in the European Union is currently about 40 MWh_{th}/cap [23]. This leads to an estimated TPED of about 400,000 TWh_{th}. More and more researchers conclude that an efficient and least cost energy system will be based on electricity [70-74] but for the same order of PE per capita as today in the developed world, about 400,000 TWh_{el} might be needed.

If such a scenario became reality, then the RE power generation would have to grow by a factor of 14 (until 2050) and 80 (until 2100) to reach this proposed level of sustainability, as shown in Figure 16 and Table 1. The years of the highest annual relative growth in RE electricity generation would be in the decades of the 2020s to the 2050s with a cumulated average annual growth rate (CAGR) of about 7.7%, which would be not an unrealistically high growth rate since the CAGR of the period 2007 – 2012 had been already 6.1%. The additional RE electricity generation per year would grow in absolute numbers as a consequence of the stable CAGR from 293 TWh (2012), to 680 TWh (2020), 1410 TWh (2030), 2960 TWh (2040), 6130 TWh (2050), 10,200 TWh (2060 and 2070). The year of the highest absolute growth would be in the 2060s. The required installation numbers for solar PV and wind energy can be roughly estimated based on lifetime and full load hours assumptions and on the relevance of the two technologies, which may be in the order of 40% of new RE electricity generation each. This could lead to a steady increase of new installed capacity of about 158 GW and 109 GW (2020), 328 GW and 226 GW (2030), 688 GW and 474 GW (2040), 1425 GW and 981 GW (2050), 2373 GW and 1634 GW (2060 and 2070) for solar PV and wind energy, respectively. The annual installations would vary a bit in the following decades but due to the reinvestment demand they would be stabilized on an annual market of about 1600 – 2700 GW for solar PV and about 1600 – 1800 for wind energy. The total installed capacities could be very roughly estimated at about 3.0 and 2.1 TW (2030), 7.5 and 5.2 TW (2040), 17.3 and 11.9 TW (2050), 66 und 46 TW (2070) and 92 and 63 TW (2100) for solar PV and wind energy, respectively. These estimates are very rough numbers, but reasonable for the chosen assumptions. Neither solar PV nor wind energy is limited in resource potential to reach such numbers [67, 68, 69].

Realizing that the transformation of the energy system has to be considered seriously would lead to significantly higher projections of RE electricity generation than stated by the WEO reports, as projected by applying logistic growth functions (Eq. 1 and Fig. 16). Based on these results from data, it can be concluded that future projections for RE generation of WEO reports are structurally too conservative and limited in their relevance.

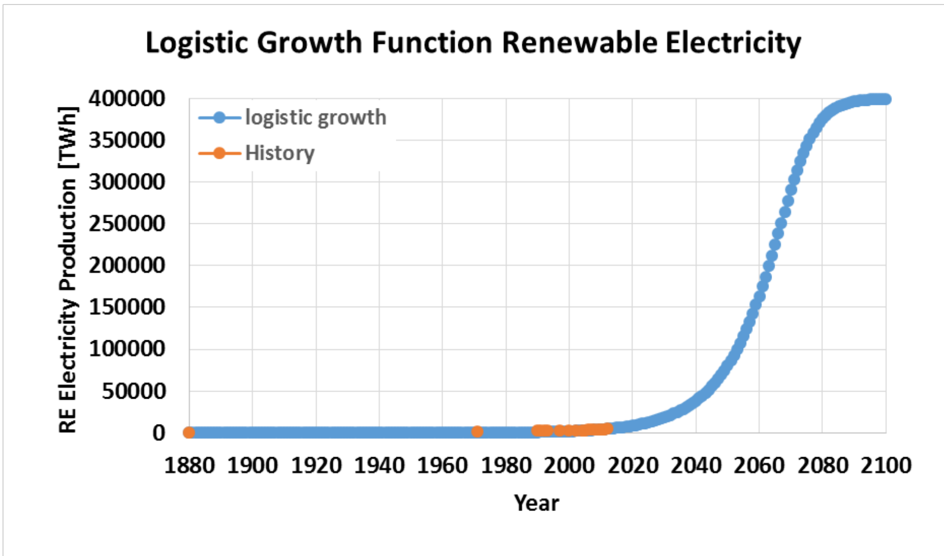


Fig. 16: Logistic growth for potential development of RE electricity production. The historic data [3-23, 75, 76] are plotted as well (orange). The parameters for the logistic growth function are according to Eq. 1: A (8 TWh), K (400000 TWh), B (0.2), v (2.7), Q (75) and M (2050).

Table 1: RE electricity generation. Tabled are the total annual generation based on Figure 16, cumulated average growth rate (CAGR) of the respective five previous years, additional RE electricity generation, new annual capacity requirements per year and total cumulated installed capacity for solar PV and wind energy. Assumptions: full load hours of 1721 (PV) [60] and 2500 (wind) [Fig. 6] and lifetime of 40 years (PV) and 30 years (wind).

	RE electricity generation	CAGR of previous 5 years	additional RE electricity generation per year	80% of new additional RE PV and Wind		80% of new additional RE PV and Wind (incl. reinvest)		total installed capacity for 80% of new additional RE	
year				PV	Wind	PV	Wind	PV	Wind
	[TWh]		[TWh]	[GW]	[GW]	[GW]	[GW]	[TW]	[TW]
2000	2899	2,20 %	64						
2005	3320	2,70 %	90						
2012	4808	6,10 %	293						
2020	8800	7,68 %	680	158	109	158	110		
2030	18400	7,68 %	1410	328	226	328	236	3.0	2.1
2040	38500	7,68 %	2960	688	474	688	521	7.5	5.2
2050	80400	7,62 %	6130	1425	981	1493	1090	17.3	11.9
2060	163800	7,22 %	10210	2373	1634	2531	1859	36.7	25.2
2070	290400	5,25 %	10210	2373	1634	2701	2107	66.1	45.5
2080	375500	1,78 %	3920	911	627	1599	1608	85.9	59.1
2090	396300	0,31 %	690	160	110	1585	1744	90.7	62.4
2100	400000	0,04 %	90	21	14	2394	1648	91.6	63.0

5. Summary

The International Energy Agency has a significant impact on both political and economic decisions of governments and stakeholders regarding energy. The WEO report published every year by the IEA estimates for the coming decades in the future how total primary energy demand and electricity generation, amongst others, will evolve for all major technologies. In this work, we analysed the potential difference between the real figures established by the newest reports and the projections of the earlier ones, as well as the different projections of each report since 1994 to 2014.

The projections for TPED (Fig. 1) and electricity generation (Fig. 2) seem to be in agreement with the global development observed until now.

The results show that projections for solar PV (in former WEOs named solar energy) (Fig. 3 and 5) and wind energy (Fig. 6) have been completely underestimated. The aggregated numbers for all new RE capacity excluding hydro power (Fig. 11) have been far from the real development witnessed due to ongoing underestimation, which is a consequence of wrongly assumed linear growth instead of logistic growth in reality. This shows in the current development phase, and may even for the next few decades, its exponential characteristic. Complaints about poor projection quality on PV are documented for the past [79], again most recently [80] and it can be expected for the future [29, 30, 81, 82]. The denial of exponential growth in the WEO reports is the key reason for the wrong projections. In the latest WEO 2015 Special Report on Energy and Climate Change [77], it is stated that the CAGR for the new capacity additions of new RE technologies (without hydro power) had been 17.4% from 2001 to 2014 and including hydro power still 15.1%. However, it remains unclear why this know error is not corrected in the WEO.

The projections for nuclear energy (Fig. 15) show significant deviations due to overestimations, except the estimates of the early 2000s. In spite of the Fukushima disaster, the most recent reports announce a tremendous upward trend. On the other hand, historic data show a significant decline approaching the WEO 2000 [9] projection.

The observed phenomenon for solar technology in particular and the group of new RE technologies (excluding hydro power) in general, that almost all reports' projections are reached a couple of decades before what was estimated by the WEO reports, as a consequence of wrongly applied growth pattern, can be clustered into three phases:

1. "New RE? - Never heard." (WEO 1994 to 1999)
2. "New RE? - Exists but not relevant." (WEO 2000 to 2009)
3. "New RE? - Relevant but not the key to fix the problems." (WEO 2010 to 2014)

However, the last phase is still missing:

4. "New RE? Which other options are available for a sustainable energy supply?"

Interestingly, Bardi [24] found very similar phases for the debate on peak-oil, which is a simple matter of geological facts, but still heavily denied.

Realizing that the transformation of the energy system has to be considered seriously and based on the megatrend of the shift to power would lead to significantly higher projections of RE electricity generation as projected by applying logistic growth functions (Fig. 16). The cumulated average growth rate for the years 2007 – 2012 reached already 6.1% and needs to reach about 7.7% for the decades up to the 2050s to follow the proposed logistic growth of RE electricity generation for a sustainable energy supply in the world. There are neither resource limitations known for an energy supply fully based on renewables nor technical limits, as a growing base of scientific publications show. However, a missing will of policy adaptation can be stated. The WEO could be of great help to signal a shift towards better policies.

The results of the analysis in this article may be a basis for governments to promote policies supporting renewable energies more than in the past and a much more aggressive climate change policy without concern for energy security. Because of progressively falling specific investment cost and increasing investments in renewable energy, one can expect a faster development of renewable energy than the WEO predicts. This is key not only for successful climate protection, but also for the economy. The faster renewables expand and replace conventional energy sources, the greater the financial turmoil and losses will be in the conventional energy sector. To avoid this, the world's governments are advised to consider the expansion of renewables well over the WEO predictions in their energy policies in order to avoid misperceptions and stranded investments.

Based on the results presented in this paper it can be concluded that future projections for RE generation of WEO reports are structurally too conservative and limited in their relevance. Furthermore, the model of the WEO for RE projections and its foundation on a structurally wrong growth pattern needs to be substantially reworked. However, policy-makers and investors may regard the WEO projections as lower limits for their worst case assumptions for ongoing global policy failure to tackle the energy-related challenges in the world. A survival strategy for a successful managing of the energy question needs substantially improved policy recommendations in the field of RE compared to the existing ones in the WEO.

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