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Limits to growth in the renewable energy sector

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ABSTRACT

It has been well documented that population growth, development of biological subsystems and the utilization of resources in ecology and economy frequently follow a logistic or sigmoid time-development. In the context of oil and gas extraction such development is known as Hubbert's peak oil theory. We observe that the logistic equation describes the historic development of nuclear and hydroelectric energy production as well. Previous studies have hypothesized that the present time fastest growing renewable technologies, wind and solar energy, will develop under similar constraints. Here, we provide evidence that the installation of these technologies follow a logistic curve. In contrast to what is commonly perceived, the specific growth rate in energy extraction from wind turbines and photovoltaics have decreased in recent years. In an optimistic scenario, where we have included forecasted data from the solar and wind associations four years into the future, the logistic model implies that the total installed capacity saturates at around 1.8 TW in 2030. This is in sharp contrast to the almost established belief that these energy technologies will experience an exponential growth far into this century.

1. Introduction

With growing concern for global warming following the increased CO_2 concentration in the atmosphere, the need for sustainable and renewable energy sources has been recognized for a long time. This is reflected in the recent agreement at the 2015 United Nations Climate Change Conference, COP 21 in Paris, stating that a cut of greenhouse gas emission (GHG) by 40–70% is necessary before 2050. This is a grand global challenge since about 80% of today's total energy supply comes from fossil fuels that involve most of the GHG emissions [1]. Furthermore, despite increased energy efficiency in some countries, the global energy use is expected to increase due to growth in population and economy. A conservative estimate is power consumption in 2050 around 30 TW as compared to about 17 TW today [2].

Thus, it is widely recognized that a green shift from mainly fossil energy sources to renewables and/or nuclear energy is necessary. Currently, the main drivers of this shift are wind power and photovoltaics. These have grown from a few to about 660 GW installed capacity (2015) since the turn of the century, i.e. at a growth rate above any other previous non-fossil energy technologies. Optimistic energy outlook scenarios predict a continuous growth well into the middle of this century [3]. The roadmap of the International Agency for Renewable Energy (IRENA) forecasts a share of renewable energy beyond 30% by 2030 [4] which is in line with the ambitions of COP 21.

The logistic equation was originally derived by Verhulst [5] in 1838 to describe the asymptotic growth patterns of biological populations, but is now used in a wide range of different disciplines [6,7]. More than 60 years ago, the idea that energy production followed similar growth patterns was analyzed, first for American oil production, known as Hubbert's peak oil theory [8], and later for all potential important energy technologies at that time [9]. In addition to production technology, finite energy resources are naturally limited by the resource availability which guarantees a maximum total production and consequently a logistic production profile.

The assumption that deployment of renewable energy resources such as wind and solar power should follow a logistic development is less intuitive. However, several studies have pointed at different 'friction' mechanisms that tend to decrease and eventually halt the growth rate in installed production capacity [10–12], and logistic approaches have been applied for regional deployment histories of both wind [13] and solar energy systems [14,15].

In this paper we analyse the global deployment history of wind and solar energy systems up to 2015. We show that the retarding growth rate of wind and solar energy resembles that of a logistic growth pattern implying a much more pessimistic forecast for the future energy mix than indicated in the IRENA roadmap. We discuss

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mechanisms that might explain the logistic development and its future implications.

2. Methods

On the differential form the logistic equation is written [5],

$$dP\,/\,dt = a(1 - P/P_{\max})P \qquad (1)$$

where t is time, $P(t)$ is here the installed capacity (GW), P_{max} is an asymptotic value, and a (dimension of inverse time) the initial specific growth rate in installed capacity. Logistic growth differs from exponential growth in that the realized growth rate, $a_r = a(1 - P/P_{\max)})$, decreases (linearly) towards zero while exponential growth is characterized by the constant growth rate, a (see Eq. (3)). Thus, a drop in the observed realized growth rate, as a function of increasing P or of time, is a clear indication for a logistic growth pattern, and below we report observed trends in a_r. The realized growth rate of installed capacity was estimated, for a particular year t_i, according to $a_r = \ln(P_{i+1}/P_i)\cdot(\Delta t)^{-1}$ where $\Delta t = t_{i+1} - t_i$.

Integration of Eq. (1) provides:

$$P = P_{\max}/(1 + e^{-a(t-t_p)}) \qquad (2)$$

Here t_p is the time when the derivative dP/dt is maximal. We have estimated P_{max}, a and t_p (Table 1) by fitting Eq. (2) to time-series data on installed energy capacity. The exponential model was also fitted to these data:

$$P = P_0 e^{at} \qquad (3)$$

where P_0 is the energy capacity for the initial year. Both the logistic and exponential models were fitted to the data by use of least square minimization and non-linear estimation by use of Statistica (Statsoft) and the estimates of the coefficients for all analyses are reported in Table 1.

3. Results

Consider in Fig. 1 the electricity generation from hydropower based on build-up of water reservoirs in Europe during a period of more than 70 years in the previous century. At some time the available sites for new dams had reached a point where the cost of building new ones became prohibitive. Then the increase in energy generation from hydropower dams has flattened and the realized growth rate, a_r, approached zero (Fig. 1 inset). Interestingly, the build-up of nuclear energy follows a similar logistic trend. After some decades of reactor development following World War II, commercial deployment of nuclear reactors took off from the end of the 1950 s and flattened out in the 1980s. In brief, and in spite of very different resource potentials, both installed capacity of hydro- and nuclear power, can be described well by a logistic curve. In Fig. 1 we also plot the rapid growth of installed photovoltaics in Europe. Again a logistic curve describes the development well with a statistically significant ($p < 0.05$) drop in the realized growth rate, a_r, as a function of time (inset Fig. 1). We may imagine that we are set back 30 years into the developing period of hydropower and nuclear energy and fit the logistic curve to the data prior to 1985 in Fig. 1. The hypothetical forecasts according to these fits resulted in predictions of $P_{\max}$ that deviates less than 20% from what turned out to be the reality (not shown). We remark that the theoretical resource potential can be considered unlimited in the case of both nuclear power and photovoltaics.

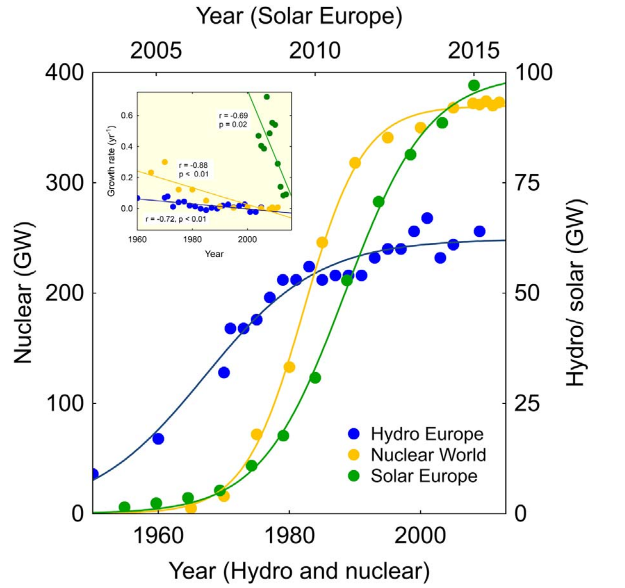

Fig. 1. : Installed global nuclear capacity (yellow bullets), European consumption of hydropower (blue) and installed European photovoltaics capacity (green) with time. The full lines are least square fits of the logistic equation (Eq. (2)). Estimates of the coefficients of this model are given in Table 1. The inset shows the temporal decline in realized growth rate, a_r (see Methods), obtained by linear regression analysis where r is the correlation coefficient and p is the probability that there is no trend in the data. Data from [29–31]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We now consider the installed capacity for wind and photovoltaics on a global level (Fig. 2). At a first glance, there appears to be a good fit of the exponential model to the wind and solar energy data with estimated growth rates, a, of 0.170–0.20 and 0.30–0.35 yr^{-1} for wind and sun respectively (Table 1). A closer inspection, however, shows evidence that the exponential model is biased (Fig. 2). The residuals, i.e. the differences between the exponential model and the data, under-, over- and then undershoot again for both wind and solar PV (red dots in the insets of Figs. 2A and B). Furthermore, similar to European solar (Fig. 1 inset), for global wind there is a statistically significant drop in the realized growth rate with time (Fig. 2C). Such drop is a clear indication of a logistic growth pattern. For solar PV, there is no overall downward trend in a_r, but there is a marked drop after 2010 (Fig. 2C). Inclusion of the stakeholders prognosis for the years after 2015 clearly strengthen the tendency for a logistic behavior (open red bullets in Fig. 2C). Although the fits of the logistic model are not perfect, the residuals are smaller and less fluctuating than those of the exponential

Table 1
Estimates of the coefficients (given as 95% confidence intervals) of the logistic (Eq. (2)) and the exponential models (Eq. (3)) that are displayed in Fig. 1–3 or commented in the text. All estimates were statistically significant ($p < 10^{-3}$) and the fitted models accounted for more than 95% of the variation in the different data sets. The coefficient P_0 of the exponential model represents the energy capacity in 1996.

Logistic model	a (yr^{-1})	P_{max} (GW)	t_p (yr)	
Hydropower Europe	0.09–0.14	60–65	1965–1969	Fig. 1
Nuclear global	0.20–0.24	364–376	1982–1983	Fig. 1
Solar Europe	0.67 – 0.84	95–104	2010–2011	Fig. 1
Wind global	0.25–0.29	640–832	2013–2015	Fig. 2
Solar global	0.47–0.55	314–397	2013–2014	Fig. 2
Combined wind and solar global	0.28–0.31	1218–1633	2015–2017	Fig. 3
Wind global including stake holder prognosis	0.24–0.26	887–984	2015–2016	text
Solar global including stake holder prognosis	0.32–0.38	665–851	2017–2018	text
Exponential model	a ($years^{-1}$)	P_0(GW)		
Wind global	0.17–0.20	10.4–16.5		Fig. 2
Solar global	0.30–0.35	0.25–0.75		Fig. 2

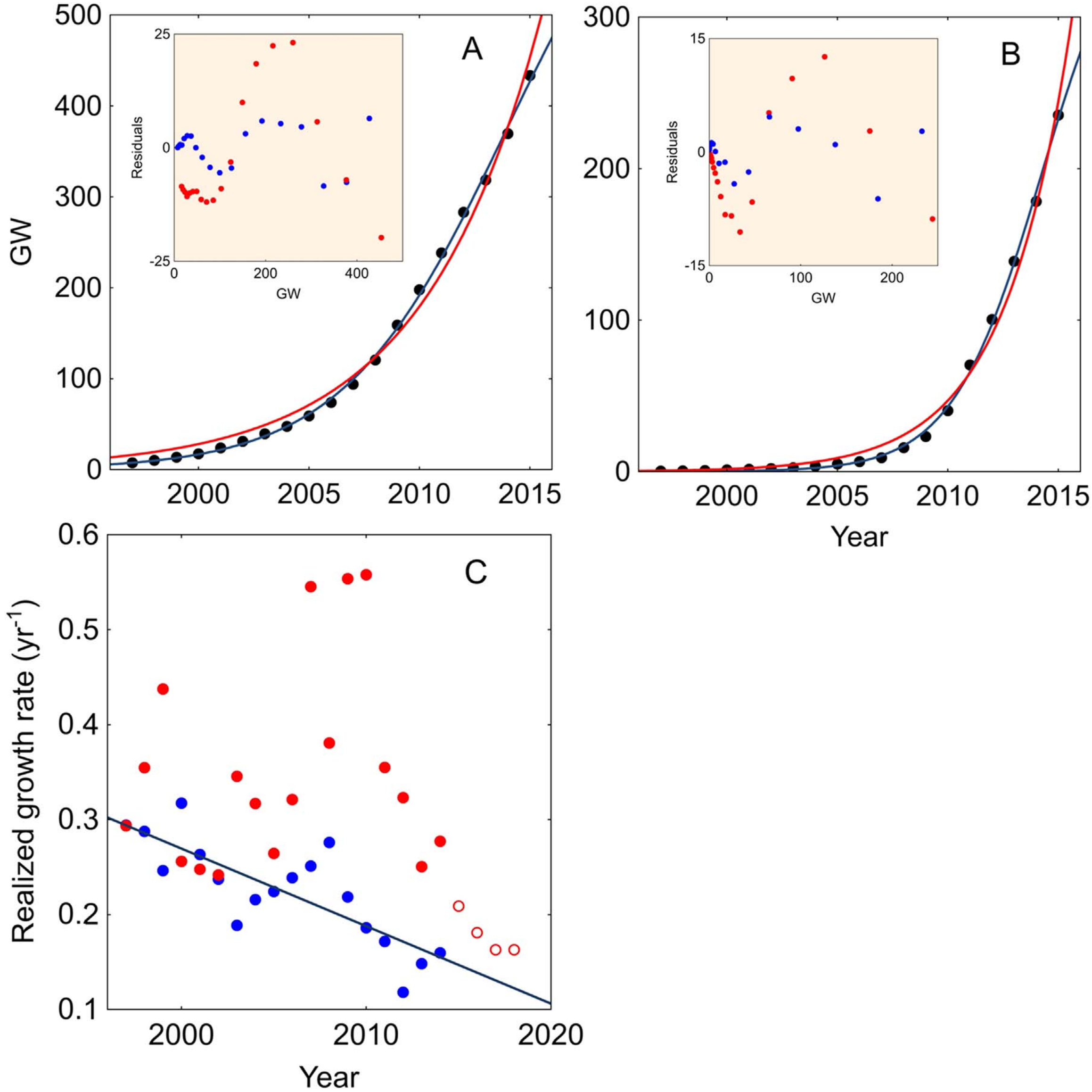

Fig. 2. : A and B: Logistic (blue lines) and exponential (red lines) fitted to historic wind and solar energy production (black bullets). The estimated coefficients of the models are reproted in Table 1. The inset figures show the residuals, i.e. the deviations between the model predicted and the observed installed capacity as a function of installed capacity. Note that this plot is also indicative for the time development because installed capacity increases monotonically with time. Blue and red bullets are residuals for the logistic and the exponential fit respectively. C: Estimated realized growth, a_r. (see Methods) of wind (blue) and solar (red) installed capacity. The open red bullets are the prognosis of solar energy from branch organizations [16,31,32]. The downward trend for growth in wind energy is statistically significant according to a linear regression analysis (blue line, $p < 10^{-4}$ and $r = -0.80$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fit, particularly in the most recent years (insets in Figs. 2A and B).

We now turn to the global installation rate of wind power and photovoltaics combined. At the end of 2015 these energy sources contributed 433 GW and 230 GW respectively. As seen in Fig. 3 the historic data matches well a logistic curve. Again, the realized growth rate shows a statistically significant decrease as a function of time (inset in Fig. 3) or as a function of capacity, P, (not shown). We also note that the stakeholder prognosis [16,17] for 2020 are within (red bullet) the indicated uncertainty of the logistic forecast, and that the realized growth rate in 2020, which is calculated from the stakeholder prognosis, is actually lying below the trend line based on the historic data (inset in Fig. 3).

4. Discussion

Which mechanisms have led to the apparent logistic behavior in wind and solar energy production? This cannot be assessed from the present data, but we comment on four potential saturation mechanisms that have been pointed at in previously published studies:

First, despite becoming increasingly competitive against other technologies, some studies [18,19] suggest that unsubsidized renewable energy, in spite of high annual learning rates [20], is presently more expensive than alternatives on a direct cost basis. Comparisons of this type are often made without taking into account all costs associated with deployment of intermittent renewable energy sources. It is well documented in the literature that these intermittent technologies have different values for the system [21,22] in the sense that they do not always lower system costs (grid + generation costs) if deployed [23], everything else being equal. If this was not the case, there would be little investment in conventional technologies today.

A second potential mechanism related to energy return on energy invested (EROI) has been thoroughly discussed in several studies [10–12]: In considering the ratio of energy produced vs. energy invested in the build-up of large renewable energy systems these studies forecast

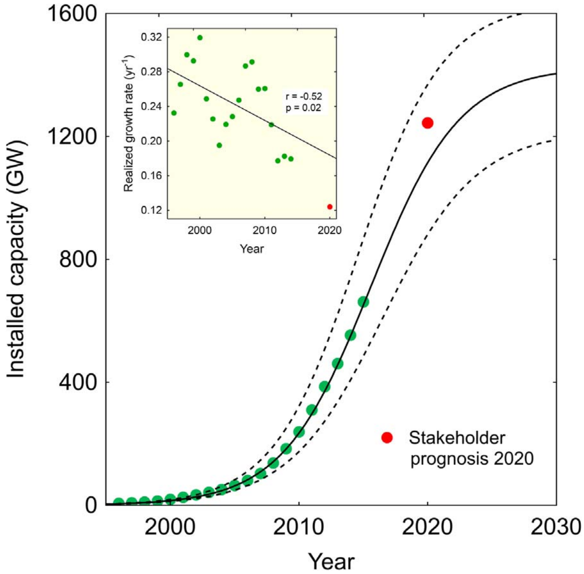

Fig. 3. : Total installed global capacity of wind power and photovoltaics combined (green bullets). The solid line is the logistic model (Eq. (2)) fitted to the data and the broken lines indicate a 95% confidence interval (estimated coefficients of the model are reported in Table 1). The inset shows the temporal decline in realized growth rate, a_r. (see Methods) obtained by linear regression analysis where r is the correlation coefficient and p is the probability that there is no trend in the data. The red bullet point is the prediction from stakeholder associations. Data from [16,17,31–33]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

an optimum level in global renewable energy production well below what is needed to satisfy the global demand. The origin of this limit was considered to be limited area and increased expenses to build energy production at increasingly more remote locations. A third saturation mechanism is finite material life times which implies that there will be an increasing need to renew existing power production sites [11]. This mechanism, however, has hardly been important so far due to the early stage, but will certainly increase with the aging of current installations in coming years.

A final saturation mechanism that applies to intermittent sources of energy, like wind and solar, is that they tend to cannibalize their own revenue streams [24]. Assuming a constant price over a 24-h period, the deployment of a limited capacity of solar PV can already make a dip in the market price for electricity in hours when solar radiation is at its strongest. Once installed, solar energy delivery has marginal costs close to zero and assuming a well-functioning market, not distorted by subsidies, an owner of solar PV will bid at a price down towards zero in order to enter the market. This drags the price down during hours with solar capacity [25]. Hence, the more solar capacity installed, the lower the price in these hours. At some stage, when the average market price is lower than the long-run marginal cost of producing solar power during hours with solar production, investors will loose interest in installing more capacity since they cannot expect positive returns on their investment. Current market designs thus limit how much solar power can be deployed in a system. Consequently, regional plans [26] for ruling out subsidies towards renewable energy without compensating with other marked changing strategies are likely to strengthen the marked contribution to a logistic pattern.

5. Conclusions

In this paper we have shown that at present wind and solar power shows early signs of logistic growth despite high learning rates and energy return on energy invested particularly within the photovoltaics section [27]. Extrapolation of the logistic time development for sun and wind combined suggests saturation of about 1.6 TW (Fig. 3) around 2030. For the most optimistic scenario in our analyses, where stakeholders prognosis are included in separate analyses for wind and sun, a saturation of 1.8 TW is indicated (sum of upper confidence limits of P_{max} for wind and sun in Table 1). This is likely much less than 10% of the global energy mix in 2030. This alarmingly low fraction will make the COP 21 ambitions on climate gas reductions hard to achieve. We are well aware of the uncertainties [8] with the logistic forecast: Technology development, e.g. in ocean wind energy, and unforeseen breakthroughs of competing energy resources, e.g. nuclear fusion, may cause the development to take a completely new route [28]. In absence of such developments, however, the present data are an early warning of a growing gap between expressed ambitions and an actual growth.

Appendix. Data of installed capacity (GW) used in analyses and figures. References for the data sources are given below

Year	Hydro Europe	Wind global	Solar global	Nuclear global	Solar Europe
1950	9				
1960	17				
1965				5	
1970	32			16	
1971	42				
1973	42				
1975	44			72	
1977	49				
1979	53				
1980				133	
1981	53				
1983	56				
1985	53			246	
1987	54				
1989	54				
1990				318	
1991	54				
1993	58				

1995	60			341	
1997	60	7.6	0.4		
1998		10.2	0.6		
1999	64	13.6	0.8		
2000		17.4	1.3	350	
2001	67	23.9	1.6		
2002		31.1	2.1		
2003	58	39.4	2.6		
2004		47.6	3.7		1.5
2005	61	59.1	5.1	368	2.4
2006		73.9	6.7		3.6
2007		93.9	9.2		5.3
2008		120.7	15.8	372	10.9
2009	64	159.1	23.2	371	17.7
2010		197.9	40.3	374	30.8
2011		238.4	70.5	370	52.9
2012		283.1	100.5	373	70.7
2013		318.6	138.9		81.4
2014		369.6	178.4		88.6
2015		432.6	229.4		97.1
Stakeholder prognosis:					
2016			278		
2017			333		
2018			392		
2019			461		
2020		705	542		

Data sources

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