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Limits to growth in the renewable energy sector

J.P. Hansen[a,*], P.A. Narbel[b,*], D.L. Aksnes[c]

[a] Department of Physics and Technology, Allegt. 55, University of Bergen, N-5007 Bergen, Norway
[b] Norwegian School of Economics, Helleveien 30, N-5045 Bergen, Norway
[c] Department of Biology, University of Bergen, Thormøhlensgt 53, N-5020 Bergen, Norway

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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

* Corresponding authors.
E-mail addresses: jan.hansen@uib.no (J.P. Hansen), patricknarbel@gmail.com (P.A. Narbel).

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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],

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

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:

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

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:

$$P = P_0 e^{at} \tag{3}$$

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

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

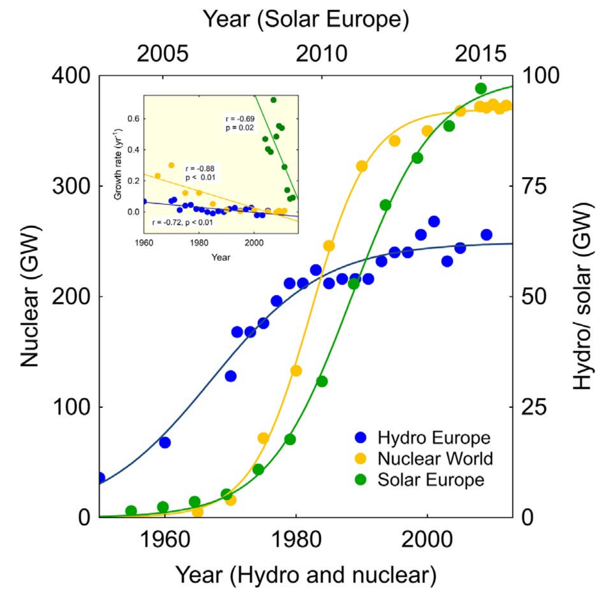

Fig. 1. : Installed global nuclear capacity (yellow bullets), European consumption of hydropower (blue) and installed European photovoltaics capacity (green) with time. The full lines are least square fits of the logistic equation (Eq. (2)). Estimates of the coefficients of this model are given in Table 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.)

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.

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