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Upper limits for renewable electricity penetration by 2050

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1. Introduction

Renewable energies, in particular new technologies such as wind, solar and advanced bio, play a central role in several climate change mitigation scenarios [IPCC, 2008]. In the recent IEA energy foresight [IEA, 2008], renewable energy stands for 21% of the global emission reductions needed by 2050. In the Shell Blueprint scenario from 2008 [Shell, 2008], even higher contributions are expected; 30% of all primary energy in 2050 would be renewable based and e.g. wind and solar together would cover over 40% of all world electricity. As most of this growth seems to come from new renewable energy technologies that represent less than one percent of the world energy today, key questions for the success will be the pace and up-scaling of these new technologies, i.e. how fast and how much could new options contribute on a global scale. In this paper, the subsequent market penetration problem will be analyzed with emphasis on finding realistic ranges for upper limits of (new) renewables by 2050. The focus is here on the power sector due to its large importance to emissions, but the approach used is applicable for primary energy as well.

The energy future can be modeled with different methods, for example macro-economic energy systems models using share allocation and optimization to find least cost energy mixes under different boundary conditions, e.g. MARKAL, PRIMES models [Fishbone, 1981; Capros, 1998]. In this paper, the penetration question is approached through microeconomics with emphasis on technology volume growth. This choice was enforced by the fact that annual increase of the new technology capacity, which not only depends on the demand for new technology but also on manufacturing capabilities, is in fact the key for long-term market shares in energy. Reaching a high share in the yearly total energy additions could lead to a positive technology lock-in which leads over time to a high overall market share. The utilization rate of fuel free renewable energy resources such as photovoltaics and wind power is not bound to the primary energy resource or reserves nor that much to any other natural resources (e.g. materials). Their limiting factors are more of financial or technical nature which need to be overcome to reach high market shares.

2. Methodology

The method employed here originates from technology diffusion theory [Mansfield, 1961; Fisher, 1971] and from large-scale energy system dynamics [Häfele, 1979] and on the observation that the rate of adaption changes over time and actually decreases with increasing market share [Lund, 2006]. Diffusion theory predicts that the yearly relative capacity increase of the new technology decreases with an increasing market share. Thus the volume increase (dV_i) depends on the market share of the new technology (f_i) and there is a correlation between the two variables [Lund, 2008]. This allows us to write the annual volume addition of the new technology in the following form

$$\frac{dV_i}{V_i} = G(f_i) \qquad (1)$$

where the function G represents the correlation between the annual volume addition and the market share of the new energy technology. The classical diffusion equation implies a logistic functional form for the correlation and is supported by some empirical observations. The logistic function can also be approximated with $dV_i/V_i \sim 1/f_i$. The functional forms of the correlation employed here are the following:

$$G_A(f_i) = \frac{1}{a_0 + a_1 e^{a_2 f_i}} \text{ (exponential model)} \qquad (2)$$

$$G_B(f_i) = b_0 + \frac{1}{b_1 + b_2 f_i} \text{ (1/f-model)} \qquad (3)$$

where the coefficients a_i and b_i are determined by fitting to real market data. The correlation functions G above were determined from a vast data set representing the growth phase of different energy sources over half a century thus linking the market growth of energy technologies to microeconomic expansion possibilities in a global energy systems context [Lund, 2008].

Figure 1 shows the correlations found between volume increase and market share for the different modeling approaches and real data points. The overall agreement is good. The model demonstrates well that in the early stage of the penetration where the market share is low, very high (two-digit) annual volume increases are expected. However, for higher market shares the annual volume additions drop well under 5 percent because of the increasing resource requirements and system inertia. This is an important observation for new energy technologies on a long-term run. For example, photovoltaics has demonstrated 30-40 percent yearly increases over the last several years, but the market share of global energy is just 0.1 percent. This means that PV growth will most likely start to decrease as its market share becomes relevant for the energy context. This is an important factor to be considered in the energy modelling and prediction context.

The cumulative capacity of the volume that determines the market share f_i is obtained by summing up the discrete volume additions over time:

$$V_i^k = V_0 + \sum_{k'=1}^{k} dV_i^{k'} \qquad (4)$$

where the superscript k stands for the time points.

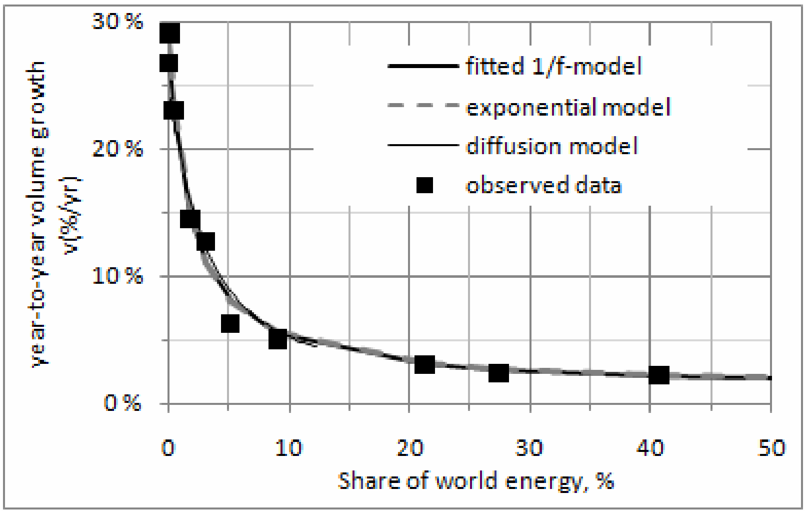

Figure 1. Summary and comparison of the energy technology growth models used in this study.

Figure 2 illustrates the market development of four renewable energy technologies along with the empirical growth model from Fig. 1. The time scale in the figure moves in practice from left to right. Wind power, biofuels and photovoltaics which can be characterized as global technologies fall quite well on the empirical growth curve, whereas solar heating underperforms clearly demonstrating that this technology has not yet taken off and may be more of a local technology option. It should also be noted that the market shares of the new renewables of all global energy are still low imposing uncertainty to how these would evolve over time to high market shares. Therefore, when looking for high growth options, it is assumed that the growth conditions up to saturation will be favorable and enable similar growth trajectories than for traditional energy sources in the past.

The empirical growth model enables to incorporate resource or system limitations and investigate their influence on market growth. One important limitation is the share of the new technology of the total annual capacity growth. This factor integrates a range of aspects such as limitations from the energy system, financial resources, manufacturing capabilities, etc. Furthermore, a high share in the annual capacity or total volume addition could mean technology lock-in into a certain new technology. A very high share exceeding 100 per cent would mean dismantling of existing traditional capacity.

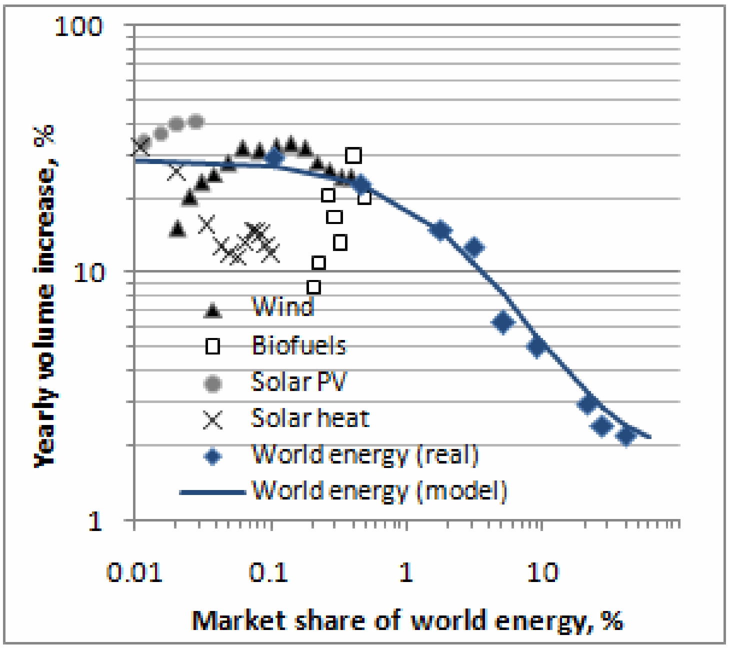

Figure 2. Historical market penetration of new renewable energy sources in global scale.

3. Results

The intention of this paper was to investigate high growth schemes for renewable energy penetration, in particular in the power sector. Using the model, several case and sensitivity studies were performed. The main results are shown below.

The renewable energy technologies considered were the following:

- Hydropower no major growth (+0.5%/a after year 2030)
- Traditional bioenergy and waste moderate growth (+4%/a)
- New renewables (wind, solar, other RES) according to the empirical growth model (Fig. 1)
- Wind and solar have entered already the market but new RES not until year 2030

The relative significance of renewable energy in the global context will depend on how much electricity demand grows. Therefore an energy efficiency driven policy path with a 1.8%/a electricity demand growth was considered in reference case.

The scenarios that stem from these assumptions are shown in Fig. 3. It should be pointed out that a present kind of energy technology market dynamics and unconstrained resource conditions are assumed here. This results in a 60% share of renewables in electricity production in 2050. The share of new renewable technologies is 43% of all electricity. Wind power comes out with the highest share among the renewable energies, or 25% (~10,000 TWh/yr) of electricity. This corresponds to about the same level of wind power as in the Shell scenarios.

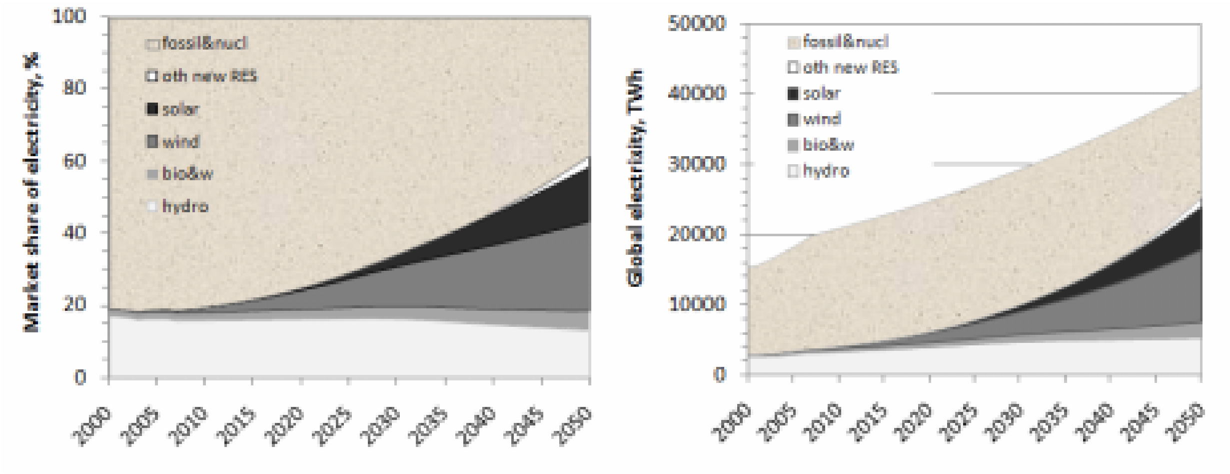

Figure 3. Global expansion scenario of renewable electricity under favourable unconstrained conditions.

What would such high growth paths of renewable energy mean in practice for the energy markets and investments? This question was investigated through the share of annual electricity additions shown in Fig.4. The total annual electricity addition corresponds to 100% on the scale shown. In the reference case, the share of a single new RES technology remains under 50 % during the fastest growth. From around 2030 onwards the total amount of RES in the scenario would exceed the annual demand increase, meaning then that the renewable energies start to replace existing traditional power capacity. Depending on the remaining value of traditional power plants, this may mean an extra financial burden. In addition, there would be total technology lock-in into renewable electricity around 2030-2035.

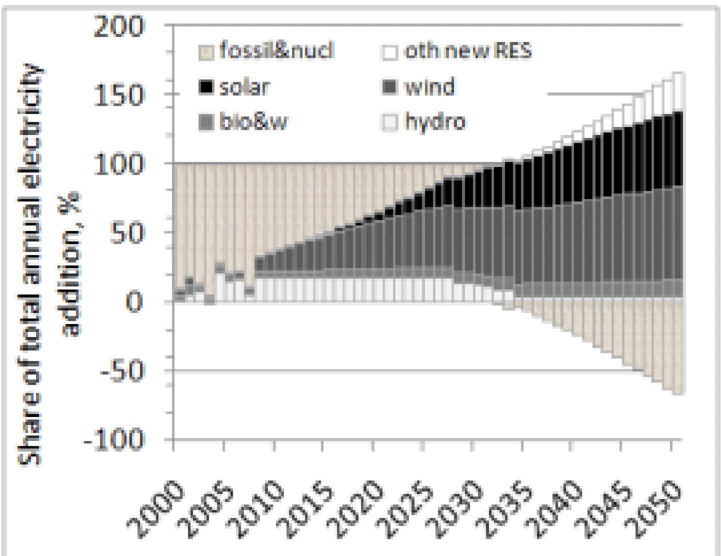

Figure 4 Share of annual electricity addition from the different energy technologies.

If we restricted the share of a single technology to 30% of the total annual volume addition, then the share of e.g. wind power would drop to 15% (6400 TWh) in 2050. Similarly, if the financial resources available were limited, the numbers given would drop. For example in case of PV which is a costly new technology, limiting the resources to 50% of the needed one, would drop the PV contribution from 6300 to 3900 TWh in 2050. A learning curve analysis was used here to estimate the effects of financial restrictions.

4. Summary

In this paper, we have investigated high growth options of renewable electricity production by year 2050. The analyses were done with an empirical market share growth model based on technology diffusion.

The results indicate that in the reference case, renewable energy could provide well over half of the global electricity in 2050, but this would require strong lock-in into RES from around year 2030 onwards. Wind power would be the most important renewable electricity technology with a 25% share of all electricity in 2050. These numbers are based on the assumption that the growth conditions are very favorable and unconstrained. Practical limitations e.g. in available financial resources or on how much renewables could be integrated annually into the global energy system may drop these figures considerably.

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