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Exploring past energy changes and their implications for the pace of penetration of new energy technologies

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ABSTRACT

Possible growth paths for new electricity generation technologies are investigated on the basis of an empirical analysis of past penetration rates. Finding and understanding high market penetration scenarios is relevant to formulating climate change mitigation strategies. The analysis shows that under favorable growth conditions, photovoltaics and wind could produce 15% and 25%, respectively, of world electricity by 2050. Under the same assumptions nuclear power could increase to 41% of world electricity. But it is unlikely that all three technology paths could be realized up to these values simultaneously and therefore the penetration rates presented here should be considered as indicative only. The results show that under positive conditions, an embryonic technology could move as a preferred option into a mainstream energy source within half a century. The introduction of growth constraints reflecting, e.g., severe economic, technical, or political limitations could reduce the above numbers by a factor of up to 2–3. The results indicate a decline in the relative year-to-year growth of new technologies when they have higher market shares. A comparison of the results with other short-term and long-term technology scenarios shows satisfactory agreement.

1. Introduction

Massive introduction of clean and sustainable energy sources will be necessary to meet the challenges of mitigating climate change. According to the UN IPCC, 50–60% of the global energy system needs to be changed in half a century [1]. In industrialized countries even more radical levels may be needed. A recent suggestion by Sir Nicholas Stern that yearly CO_2 emissions should be limited to 2 tons CO_2/capita by 2050 would mean an 80% reduction from the present level for the European Union [2]. Limiting the rise of CO_2 to a level that keeps climate change moderate would, in practice, require zero-emission power production and near zero-emission transport.

Such CO_2 emission stabilization targets would require the massive introduction of clean technologies onto the market, along with energy being used more efficiently than today. There is a range of scenarios envisioning how this could be accomplished employing different technology options [1,3–5]. Under the present trend, though, fossil fuels will dominate far into the future.

From a historical perspective the global energy system displays considerable inertia. Research in the late 1970s at the International Institute of Applied System Analysis (IIASA) showed that it had taken from 50 up to 100 years to witness radical changes in the market shares of energy sources on a global scale [6]. In the short term the energy system looks almost static. The time frame for reducing emissions radically (ca. 40–50 years) is thus challenging compared to the historical pace of energy change.

A most relevant question is, indeed, how fast new energy technologies could be introduced on a large scale. In this paper, this is approached through investigating the energy changes of comparable time intervals in the past, and interconnecting the dynamics of change of an individual energy technology to the global energy system. Finding upper limits for the growth of energy technologies empirically is of particular interest here, but so is how practical limitations such as resource constraints could affect this growth. Instead of modeling energy systems, an approach focusing on the industrial capacity and the volume growth of energy technologies was chosen. On the basis of empirical observations on the changes in market share of energy sources and the above analytical frame, the future penetration paths of new energy technologies are outlined.

Modeling changes in the energy system and making future predictions can be based on several different approaches, such as the following:

1. energy systems modeling in which the market shares are determined on the basis of the interaction of the demand and

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Nomenclature

E	primary energy
f	market share
g	function
GDP	gross domestic product
PPP	purchasing power parity
PV	photovoltaics
t	time
V	volume, capacity
α	adoption rate in the diffusion model
β	year-to-year growth rate
Δ	change
ϕ	learning rate
ΔV	yearly volume change ($=\mathrm{d}V/\mathrm{d}t$)

Subscripts

i	energy source or technology
k	time point, step
0	starting point, initial state

supply curves of different energy sources, represented by their marginal cost;
2. technology diffusion models that are based on the diffusion theory and adoption of innovations (S-shaped curves);
3. technology learning and experience curves that relate the unit cost of a new technology to the cumulative experience or volume installed or produced, and
4. historical trends and future assumptions of the capacity of the new technology.

The first category of models includes sophisticated tools for energy forecasting and planning such as the MARKAL [7,8] model, which uses cost optimization to identify least-cost mixes of energy technologies to meet the energy demand, given the constraints of natural resources. Other macro-level optimization/equilibrium models include PRIMES [9], MERGE [10], EFOM [11], BESOM [12], NEMS [13], and ECLIPSE [14]. Special models for analyzing large shares of renewable energy in the electricity system include the EnergyPLAN model, which can used for a more detailed analysis of socioeconomic and system aspects of electricity systems [15,16].

The methodology used here is an empirical interpolation model making use of historical observations on energy change. The penetration of new energy technologies is based on a technology-specific volume or capacity growth estimation. The study focuses mainly on power production, which represents close to 30% of all greenhouse gas emissions [17]. Electricity production is one of the most relevant sectors for energy and climate change and will be even more so in the future, as the demand for electricity grows faster than the primary energy [4]. As half of all electricity is still coal-based [17], radical changes may be necessary here in order to meet the emission reduction targets.

2. Methodology for modeling energy change

2.1. General observations

The diffusion of a new technology has distinctive phases, starting with a slow market entry, followed by a growth phase and finally ending in market saturation [18]. At the beginning the market share of a new technology is negligible, in spite of any yearly capacity growth rate. When entering higher market shares that are important for the relevance of the energy, the growth rates are expected to decrease as a result of different limitations on physical and financial resources, infrastructure, etc. Fig. 1 demonstrates the above observation on a global scale, based on data from [19]. Over the past 40 years the observed yearly variations in the volume changes of the different energy sources have ranged from a few percent per year up to percentages countable in tens. New energy sources show high growth rates, whereas traditional energy sources with high market shares tend to grow much more slowly and in a manner closer to the average growth of the energy demand.

2.2. Analytical framework

The above observations were used as a basis to define the relationships between the changes in volume (ΔV_i) and market shares (f_i) of energy technologies.

There are different methods available to describe market penetration and changes in market shares. In sophisticated energy system and equilibrium models [7–14,20] the effects of supply- and demand-side factors on market penetration can be considered through details such as the cost of the new technology, the cost-supply curves, the market structure, etc. In this paper and in classical technology diffusion models, penetration is described in a simpler way, through parameterization. On the other hand, if favorable or almost ideal growth conditions are assumed, as in this paper, several critical factors, such as the cost and supply issues, can be overcome. The literature on diffusion models is vast and comprehensive reviews can be found, e.g. in [21–23]. The mathematical models used for diffusion typically yield an S-shaped penetration curve, which may be either symmetric or asymmetric around the inflection point. These models are capable of describing both adoption and substitution processes for the new technology. Diffusion models have been successfully applied in many technology fields [24] and in energy as well [25,26]. Marchetti and Nakicenovic [27] used a two-parameter S-shaped logistic substitution model to study changes in the global energy system and predict the future market shares of energy sources.

In the classical diffusion model, the diffusion results from the spread of information, which originates from analogies in the epidemic theories of diffusion. These types of models overlook several important factors that affect diffusion. In more sophisticated diffusion models, such as the probit or hazard models, a range of different factors influencing the underlying decision-making process of the diffusion can be taken into account better, for example the cost of adopting the new technology [33]. Rose and

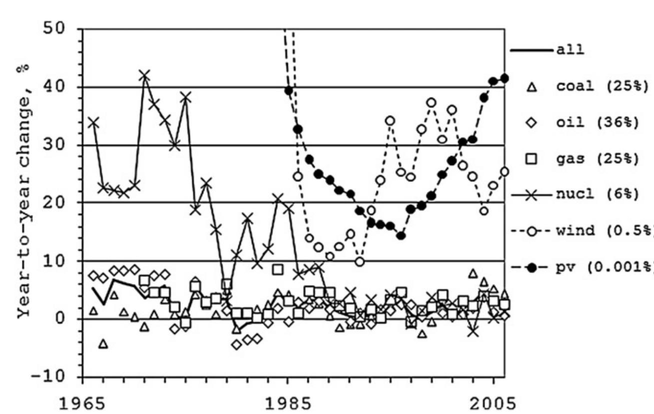

Fig. 1. Year-to-year volume (dV/V) changes in global primary energy. The percentage in brackets in the legend are the present world market shares of energy sources (f_i).