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Growth curves and sustained commissioning modelling of renewable energy: Investigating resource constraints for wind energy

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HIGHLIGHTS

- Growth rates and service life is important when evaluating energy transitions.
- A *sustained commissioning model* is suggested for analysing renewable energy.
- Natural resource requirements for renewable energy are connected to growth rates.
- Arguments by recent studies ruling out physical constraints appear inadequate.

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ABSTRACT

Several recent studies have proposed fast transitions to energy systems based on renewable energy technology. Many of them dismiss potential physical constraints and issues with natural resource supply, and do not consider the growth rates of the individual technologies needed or how the energy systems are to be sustained over longer time frames. A case study is presented modelling potential growth rates of the wind energy required to reach installed capacities proposed in other studies, taking into account the expected service life of wind turbines. A sustained commissioning model is proposed as a theoretical foundation for analysing reasonable growth patterns for technologies that can be sustained in the future. The annual installation and related resource requirements to reach proposed wind capacity are quantified and it is concluded that these factors should be considered when assessing the feasibility, and even the sustainability, of fast energy transitions. Even a sustained commissioning scenario would require significant resource flows, for the transition as well as for sustaining the system, indefinitely. Recent studies that claim there are no potential natural resource barriers or other physical constraints to fast transitions to renewable energy appear inadequate in ruling out these concerns.

1. Introduction

The global energy system is dominated by fossil fuels with oil, natural gas and coal making up a total of more than 80% of the primary energy supply (IEA, 2013a). Fossil fuels are finite resources that cannot be used indefinitely, and the combustion of these fuels cause environmental damage, such as anthropogenic climate change (Hook and Tang, 2013). Replacing the use of fossil fuels with different sources of renewable energy is often considered as an important part of a more sustainable development process (Lund, 2007), and a wide range of studies have suggested future energy systems based on different renewable energy technologies. These studies can be quite different in nature, utilizing different methodologies and proposing widely different energy systems (Grunwald, 2011). A few recent peer reviewed studies stand out by proposing future energy systems almost completely based on energy from the wind and the sun, claimed to be achievable as soon as the year 2050, or even more rapidly by 2030 (García-Olivares et al., 2012; Jacobson and Delucchi, 2009; Kleijn and Van der Voet, 2010).

Substituting the entire current energy system based on fossil fuels with renewable energy technologies involves up-scaling a disparate set of small scale industries, and the timeframe to do this within only a couple of decades, can appear optimistic. The implications of the fast growth of the renewable energy technologies needed to do this are often not adequately addressed in the studies proposing future energy systems based on renewable energy. The question of how these energy systems are then to be sustained over a longer time scale are usually not considered. This study aims to add the perspectives of time and scale to evaluating the feasibility of fast energy transitions by taking account of

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annual growth rates needed to reach proposed future energy systems as well as investigating how an energy system based on renewable energy technologies could be sustained in the long run. This is mainly done by modelling growth patterns needed to reach the installed capacities of wind energy proposed in other studies, taking account of the life expectancies and need for replacement of technology, using wind energy as an example. The requirement of natural resources for the construction of wind energy is quantified on an annual basis to examine the impact on views of potential material constraints.

The growth of renewable energy technologies needed for an energy transition must inevitably come with the growth of an industry capable of manufacturing and installing that technology, capital to finance these investments, as well as an increased demand for certain natural resources. Renewable energy technologies such as wind and solar energy are more metal intensive than current energy sources and a transition to renewable energy would increase demand for many different metals (Kleijn et al., 2011). Several different critical metals have been identified as potential bottlenecks in the deployment of "*low-carbon energy technologies*" (Moss et al., 2011). It has also been argued that a shift to an energy system based on renewable energy would inevitably be largely driven by fossil fuels, and a fast growth of renewables would actually add new fossil fuel demand to current demand during a transition period (Moriarty and Honnery, 2009).

The concept of "*energy return on investment*" (EROI) appears lower for renewable energy technologies than many conventional fossil fuels we currently rely on for our energy supply (Hall et al., 2013). Concerning solar photovoltaics (PV), it has been suggested that high energy input for the production of crystalline silicon solar cells could be a constraint for the growth of this technology, while current thin film technologies could never reach significant production levels due to the use of scarce materials (Tao et al., 2011). Dale and Benson (2013) even claim that the solar PV industry has not yet paid back any net energy to society, partly due to its high relative growth rates, and concludes that both the timing and magnitude of energy inputs and outputs are important factors in determining an energy balance for the solar industry. Others raise issues with the variable production of electrical energy from wind and solar energy as well as the large amount of capital needed for investment in new energy production as potential constraints on this development (Trainer, 2012, 2013). What is not as commonly discussed is how the actual growth patterns of the different energy technologies affect these potential constraints, or how the energy systems are to be sustained over a longer period of time.

This study investigates how different growth patterns reaching proposed installed capacities of wind energy affects potential constraints connected to annual commissioning capacity and resource requirements. First, the proposed energy futures used for the modelling are presented, and the models as well as the underlying assumptions are described. Then, the resulting growth patterns and the related annual commissioning and resource requirements are quantified. The results, the models used as well as different ways to assess natural resource constraints and other potential constraints for growth of renewable energy technology are discussed. Finally, the main conclusions and potential policy implications of the findings are presented.

2. Methodology

2.1. Installed wind capacity

Jacobson and Delucchi (2009) describe an energy system consisting of 51% wind energy and 40% solar energy that is "*technically possible*" to achieve before 2030. This scenario is further elaborated on in Jacobson and Delucchi (2011) and Delucchi and Jacobson (2011), where the time frame is postponed due to difficulties in implementing the necessary policies by 2030, but it is still said to be technically feasible to achieve by 2030. Kleijn and Van der Voet (2010) present a similar scenario, with slightly more wind energy but many times more solar PV, since the total energy demand is assumed to be much larger. García-Olivares et al. (2012) propose an energy mix similar to the Jacobson and Delucchi (2009) scenario, but state that solar PV is unlikely to be able to reach these levels due to constraints induced by scarce materials used for solar PV technology and propose using concentrating solar power (CSP) instead. Table 1 summarizes the main features of these three studies as well as the current situation as of 2012.

The studies described in Table 1 all propose energy systems completely based on renewable energy technology, with wind and solar energy making up almost the entire global energy supply by 2030 or 2050. Although important differences occur between the different studies, some interesting similarities exist. While the solar energy contributions vary greatly both in size and technologies chosen, the assumed contribution from wind is very similar between the studies, with suggested installed capacities ranging from 18 to 24 TW. All three studies discuss potential constraints caused by natural resources and conclude that this factor will likely not constrain the development towards the proposed energy future. The growth patterns needed for the individual technologies

Table 1
Summary of the main features of proposed energy systems used in the case study. Installed capacities of wind, solar PV and CSP, which contributes with over 90% of the energy supply in all the studies are described, as well as assumed total annual energy demand and year when the scenario is to be fulfilled. The actual numbers as of 2012 are presented for comparison.

Study	Wind energy [TW]	Solar PV [TW]	CSP [TW]	Primary energy demand [EJ]	Realization year
Jacobson and Delucchi (2009, 2011)	19	17	15	363[a]	2030 (2050)[b]
Kleijn and Van der Voet (2010)	24	317[c]	–	1278	2050
García-Olivares et al. (2012)	18–19	–	18[d]	363[e]	2030
Actual	0.28[f]	0.1[f]	0.0025[f]	522[g]	2012

[a] Stated as 11.5 TW power demand.
[b] Jacobson and Delucchi (2011) state that Jacobson and Delucchi (2009) found it technically feasible to reach the proposed energy future by 2030, but also that it is likely to happen later due to the "difficulty in implementing all necessary policies by then.", and suggest producing all new energy with renewables by 2030 and replace all the pre-existing energy by 2050 instead. Still it is clearly stated in both papers that it is deemed technically feasible by 2030, which is what is interesting in this study, and the year 2030 is used.
[c] Given as a total annual energy production from solar PV of 1000 EJ and a PV "efficiency" of 10%, seemingly used as what is commonly called capacity factor.
[d] 15 TW of Stirling plants/air cooled CSP with capacity factors of 0.25 and 2.9 TW with capacity factors of 0.4–0.75.
[e] Assumes the same energy demand as Jacobson and Delucchi (2009).
[f] Source: REN21 (2013).
[g] Source: BP (2013).