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Towards a sustainable global energy supply infrastructure: Net energy balance and density considerations ☆

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ABSTRACT

This paper employs a framework of dynamic energy analysis to model the growth potential of alternative electricity supply infrastructures as constrained by innate physical energy balance and dynamic response limits. Coal-fired generation meets the criteria of longevity (abundance of energy source) and scalability (ability to expand to the multi-terawatt level) which are critical for a sustainable energy supply chain, but carries a very heavy carbon footprint. Renewables and nuclear power, on the other hand, meet both the longevity and environmental friendliness criteria. However, due to their substantially different energy densities and load factors, they vary in terms of their ability to deliver net excess energy and attain the scale needed for meeting the huge global energy demand. The low power density of renewable energy extraction and the intermittency of renewable flows limit their ability to achieve high rates of indigenous infrastructure growth. A significant global nuclear power deployment, on the other hand, could engender serious risks related to proliferation, safety, and waste disposal. Unlike renewable sources of energy, nuclear power is an unforgiving technology because human lapses and errors can have ecological and social impacts that are catastrophic and irreversible. Thus, the transition to a low carbon economy is likely to prove much more challenging than early optimists have claimed.

1. Introduction

Of all the challenges confronting the world today, none is likely to prove as daunting or vital to the global economy and the very future of this planet, as that of energy. Providing sufficient energy to meet the requirements of a growing world population with rising living standards will be a difficult task. Doing it without exacerbating the risks of climate disruption will be an even more challenging undertaking. It will require a significant shift in the historic pattern of fossil fuel use and a major transformation of the global energy system. The relatively short timescale of the necessary transition to a low carbon economy is likely to prove especially challenging. There are fears that a very rapid transition to a renewable energy economy could lead to the cannibalization of energy from existing power plants and thus exacerbate the current global energy scarcity (Pearce, 2008a, 2009; Kenny et al., 2010). Moreover, energy transitions take time, with major innovations in the past having taken decades to diffuse and even longer to have the supporting infrastructures developed (Smil, 2010).

There are high expectations that technological innovation will play a critical role in facilitating the transition to a cleaner and more efficient energy economy, and considerable excitement about the growing importance of renewable technologies in the future energy mix (van der Zwaan, 2006). Already, as part of their efforts to reduce greenhouse gas emissions and improve the security of their energy supply, many governments have made similarly worded pronouncements and set ambitious goals for sourcing a significant portion of electricity generation from renewables. However, the transition to a renewable energy system will be challenging because of the modest energy density of the alternative fuels, the low conversion efficiency and power density of renewable energy extraction, and problems of intermittency (which lead to low load factors). This transition is further complicated by the frequent location of renewable resources away from the major population centers, the uneven geographic distribution of these resources around the globe, and the massive scale of the prospective shift. Indeed, there is still considerable variance in the estimates of the basic performance metrics of renewable technologies. Thus the promises of various substitute technologies in the transition toward increased decarbonization must be subjected to a careful reality check.

☆The findings, interpretations, and conclusions of this paper are the authors' own and should not be attributed to the World Bank, its Executive Board of Directors, and any of its member countries, or the Argonne National Laboratory.

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One should keep in mind that during the 1970s, proponents of nuclear power in the United States were predicting that it would largely replace coal-fired generation by the year 2000. Similarly, during the early 1980s, proponents of small-scale, distributed, green energies (solar, wind, biofuels) were predicting that these technologies would supply between 30% and 50% of the country's electricity needs by the first decade of the 21st century (Smil, 2008). Both of these predictions turned out to be wildly optimistic.

In this paper we develop a dynamic energy analysis framework to model the growth potential of alternative electricity supply infrastructures as constrained by innate physical energy balance and dynamic response limits. Both a set of existing and novel figures of merit are utilized for evaluating the technological options for energy growth under such dynamic constraints. We focus in particular on modelling the "doubling time" metric, which measures the time interval required for a given energy facility to produce and accumulate enough excess energy, after making a contribution to national energy demand, to construct new infrastructure so as to double its power output. In other words, this metric measures the capability of a given energy infrastructure to sustain and reproduce itself from its own output while making sufficient residual energy available for societal use. The doubling time metric for a given energy facility summarizes several fundamental characteristics of its underlying technology, including the: capacity factor; amount of energy required for constructing and emplacing a unit of nameplate capacity; fraction of the facility's gross energy output used for its operation and maintenance; time required for constructing and emplacing a new facility; and the effective lifetime of the facility.

In proposing this metric for self-sustained growth we are mindful of the fact that in the real world, energy manufacturers very rarely, if ever, constrain their factories to self-generated power. Indeed, the future energy supply will likely continue to rely on infrastructures comprised of a mix of technologies in which excess energy can be diverted from high energy surplus/high capacity factor assets (e.g. fossil fuels) to help systems with lower energy surplus/capacity factors and requiring large up-front energy investments for their emplacement (e.g. renewable technologies) grow faster. Moreover, there are a number of different potential pathways characterizing the transition from a fossil fuel powered economy to a renewable energy base. Our proposed metric is not intended to contribute towards defining the optimal transition path. What we seek instead is to evaluate whether the up-front energy investment in the context of a rapid scale up of renewable generation is likely to impose a heavy burden on existing energy resources and thus exacerbate the current scarcity and price volatility.[1] If the doubling time of a given low-carbon technology is short, it will be possible to rapidly scale up its generation by bootstrapping its own energy production to finance in energy terms its own growth. On the other hand, if the doubling time of renewable technologies is very long then the rapid transition to a low carbon, renewable energy economy could prove more challenging—even if we manage to continuously be on the optimal transition path that minimizes the needed energy subsidy from high carbon fossil fuel facilities.

Our emphasis on the technical headroom of alternative generating technologies does not seek to supplant the time-honored economic cost-benefit analysis. Nor does it question the power of the incentives provided by market pricing mechanisms for the efficient allocation of scarce energy resources. However, the solutions to the twin challenges of energy and climate change are likely to prove complex, with several important technical (scientific and engineering) and social (economic, political) dimensions to consider. The dynamic energy analysis that we employ in this paper provides a deeper understanding of the powerful physical constraints the alternative generating technologies must respect—constraints that cannot be relaxed through economic policy measures.[2] As such, our dynamic energy balance framework can facilitate a technical reality check on the potential of these technologies to have an impact on the scale required by the global energy problem.

2. Transition towards a sustainable global energy supply infrastructure

The 21st century is likely to witness a transition to a new energy supply infrastructure that supports the tenets of sustainable development. Key requirements of the enabling energy supply chain will include:

- scalability—ability to expand to the multi-terawatt level;
- environmental friendliness—minimal carbon footprint;
- capacity to deliver net excess energy;
- longevity—abundance of energy source.

According to the International Energy Agency (IEA), assuming no change in government policies, world primary energy demand is projected to rise from 12,271 to 18,048 million tonnes of oil equivalent (Mtoe) between 2008 and 2035—an increase of 47%. Electricity demand is projected to grow from 20,183 to almost 38,423 terawatt-hours (TWh) during the same period—an increase of 90%. To meet these needs, the world's electricity generating capacity will have to increase from about 4719 GW in 2008 to 8875 GW in 2035, requiring approximately 4156 GW of capacity additions—almost four times the US generating capacity in 2008 (IEA, 2010). Thus the scale of the energy challenge is enormous—it is at the multi-terawatt level.

Climate change is rapidly becoming the defining environmental, economic, and political challenge of our era. With growing concerns about anthropogenic greenhouse warming and climate disruption, the pressures to curtail carbon dioxide emissions from coal-fired electricity generation are likely to escalate sharply. This gives rise to one of the central challenges in global energy policy: in the context of a carbon-constrained world, what energy supply infrastructures will provide the estimated additional 4156 GW of new electricity generation capacity that it is estimated the world will need by 2035? In view of the projected large absolute increase in global energy demand, such infrastructures will clearly need to display substantial scalability—i.e. ability to expand to the multi-terawatt level. Moreover, to meet the requirements of long-term security of supply and sustainability, these energy sources should be indigenous, abundant, and with a minimal carbon footprint.

Generation of net excess energy by a given supply infrastructure is a key determinant of its ability to facilitate economic growth. Throughout several centuries of recent history, industrialization and economic growth were facilitated by the emergence of fossil fuels-based energy supply infrastructures capable of delivering increased and highly concentrated net surplus energy.

[1] During the early stages of the transition there will not be self-replication of low-carbon systems but self-destruction of high-carbon ones. After the high-carbon systems are largely replaced, the low-carbon systems will then have to self-replicate. Our proposed analysis and the doubling time metric can be useful in evaluating the ability of alternative generating systems to self-replicate.

[2] As Koonin (2008) astutely observed "…you won't repeal the 2nd law of thermodynamics by taxing entropy!".