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The feasibility of 100% renewable electricity systems: A response to critics☆

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ABSTRACT

The rapid growth of renewable energy (RE) is disrupting and transforming the global energy system, especially the electricity industry. As a result, supporters of the politically powerful incumbent industries and others are critiquing the feasibility of large-scale electricity generating systems based predominantly on RE. Part of this opposition is manifest in the publication of incorrect myths about renewable electricity (RElec) in scholarly journals, popular articles, media, websites, blogs and statements by politicians. The aim of the present article is to use current scientific and engineering theory and practice to refute the principal myths. It does this by showing that large-scale electricity systems that are 100% renewable (100RElec), including those whose renewable sources are predominantly variable (e.g. wind and solar PV), can be readily designed to meet the key requirements of reliability, security and affordability. It also argues that transition to 100RElec could occur much more rapidly than suggested by historical energy transitions. It finds that the main critiques published in scholarly articles and books contain factual errors, questionable assumptions, important omissions, internal inconsistencies, exaggerations of limitations and irrelevant arguments. Some widely publicised critiques select criteria that are inappropriate and/or irrelevant to the assessment of energy technologies, ignore studies whose results contradict arguments in the critiques, and fail to assess the sum total of knowledge provided collectively by the published studies on 100RElec, but instead demand that each individual study address all the critiques' inappropriate criteria. We find that the principal barriers to 100RElec are neither technological nor economic, but instead are primarily political, institutional and cultural.

> *We were once afraid of what would happen when wind energy generation reached 5% of the total consumption. We then worried about approaching 10% – would the system be able to cope? Some years later, we said that 20% had to be the absolute limit! However, in 2016, Danish wind turbines produced more than the total electricity consumption for 317 h of the year, and we barely give this any thought.*
>
> Peter Jørgensen, Vice President Associated Activities, Energinet.dk [1]

1. Introduction

The energy sector is the largest contributor to global greenhouse gas (GHG) emissions, being responsible for about 35% of emissions [2]. Electricity generation, in particular, produces 25% of global GHG emissions [2]. However, in countries where the majority of electricity generation is produced by combusting coal (e.g. Poland, Estonia, China, Australia, South Africa), electricity is responsible for much larger proportions of national emissions [3]. Furthermore, transitioning electricity to low-carbon sources can reduce global GHG emissions by a much larger proportion than 25%, because electricity is generally regarded as the least difficult of the end-use energy forms to transform and, in a low or zero emission future, most transport and heat can also be energized directly or indirectly from low-carbon electricity [4]. The exceptions to a direct all-electric future are (i) low-temperature heating and cooling, some of which can be provided directly by solar thermal collectors and some by using waste heat from various sources (e.g. cogeneration) and the rest by electric heat pumps; and (ii) transport by air and on long distance rural roads, which in future could be provided by renewable fuels. The latter include biofuels produced sustainably, and hydrogen and ammonia produced by using renewable electricity.

Hence the debate about the future sources of low-carbon electricity is a very important one for climate mitigation. Can the low-carbon future be predominantly or entirely based on a combination of renewable energy (RE) and energy efficiency (EE), or will the mix have to contain significant contributions from nuclear power and or fossil fuels with

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carbon capture and storage (CCS)?

The climate stabilization wedges scenarios [5] and the recent International Energy Agency (IEA) global scenarios [4,6,7] contain mixes of RE, EE, fossil fuels with and without CCS, and nuclear power. They include all technically feasible technologies in their scenarios, including those that are not, strictly speaking, commercially available, such as coal CCS and bioenergy CCS. Although still frequently cited by supporters of fossil fuels with CCS and nuclear power, the scenarios by Pacala & Socolow [5] are outdated in terms of their choices of RE technologies – omitting rooftop solar photovoltaics (PV), additional hydro and bioenergy – and their potential. They offer little analytic support for their assumption of the future need for fossil fuels or nuclear power.

However, IEA's Beyond 2 °C Scenario (B2DS) [4], which is 'pushing the limits' according to its author, is a big step forward, because it has 78% of electricity generation in 2060 coming from RE. But IEA still appears to be influenced by its fossil fuel past, assuming that in 2060 coal use will be 22% of today's level, although it posits that all of this will come from power stations equipped with CCS, and also that there will be a significant use of oil and natural gas without CCS. IEA claims that B2DS 'avoids long-term lock-in of emissions-intensive infrastructure' [4], but that's questionable given the presence of fossil fuels in 2060 after 43 years of transition. Coal mines, oil refineries and liquid petroleum gas terminals would still have to be locked in at least to 2050 in order to give the B2DS scenario outcome for 2060.

Because funding for future energy systems is limited, policy choices on future energy sources and technologies have to be made urgently, based on up-to-date scenarios and technology assessments. An important factor in energy policy decisions must be the recognition that a RE future offers substantial advantages compared with fossil fuels and nuclear power, including:

- reduction and possible ultimate elimination of GHG emissions from the energy sector;
- reductions in air and water pollution, water use and land degradation;
- reductions in respiratory diseases and cancers from pollution;
- energy security for as long as human societies exist;
- a cap on energy costs, because most RE sources have no fuel costs and their capital costs are declining;
- more local jobs, per unit of energy generated, than fossil or nuclear power [8,9];
- reduced risk of nuclear accidents, nuclear proliferation and hence nuclear war [10,11].

Furthermore, community RElec projects, which were the foundation of the energy transition in Denmark and Germany [12], increase local self-reliance, reducing the political power of the large energy utilities and the fossil and nuclear power industries, while fostering small businesses and local employment. Distributed RElec is much more compatible with a healthy environment, social justice and a steady-state economy on a finite planet [13,14], than a centralised energy system based on fossil fuels or nuclear energy.

A few RE technologies, namely large-scale hydro and some bioenergy projects, can have substantial adverse environmental impacts. However, large hydro-electric dams, that flood pristine environments and displace large populations, can be constrained by environmental regulation for best practice, as can bioenergy projects that compete with food production, demolish primary forest, deplete soil nutrients or generate more GHG emissions than they save. In contrast, pumped hydro based on small dams [15,16] and bioenergy from crop residues [17,18] have low environmental impacts and so can be included in ecologically sustainable RE mixes.

This review examines the feasibility of large-scale electricity supply-demand systems based on 100RElec and the technical, economic, institutional and political challenges that must be overcome in order to achieve it. By showing how 100RElec can satisfy the key criteria of reliability, security and affordability, and by arguing that a rapid transition timescale is technically and economically possible, it refutes the principal myths propagated by critics of 100RElec. Unlike previous refutations of critiques of 100RElec (referenced below), which each replied to a single critique paper, the present paper replies to multiple critiques of 100RElec within the framework of reliability, security, affordability and timescale. In particular, it examines critically the critiques of 100RElec by Brook & Bradshaw, by Heard and by Smil (references below) within the framework of the four key criteria.

The study includes systems where RE contributes the major proportion of electricity, but less than 100%, however for brevity we refer to all these systems as 100RElec. While recognizing that EE can play a substantial and possibly a major role in the transition to an ecologically sustainable energy system [4,19], the present paper focuses on RE and RElec in particular.

Close to 100RElec (annual averages) is already well-established in countries and states/provinces with large hydro-electric resources, e.g. Iceland, Norway, New Zealand, Bhutan and Tasmania. However, providing a reliable 100RElec system is more challenging in regions that have little or no conventional hydro potential and hence require large contributions from variable RE, such as wind and solar photovoltaics (PV). Critics of 100RElec have focused mainly on these systems. Hence this paper focuses on 100RElec systems in which variable RE forms the major proportion of annual electricity generation. Over the past 20 years or so, wind and solar PV have rapidly become cheaper and so dozens of scenario studies have been published in which electricity is predominantly or entirely generated from these variable RElec sources (see the selected studies in Table 1). Many of these scenario studies contain simulations of the operation of electricity supply-demand systems based on time-steps of one hour or less and real data spanning time-periods of 1–6 years.

Table 1
Selected renewable energy scenario studies.

Region	Sector studied	Includes simulations[a]?	Reference
Whole world	Energy		[38]
	Energy		[39,40]
	Energy		[41]
	Electricity	Y	[42]
	Energy	Y	[43]
	Energy		[4,6,7]
Whole of Europe	Electricity	Y	[44–49]
	Energy	Y	[50]
Nations			
Australia	Electricity	Y	[51–57]
China	Electricity	Y	[58]
Croatia	Electricity		[59]
Denmark	Energy	Y	[60]
	Energy	Y	[61]
Germany	Electricity + heat	Y	[62,63]
Ireland	Energy	Y	[64]
Japan	Energy		[65,66]
Macedonia	Energy	Y	[67]
New Zealand	Electricity	Y	[68,69]
Northern Europe	Energy		[70]
Portugal	Electricity	Y	[71,72]
UK	Energy		[73]
	Energy + some non-energy industry		[74]
USA	Electricity	Y	[75–77]
	Energy	Y	[78,79]
States/provinces, etc.			
California	Electricity	Y	[80,81]
PJM transmission region, USA	Electricity	Y	[82]

Note: a. Simulations with time-steps of 1 h or less are identified with Y in Column 3.