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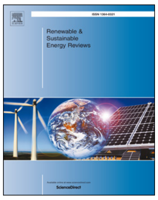

The feasibility of 100% renewable electricity systems: A response to critics[☆]

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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.

The low, still declining costs of RElec technologies and their consequent rapid growth are disrupting and transforming the electricity industry. In wholesale electricity markets, the very low operating costs of wind and solar farms are reducing wholesale electricity prices and hence reducing the capacity factors of coal-fired and nuclear power stations and driving their closure via the Merit Order Effect [20–25]. In retail electricity markets, the growth of rooftop solar and other small-to-medium scale RElec technologies on the customer side of the meter has reduced and in some cases ended growth in demand for grid electricity in several countries [26–28], threatening electricity distributors and retailers with the prospect of a 'death spiral' [10,29].

As a result, supporters of the politically powerful incumbent industries, together with climate and RE skeptics, are critiquing the feasibility of large-scale electricity generating systems based on 100RElec. Incumbents include electricity utilities (generators, distribution network service providers and retailers), fossil fuel and nuclear power proponents, and large electricity users such as aluminium smelters which generally buy bulk electricity at very low wholesale prices. Many critiques of RE are authored by nuclear power proponents, e.g. [30–32], supplemented by a few whose authors don't clearly identify their preferences for energy futures [33–36]. Another author, Smil [37], argues that the transition to an energy future must have a similar long timescale as historical energy transitions.

Therefore, as well as reviewing of the key issues of reliability (Section 2), security (Section 3) and affordability (Section 4) of 100RElec, and the timescale of the transition (Section 6), the present paper examines critically the principal arguments of these prolific RE critics (Sections 5, 6 and parts of Sections 2–4). We draw upon a larger subset of predominantly RElec scenarios than considered by the critics, show that the criteria chosen by the critics for assessing 100RElec studies are inappropriate, use the standard definitions of the criteria of reliability and security (unlike some critics, e.g. [30,31]), and come to a different conclusion. Technical terms used in this paper are defined in Box 1.

2. Reliability

Reliability is a measure the ability of the whole electricity supply system to meet demand. Generation reliability is generally measured either by the Loss of Load Probability (LOLP, the expectation value of the probability that supply fails to meet demand), or the proportion of unserved energy demand over a year, or by the frequency and duration of outages, i.e. failures to meet demand, [83]. These definitions are realistic, because they acknowledge that reliability is a property of the whole demand-supply system and that a perfectly reliable system is impossible – it would require infinite back-up and hence would have infinite cost. Nevertheless, very high levels of reliability are achieved in most industrialised countries: e.g. LOLP of a few hours per year in many U.S. states or unserved energy of 0.002% of annual demand in Australia [84]. Some RE critics fail to use the standard electric power engineering approach to reliability: for instance, Brook & Bradshaw [30] confuse it with dispatchability of individual power stations, while Heard et al. [31] confuse it with the presence or absence of base-load power stations in the supply system. Their invented definitions enable them to claim incorrectly that generation systems based on 100RElec are 'unreliable'.

Reliable generating systems, based on annual RElec of 80–100% of total generation, are already a reality in places that have a large proportion of hydro with dams, such as Iceland, New Zealand, Norway, Bhutan and Tasmania. However, providing a reliable 100RElec system is more challenging in places with little or no conventional hydro potential, such as Denmark and South Australia.

Nevertheless, several regions with negligible conventional hydro resources are already generating reliably about 100% net of their annual electricity from renewables: for example, the north German states Schleswig-Holstein and Mecklenburg-Vorpommern [85,86] and the Danish island of Samsø [87]. In 2016 Denmark generated 42% of its annual electricity consumption from wind [88], while South Australia generated 48% of its total electricity generation from variable RElec sources, wind plus rooftop solar [89].

In four US states (Iowa, Kansas, Oklahoma, South Dakota) in 2017, wind energy has reached or exceeded 30% of annual generation [90]. In each of the above examples, partial back-up is provided by transmission line connections to neighbouring countries or states, and no reliability problems have been reported. Indeed, Denmark has one of the highest levels of reliability/security of supply in Europe [1,91]. South Australia [92,93] and Denmark [1] have already operated without problems on 100RElec for continuous periods of over one day; Scotland (which supplements its wind with hydro) for four days [94]. This is an indication that the challenges of extending reliable 100RElec to periods of years and decades are much less difficult than claimed by RE critics. It should be mentioned that on 28 September 2016 tornadoes severely damaged three major transmission lines and blacked-out the whole of South Australia (SA). Some politicians and critics of RE seized the opportunity to blame the blackout on SA's wind farms [95], but the event was much more complex and the tripping (drop-out) of several wind farms was avoidable (see Appendix).

To explore the reliability and affordability of large-scale electricity generating systems with high penetrations of variable RElec, many research groups around the world have backed up their scenario studies with computer simulation models of the operation of the large-scale

Box 1
: Definitions of technical terms.

Dispatchable technologies can supply power on demand. All dispatchable sources have some kind of energy storage, e.g. dam, battery, thermal storage, fuel store.

Flexible technologies can be started and stopped at short notice and power output (or load) can be varied rapidly to meet varying demand and to compensate for varying supply. E.g. hydro with dam, open-cycle gas turbine, battery, concentrated solar thermal (CST) with thermal storage, contracted demand management.

Reliability is a measure the ability of generation by the whole system to meet demand. It is measured by e.g. Loss of Load Probability (the average probability that supply fails to meet demand), or the proportion of unserved energy demand over a year.

Security, the technical term, is a measure of the ability of the power system to tolerate disturbances and hence maintain electricity supply to consumers.

A ***base-load*** power station is one that can operate 24/7 at close to its rated generating capacity, except when it breaks down or undergoes routine maintenance.

A ***peak-load*** power station is one that is flexible and dispatchable, and is used to compensate for rapid variations in demand and supply by base-load and RE power stations.

Capacity factor of a power station is its annual average power output (usually averaged over one or more years) divided by its generating capacity aka rated power.

electricity supply-demand system (Table 1). This tool is particularly helpful for understanding how regions with little or no hydro, and low-capacity (or no) transmission connections to their neighbours, can have reliable generating systems based on 100RElec. Cost data and results are included in several of the models.

Conceptually, the simulations are simple. In each time-step of (usually, but not always) one hour, actual electricity demand in the country or region of interest is balanced with actual or synthetic data on RE supply. In most studies where there is little conventional hydro potential, the principal RElec sources are the cheapest, namely wind and solar PV, both variable sources. Many of the studies, for example those by Elliston et al. [51–54] that simulate the Australian National Electricity Market (NEM), use only commercially available technologies scaled-up to meet demand.

Contrary to popular misconception, not all RE is variable on short timescales (seconds to hours). To achieve reliability, variable renewables can be supplemented by flexible, dispatchable RE technologies such as hydro-electricity with dams, concentrated solar thermal (CST) with thermal storage, batteries, geothermal, and gas turbines fueled on renewable gases or liquids. The choice from this menu depends on the availability of RE resources in the region of interest, e.g. CST cannot operate in diffuse sunlight. (See Box 1 for definitions of ‘flexible’, ‘dispatchable’, etc.)

Computer simulations with hourly (or less) time-steps spanning 1–6 years show that 100RElec systems can be as reliable as conventional systems without the presence of any base-load power stations. Furthermore, in the Australian NEM, which has no transmission connection to an external grid, an optimal economic mix with 77% of annual electricity generation from variable RElec (wind plus solar PV) together with 23% of annual generation from dispatchable RElec (CST, existing hydro and biofuelled gas turbines) can still meet the reliability criterion (Table B.13 of [54]). Also in the NEM, simulation modelling by Blakers et al. [57] achieves reliability with 90% variable RElec balanced by 10% dispatchable RElec (which comprises mostly new pumped hydro and existing bioenergy), however their mix is not optimized economically. The reliability results in some of the studies are based on tens of thousands of hourly simulations in order to find a low-cost mix of RElec technologies and to perform sensitivity analyses to e.g. adding transmission links and/or using different operating strategies for storage. With a diversity of RE technologies and their geographic locations, the Australian simulations find that only a relatively small amount of storage or back-up is required for reliability.

In addition to choosing an appropriate mix of variable and dispatchable sources/technologies, variability is reduced and reliability increased by dispersing wind and solar farms geographically and connecting them by additional transmission lines where necessary [96–98].

Some critics raise the question about how a 100RElec system based predominantly on variable RE can maintain supply during rare periods of several days when there is simultaneously very little wind and solar power over a wide geographic region. Such periods have been named ‘Dunkelflaute’ (dark doldrums) in Germany [99]. Contrary to the statement of the problem by critics, the challenge is not to substitute for variable RElec continuously over several days, because:

i. Solar PV and solar hot water systems with flat-plate collectors still operate during overcast conditions, although well below their rated power.
ii. The critical periods are generally of extent 1–3 h during and around the peaks in demand.

This means that 100% back-up of variable RElec with dispatchable RE or fossil is unnecessary for maintaining reliability and that the back-up that is required only has to operate for several hours at a time and hence base-load power stations are not suited to the task. However, if the Dunkelflaute lasts for (say) one week in winter/summer, up to 14 demand peaks may have to be met, exhausting batteries and the small dams of off-river pumped hydro. In such rare events, open-cycle gas turbines (OCGTs), reciprocating engines and contracted demand management can play a vital role. In the immediate future, OCGTs and reciprocating engines may have to operate on fossil fuels, but in the longer term they can run on renewable fuels (e.g. biofuels, hydrogen, ammonia).

In the context of reliability, the ‘assessment’ of simulation modelling by Heard et al. [31] penalized individual studies for not having time-steps less than five minutes. However, the notion that every simulation study should have such tiny time-steps is absurd on both empirical and logical grounds. The 2015 simulations of the US system by Jacobson et al. [78] had time-steps of 30 s for six years, sufficient to show that choosing such a short time-step does not give qualitatively different results. This should be obvious on logical grounds too, because of the smoothing effect on output produced by the geographic dispersion within and between wind and solar farms. For example, in a wind farm of spatial extent 20 km, a sudden reduction in wind speed from 20 km/h to below the cut-in wind speed would take one hour to propagate across the wind farm and half a day to propagate to another wind farm 240 km distant.

Contrary to unsupported claims by pro-nuclear RE critics [31,32] that base-load power stations are essential, several of the simulation studies achieve reliability with zero or negligible base-load capacity, e.g. [45,46,51–54,57,82]. Furthermore, base-load power stations are poor partners for variable RElec, because of the former's relative inflexibility in operation [100,101]. Flexible, dispatchable power stations and storage technologies [45,46,49], together with demand response [102,103], are the appropriate partners.

3. Security

Three meanings of ‘security’ are considered here. The first two are popular uses of the term and their achievement by RE is self-evident. The third, a technical definition, has become important in the debate about 100RE.

i. RE has security of supply for billions of years, because all except one source depends directly or indirectly on the Sun. The exception, geothermal power, has lifetimes ranging from decades to centuries, depending upon the size of reservoir tapped.
ii. Provided that a RElec system is more distributed and interconnected than a conventional generating system based on centralized power station, it is potentially more secure against natural impacts (e.g. storms, floods) and sabotage than a conventional system. However, to be *actually* more secure, it must also meet the requirements of the third meaning.
iii. In electric power engineering, ‘security’ is a technical term denoting the ability of the power system to tolerate disturbances and hence maintain electricity supply to consumers [104]. Security is achieved by operating the system in a stable state and within the required bounds of a number of technical parameters such as frequency and voltage of alternating current, fault current levels and the operation of equipment within its design limits. It is discussed in the following subsection.

3.1. *Security, in the technical sense*

A disturbance in the system can result from e.g. the unexpected failure of a power station, the physical collapse or overloading of a major transmission line, or a sudden change in demand. This in turn may cause an imbalance between supply and demand, resulting in a change in frequency and voltage of the alternating current. If supply is greater than demand, the frequency is greater than the specified level, which is 60 Hz (cycles per second) in USA and 50 Hz in most other countries. Conversely, if supply is less than demand, the frequency is less than the specified level. In the past, frequency was generally

Table 2
Properties of stability and resilience measures for frequency control.
Sources: The authors, based on literature survey.

Technology	Principal purpose: stability or resilience	Speed of response to disturbance	Cost	Time to disseminate addtional technologies[a] (years)	Comment
Contracted demand reduction	Resilience	100–400 millisec.	Low	0.5–2	Contracts and smart switches required
Batteries	Resilience	# 10 millisec.	High but declining rapidly	1–2	Gigafactories under construction will shrink costs
Variable RE + inverter or power electronics	Both	# millisec.	Low	1–2	Inertia of rotating wind turbine blades is small; main contribution from synthetic inertia
Synchronous condenser	Both	# millisec	Medium	1–2	Commercial technology
Dispatchable RE	Stability	Seconds to minutes	Low	0–1	Changes to market rules may be required
Hydro with large dams	Stability	# minutes	High	7–10 for new systems	New large dams are limited by limited remaining resource, environmental & social impacts
Additional generators on existing dams	Both	# minutes	Medium	3–5	Studies of potential required
Off-river pumped hydro	Resilience	# minutes	Medium	3–5	Commercial technology; studies of potential required
CST with thermal storage	Both	# seconds	High, but declining	2–3	Commercial technology with small global market so far
Open-cycle gas turbines & reciprocating engines burning renewable fuels	Both	10 min from cold; less than a minute when hot	Low	0.5–1	Low capital cost; high operating cost. Initially they will combust fossil fuels while RE fuels are being developed
New major transmission lines	Stability	N/A.	High	7–10	Land access is partly responsible for long dissemination time.

Notes: a. Time to make a significant contribution to whole generation system. # denotes 'several'.

maintained by the inertia of the heavy rotating turbines driven by boilers in conventional base-load power stations. With the gradual phase-out of base-load stations, new ways of controlling frequency are being implemented.

Two separate but related aspects can be distinguished, although the boundary between them is fuzzy. The first is maintaining frequency stability in the absence of significant disturbance and in the absence of inertia provided by the heavy rotating machinery of base-load power stations. RElec systems with turbines – e.g. hydro, CST, OCGTs – contribute inertia while operating. However, these dispatchable, flexible technologies are not generally operated continuously in a 100RElec system. In addition, variable RE systems can provide 'synthetic' inertia, because their output passes through power electronic devices such as inverters to control frequency and voltage before entering the grid. The second aspect of frequency control is resilience, the ability to restore the required frequency in response to a significant disturbance of stability and hence frequency. The following technologies and measures are commercially available but require different time-periods for widespread dissemination:

i. All existing, dispatchable RE sources listed above are ready to contribute immediately, although in some electricity markets institutional arrangements may be needed to bring them online when required by the market operator.
ii. Contracted rapid demand management for critical periods can be expanded. It already exists for a few large industrial interruptible loads (e.g. aluminium smelters) and could be readily extended to households, commercial and small industrial consumers by rolling out 'smart' software, switches and other devices [103–105].
iii. With minor modifications to generator controls and operational strategies, wind, solar PV (including rooftop) and batteries can contribute. (Grid-tied inverters follow the grid frequency and so cannot in general contribute to frequency control or response.) They can provide both resilience and 'synthetic inertia' as opposed to the physical inertia provided by heavy rotating machinery [104,106].
iv. Synchronous condensers can be installed in the grid. This is a well-established technology for providing reactive power and adjusting the phase difference between current and voltage (i.e. power factor) in industrial settings and on a transmission grid. It can control voltage and frequency [104].
v. Additional hydro generators can be installed on existing dams. The potential for this is limited in most regions.
vi. Some regions with negligible potential for conventional hydro may have considerable potential for off-river pumped hydro, especially at coastal sites (e.g. South Australia). These technologies will have small dams and large elevation differences, so that they can deliver high power for short periods (hours to days), the key periods for handling the variability of wind and solar PV [15,16].
vii. Improved transmission interconnection between regions will strengthen security, both in the technical and popular senses.

With the exception of batteries, the first three of these measures are inexpensive and the first four can be rolled out rapidly (0.5–2 years) as required. The prices of batteries are dropping rapidly as mass production is scaled up. New off-river pumped hydro projects may take 3–5 years to plan and build. Major long-distance high-voltage transmission lines are expensive (very expensive where undergrounded) and take much longer (7–10 years) to plan and construct.

The speed of response to a disturbance varies with the type of response. Batteries and contracted demand reduction can be brought online automatically in several milliseconds. At a grid frequency of 50 or 60 Hz, this response occurs within a small fraction of a wavelength of the alternating current and voltage. Some dispatchable RE technologies (e.g. hydro with dam, CST with thermal storage) can increase or reduce their output within tens of seconds to minutes: similarly for variable RE (e.g. wind and solar PV) without inverters. If variable RElec technologies are operated slightly below their maximum possible output for prevailing weather conditions during periods when a disturbance appears likely, they can also increase their output almost instantly and maintain that increase for a brief period [106]; there is of course a small economic penalty for operating variable RElec in this manner.

The fast response measures can buy time for the slower back-up to come online. Aeroderivative, open-cycle, gas turbines can reach full power from a cold start in about 10 min. However, if they are already hot, they can vary their output within seconds. Reciprocating engines can also contribute to stability on this time-scale and do so in Denmark [107]

Thus a mix of different measures, with different response speeds and energy storage capacities, is required. Table 2 summarises the properties of different measures for controlling frequency. Only qualitative measures of cost are given, because costs are declining rapidly as market sizes are increasing.

4. Economics

Reverse auctions and tenders provide a very recent (2016–2017) window on the rapidly declining prices of wind and solar PV. In several Latin American countries in 2016, on-shore wind and solar PV without subsidies are competitive with conventional electricity technologies (see reports in RenewEconomy). In Denmark, off-shore wind prices fell to an average of USD 60/MWh [108]; the winning bid for the 600 MW Kriegers Flak off-shore wind farm was just EUR 50/MWh (DKK 0.372/kWh) for the first 30 TWh generated, excluding cost of grid connection to shore, which under Danish rules is socialised among all electricity consumers [109]. In the UK in 2017 the Hornsea Project 2 offshore wind farm won a contract at 57.5 £ /MWh (about USD 76/MWh) for a 2021/22 start up [104]. For comparison, the contract price for the proposed new Hinkley C nuclear power station in the UK is 92.5 £ /MWh (2012 pounds), escalating with inflation for 35 years [110]. Bloomberg New Energy Finance finds that large-scale wind and solar PV can now, or almost, 'compete directly with a new coal or gas plants in the absence of subsidies… in all major markets' [111].

Earlier data (2014–2015) come from the USA. Lazard [112] estimated the *unsubsidized* levelized costs of energy (excluding grid connection) from electricity technologies in the USA to be, in USD/MWh: for on-shore wind farms 32–77; solar PV farms 58–70; CST with thermal storage 119–181 and nuclear 97–136. For RElec the wide cost ranges reflect mainly geographic location, as confirmed for the Power Purchase Agreement (PPA) prices of wind farms in 2014–2015 from the U.S. Department of Energy (see Fig. 45 of [113]) which were around USD 20/MWh in the windy interior region increasing to about USD 50/MWh in the western region.

In several countries and states, feed-in tariffs (FiTs) for RElec have been cut dramatically to levels approximately equal to wholesale electricity prices and hence cannot be considered as subsidies. The 2017 German Renewable Energy Law (EEG 2017) replaced FiTs with reverse auctions or tenders, except for small projects [114,115]. FiTs are only used to a limited extent in the USA [116]; however most states have renewable portfolio standards [117] which are currently under threat. In the Australian states FiTs are not generally mandatory although two of the six states have (low) mandatory minima; in the other states retailers offer FiTs ranging from zero to around the wholesale price of electricity [118].

In both the scholarly and popular literature, RE critics misrepresent the ongoing transformation of the economics of solar PV and wind: e.g. they halve actual cost of coal or nuclear generation and double actual RE costs, claiming incorrectly that RE requires vast amounts of back-up [119]. Some critics even assert that coal or nuclear stations with the same generating capacity have to be kept running continuously just as back-up for RE systems. This is refuted by the simulation studies discussed above and by practical experience: e.g. South Australia's two coal-fired power stations were shut down in part because they couldn't compete in the market with wind [120]. The state's remaining base-load station (gas-fired) is expected to close soon. However, in some systems additional peak-load stations may be required. OCGTs, in particular, have low capital costs and, provided they are operated infrequently and for brief periods, low annual operating costs. Thus they can play the role of reliability insurance with a low premium. However, the market rules (and gaming of the rules) in countries with high gas prices entail that OCGTs can push up the spot prices of wholesale electricity to high levels while they are operating [121]. This problem can be addressed by modification of the rules, e.g. requiring that both dispatch and settlement of spot prices take place simultaneously every five minutes [122].

For households and businesses that use most of their electricity in daytime, rooftop solar PV is generally cheaper than retail electricity from the grid and generally cost-effective even where feed-in tariffs are very low (e.g. [123]). Battery prices are declining rapidly as the market grows and so it is likely that, within a few years, rooftop solar systems with batteries will become generally competitive with grid electricity for households and businesses that use most of their electricity in evenings. Most suburban owners will remain grid-connected as back-up for the occasional long overcast periods.

5. Case studies of RE denial

This section examines critically the principal arguments of some of the most prolific RE critics who publish in the scholarly energy literature and the popular press.

An approach used by biologists Brook and Bradshaw [30] is to set up a framework to compare RElec with nuclear power, choose dubious assessment criteria that favour nuclear power and disadvantage RE, claim incorrectly that their method is objective, and show that nuclear power satisfies their criteria while RE doesn't. For example, they require *each* RElec power station in a system to be dispatchable, although both simulations and practical experience show that this is unnecessary for a reliable generating system. As discussed in Section 2, reliability is a property of the whole system, not individual power stations.

Contrary to all the evidence reviewed in [124], Brook and Bradshaw [30] reject from their choice of assessment criteria nuclear power's contribution to the proliferation of nuclear weapons and thus to the risk of nuclear war [10,11]. Furthermore, in assigning a score to their 'safety' criterion, they appear to consider only short-term deaths from acute radiation syndrome and to ignore the major contribution, namely cancer deaths that appear over several decades. Thus, in downplaying the potential huge impacts of nuclear accidents and nuclear war, they fail to take a scientific risk approach, which recognizes that low-probability high-impact events must be considered. Although risk analysis is a complex field, at bare minimum they could consider risk as the probability of an event multiplied by the potential impact [125]. They exaggerate greatly the land-use by RElec, quoting the land spanned by a wind farm, ignoring the fact that the land actually occupied by the wind farm is typically 1–3% of the land spanned [126] and almost all spanned farmland can continue to be used for agriculture. These fundamental flaws were exposed subsequently in three peer-reviewed refutations [124,127,128], showing that Brook and Bradshaw's choice of criteria and their scores for the criteria were subjective and biased.

Heard, Brook, Wigley and Bradshaw [31] use a similar approach in a recent review article that claims to be a 'comprehensive' critique of simulation modelling of 100RElec. Again, several of their assessment criteria are unnecessary or irrelevant. For example, in addition to their unnecessary requirement that each simulation study have time-steps less than five minutes (discussed in our Section 2), they demand that each 100RElec scenario consider a high growth in future demand for electricity. This again is unnecessary for most regions, because demand and supply can easily be rescaled in these simulations without significantly affecting the results for reliability, security and affordability. The only limit on future RElec supply is land-use, and this limit is a long way off in most countries. Japan and South Korea are among the exceptions, on account of their limited areas of marginal land and limited off-shore wind potential. The options of these countries are imports of RElec by transmission line and renewable fuels by tanker, high densities of on-shore wind and of building-integrated PV, and a substantial development of hydrogen storage (see chapter 13 of [129]). In northern Europe, off-shore wind farms can make a substantial contribution, particularly now that costs are falling rapidly.

A related argument by RE critics is that 'To rely on contraction in total primary energy in 2050 compared to today…is therefore implausible' [31]. Granted that human population growth will continue and economic growth too, especially in less developed regions, this can be offset to a large degree by the huge untapped potential for efficient energy use and efficient energy generation resulting from the transition to renewable electricity and heat, together with electric vehicles [4,43,78]. When RElec substitutes for fossil electricity, one unit of RElec can substitute for about three units of fossil primary energy, because of the low efficiency of combusting fossil fuels in generating electricity. Thus primary energy for electricity generation (and hence GHG emissions) can be reduced by a factor of about three. When electric vehicles are substituted for oil-fueled vehicles with internal combustion engines, primary energy use for transport is at least halved. Additional energy savings will result from the ending of the energy intensive industries of mining fossil fuels and oil refining. See also our comment in Section 6 on Smil's mistaken emphasis on primary energy when end-use energy (or, even more fundamentally, energy services) are the basic requirement.

Instead of assessing the feasibility of 100RElec for the 'whole electricity system', which Heard et al. [31] (p.1123) acknowledge is necessary, they actually demand unreasonably in the same article that each individual publication has to satisfy all their criteria chosen for the whole field (as witness their Table 1). In reality, most scholarly research is done in incremental steps and the whole body of research on a particular issue must be considered. But Heard et al. select single papers and single topics from research groups, instead of considering the whole body of relevant research, and omit the large body of recent research from Europe. These publications by these authors generalize inappropriately from very few examples. Their critiques confuse scenarios with forecasts and contain illogical and misleading arguments, internal inconsistencies, errors of fact, outdated data and inappropriate references [124,127,128].

In 2015 Jacobson and colleagues published in PNAS a detailed scenario study showing how the whole US energy system (electricity, transportation, heating/cooling and industry) could operate on 100RE based on wind, water and solar [79]. They addressed grid reliability with a simulation spanning six years. Wind and solar time series data with time-steps of 30 s were obtained from a 3D global weather model that simulates real events. They calculated both economic and social costs. In 2017 a critique was published by Clack et al. in PNAS, claiming that 'this work used invalid modelling tools, contained modelling errors, and made implausible and inadequately supported assumptions' [33]. In reply Jacobson et al. [78] argued point by point that the premise and all error claims were demonstrably false and they reaffirmed their original conclusions.

Our assessment is that Jacobson et al. [78] have clearly refuted all but one of Clack et al. [33] error claims. The exception is Jacobson's assumption of a huge and unrealistic increase in hydro capacity by installing additional turbines on existing dams, in order to assist in balancing variable RElec. However, this is a minor 'error', because a large part of the additional hydro could be replaced by alternatives such as CST with thermal storage, OCGTs fueled by renewable hydrogen or ammonia, new off-river pumped hydro and batteries. Of particular concern is that PNAS published the Clack et al. [33] article as a Research Report instead of a Letter to the Editor, although the article contained no original research – it only criticised a genuine research paper with claims that generally don't stand up to examination.

The stated motivation of another critic, Ted Trainer, is his concern that, if RE could power industrial society, his case for 'a simpler way' would be undermined [130,131]. While the lead author of the present article agrees with Trainer that we must transition to a steady-state economy with lower throughput, he rejects the logic of Trainer's stated motivation for critiquing RE. There are much stronger reasons for supporting the transition to a steady-state economy with low throughput [14,132,133] than questioning the capacity of RE. Furthermore, Trainer's arguments against 100RE being able to supply industrial society are incorrect.

For example, a paper by Lenzen et al. [56], coauthored by Trainer, overestimates the cost of Australian wind farms by choosing their average capacity factor (a measure of annual output, see Box) to be much lower (at 20%) than the observed average values (weighted according to capacity), which fluctuate around 33% from year to year, (e.g. see Appendix A.2 of [93,134]). Lenzen et al. attempt to justify this choice by claiming incorrectly that a large proportion of generated wind energy is actually curtailed, i.e. cannot be fed into the grid, during periods of high wind and low demand, because 'installed capacity in renewable grids can reach three to five times demand, resulting in significant capital cost and some plant sitting idle for much of the time' [56]. Although the references cited to support this sweeping statement [80,82] do have scenarios with total installed capacity 2.5–3 times demand respectively, the statement quoted from [56] is exaggerated and misleading, because the context implies incorrectly that the high installed capacity is entirely due to variable RElec and the statement ignores the trade-off between RElec capacity and storage discussed in [82]. Subsequent reductions in the prices of battery storage and CST with thermal storage will shift the balance away from capacity to storage. Furthermore, the amount of capacity depends on the generation mix assumed: e.g. the mixes chosen by [82] included expensive hydrogen storage and no (low-cost) OCGTs. In contrast, the mixes in the UNSW scenarios of the Australian National Electricity Market with 100RElec (Table B.13 of [54]), include a small dispatchable contribution from OCGTs operating on biofuels. Under conditions of optimal economic mix, these scenarios operate reliably with up to 70% of annual electricity generation supplied by wind and 7.3% supplied by solar PV, bringing the total variable RElec contribution to 77%. The wind and solar PV capacities in this scenario are 44.8 and 5.1 GW respectively ([54] Table A.10) and the maximum demand is 33.6 GW [51] and so variable RElec has a capacity of just 1.5 times maximum demand.

Trainer's curtailment assumption ignores the possibility that 'excess' wind power in one region of the grid can be exported to another region of the grid, subject to the availability and capacity of transmission lines. Furthermore, 'excess' wind and solar power that's currently curtailed occasionally when electricity demand is low, can in the near future be used to power intermittent loads such as pumping water from a low to a high reservoir during off-peak periods. Trainer [34] rejects conventional pumped hydro with big dams on the grounds that the resource is limited, but gives no weight in [34] or in [56] to the large potential for installing off-river pumped hydro, a commercially available dispatchable technology, even in a dry continent such as Australia [15,16]. In South Australia, a very dry state with no potential for conventional hydro, sea-water pumped hydro is currently under investigation [15]. Excess variable RElec can also be transferred from electricity generation to another sub-sector of the energy sector – e.g. power to gas for heating; power to batteries, gas or liquid fuels for transport – or even to another sector of the economy, e.g. power to chemicals. This is known as 'sector coupling' [135]. It already exists for fossil fuels, e.g. using natural gas from a pipeline for electricity, heat, transport and chemicals.

According to Trainer, another consequence of having high wind capacity results in high capital cost, which he claims incorrectly is not taken into account in cost calculations. This claim, which Trainer has made in several articles from 2012 to 2017 [34–36], is false because the capital cost was already quite low in 2012, is even lower in real terms in

2017, and is *always* taken into account in peer-reviewed economic calculations. Although Trainer's error was pointed out to him by Jacobson & Delucchi [136] (p.642), he continues to repeat it [36].

Another repeated Trainer error [34,35,137], also pointed out by Jacobson & Delucchi [136], is the incorrect notion that embodied energy adds to the economic costs of RElec technologies. Incidentally, Trainer's response to [136] fails to address all but one of the points made in their critique. On the single point he does address, Trainer continues to confuse embodied energy with monetary costs.

The notion that 'excess' capacity is 'sitting idle for much of the time' also demands closer examination. In an entirely fossil-fueled grid, OCGTs with capacity factors in the range 2–10% play a vital role in supplying peak power. They have low capital cost and, provided they have low capacity factors, low annual fuel costs. Even when they are not operating, they provide reliability insurance with a low annual premium for handling unforeseen rapid changes in supply and demand, and/or assisting in system restart after blackouts. Similarly, nowadays wind and solar farms can be justified economically (see Section 4) even though they only operate at full capacity for limited periods.

6. Transition timescale

A leading critic of the belief that the transition to a predominantly RE system could be made rapidly, is Smil [37]. Unlike several of the other RE critics, Smil is not a nuclear power proponent, recognizing that 'the combined challenges of risk perception, public acceptance, permanent waste storage, and nuclear weapons proliferation do not make any early vigorous and widespread renaissance very likely'. His position on RE is based primarily on his extensive, detailed, historical research on previous energy transitions and so must be examined closely. In Chapter 5 of his book [37], Smil argues that 'the process of restructuring the modern high-energy industrial and postindustrial civilization on the basis of nonfossil, that is, overwhelmingly renewable, energy flows will be much more challenging that [sic] was replacing wood by coal and then coal by hydrocarbons.' To reply in detail to Smil's case would require a book of similar length to his. However, to question his conclusions, it's sufficient to examine critically his key assumptions.

Before doing so, it should be mentioned that [37] is apparently inconsistent in its broad estimates of global transition timescales, stating in some places that that 'multidecadal transitions are unavoidable' and elsewhere referring to 'the multigenerational dimension of energy transition'. If the 'multidecadal' is interpreted as accepting a 2050 global target for 100RE, then we would agree with Smil and debate would be unnecessary. However, the whole thrust of his historical and industrial restructuring arguments points to a longer, multigenerational transition and so the debate continues. His key assumptions and their flaws are as follows.

Smil's Assumption 1: 'changing the sources of electricity is much easier than changing the makeup of primary fuel supply' and *'most of the renewable targets defined by more than 160 countries apply only to electricity generation'*.

Smil cites very few RE scenarios and so appears to be unaware that most scenarios for 100RE involve transitioning most or all transport and non-electrical heat to direct and indirect forms of RElec (see our Section 1). Hence, a predominantly RElec future will automatically change the primary energy inputs and become a predominantly RE future. Furthermore, his focus on the challenge of transitioning primary fuel supply puts the cart before the horse. When RElec and EE reduce end-use energy by a certain amount, they can substitute for approximately three times that amount of energy in primary fossil fuels used for electricity generation. This is because of the low efficiency of conversion of fossil fuels into electricity. Transitioning electricity is the key.

Smil's Assumption 2: The successful transition of a few countries is irrelevant to a global transition.

Contrary to Smil's belief, we respond that the successful examples mentioned in Section 2 are relevant (i) as the pathfinders for other regions, demonstrating how reliability, security and affordability can be achieved; and (ii) because they continue to drive down the costs of RE technologies for the rest of the world, which will experience an even easier transition than the leaders. Germany's success in driving the market for solar PV, and so bringing down its costs, brought China into manufacturing PV with further reductions in costs. Thus the successful examples are relevant both as symbols and in practice.

Smil's Assumption 3: Wind and solar power must be scaled up by increasing the size of wind turbines and efficiency of conversion to impossible levels.

Smil overlooks the significance of the fact that wind and solar technologies are mass-produced in factories and so the principal increase in capacity comes from rapidly producing more wind turbines and solar modules. Bigger, more efficient wind turbines and solar modules play a minor role in the scale-up; they merely supplement the major role of market growth in reducing costs.

Why should the world be intimidated by the prospect of building '3.8 million 5-MW wind turbines, 40,000 300-MW central solar plants, 40,000 300-MW solar PV plants, 1.7 billion 3-kW rooftop PV installations, etc.' [37], when there are over one billion motor vehicles on the road today [138] and annual sales of cars and light commercial vehicles alone were 88 million in 2016 [139]? Mass-production of wind turbines and solar modules (for both PV and CST), with rapid on-site installation, is an entirely different process from the slow on-site construction of coal-fired and nuclear power stations. There are billions of devices connected to the Internet and these were mostly deployed in under 20 years.

As discussed in Section 4, the actual economic cost of the RElec technologies would be similar to that incurred by continuing with business-as-usual. If we include the environmental and health costs of the 100RElec and business-as-usual scenarios, e.g. via a carbon price, the former is likely to be much less expensive than the latter. If fossil fuel power stations are replaced with RElec and EE at the end of their operating lives, 100RElec could be achieved by 2050 and stranded assets would be limited to long-lived infrastructure, such as a few transmission lines and gas pipelines that would be no longer useful. However, a very rapid transition triggered, for example, by the collapse of the West Antarctic Ice Shelf [140] could produce huge stranded assets. Then the choice between uninhabitable coastal cities and stranded assets should be clear.

Smil's Assumption 4: 'no-carbon, steel, cement, ammonia, and plastics will be a multigenerational process'

Transitioning steel and cement is indeed a challenge that requires more attention in cutting GHG emissions, but primarily involves changing *non-energy* industrial processes and so is of low relevance to the energy transition. However, development is proceeding for these materials and processes: carbon for reducing iron oxide to iron can be obtained without CO_2 emissions from biomass [141], as it was in several countries in World War 2, and also potentially by electrolysis [165]; low-carbon alternatives to Portland cement are under development [142,143], but face resistance from incumbents; plastics can be made from biomass; and ammonia can be made by combining atmospheric nitrogen with renewable hydrogen produced by using RE [144]. The non-energy industrial transition needs more funding for research, development, demonstration and early commercialization, but this is not a valid argument that the *energy* transition will be multi-generational.

Smil's Assumption 5: R&D is the key to the energy transition

Smil appears to share this assumption with Bill Gates, whom he mentions in making this point, despite the fact that many simulation models of 100RElec use only commercially available technologies to achieve reliable, secure systems. While more R&D is vital for ecologically sustainable production of steel, cement, and plastics, it is not of primary importance for energy technologies. Of course, it will always be needed to make improvements, but a massive increase in funding for energy R&D would be a diversion from the principal task of building the market for RE, by means of targets, carbon pricing, finance, reverse auctions with contracts-for-difference, fair feed-in tariffs, education and training [10,145,146].

Smil's Assumption 6: The transition to RE is likely to be slow, because it faces challenges similar to those of the slow historical energy transitions.

Smil's arguments in support of this assumption, and our responses, are as follows:

i. *The rate of increase in efficiencies of RE technologies is slow.*
See our response to Assumption 2 (above), which argues that this has low relevance in the face of mass production of wind and solar technologies.

ii. *The rapid decline in cost of RE technologies and their high annual growth rates are nothing special for the early stages of dissemination of new technologies.*
We respond that two key RE technologies, wind and solar PV, are now becoming economically competitive with fossil fuels (Section 4) and that opens the prospect of greatly increased growth rates. Reliability and security also have several low-cost options, as discussed in Sections 2 and 3.

iii. *The transition to fossil fuels was faced with huge infrastructure requirements and the world is locked into them.*

While we agree with Smil to the extent that some new transmission spines and pipelines will be needed in a RE future, and that they take longer to build than RElec power stations, we submit that much of the existing infrastructure, apart from coal and nuclear power stations and oil refineries, can serve the new future. Like it or not, other fossil fuel infrastructure (e.g. coal-fired power stations, oil refineries) may become stranded assets.

Smil's Assumption 7: Scenarios by the International Energy Agency give a modest future role to RE.

Like [31], Smil identifies scenarios by politically influential energy organisations with credible predictions. However, a scenario is a ‘what-if?’ thought experiment: given certain assumptions, what are the consequences? The IEA has been criticised for consistently underestimating the growth in RE over many years [147,148]. Its assumptions and hence its choice of scenarios reflect its origin in the fossil fuel framework of 1974 [149]. Recently IEA has begun to catch up with RE developments and its B2DS scenario discussed in Section 1 envisages 78% of electricity from renewables in 2060. However, it still contains a significant contribution from fossil fuels (see Section 1). Future growth in RE does not have to be constrained by IEA scenarios.

Because the above seven assumptions by Smil are questionable to say the least, the case that the transition to RE will take longer than historical energy transitions has no basis. On the other hand, the fact that wind turbines, solar PV, CST, batteries and EE technologies can be mass produced rapidly and are less expensive than new fossil fueled and nuclear power stations, gives confidence that a rapid transition to RE and EE is technically and economically possible. However, a study of transition dynamics is beyond the scope of this paper.

7. Discussion: barriers to 100RE

Reviewing research by others and the present authors, this paper has shown that well-designed 100RElec systems meet the basic requirements of reliability, affordability, security and low environmental impact. Since the principal barriers to a rapid transition to 100RElec, and beyond that to 100RE, are no longer technical or economic, what are they? In Australia, the world's biggest exporter of coal, Prime Minister Malcolm Turnbull criticised the Queensland state government's ‘reckless’ plans to ensure Queensland's energy supply is carbon neutral by 2050 and said Australia had an interest in ensuring the future of coal [150]. UK Energy Secretary Amber Rudd attempted to justify the decision to build the proposed Hinkley Point C nuclear power station at huge cost on the grounds that ‘we have to secure baseload [electricity]’ [151]. In the USA, President Trump appointed climate sceptic Rick Perry [152] as Secretary of the Department of Energy, and RE opponent Daniel Simmons to head the Department's Office of Energy Efficiency and Renewable Energy (OEERE) [153]. Secretary Perry suggested that increased reliance on RE sources like wind and solar might make the grid unreliable, given they only work when the sun is shining and the wind is blowing, creating national security concerns [154]. According to the Energy & Policy Institute, Simmons previously worked for special interest groups that lobbied Congress to eliminate OEERE [155]. Clearly political ideology and the capture of governments by powerful vested interests is a major barrier. Critics of RE who misrepresent RE can be seen as part of that political barrier, giving support to politicians who are unduly influenced by incumbent industries.

The arguments of the critics of 100RElec and, beyond that, 100RE are primarily technical ones. As demonstrated in this response, these critiques are flawed through inadequate understanding of the engineering, scientific and quantitative modelling literature. This is not surprising, because only a few of the authors of those RE critiques have qualifications in physical science or engineering or quantitative modelling. What is surprising is that the critics continue to use invalid assumptions and methods, and to repeat discredited arguments. The fact that the critics' articles have been published, and continue to be published, in international journals raises questions about the quality and objectivity of the peer reviews they have received.

In the context of the debate about energy futures, it should be noted that Brook and Bradshaw organised a letter and media release entitled ‘Nuclear should be in the energy mix for biodiversity’ [156] and, by citing their journal paper [30] as the basis of the statement, obtained signatures from 75 conservation scientists [157].

By critiquing the capacity of RE to substitute for fossil fuels and nuclear power, vested interests are having a similar effect to the former campaign by the tobacco industry to sow doubts about the serious adverse health impacts of their product and hence delay action. Vested interests are arguably the major barrier to a RE future. However, the rapid growth and declining costs of RE are weakening their influence.

Another barrier results from the situation that some countries, such as Australia, are still dominated by neoliberal economic rhetoric of ‘leave it to the market’ in a system where market failure is endemic and electricity market rules favour the incumbents [158–160]. This is recognized by supporters of RE, who are calling for a modification to the Australian National Electricity Objective in order to cut GHG emissions [161] and for a change in National Electricity Market rule that determines the spot price at 30-min intervals while dispatching power stations at 5-min intervals [162]. Additional rule changes are required to include demand response and energy efficiency into the market, to encourage a reliable and secure mix of RElec technologies as 100RElec is approached, and to give incentives to the construction of new low-carbon power stations as required [159,162].

Resistance to the RElec transition also comes from utilities clinging to their traditional, business models that are failing as the result of the Merit Order Effect and the early stages of a ‘death spiral’ (see Section 1), and from a few older power engineers, who still desire a supply system that follows an unmanageable load, comprising a mix of conventional base-, intermediate- and peak-load power stations, all of which are dispatchable, and cannot envisage a system that contains a large fraction of variable RElec and where demand can be modified almost instantaneously.

8. Concluding remarks

Electricity supply systems, operating on 100% renewable energy with the major proportion from variable renewables, are technically feasible, reliable and affordable for many countries and regions of the world. This is even true if future RElec is limited to technologies that are commercially available now. Regions with insufficient local RE resources will in future be able to import RE via transmission line [163] and/or tanker carrying renewable fuels. RE's environmental and health impacts are much less than those of fossil fuels and, within a risk framework that recognizes low-probability high-impact events, nuclear power. RE contributes to community development and participatory democracy, and is compatible with a steady-state economy. A 100% RElec system can provide directly, and indirectly via renewable fuels, all future energy use, including transport and heat.

The principal barriers that are slowing the transition are the political power of the incumbent fossil fuel, nuclear and electricity industries, bolstered by misinformation disseminated by RE critics, and existing institutions such as market rules that are inappropriate for climate mitigation and discourage RElec and flexible, dispatchable power stations.

The inertia against change can be overcome by the growing public awareness of the increasing impacts of climate change, the competitive economics of RElec, and positive visions of a cleaner, healthier, more sustainable future. However, because time is of the essence, community groups and the population at large must increase pressure on governments to resist vested interests and transition to 100RElec and then 100RE.

Declarations of interest

None.

Appendix A. : Black System South Australia

The final report of the Australian Energy Market Operator [164] on the state-wide blackout of South Australia on 28 September 2016, summarises the event as follows:

The damage to these three transmission lines caused them to trip, and a sequence of faults in quick succession resulted in six voltage dips on the SA grid over a two-minute period at around 4.16 p.m.

As the number of faults on the transmission network grew, nine wind farms in the mid-north of SA exhibited a sustained reduction in power as a protection feature activated. For eight of these wind farms, the protection settings of their wind turbines allowed them to withstand a pre-set number of voltage dips within a two-minute period. Activation of this protection feature resulted in a significant sustained power reduction for these wind farms. A sustained generation reduction of 456 MW (MW) occurred over a period of less than seven seconds.

The reduction in wind farm output caused a significant increase in imported power flowing through the Heywood Interconnector [from the neighbouring state of Victoria]. Approximately 700 ms (ms) after the reduction of output from the last of the wind farms, the flow on the Victoria–SA Heywood Interconnector reached such a level that it activated a special protection scheme that tripped the interconnector offline.

The SA power system then became separated (“islanded”) from the rest of the NEM. Without any substantial load shedding following the system separation, the remaining generation was much less than the connected load and unable to maintain the islanded system frequency. As a result, all supply to the SA region was lost at 4.18 p.m. (the Black System). AEMO's analysis shows that following system separation, frequency collapse and the consequent Black System was inevitable.

AEMO concluded inter alia:

- Wind turbines successfully rode through grid disturbances. It was the action of a control setting responding to multiple disturbances that led to the Black System. Changes made to turbine control settings shortly after the event has removed the risk of recurrence given the same number of disturbances.
- Had the generation deficit not occurred, AEMO's modelling indicates SA would have remained connected to Victoria and the Black System would have been avoided.

Wind and solar PV capacity continues to grow in SA and the state government is funding (initially) 100 MW/129 MWh of batteries and new government-controlled gas turbines, and is exploring demand reduction measures.

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