Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'

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A B S T R A C T

A recent article 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems' claims that many studies of 100% renewable electricity systems do not demonstrate sufficient technical feasibility, according to the criteria of the article's authors (henceforth 'the authors'). Here we analyse the authors' methodology and find it problematic. The feasibility criteria chosen by the authors are important, but are also easily addressed at low economic cost, while not affecting the main conclusions of the reviewed studies and certainly not affecting their technical feasibility. A more thorough review reveals that all of the issues have already been addressed in the engineering and modelling literature. Nuclear power, which the authors have evaluated positively elsewhere, faces other, genuine feasibility problems, such as the finiteness of uranium resources and a reliance on unproven technologies in the medium- to long-term. Energy systems based on renewables, on the other hand, are not only feasible, but already economically viable and decreasing in cost every year.

1. Introduction

There is a broad scientific consensus that anthropogenic greenhouse gas emissions should be rapidly reduced in the coming decades in order to avoid catastrophic global warming [1]. To reach this goal, many scientific studies ([2–61] are discussed in this article) have examined the potential to replace fossil fuel energy sources with renewable energy. Since wind and solar power dominate the expandable potentials of renewable energy [3], a primary focus for studies with high shares of renewables is the need to balance the variability of these energy sources in time and space against the demand for energy services.

The studies that examine scenarios with very high shares of renewable energy have attracted a critical response from some quarters, particularly given that high targets for renewable energy are now part of government policy in many countries [62,63]. Critics have challenged studies for purportedly not taking sufficient account of: the variability of wind and solar [64,65], the scaleability of some storage technologies

[66], all aspects of system costs [64,65], resource constraints [67,68], social acceptance constraints [68], energy consumption beyond the electricity sector [68], limits to the rate of change of the energy intensity of the economy [68] and limits on capacity deployment rates [69,68]. Many of these criticisms have been rebutted either directly [70–72] or are addressed elsewhere in the literature, as we shall see in the following sections.

In the recent article 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems' [73] the authors of the article (henceforth 'the authors') analysed 24 published studies (including [3–9,12,13,10,11]) of scenarios for highly renewable electricity systems, some regional and some global in scope. Drawing on the criticisms outlined above, the authors chose feasibility criteria to assess the studies, according to which they concluded that many of the studies do not rate well.

In this response article we argue that the authors' chosen feasibility criteria may in some cases be important, but that they are all easily addressed both at a technical level and economically at low cost. We

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therefore conclude that their feasibility criteria are not useful and do not affect the conclusions of the reviewed studies. Furthermore, we introduce additional, more relevant feasibility criteria, which renewable energy scenarios fulfil, but according to which nuclear power, which the authors have evaluated positively elsewhere [74–76], fails to demonstrate adequate feasibility.

In Section 2 we address the definition and relevance of feasibility versus viability; in Section 3 we review the authors' feasibility criteria and introduce our own additional criteria; in Section 4 we address other issues raised by [73]; finally in Section 5 conclusions are drawn.

2. Feasibility versus viability

Early in their methods section, the authors define *feasibility* to mean that something is technically possible in the world of physics 'with current or near-current technology'. They distinguish feasibility from socio-economic *viability*, which they define to mean whether it is possible within environmental and social constraints and at a reasonable cost. While there is no widely-accepted definition of feasibility [77], other studies typically include economic feasibility in their definition [78–82], while others also consider social and political constraints [83,68]. For the purposes of this response article, we will keep to the authors' definitions of feasibility and viability.

One reason that few studies focus on such a narrow technical definition of feasibility is that, as we will show in the sections below, there are solutions using today's technology for all the feasibility issues raised by the authors. The more interesting question, which is where most studies rightly focus, is how to reach a high share of renewables in the most cost-effective manner, while respecting environmental, social and political constraints. In other words, viability is where the real debate should take place. For this reason, in this paper we will assess both the feasibility and the viability of renewables-based energy systems.

Furthermore, despite their declared focus on feasibility, the authors frequently mistake viability for feasibility. Examples related to their feasibility criteria are examined in more detail below, but even in the discussion of specific model results there is confusion. The authors frequently quote from cost-optimisation studies that 'require' certain investments. For example they state that [84] 'required 100 GWe of nuclear generation and 461 GWe of gas' and [85] 'require long-distance interconnector capacities that are 5.7 times larger than current capacities'. Optimisation models find the most cost-effective (i.e. viable) solutions within technical constraints (i.e. the feasible space). An optimisation result is not necessarily the only feasible one; there may be many other solutions that simply cost more. More analysis is needed to find out whether an investment decision is 'required' for feasibility or simply the most cost-effective solution of many. For example, the 100 GWe of nuclear in [84] is fixed even before the optimisation, based on existing nuclear facilities, and is therefore not the result of a feasibility study. However, the authors do acknowledge that their transmission feasibility criteria 'could arguably be regarded as more a matter of viability than feasibility'.

Finally, when assessing economic viability, it is important to keep a sense of perspective on costs. If Europe is taken as an example, Europe pays around 300–400 billion € for its electricity annually.[1] EU GDP in 2016 was 14.8 trillion € [86]. Expected electricity network expansion costs in Europe of 80 billion € until 2030 [89] may sound high, but once these costs are annualised (e.g. to 8 billion €/a), it amounts to only 2% of total spending on electricity, or 0.003 €/kWh.

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[1] Own calculation based on price and (incomplete) consumption data from Eurostat [86] for 2015. It includes energy supply (around 50%), network costs (around 20%), taxes and surcharges (around 30%); it excludes indirect costs, such as those caused by environmental pollution [87] and climate change [88].

3. Feasibility criteria

The authors define feasibility criteria and rate 24 different studies of 100% renewable scenarios against these criteria. According to the chosen criteria, many of the studies do not rate highly.

In the sections below we address each feasibility criterion mentioned by the authors, and some additional ones which we believe are more pertinent. In addition, we discuss the socio-economic viability of the feasible solutions.

We observe that the authors' choice of criteria, the weighting given to them and some of the scoring against the criteria are somewhat arbitrary. As argued below, there are other criteria that the authors did not use in their rating that have a stronger impact on feasibility (such as resource constraints and technological maturity); based on the literature review below, the authors' criteria would receive a much lower weighting than these other, more important criteria; and the scoring of some of the criteria, particularly for primary energy, transmission and ancillary services, seems coarse and subjective. Regarding the scoring, for demand projections the studies are compared with a spectrum from the mainstream literature, but no uncertainty bound is given, just a binary score; for transmission there is no nuance between studies that use blanket costs for transmission, or only consider cross-border capacity, or distribution as well as transmission networks; and no weighting is given to the importance of the different ancillary services.

Finally, note that while some of the studies chosen by the authors consider the electricity sector only, other studies include energy demand from other sectors such as transport, heating and industry, thereby hindering comparability between the studies.

3.1. Their feasibility criterion 1: Demand projections

The authors criticise some of the studies for not using plausible projections for future electricity and total energy demand. In particular, they claim that reducing global primary energy consumption demand is not consistent with projected population growth and development goals in countries where energy demand is currently low.

Nobody would disagree with the authors that any future energy scenario should be compatible with the energy needs of every citizen of the planet. A reduction in electricity demand, particularly if heating, transport and industrial demand is electrified, is also unlikely to be credible. For example, both the Greenpeace Energy [R]evolution [6,90] and WWF [5] scenarios, criticised in the paper, see a significant increase in global electricity consumption; another recent study [35] of 100% renewable electricity for the globe foresees a doubling of electricity demand between 2015 and 2050, in line with IEA estimates for electricity [91].

However, the authors chose to focus on primary energy, for which the situation is more complicated, and it is certainly plausible to decouple primary energy consumption growth from meeting the planet's energy needs. Many countries have already decoupled primary energy supply from economic growth; Denmark has 30 years of proven history in reducing the energy intensity of its economy [92].

There are at least three points here: i) primary energy consumption automatically goes down when switching from fossil fuels to wind, solar and hydroelectricity, because they have no conversion losses according to the usual definition of primary energy; ii) living standards can be maintained while increasing energy efficiency; iii) renewables-based systems avoid the significant energy usage of mining, transporting and refining fossil fuels and uranium.

Fig. 1 illustrates how primary energy consumption can decrease by switching to renewable energy sources, with no change in the energy services (blue) delivered. Using the 'physical energy accounting method' used by the IEA, OECD, Eurostat and others, or the 'direct equivalent method' used by the IPCC, the primary energy consumption of fossil fuel power plants corresponds to the heating value, while for wind, solar and hydro the electricity output is counted. This
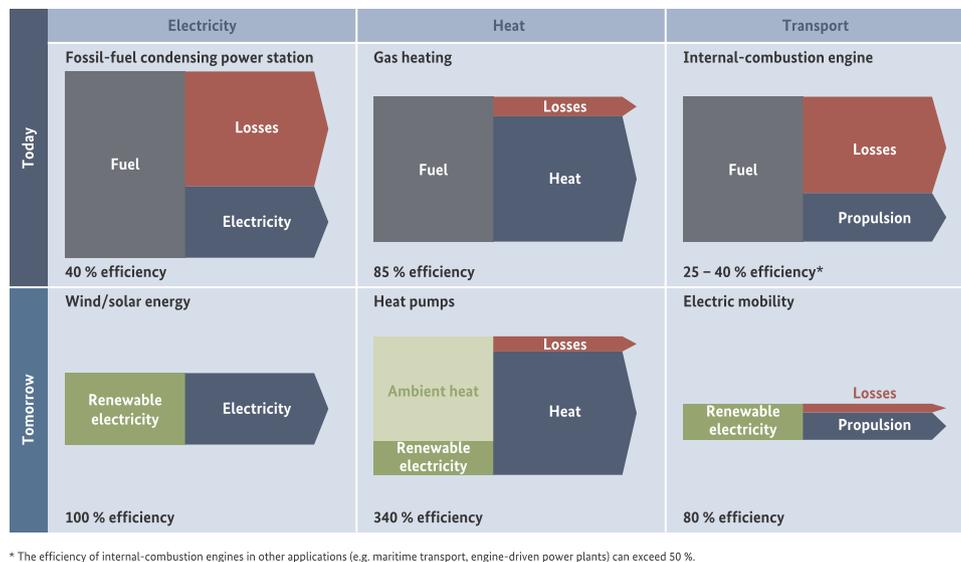
* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

Fig. 1. Primary energy consumption (grey and green) versus useful energy services (blue) in today's versus tomorrow's energy system. (Reproduced with permission from [93], page 86; based on [94]) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

automatically leads to a reduction in the primary energy consumption of the electricity sector when switching to wind, solar and hydro, because they have no conversion losses (by this definition).

In the heating sector, fossil-fuelled boilers dominate today's heating provision; here, primary energy again corresponds to the heating value of the fuels. For heat pumps, the heat taken from the environment is sometimes counted as primary energy [95,96], sometimes not [5]; in the latter case the reduction in primary energy consumption is 60–75% [97], depending on the location and technology, if wind, solar and hydro power are used. Cogeneration of heat and power will also reduce primary energy consumption. In addition, district heating can be used to recycle low-temperature heat that would otherwise be lost, such as surplus heat from industrial processes [98–100]. For biomass, solar thermal heating and resistive electric heating from renewables there is no significant reduction in primary energy compared to fossil-fuelled boilers.

In transport, the energy losses in an internal combustion engine mean that switching to more efficient electric vehicles running on electricity from wind, solar and hydro will reduce primary energy consumption by 70% or more [46] for the same service.

If statistics from the European Union in 2015 [101] are taken as an example, taking the steps outlined in Fig. 1 would reduce total primary energy consumption by 49%[2] without any change in the delivered energy services. (Final energy consumption would also drop by 33%.) A reduction of total primary energy of 49% would allow a near doubling of energy service provision before primary energy consumption started to increase. This is even before efficiency measures and the consumption from fuel processing are taken into account.

The primary energy accounting of different energy sources presented in this example is already enough to explain the discrepancies between the scenarios plotted in Fig. 1 of [73], where the median of non-NGO global primary energy consumption increases by around 50% between 2015 and 2050, while the NGOs Greenpeace and WWF see light reductions. As an example of a non-NGO projection with high primary energy demand, many IPCC scenarios with reduced greenhouse

gas emissions rely on bioenergy, nuclear and carbon capture from combustion [102], whereas the NGOs Greenpeace [6] and WWF [5] have high shares of wind and solar. The IPCC scenarios see less investment in wind and solar because of conservative cost assumptions, with some assumptions for solar PV that are 2–4 times below current projections [103,34]; with improved assumptions, some authors calculate that PV could dominate global electricity by 2050 with a share of 30–50% [104]. Another study of 100% renewable energy across all energy sectors in Europe [22] sees a 10% drop in primary energy supply compared to a business-as-usual scenario for 2050, with bigger reductions if synthetic fuels for industry are excluded.

The authors chose to concentrate on primary energy consumption, but for renewables, as argued above, it can be a misleading metric (see also the discussion in [96]). The definitions of both primary and final energy are suited for a world based on fossil fuels. What really matters is meeting people's energy needs (the blue boxes in Fig. 1) while also reducing greenhouse gas emissions.

Next we address energy efficiency that goes beyond just switching fuel source. There is plenty of scope to maintain living standards while reducing energy consumption: improved building insulation and design to reduce heating and cooling demand, more efficient electronic devices, efficient processes in industry, better urban design to lower transport demand, more public transport and reductions in the highest-emission behaviour. These efficiency measures are feasible, but it is not clear that they will all be socio-economically viable.

For example, in a study for a 100% renewable German energy system (including heating and transport) [30] scenarios were considered where space heating demand is reduced by between 30% and 60% using different retrofitting measures. Another study for cost-optimal 100% renewables in Germany [105] shows similar reductions in primary energy in the heating sector from efficiency measures and the uptake of cogeneration and heat pumps.

The third point concerns the upstream costs of conventional fuels. It was recently estimated that 12.6% of all end-use energy worldwide is used to mine, transport and refine fossil fuels and uranium [36]; renewable scenarios avoid this fuel-related consumption.

One final, critical point: even if future demand is higher than expected, this does not mean that 100% renewable scenarios are infeasible. As discussed in Section 3.6, the global potential for renewable generation is several factors higher than any demand forecasts. There is plenty of room for error if forecasts prove to underestimate demand growth: an investigation into the United States Energy Information

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[2] This would involve switching from thermal power plants (average efficiency 35% [101]) to wind and solar generators for all electricity, using heat pumps (average coefficient of performance of 3) for space and water heating, and using electricity instead of internal combustion in road vehicles (reducing final energy consumption here by a factor of 3.5 [46]). No reduction in primary energy is assumed for remaining energy sectors (non-electric industrial demand, aviation and shipping).
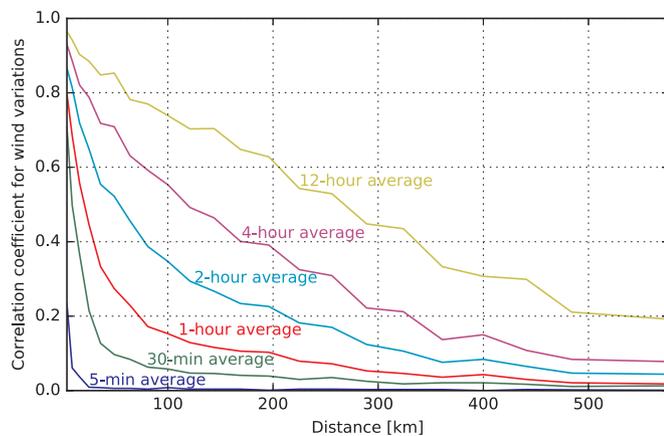
Fig. 2. Correlation of variations in wind for different time scales in Germany. (Reproduced with permission and data from [110,111]).

Administration's Annual Outlook [106] showed systematic underestimation of total energy demand by an average of 2% per year after controlling for other sources of projection errors; over 35 years this would lead to an underestimate of around factor 2 (assuming other sources of growth are not excessive); reasonable global potentials for renewable energy could generate on average around 620 TW [3], which is a factor 30 higher than business-as-usual forecasts for average global end-use energy demand of 21 TW in 2050 [36].

3.2. Their feasibility criterion 2a: Simulation time resolution

The authors stress that it is important to model in a high time resolution so that all the variability of demand and renewables is accounted for. They give one point to models with hourly resolution and three points to models that simulate down to 5 min intervals.

It is of course important that models have enough time resolution to capture variations in energy demand (e.g. lower electricity consumption at 3 a.m. than at 3 p.m.) and variations in wind and solar generation, so that balancing needs, networks and other flexibility options can be dimensioned correctly. However, the time resolution depends on the area under consideration, since short-term weather fluctuations are not correlated over large distances and therefore balance out. This criterion should rather read 'the time resolution should be appropriate to the size of the area being studied, the weather conditions found there and the research question'. Models for whole countries typically use hourly simulations, and we will argue that this is sufficient for long-term energy system planning.

After all, why do the authors stop at 5 min intervals? For a single wind turbine, a gust of wind could change the feed-in within seconds (the inertia of the rotor stops faster changes). Similarly, a cloud could cover a small solar panel in under a second. Individuals can change their electricity consumption at the flick of a switch.

The reason modelling in this temporal detail is not needed is the statistical smoothing when aggregating over a large area containing many generators and consumers. Many of the studies are looking at the national or sub-national level. By modelling hourly, the majority of the variation of the demand and variable renewables like wind and solar over these areas is captured; if there is enough flexibility to deal with the largest hourly variations, there is enough to deal with any intra-hour imbalance. Fig. 2 shows correlations in variations (i.e. the differences between consecutive production values) in wind generation at different time and spatial scales.[3] Changes within 5 min are

uncorrelated above 25 km and therefore smooth out in the aggregation. Further analysis of sub-hourly wind variations over large areas can be found in [108,109].

For solar photovoltaics (PV) the picture is similar at shorter time scales: changes at the 5-min level due to cloud movements are not correlated over large areas. However, at 30 min to 1 h there are correlated changes due to the position of the sun in the sky or the passage of large-scale weather fronts. The decrease of PV output in the evening can be captured at one-hour resolution and there are plenty of feasible technologies available for matching that ramping profile: flexible open-cycle gas turbines can ramp up within 5–10 min, hydroelectric plants can ramp within minutes or less, while battery storage and demand management can act within milliseconds. For ramping down, solar and wind units can curtail their output within seconds.

The engineering literature on sub-hourly modelling confirms these considerations. Several studies consider the island of Ireland, which is particularly challenging since it is an isolated synchronous area, is only 275 km wide and has a high penetration of wind. One power system study for Ireland with high share of wind power [112] varied temporal resolution between 60 min and 5 min intervals, and found that the 5 min simulation results gave system costs just 1% higher than hourly simulation results; however, unit commitment constraints and higher ramping and cycling rates could be problematic for older thermal units (but not for the modern, flexible equipment outlined above). Similarly, [113,114] see not feasibility problems at sub-hourly time resolutions, but a higher value for flexible generation and storage, which can act to avoid cycling stress on older thermal plants. In [115] the difference between hourly and 15-min simulations in small district heating networks with high levels of wind power penetration was considered and it was found that 'the differences in power generation are small' and 'there is [no] need for higher resolution modelling'.

To summarise, since at large spatial scales the variations in aggregated load, wind and solar time series are statistically smoothed out, none of the large-scale model results change significantly when going from hourly resolution down to 5-min simulations. Hourly modelling will capture the biggest variations and is therefore adequate to dimension flexibility requirements. (Reserve power and the behaviour of the system in the seconds after faults are discussed separately in Section 3.5.) Sub-hourly modelling may be necessary for smaller areas with older, inflexible thermal power plants, but since flexible peaking plant and storage are economically favoured in highly renewable systems, sub-hourly modelling is less important in the long-term.

Simulations with intervals longer than one hour should be treated carefully, depending on the research question [116].

3.3. Their feasibility criterion 2b: Extreme climatic events

The authors reserve a point for studies that include rare climatic events, such as long periods of low sun and wind, or years when drought impacts the production of hydroelectricity.

Periods of low sun and wind in the winter longer than a few days can be met, where available, by hydroelectricity, dispatchable biomass, demand response, imports, medium-term storage, synthetic gas from power-to-gas facilities (the feasibility of each of these is discussed separately below) or, in the worst case, by fossil fuels.

From a feasibility point of view, even in the worst possible case that enough dispatchable capacity were maintained to cover the peak load, this does not invalidate these scenarios. The authors write "ensuring stable supply and reliability against all plausible outcomes…will raise costs and complexity". Yet again, a feasibility criterion has become a viability criterion.

So what would it cost to maintain an open-cycle gas turbine (OCGT) fleet to cover, for example, Germany's peak demand of 80 GW? For the OCGT we take the cost assumptions from [117]: overnight investment cost of 400 €/kW, fixed operation and maintenance cost of 15 €/kW/a, lifetime of 30 years and discount rate of 10%. The latter two figures

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[3] Note that for time series of production values (i.e. not the differences) the correlation does not decrease as rapidly as shown here and can remain high for hundreds of kilometres [107].

given an annuity of 10.6% of the overnight investment cost, so the annual cost per kW is 57.4 €/kW/a. For a peak load of 80 GW, assuming 90% availability of the OCGT, the total annual cost is therefore 5.1 billion €/a. Germany consumes more than 500 TWh/a, so this guaranteed capacity costs less than 0.01 €/kWh. This is just 7.3% of total spending on electricity in Germany (69.4 billion € in 2015 [118]).

We are not suggesting that Germany builds an OCGT fleet to cover its peak demand. This is a worst-case rhetorical thought experiment, assuming that no biomass, hydroelectricity, demand response, imports or medium-term storage can be activated, yet it is still low cost. Solutions that use storage that is already in the system are likely to be even lower cost. However, some OCGT capacity could also be attractive for other reasons: it is a flexible source of upward reserve power and it can be used for other ancillary services such as inertia provision, fault current, voltage regulation and black-starting the system. A clutch can even be put on the shaft to decouple the generator from the turbine and allow the generator to operate in synchronous compensator mode, which means it can also provide many ancillary services without burning gas (see the discussion on ancillary services in Section 3.5).

Running the OCGT for a two-week-long low-sun-and-wind period would add fuel costs and possibly also net CO_2 emissions (which would be zero if synthetic methane is produced with renewable energy or low if the carbon dioxide produced is captured and stored or used). Any emissions must be accounted for in simulations, but given that extreme climatic events are by definition rare (two weeks every decade is 0.4% of the time; the authors even speak of once-in-100-year events), their impact will be small.

A recent study of seven different weather years (2006–2012), including extreme weather events, in Europe for a scenario with a 95% CO_2 reduction compared to 1990 in electricity, heating and transport [119] came to similar conclusions. The extreme events do not affect all countries simultaneously so, for example, Germany can cover extreme events by importing power from other countries. If for political reasons each country is required to cover its peak load on a national basis, the extra costs for capacity are at most 3% of the total system costs.

For systems that rely on hydroelectricity, the authors are right to point out that studies should be careful to include drier years in their simulations. Beyond the examples they cite, Brazil's hydroelectric production has been restricted over the last couple of years due to drought, and there are periodic drier years in Ethiopia, Kenya and Scandinavia, where in the latter inflow can drop to 30% below the average [108].

However, in most countries, the scenarios rely on wind and solar energy, and here the dispatchable power capacity of the hydro is arguably just as important in balancing wind and solar as the total yearly energy contribution, particularly if pumping can be used to stock up the hydro reservoirs in times of wind and solar abundance [7,54].

Note that nuclear also suffers from planned and unplanned outages, which are exacerbated during droughts and heatwaves, when the water supplies for river-cooled plants are either absent or too warm to provide sufficient cooling [120]. This problem is likely to intensify given rising demand for water resources and climate change [120].

3.4. Their feasibility criterion 3: Transmission and distribution grids

The authors criticise many of the studies for not providing simulations of the transmission (i.e. high voltage long-distance grid) and distribution (i.e. lower voltage distribution from transmission substations to consumers) grids. Again, this is important, but not as important as the authors assume. Feasibility is not the issue (there are no technical restrictions on expanding the grid), but there are socio-economic considerations. Many studies that do not model the grid, do include blanket costs for grid expansion (e.g. from surveys such as [121–123]).

On a cost basis, the grid is not decisive either: additional grid costs tend to be a small fraction of total electricity system costs (examples to follow, but typically around 10–15% of total system costs in Europe [124–127,21,42,123]), and optimal grid layouts tend to follow the

cheapest generation, so ignoring the grid is a reasonable first order approximation. Where it can be a problem is if public acceptance problems prevent the expansion of overhead transmission lines, in which case the power lines have to be put underground (typically 3–8 times more expensive than overhead lines) or electricity has to be generated more locally (which can drive up costs and may require more storage to balance renewables). Public acceptance problems affect cost, i.e. economic viability, not feasibility.

How much the distribution grid needs to be expanded also depends on how much the scenario relies on decentralised, rooftop PV generation. If all wind and utility-scale PV is connected to the transmission grid, then there is no need to consider distribution grids at all. Regardless of supply-side changes, distribution grids may have to be upgraded in the future as electricity demand from heating and electric vehicles grows (although this is not obvious: distribution grids are often over-dimensioned for the worst possible simultaneous peak demand, and more intelligent network infrastructure, demand management or storage could avoid distribution grid upgrades).

Now to some examples of transmission and distribution grid costing.

A study by Imperial College, NERA and DNV GL for the European electricity system to 2030 [124] examined the consequences for both the transmission and distribution grid of renewable energy penetration up to 68% (in their Scenario 1). For total annual system costs of 232 billion €/a in their Scenario 1, 4 billion €/a is assigned to the costs of additional transmission grid investments and 18 billion €/a to the distribution grid. If there is a greater reliance on decentralised generation (Scenario 1(a)-DG), additional distribution grid costs could rise to 24 billion €/a.

This shows a typical rule of thumb: additional grid costs are around 10–15% of total system costs. But this case considered only 68% renewables.

The distribution grid study of 100% renewables in the German federal state of Rhineland-Palatinate (RLP) [125] also clearly demonstrates that the costs of generation dwarf the grid costs. Additional grid investments vary between 10% and 15% of the total costs of new generation, depending on how smart the system is. Again, distribution upgrade costs dominate transmission costs.

In its worst case the Germany Energy Agency (DENA) sees a total investment need of 42.5 billion € in German distribution grids by 2030 for a renewables share of 82% [128]. Annualised to 4.25 billion €/a, this is just 6.2% of total spending on electricity in Germany (69.4 billion € in 2015 [118]).

Another study for Germany with 100% renewable electricity showed that grid expansion at transmission and distribution level would cost around 4–6 billion €/a (with a big uncertainty range reaching from 1 to 12 billion €/a) [123].

Many studies look at the transmission grid only. The 2016 Ten Year Network Development Plan (TYNDP) [89] of the European Transmission System Operators foresees 70–80 billion € investment needs in Europe for 60% renewables by 2030, which annualises to 2% of total electricity spending of 400 billion €/a (the 0.001 to 0.002 €/kWh extra costs are compensated by a resulting reduction in wholesale electricity prices of 0.0015 to 0.005 €/kWh [89]). The authors criticise the Greenpeace Energy [R]evolution scenario [6,90] for excluding grid and reliability simulations, but in fact Greenpeace commissioned transmission expansion studies for Europe using hourly simulations, one for 77% renewables by 2030 [126] (60 billion € investment by 2030, i.e. 1.5% of spending) and one for 97% renewables by 2050 [127] (149–163 billion € investment for 97% renewables by 2050, i.e. 4% of spending). Beyond Europe, other studies with similar results look at the United States [84], South and Central America [48], and Asia [39,16].

The authors quote studies that look at optimal cross-border transmission capacity in Europe at very high shares of renewables, which show an expansion of 4–6 times today's capacities [85,129]. It is worth pointing out that these studies look at the international interconnectors, not the full transmission grid, which includes the transmission lines

within each country. The interconnectors are historically weak compared to national grids[4] and restricted by poor market design and operation [130]; if a similar methodology to [85,129] is applied to a more detailed grid model with nodal pricing, the expansion is only between 25% and 50% more than today's capacity [42]. Furthermore, cost-optimal does not necessarily mean socially viable; there are solutions with lower grid expansion and hence higher public acceptance, but higher storage costs to balance renewables locally [42].

3.5. Their feasibility criterion 4: Ancillary services

Finally, we come to ancillary services. Ancillary services are additional services that network operators need to stabilise and secure the electricity system. They are mostly provided by conventional dispatchable generators today. Ancillary services include reserve power for balancing supply and demand in the short term, rotating inertia to stabilise the frequency in the very short term, synchronising torque to keep all generators rotating at the same frequency, voltage support through reactive power provision, short circuit current to trip protection devices during a fault, and the ability to restart the system in the event of a total system blackout (known as 'black-starting'). The authors raise concerns that many studies do not consider the provision of these ancillary services, particularly for voltage and frequency control. Again, these concerns are overblown: ancillary services are important, but they can be provided with established technologies (including wind and solar plants), and the cost to provide them is second order compared to the costs of energy generation.

We consider fault current, voltage support and inertia first. These services are mostly provided today by synchronous generators, whereas most new wind, solar PV and storage units are coupled to the grid with inverters, which have no inherent inertia and low fault current, but can control voltage with both active and reactive power.

From a feasibility point of view, synchronous compensators could be placed throughout the network and the problem is solved, although this is not as cost effective as other solutions. Synchronous compensators (SC), also called synchronous condensers, are essentially synchronous generators without a prime mover to provide active power. This means they can provide all the ancillary services of conventional generators except those requiring active power, i.e. they can provide fault current, inertia and voltage support just like a synchronous generator. Active power is then provided by renewable generators and storage devices.

In fact, existing generators can be retrofitted to be SC, as happened to the nuclear power plant in Biblis, Germany [131], or to switch between generation mode and SC mode; extra mass can be added with a clutch if more inertia is needed (SC have an inertia time constant of 1–2 s [132,133], compared to typical conventional generators with around 6 s). SC are a tried-and-tested technology and have been installed recently in Germany [134], Denmark, Norway, Brazil, New Zealand and California [135]. They are also used in Tasmania [136], where 'Hydro Tasmania, TasNetworks and AEMO have implemented many successful initiatives that help to manage and maintain the security of a power system that has a high penetration of asynchronous energy sources…Some solutions implemented in Tasmania have been relatively low cost and without the need for significant capital investment' [136]. In Denmark, newly-installed synchronous compensators along with exchange capacity with its neighbours allow the power system to operate without any large central power stations at all [137]. In 2017 the system operated for 985 h without central power stations, the longest continuous period of which was a week [138]. SC were also one of the options successfully shown to improve stability during severe faults in a study of high renewable penetration in the United States

Western Interconnection [139,140]. The study concluded 'the Western Interconnection can be made to work well in the first minute after a big disturbance with both high wind and solar and substantial coal displacement, using good, established planning and engineering practice and commercially available technologies'. In a study for the British transmission system operator National Grid [141] it was shown that 9 GVAr of SC would stabilise the British grid during the worst fault even with 95% instantaneous penetration of non-synchronous generation. (Britain is tricky because it is not synchronous with the rest of Europe and can suffer small signal angular instability between England and Scotland.)

So how cost-effective would synchronous compensators be? There is a range of cost estimates in the literature [142,143,132,144], the highest being an investment cost of 100 €/kVAr with fixed operating and maintenance costs of 3.5 €/kVAr/a [144] (it would be around a third cheaper to retrofit existing generators [132]). For Great Britain, the 9 GVAr of SC would cost 129 million € per year, assuming a lifetime of 30 years and a discount rate of 10%. That annualises to just 0.0003 €/kWh. (SC also consume a small amount of active power [145,132], but given that they would run when marginal electricity costs are very low thanks to high wind and solar feed-in, this cost would be negligible.)

Synchronous condensers are an established, mature technology, which provide a feasible upper bound on the costs of providing non-active-power-related ancillary services. The inverters of wind, solar and batteries already provide reactive power for voltage control and can provide the other ancillary services, including virtual or synthetic inertia, by programming the functionality into the inverter software [146]. Inverters are much more flexible than mechanics-bound synchronous generators and can change their output with high accuracy within milliseconds [147]. The reason that wind and solar plants have only recently been providing these services is that before (i.e. at lower renewable penetration) there was no need, and no system operators required it. Now that more ancillary services are being written into grid codes [148], manufacturers are providing such capabilities in their equipment. Frequency control concepts for inverters that follow a stiff external grid frequency and adjust their active power output to compensate for any frequency deviations are already offered by manufacturers [149]. Next generation 'grid-forming' inverters will also be able to work in weak grids without a stiff frequency, albeit at the cost of increasing the inverter current rating (e.g. by 20–50%). A survey of different frequency-response technologies in the Irish context can be found in [150]. Recent work for National Grid [151,152] shows that with 25% of inverters operating as Virtual Synchronous Machines (VSM), the system can survive the most severe faults even when approaching 100% non-synchronous penetration. The literature in the control theory community on the design and stability of grid-forming inverters in power systems is substantial and growing, and includes both extensive simulations and tests in the field [153–159].

Protection systems often rely on synchronous generators to supply fault current to trip over-current relays. Inverters are not well-suited to providing fault current, but this can be circumvented by replacing over-current protection with differential protection and distance protection [160,146], both of which are established technologies.

Next, we consider balancing reserves. Balancing power can be provided by traditional providers, battery systems, fast-acting demand-side-management or by wind and solar generators (upward reserves are provided by variable renewable plants by operating them below their available power, called 'delta' control). There is a wide literature assessing requirements for balancing power with high shares of renewables. In a study for Germany in 2030 with 65 GW PV and 81 GW wind (52% renewable energy share), no need is seen for additional primary reserve, with at most a doubling of the need for other types of reserves [161]. It is a similar story in the 100% renewable scenario for Germany of Kombikraftwerk 2 [162]. (Maintaining reserves in Germany cost 315.9 million € in 2015 [163].) There is no feasibility problem here either.

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[4] The TYNDP [89] will double cross-border capacities by 2030, but total circuit length will only grow by around 25%.

Another ancillary service the authors mention is black-start capability. This is the ability to restart the electricity system in the case of a total blackout. Most thermal power stations consume electricity when starting up (e.g. powering pumps, fans and other auxiliary equipment), so special provisions are needed when black-starting the system, by making sure there are generators which can start without an electricity supply. Typically system operators use hydroelectric plants (which can generate as soon as the sluice gate is opened), diesel generators or battery systems, which can then start a gas turbine, which can then start other power plants (for example). Maintaining conventional capacity for black-start is inexpensive compared to system costs, as shown in Section 3.3; in a study for Germany in 2030 [161] with 52% renewables, no additional measures for black-starting were deemed necessary, contrary to the interpretation in [73]; finally, decentralised renewable generators and storage could also participate in black-starting the system in future [162]. The use of battery storage systems to black-start gas turbines has recently been demonstrated in Germany [164] and in a commercial project in California [165].

Nuclear, on the other hand, is a problem for black-starting, since most designs need a power source at all times, regardless of blackout conditions, to circulate coolant in the reactor and prevent meltdown conditions. This will only exacerbate the need for backup generation in a total blackout. Nuclear is sometimes not used to provide primary reserves either, particularly in older designs, because fast changes in output present operational and safety concerns.

3.6. Our feasibility criterion 5: Fuel source that lasts more than a few decades

Here we suggest a feasibility criterion not included on the authors' list: The technology should have a fuel source that can both supply all the world's energy needs (not just electricity, but also transport, heating and industrial demand) and also last more than a couple of decades.

Traditional nuclear plants that use thermal-neutron fission of uranium do not satisfy this feasibility criterion. In 2015 there were 7.6 million tonnes of identified uranium resources commercially recoverable at less than 260 US$/kgU [166].[5] From one tonne of natural uranium, a light-water reactor can generate around 40 GWh of electricity.

In 2015, world electricity consumption was around 24,000 TWh/a [168]. Assuming no rise in electricity demand and ignoring non-electric energy consumption such as transport and heating, uranium resources of 7.6 million tonnes will last 13 years. Reprocessing, at higher cost, might extend this by a few more years. Including non-electric energy consumption would more than halve this time.

For renewables, exploitable energy potentials exceed yearly energy demand by several orders of magnitude [169] and, by definition, are not depleted over time. Even taking account of limitations of geography and material resources, the potentials for the expansion of wind, solar and storage exceed demand projections by several factors [3].

As for 'following all paths' and pursuing a mix of renewables and nuclear, they do not mix well: because of their high capital costs, nuclear power plants are most economically viable when operated at full power the whole time, whereas the variability of renewables requires a flexible balancing power fleet [170]. Network expansion can help the penetration of both renewables and inflexible plant [171], but this would create further pressure for grid expansion, which is already pushing against social limits in some regions.

This feasibility criterion is not met by standard nuclear reactors, but could be met in theory by breeder reactors and fusion power. This brings us to our next feasibility criterion.

3.7. Our feasibility criterion 6: Should not rely on unproven technologies

Here is another feasibility criterion that is not included on the authors' list: Scenarios should not rely on unproven technologies. We are not suggesting that we should discontinue research into new technologies, rather that when planning for the future, we should be cautious and assume that not every new technology will reach technical and commercial maturity.

The technologies required for renewable scenarios are not just tried-and-tested, but also proven at a large scale. Wind, solar, hydro and biomass all have capacity in the hundreds of GWs worldwide [63]. The necessary expansion of the grid and ancillary services can deploy existing technology (see Sections 3.4 and 3.5). Heat pumps are used widely [172]. Battery storage, contrary to the authors' paper, is a proven technology already implemented in billions of devices worldwide (including a utility-scale 100 MW plant in South Australia [173] and 700 MW of utility-scale batteries in the United States at the end of 2017 [174]). Compressed air energy storage, thermal storage, gas storage, hydrogen electrolysis, methanation and fuel cells are all decades-old technologies that are well understood. (See Section 4.1 for more on the feasibility of storage technologies.)

On the nuclear side, for the coming decades when uranium for thermal-neutron reactors would run out, we have breeder reactors, which can breed more fissile material from natural uranium or thorium, or fusion power.

Breeder reactors are technically immature (with a technology readiness level between 3 and 5 depending on the design [175]), more costly than light-water reactors, unreliable, potentially unsafe and they pose serious proliferation risks [176]. Most fast-neutron breeder reactors rely on sodium as a coolant, and since sodium burns in air and water, it makes refueling and repair difficult. This has led to serious accidents in fast breeder reactors, such as the major sodium fire at the Monju plant in 1995. Some experts consider fast breeders to have already failed as a technology option [176,177]. The burden of proof is on the nuclear industry to demonstrate that breeder reactors are a safe and commercially competitive technology.

Fusion power is even further from demonstrating technical feasibility. No fusion plant exists today that can generate more energy than it requires to initiate and sustain fusion. Containment materials that can withstand the neutron bombardment without generating long-lived nuclear waste are still under development. Even advocates of fusion do not expect the first commercial plant to go online before 2050 [178]. Even if it proves to be feasible and cost-effective (which is not clear at this point), ramping up to a high worldwide penetration will take decades more. That is too late to tackle global warming [179].

4. Other issues

In this section we address other issues raised by the authors of [73] during their discussion of their feasibility criteria.

4.1. Feasibility of storage technologies

The authors write "widespread storage of energy using a range of technologies (most of which - beyond pumped hydro - are unproven at large scales, either technologically and/or economically)".

Regarding battery storage, it is clear that there is the potential to exploit established lithium ion technology at scale and at low cost [180–182]. The technology is already widely established in electronic devices and increasingly in battery electric vehicles, which will in future provide a regular and cheap source of second-life stationary batteries. A utility-scale 100 MW plant was installed in the South Australian grid in 2017 [173] and there was already 700 MW of utility-scale batteries in the United States at the end of 2017 [174]. Further assessments of the potential for lithium ion batteries can be found in [3]. Costs are falling so fast that hybrid PV-battery systems are already

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[5] There are further speculative and unconventional uranium resources, including in sea water, but the cost and energy required to extract them make them unviable [167].

or soon will be competitive with conventional systems in areas with good solar resources [183,184].

Many other electricity storage devices have been not just demonstrated but already commercialised [185], including large-scale compressed air energy storage. Technologies that convert electricity to gas, by electrolysing hydrogen with the possibility of later methanation, are already being demonstrated at megawatt scale [186,187]. Hydrogen could either be fed into the gas network to a certain fraction, used in fuel cell vehicles, converted to other synthetic fuels, or converted back into electricity for the grid. Fuel cells are already manufactured at gigawatt scale, with 480 MW installed in 2016 [188]. By using the process heat from methanation to cover the heat consumption of electrolysis, total efficiency for power-to-methane of 76% has recently been demonstrated in a freight-container-sized pilot project, with 80% efficiency in sight [189].

Moreover, in a holistic, cross-sectoral energy systems approach that goes beyond electricity to integrate all thermal, transport and industrial demand, it is possible to identify renewable energy systems in which all storage is based on low-cost well-proven technologies, such as thermal, gas and liquid storage, all of which are cheaper than electricity storage [190]. These sectors also provide significant deferrable demand, which further helps to integrate variable renewable energy [191,29,46]. Storage capacity for natural gas in the European Union is 1075 TWh as of mid 2017 [192].

4.2. Feasibility of biomass

The authors criticise a few studies for their over-reliance on biomass, such as one for Denmark [10] and one for Ireland [11]. There are legitimate concerns about the availability of fuel crops, environmental damage, biodiversity loss and competition with food crops [193]. More recent studies, including some by the same researchers, conduct detailed potential assessments for biomass and/or restrict biomass usage to agricultural residues and waste [194,98,195,22]. Other studies are even more conservative (or concerned about air pollution from combustion products [87]) and exclude biomass altogether [41,3,7,36,46], while still reaching feasible and cost-effective energy systems.

4.3. Feasibility of carbon capture

Capturing carbon dioxide from industrial processes, power plants or directly from the air could also contribute to mitigating net greenhouse gas emissions. The captured carbon dioxide can then be used in industry (e.g. in greenhouses or in the production of synthetic fuels) or sequestered (e.g. underground). While some of the individual components have been demonstrated at commercial scale, hurdles [196–198] include cost, technical feasibility of long-term sequestration without leakage, viability for some concepts (such as direct air capture (DAC), the lowest cost version of which is rated at Technology Readiness Level (TRL) 3–5 [199]), other air pollutants from combustion and imperfect capture when capturing from power plants, lower energy efficiency, regulatory issues, public acceptance of sequestration facilities [200] and systems integration.

Studies at high time resolution that have combined renewables and power plants with carbon capture and sequestration (CCS) suggest that CCS is not cost effective because of high capital costs and low utilisation [201]. However, DAC may be promising for the production of synthetic fuels [29,202,203] and is attractive because of its locational flexibility and minimal water consumption [204,205]. Negative emissions technologies (NET), which include DAC, bioenergy with CCS, enhanced weathering, ocean fertilisation, afforestation and reforestation, may also be necessary to meet the goals of the Paris climate accord [206–209]. Relying on NET presents risks given their technical immaturity, so further research and development of these technologies is required [206,210–212].

4.4. Viability of renewable energy systems

In the sections above we have shown that energy systems with very high shares of renewable energy are both feasible and economically viable with respect to primary energy demand projections, matching short-term variability, extreme events, transmission and distribution grids, ancillary services, resource availability and technological maturity. We now turn to more general points of social and economic viability.

With regard to social viability, there are high levels of public support for renewable energy. In a survey of European Union citizens for the European Commission in 2017, 89% thought it was important for their national government to set targets to increase renewable energy use by 2030 [213]. A 2017 survey of the citizens of 13 countries from across the globe found that 82% believe it is important to create a world fully powered by renewable energy [214]. A 2016 compilation of surveys from leading industrialised countries showed support for renewables in most cases to be well over 80% [215]. Concerns have been raised primarily regarding the public acceptance of onshore wind turbines and overhead transmission lines. Repeated studies have shown that public acceptance of onshore wind can be increased if local communities are engaged early in the planning process, if their concerns are addressed and if they are given a stake in the project outcome [216–218]. Where onshore wind is not socially viable, there are system solutions with higher shares of offshore wind and solar energy, but they may cost fractionally more [219]. The picture is similar with overhead transmission lines: more participatory governance early in the planning stages and local involvement if the project is built can increase public acceptance [220,221]. Again, if overhead transmission is not viable, there are system solutions with more storage and underground cables, but they are more expensive [42]. The use of open data and open model software can help to improve transparency [222–224].

Next we turn to the economic viability of bulk energy generation from renewable sources. On the basis of levelised cost, onshore wind, offshore wind, solar PV, hydroelectricity and biomass are already either in the range of current fossil fuel generation or lower cost [225]. Levelised cost is only a coarse measure [226], since it does not take account of variability, which is why integration studies typically consider total system costs in models with high spatial and temporal resolution. Despite often using conservative cost assumptions, integration studies repeatedly show that renewables-based systems are possible with costs that are comparable or lower than conventional fossil-fuel-based systems [2–61], even before aspects such as climate impact and health outcomes are considered.

For example, focusing on results of our own research, a global switch to 100% renewable electricity by 2050 would see a drop in average system cost from 70 €/MWh in 2015 to 52 €/MWh in 2050 [35]. This study modelled the electricity system at hourly resolution for an entire year for 145 regions of the world. Considering all energy sectors in Europe, costs in a 100% renewable energy scenario would be only 10% higher than a business-as-usual scenario for 2050 [22].

The low cost of renewables is borne out in recent auctions, where, for example, extremely low prices have been seen for systems that include storage in the United States due to come online in 2023 (a median PV-plus-battery price of 36 US$/MWh and a median wind-plus-storage price of 21 US$/MWh [184]).

4.5. Viability of nuclear power

Following the authors, we have focussed above on the technical feasibility of nuclear. For discussions of the socio-economic viability of nuclear power, i.e. the cost, safety, decommissioning, waste disposal, public acceptance, terrorism and nuclear-weapons-proliferation issues resulting from current designs, see for example [227,3,167,228].

4.6. Other studies of 100% renewable systems

At the time the authors submitted their article there were many other studies of 100% or near-100% renewable systems that the authors did not review. Most studies were simulated with an hourly resolution and many modelled the transmission grid, with examples covering the globe [14,15], North-East Asia [16], the Association of South-East Asian Nations (ASEAN) [17], Europe and its neighbours [18], Europe [19–23], South-East Europe [24], the Americas [25], China [26], the United States [27], Finland [28], Denmark [29], Germany [30], Ireland [31], Portugal [32] and Berlin-Brandenburg in Germany [33].

Since then other 100% studies have considered the globe [34–37], Asia [38], Southeast Asia and the Pacific Rim [39], Europe [40–46], South-East Europe [47], South and Central America [48], North America [49], India and its neighbours [50,51], Australia [52,53], Brazil [54], Iran [55], Pakistan [56], Saudi Arabia [57], Turkey [58], Ukraine [59] the Canary Islands [60] and the Åland Islands [61].

4.7. Places already at or close to 100% renewables

The authors state that the only developed nation with 100% renewable electricity is Iceland. This statement ignores countries which come close to 100% and smaller island systems which are already at 100% (on islands the integration of renewables is harder, because they cannot rely on their neighbours for energy trading or frequency stability), which the authors of [73] chose to exclude from their study.

Countries which are close to 100% renewable electricity include Paraguay (99%), Norway (97%), Uruguay (95%), Costa Rica (93%), Brazil (76%) and Canada (62%) [146]. Regions within countries which are at or above 100% include Mecklenburg-Vorpommern in Germany, Schleswig-Hostein in Germany, South Island in New Zealand, Orkney in Scotland and Samsø along with many other parts of Denmark.

This list mostly contains examples where there is sufficient synchronous generation to stabilise the grid, either from hydroelectricity, geothermal or biomass, or an alternating current connection to a neighbour. There are also purely inverter-based systems on islands in the South Pacific (Tokelau [229] and an island in American Samoa) which have solar plus battery systems. We could also include here any residential solar plus battery off-grid systems.

Another relevant example is the German offshore collector grids in the North Sea, which only have inverter-based generators and consumption. Inverter-interfaced wind turbines are connected with an alternating current grid to an AC-DC converter station, which feeds the power onto land through a High Voltage Direct Current cable. There is no synchronous machine in the offshore grid to stabilise it, but they work just fine (after teething problems with unwanted harmonics between the inverters).

Off-planet, there is also the International Space Station and other space probes which rely on solar energy.

4.8. South Australian blackout in September 2016

The authors implicitly blame wind generation for the South Australian blackout in September 2016, where some wind turbines disconnected after multiple faults when tornadoes simultaneously damaged two transmission lines (an extreme event). According to the final report by the Australian Energy Market Operator (AEMO) on the incident [230] "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 [have] removed the risk of recurrence given the same number of disturbances." AEMO still highlights the need for additional frequency control services, which can be provided at low cost, as outlined in Section 3.5.

5. Conclusions

In 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems' [73] the authors called into question the feasibility of highly renewable scenarios. To assess a selection of relevant studies, they chose feasibility criteria that are important, but not critical for either the feasibility or viability of the studies. We have shown here that all the issues can be addressed at low economic cost. Worst-case, conservative technology choices (such as dispatchable capacity for the peak load, grid expansion and synchronous compensators for ancillary services) are not only technically feasible, but also have costs which are a magnitude smaller than the total system costs. More cost-effective solutions that use variable renewable generators intelligently are also available. The viability of these solutions justifies the focus of many studies on reducing the main costs of bulk energy generation.

As a result, we conclude that the 100% renewable energy scenarios proposed in the literature are not just feasible, but also viable. As we demonstrated in Section 4.4, 100% renewable systems that meet the energy needs of all citizens at all times are cost-competitive with fossil-fuel-based systems, even before externalities such as global warming, water usage and environmental pollution are taken into account.

The authors claim that a 100% renewable world will require a 're-invention' of the power system; we have shown here that this claim is exaggerated: only a directed evolution of the current system is required to guarantee affordability, reliability and sustainability.

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