



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

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ARTICLE INFO

Keywords:

Renewables
Wind power
Solar power
Power transmission
Ancillary services
Reliability

ABSTRACT

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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<https://doi.org/10.1016/j.rser.2018.04.113>

Received 16 September 2017; Received in revised form 12 April 2018; Accepted 23 April 2018

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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.

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

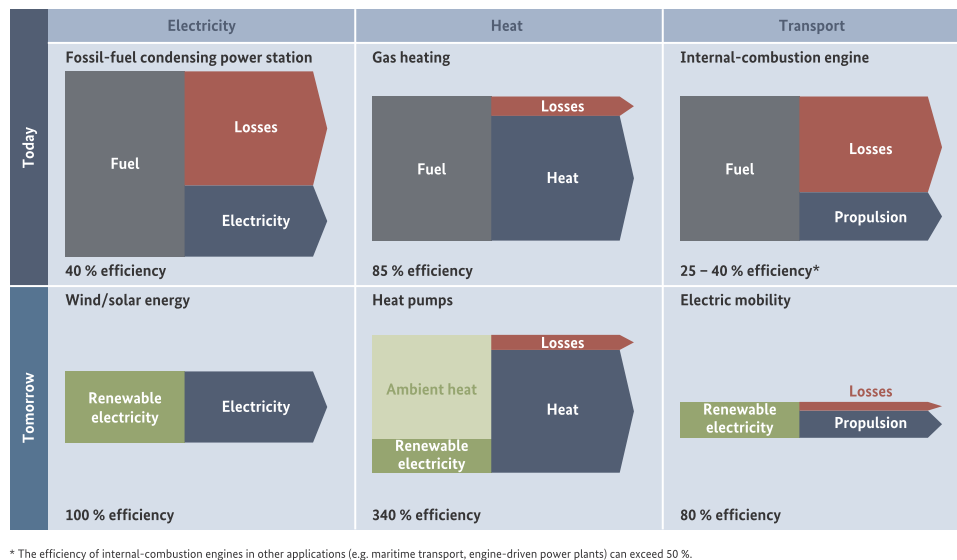


Fig. 1. Primary energy consumption (grey and green) versus useful energy services (blue) in today's versus tomorrow's energy system. (Reproduced with permission from [93], page 86; based on [94]) (For interpretation of the references to colour in this figure legend, the reader is referred to the web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

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).

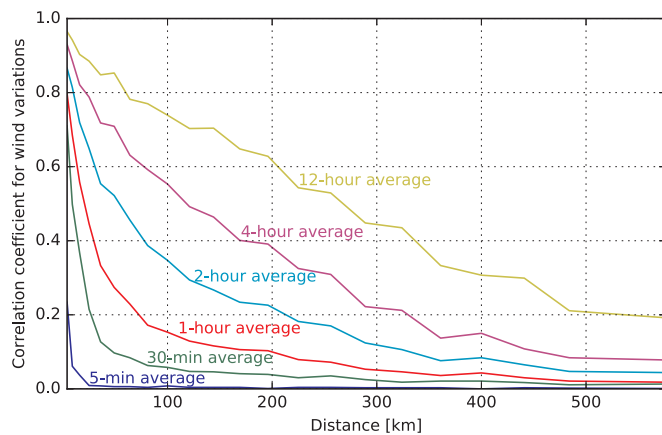


Fig. 2. Correlation of variations in wind for different time scales in Germany. (Reproduced with permission and data from [110,111]).

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

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].

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

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 CO₂ 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% CO₂ 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 justifiable 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 grids⁴ 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.

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.

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].

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

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 electrolysis of 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-Holstein 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.

Acknowledgements

We thank Thomas Ackermann, Florian Dörfler, Ben Elliston, Veit Hagenmeyer, Bri-Mathias Hodge, Jonas Hörsch, Nick Miller, Robbie Morrison, Antje Orths, Mirko Schäfer, David Schlachtberger, Charlie Smith, Bo Tranberg and Helge Urdal for helpful discussions, suggestions and comments. For their permission to reproduce the figures we thank the German Federal Ministry for Economic Affairs and Energy (Fig. 1) and Bernhard Ernst (Fig. 2). T.B. acknowledges funding from the Helmholtz Association under grant no. VH-NG-1352 and from the German Federal Ministry of Education and Research (BMBF) under grant no. 03SF0472C. T.B., H.L. and B.V.M. acknowledge funding from the RE-INVEST project under grant number 6154-00022B from the Innovation Fund Denmark. The responsibility for the contents lies with the authors.

References

- [1] Core Writing Team R, Pachauri L, Meyer (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. <<https://www.ipcc.ch/report/ar5/syr/>>.
- [2] Cochran J, Mai T, Bazilian M. Meta-analysis of high penetration renewable energy scenarios. *Renew Sustain Energy Rev* 2014;29:246–53. <http://dx.doi.org/10.1016/j.rser.2013.08.089>.
- [3] Jacobson M, Delucchi M. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 2011;39(3):1154–69. <http://dx.doi.org/10.1016/j.enpol.2010.11.040>.
- [4] Delucchi M, Jacobson M. Providing all global energy with wind, water, and solar power, Part II: reliability, system and transmission costs, and policies. *Energy Policy* 2011;39(3):1170–90. <http://dx.doi.org/10.1016/j.enpol.2010.11.045>.
- [5] The energy report: 100% renewable energy by 2050, Tech. rep., World Wildlife Fund (WWF), <<http://www.ecofys.com/files/files/ecofys-wwf-2011-the-energy-report.pdf>>; 2011.
- [6] Teske S, Muth J, Sawyer S, Pregarer T, Simon S, Naegler T, O’Sullivan M. energy [f] evolution: a sustainable world energy outlook, 4th edition, Tech. rep., Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC); 2012.
- [7] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc Natl Acad Sci USA* 2015;112(49):15060–5. <http://dx.doi.org/10.1073/pnas.1510028112>.
- [8] Elliston B, Diesendorf M, MacGill I. Simulations of scenarios with 100% renewable

- electricity in the Australian National Electricity Market. Energy Policy 2012;45:606–13. <http://dx.doi.org/10.1016/j.enpol.2012.03.011>.
- [9] Elliston B, MacGill I, Diesendorf M. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. Energy Policy 2013;59(0):270–82. <http://dx.doi.org/10.1016/j.enpol.2013.03.038>.
- [10] Lund H, Mathiesen B. Energy system analysis of 100% renewable energy systems - The case of Denmark in years 2030 and 2050. Energy 2009 34 (5) 524 – 531, 4th Dubrovnik Conference. <http://dx.doi.org/10.1016/j.energy.2008.04.003>.
- [11] Connolly D, Lund H, Mathiesen B, Leahy M. The first step towards a 100% renewable energy-system for Ireland, Applied Energy 2011 88 (2) 502 – 507, the 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik September/October 2009. <http://dx.doi.org/10.1016/j.apenergy.2010.03.006>.
- [12] Schellekens G, Battaglini A, Lilliestam J, McDonnell J, Patt A. 100% renewable electricity: A roadmap to 2050 for Europe and North Africa, Tech. rep., PriceWaterhouseCoopers; 2010.
- [13] Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempton W. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. J Power Sources 2013;225:60–74. <http://dx.doi.org/10.1016/j.jpowsour.2012.09.054>.
- [14] Grossmann WD, Grossmann I, Steininger KW. Distributed solar electricity generation across large geographic areas, Part I: a method to optimize site selection, generation and storage. Renew Sustain Energy Rev 2013;25:831–43. <http://dx.doi.org/10.1016/j.rser.2012.08.018>.
- [15] Pleßmann G, Erdmann M, Hlusiak M, Breyer C. Global Energy Storage Demand for a 100% Renewable Electricity Supply, Energy Procedia 46 (2014) 22 – 31, th International Renewable Energy Storage Conference and Exhibition (IRES 2013). <https://doi.org/10.1016/j.egypro.2014.01.154>.
- [16] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90. <http://dx.doi.org/10.1016/j.enconman.2016.01.019>.
- [17] Huber M, Roger A, Hamacher T. Optimizing long-term investments for a sustainable development of the asean power system. Energy 2015;88:180–93. <http://dx.doi.org/10.1016/j.energy.2015.04.065>.
- [18] Czisch G. Szenarien zur zukünftigen Stromversorgung: Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien (Ph.D. Thesis). Universität Kassel; 2005 <https://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-200604119596/1/DissVersion0502.pdf>.
- [19] Steinke F, Wolfrum P, Hoffmann C. Grid vs. storage in a 100% renewable Europe. Renew Energy 2013;50:826–32. <http://dx.doi.org/10.1016/j.renene.2012.07.044>.
- [20] Rasmussen MG, Andresen GB, Greiner M. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy 2012;51:642–51. <http://dx.doi.org/10.1016/j.enpol.2012.09.009>. [Renewable Energy in China].
- [21] Hagspiel S, Jägemann C, Lindenburger D, Brown T, Cherevatskiy S, Tröster E. Cost-optimal power system extension under flow-based market coupling. Energy 2014;66:654–66. <http://dx.doi.org/10.1016/j.energy.2014.01.025>.
- [22] Connolly D, Lund H, Mathiesen B. Smart energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. <http://dx.doi.org/10.1016/j.rser.2016.02.025>.
- [23] Bussar C, Stöcker P, Cai Z, LM Jr., Magnor D, Wiernes P, van Bracht N, Moser A, Sauer DU. Large-scale integration of renewable energies and impact on storage demand in a European renewable power system of 2050 Sensitivity study, J Energy Storage 2016, 6, 1 – 10. URL <https://doi.org/10.1016/j.est.2016.02.004>.
- [24] Dominkovi D, Baekovi I, osi B, Krajai G, Pukec T, Dui N, et al. Zero carbon energy system of south east europe in 2050. Appl Energy 2016;184:1517–28. <http://dx.doi.org/10.1016/j.apenergy.2016.03.046>.
- [25] Grossmann WD, Grossmann I, Steininger KW. Solar electricity generation across large geographic areas, Part II: a Pan-American energy system based on solar. Renew Sustain Energy Rev 2014;32:983–93. <http://dx.doi.org/10.1016/j.rser.2014.01.003>.
- [26] Huber M, Weissbart C. On the optimal mix of wind and solar generation in the future Chinese power system. Energy 2015;90:235–43. <http://dx.doi.org/10.1016/j.energy.2015.05.146>.
- [27] Becker S, Frew BA, Andresen GB, Zeyer T, Schramm S, Greiner M, et al. Features of a fully renewable US electricity system: optimized mixes of wind and solar PV and transmission grid extensions. Energy 2014;72:443–58. <http://dx.doi.org/10.1016/j.energy.2014.05.067>.
- [28] Child M, Breyer C. Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. Renew Sustain Energy Rev 2016;66:517–36. <http://dx.doi.org/10.1016/j.rser.2016.07.001>.
- [29] Mathiesen B, Lund H, Connolly D, Wenzel H, Østergaard P, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. <http://dx.doi.org/10.1016/j.apenergy.2015.01.075>.
- [30] Palzer A, Henning H-M. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: results. Renew Sustain Energy Rev 2014;30:1019–34. <http://dx.doi.org/10.1016/j.rser.2013.11.032>.
- [31] Connolly D, Mathiesen B. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1(0):7–28. <http://dx.doi.org/10.5278/ijsep.2014.1.2>.
- [32] Fernandes L, Ferreira P. Renewable energy scenarios in the Portuguese electricity system. Energy 2014;69:51–7. <http://dx.doi.org/10.1016/j.energy.2014.02.098>.
- [33] Moeller C, Meiss J, Mueller B, Hlusiak M, Breyer C, Kastner M, et al. Transforming the electricity generation of the Berlin-Brandenburg region, Germany. Renew Energy 2014;72:39–50. <http://dx.doi.org/10.1016/j.renene.2014.06.042>.
- [34] Breyer C, Bogdanov D, Gulagi A, Aghahosseini A, Barbosa LS, Koskinen O, et al. On the role of solar photovoltaics in global energy transition scenarios. Prog Photovolt: Res Appl 2017;25(8):727–45. <http://dx.doi.org/10.1002/pip.2885>. [pIP-16-176.R2].
- [35] Breyer C, Bogdanov D, Aghahosseini A, Gulagi A, Child M, Oyewo AS, Farfan J, Sadovskaia K, Vainikka P. Solar photovoltaics demand for the global energy transition in the power sector, Prog Photovolt: Res Appl n/a–n/aPIP-17-137.R1. <http://dx.doi.org/10.1002/pip.2950>.
- [36] Jacobson MZ, Delucchi MA, Bauer ZA, Goodman SC, Chapman WE, Cameron MA, et al. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 2017;1:1–14. <http://dx.doi.org/10.1016/j.joule.2017.07.005>.
- [37] Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (wvs) for all purposes, Renewable Energy <https://doi.org/10.1016/j.renene.2018.02.009>.
- [38] Gulagi A, Bogdanov D, Fasihi M, Breyer C. Can Australia Power the Energy-Hungry Asia with Renewable Energy?, Sustainability 9 (2). <https://doi.org/10.3390/su9020233>.
- [39] Gulagi A, Bogdanov D, Breyer C. A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim, Energies 10 (5). <https://doi.org/10.3390/en10050583>.
- [40] Pleßmann G, Blechinger P. How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. Energy Strategy Rev 2017;15:19–32. <http://dx.doi.org/10.1016/j.esr.2016.11.003>.
- [41] Schlachtberger D, Brown T, Schramm S, Greiner M. The benefits of cooperation in a highly renewable European electricity network. Energy 2017;134:469–81. <http://dx.doi.org/10.1016/j.energy.2017.06.004>.
- [42] Hörsch J, Brown T. The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios. In: Proceedings of 14th International Conference on the European Energy Market (EEM 2017), 2017. <https://arxiv.org/abs/1705.07617>.
- [43] Gils HC, Scholz Y, Pregger T, de Tena DL, Heide D. Integrated modelling of variable renewable energy-based power supply in Europe. Energy 2017;123:173–88. <http://dx.doi.org/10.1016/j.energy.2017.01.115>.
- [44] Eriksen EH, Schwenk-Nebbe LJ, Tranberg B, Brown T, Greiner M. Optimal heterogeneity in a simplified highly renewable European electricity system. Energy 2017;133:913–28. <http://dx.doi.org/10.1016/j.energy.2017.05.170>.
- [45] Cebulla F, Naegler T, Pohl M. Electrical energy storage in highly renewable european energy systems: capacity requirements, spatial distribution, and storage dispatch. J Energy Storage 2017;14:211–23. <http://dx.doi.org/10.1016/j.est.2017.10.004>.
- [46] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system. <https://arxiv.org/abs/1801.05290>.
- [47] Pleßmann G, Blechinger P. Outlook on South-East European power system until 2050: Least-cost decarbonization pathway meeting EU mitigation targets, Energy <https://doi.org/10.1016/j.energy.2017.03.076>.
- [48] Barbosa LdsNS, Bogdanov D, Vainikka P, Breyer C. Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America. PLoS One 2017;12(3):1–28. <http://dx.doi.org/10.1371/journal.pone.0173820>.
- [49] Aghahosseini A, Bogdanov D, Breyer C. A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions, Energies 10 (8). <https://doi.org/10.3390/en10081171>.
- [50] Gulagi A, Bogdanov D, Breyer C. The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India, J Energy Storage <https://doi.org/10.1016/j.est.2017.11.012>.
- [51] Gulagi A, Choudhary P, Bogdanov D, Breyer C. Electricity system based on 100% renewable energy for India and SAARC. PLoS One 2017;12(7):1–27. <http://dx.doi.org/10.1371/journal.pone.0180611>.
- [52] Blakers A, Lu B, Stocks M. 100% renewable electricity in Australia. Energy 2017;133:471–82. <http://dx.doi.org/10.1016/j.energy.2017.05.168>.
- [53] Lu B, Blakers A, Stocks M. 90-100% renewable electricity for the South West Interconnected System of Western Australia. Energy 2017;122:663–74. <http://dx.doi.org/10.1016/j.energy.2017.01.077>.
- [54] de Souza Noel Simas Barbosa L, Orozco JF, Bogdanov D, Vainikka P, Breyer C. Hydropower and Power-to-gas Storage Options: The Brazilian Energy System Case, Energy Procedia 99 (2016) 89 – 107, 10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany. <https://doi.org/10.1016/j.egypro.2016.10.101>.
- [55] Aghahosseini A, Bogdanov D, Ghorbani N, Breyer C. Analysis of 100% renewable energy for Iran in 2030: integrating solar PV, wind energy and storage, Int J Environ Sci Technol <https://doi.org/10.1007/s13762-017-1373-4>.
- [56] Sadiqa A, Gulagi A, Breyer C. Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. Energy 2018;147:518–33. <http://dx.doi.org/10.1016/j.energy.2018.01.027>.
- [57] Caldera U, Bogdanov D, Afanasyeva S, Breyer C. Role of Seawater Desalination in the Management of an Integrated Water and 100% Renewable Energy Based Power Sector in Saudi Arabia, Water 10 (1). <https://doi.org/10.3390/w10010003>.
- [58] Kilickaplan A, Bogdanov D, Peker O, Caldera U, Aghahosseini A, Breyer C. An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050.

- Sol Energy 2017;158:218–35. <http://dx.doi.org/10.1016/j.solener.2017.09.030>.
- [59] Child M, Breyer C, Bogdanov D, Fell H-J. The role of storage technologies for the transition to a 100% renewable energy system in Ukraine, Energy Procedia 135 (2017) 410–423, 11th International Renewable Energy Storage Conference, IRES 2017, 14–16 March 2017, Düsseldorf, Germany. <https://doi.org/10.1016/j.egypro.2017.09.513>.
- [60] Gils HC, Simon S. Carbon neutral archipelago - 100% renewable energy supply for the Canary Islands. Appl Energy 2017;188:342–55. <http://dx.doi.org/10.1016/j.apenergy.2016.12.023>.
- [61] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the land Islands in 2030. Energy Convers Manag 2017;137:49–60. <http://dx.doi.org/10.1016/j.enconman.2017.01.039>.
- [62] Martinot E, Dienst C, Weiliang L, Qimin C. Renewable energy futures: targets, scenarios, and pathways. Annu Rev Environ Resour 2007;32(1):205–39. <http://dx.doi.org/10.1146/annurev.energy.32.080106.133554>.
- [63] Renewables 2017 Global Status Report, Tech. rep., REN21; 2017.
- [64] Trainer T. Can renewables etc. solve the greenhouse problem? The negative case. Energy Policy 2010;38(8):4107–14. <http://dx.doi.org/10.1016/j.enpol.2010.03.037>.
- [65] Trainer T. A critique of Jacobson and Delucchi's proposals for a world renewable energy supply. Energy Policy 2012;44:476–81. <http://dx.doi.org/10.1016/j.enpol.2011.09.037>.
- [66] Clack CTM, Qvist SA, Apt J, Bazilian M, Brandt AR, Caldeira K, et al. Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. Proc Natl Acad Sci USA 2017;114(26):6722–7. <http://dx.doi.org/10.1073/pnas.1610381114>.
- [67] Trainer T. Can Europe run on renewable energy? A negative case. Energy Policy 2013;63:845–50. <http://dx.doi.org/10.1016/j.enpol.2013.09.027>.
- [68] Loftus PJ, Cohen AM, Long JCS, Jenkins JD. A critical review of global decarbonization scenarios: what do they tell us about feasibility? Wiley Interdiscip Rev: Clim Change 2015;6(1):93–112. <http://dx.doi.org/10.1002/wcc.324>.
- [69] Smil V. Energy transitions: history, requirements, prospects. Praeger Publishers; 2010.
- [70] Delucchi MA, Jacobson MZ. Response to a critique of Jacobson and Delucchi's proposals for a world renewable energy supply by Ted Trainer. Energy Policy 2012;44:482–4. <http://dx.doi.org/10.1016/j.enpol.2011.10.058>.
- [71] Jacobson MZ, Delucchi MA. Response to Trainer's second commentary on a plan to power the world with wind, water, and solar power. Energy Policy 2013;57:641–3. <http://dx.doi.org/10.1016/j.enpol.2012.11.014>.
- [72] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims. Proc Natl Acad Sci USA 2017;114(26):E5021–3. <http://dx.doi.org/10.1073/pnas.1708069114>.
- [73] Heard B, Brook B, Wigley T, Bradshaw C. Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33. <http://dx.doi.org/10.1016/j.rser.2017.03.114>.
- [74] Brook BW, Bradshaw CJA. Key role for nuclear energy in global biodiversity conservation. Conserv Biol 2015;29(3):702–12. <http://dx.doi.org/10.1111/cobi.12433>.
- [75] Heard BP, Brook BW. Closing the cycle: how South Australia and Asia can benefit from re-inventing used nuclear fuel management. Asia Pac Policy Stud 2017;4(1):166–75. <http://dx.doi.org/10.1002/app5.164>. [aPPS-2016-0025.R2].
- [76] Brook BW, Bleses T, Wigley TML, Hong S. Silver buckshot or bullet: Is a future 'energy mix' necessary?, Sustainability 10 (2). <https://doi.org/10.3390/su10020302>.
- [77] Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, Krey V, Kriegler E, Löschel DMA, Paltsev S, Rose S, Shukla P, Tavoni M, van der Zwaan B, van Vuuren D. Assessing Transformation Pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx J. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. <https://www.ipcc.ch/report/ar5/wg3/>.
- [78] Kaldellis J, 4 - feasibility assessment for stand-alone and hybrid wind energy systems. In: J. Kaldellis (Ed.), Stand-Alone and Hybrid Wind Energy Systems, Woodhead Publishing Series in Energy, Woodhead Publishing, 2010, pp. 102–161. <https://doi.org/10.1533/9781845699628.1.102>.
- [79] Bekele G, Palm B. Feasibility study for a standalone solar-wind-based hybrid energy system for application in Ethiopia. Appl Energy 2010;87(2):487–95. <http://dx.doi.org/10.1016/j.apenergy.2009.06.006>.
- [80] Castro-Santos L, Filgueira-Vizoso A, Carral-Couce L, Ángel Fraguera Formoso J. Economic feasibility of floating offshore wind farms. Energy 2016;112:868–82. <http://dx.doi.org/10.1016/j.energy.2016.06.135>.
- [81] Rodrigues S, Torabikalaki R, Faria F, Cafófo N, Chen X, Ivaki AR, et al. Economic feasibility analysis of small scale pv systems in different countries. Sol Energy 2016;131:81–95. <http://dx.doi.org/10.1016/j.solener.2016.02.019>.
- [82] Tsupari E, Arponen T, Hankalin V, Kärki J, Kouri S. Feasibility comparison of bioenergy and CO₂ capture and storage in a large combined heat, power and cooling system. Energy 2017;139:1040–51. <http://dx.doi.org/10.1016/j.energy.2017.08.022>.
- [83] Ridjan I, Mathiesen BV, Connolly D, Dui N. The feasibility of synthetic fuels in renewable energy systems. Energy 2013;57:76–84. <http://dx.doi.org/10.1016/j.energy.2013.01.046>.
- [84] MacDonald AE, Clack CTM, Alexander A, Dunbar A, Wilczak J, Xie Y. Future cost-competitive electricity systems and their impact on US CO₂ emissions. Nat Clim Change 2017;6:526–31. <http://dx.doi.org/10.1038/nclimate2921>.
- [85] Rodriguez R, Becker S, Andresen G, Heide D, Greiner M. Transmission needs across a fully renewable European power system. Renew Energy 2014;63:467–76. <http://dx.doi.org/10.1016/j.renene.2013.10.005>.
- [86] Eurostat, Eurostat, <http://ec.europa.eu/eurostat/>, Online, retrieved June 2017.
- [87] Millstein D, Wisner R, Bolinger M, Barbosa G. The climate and air-quality benefits of wind and solar power in the United States, Nature Energy 6 (17134). <https://doi.org/10.1038/nenergy.2017.134>.
- [88] Arent D, Tol R, Faust E, Hella J, Kumar S, Strzepek K, Tóth F, Yan D. Key economic sectors and services. In: Field C, Barros V, Dokken D, Mach K, Mastrandrea M, Bilir T, Chatterjee M, Ebi K, Estrada Y, Genova R, Girma B, Kissel E, Levy A, MacCracken S, Mastrandrea P, White L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, pp. 659–708. https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIAR5-Chap10_FINAL.pdf.
- [89] European Network of Transmission System Operators for Electricity, Ten-Year Network Development Plan (TYNDP) 2016, Tech. rep., ENTSO-E (2016).
- [90] Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T. energy [r]evolution: a sustainable world energy outlook, 5th edition, Tech. rep., Greenpeace International, Global Wind Energy Council (GWEC), SolarPowerEurope (2015).
- [91] IEA, World Energy Outlook 2016, Tech. rep. (2016). URL <https://www.iea.org/weo/>.
- [92] Lund H. Renewable energy systems: a smart energy systems approach to the choice and modeling of 100% renewable solutions. 2nd eda Academic Press (Elsevier); 2014.
- [93] An electricity market for Germany's energy transition: White Paper, Tech. rep., German Federal Ministry for Economic Affairs and Energy (BMWi), <https://www.bmwi.de/Redaktion/EN/Publikationen/whitepaper-electricity-market.html>; 2015.
- [94] Comments on the Green Paper 'Ein Strommarkt für die Energiewende', Tech. rep., Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), status 16. 06.2015, available at http://www.bmwi.de/BMWi/Redaktion/PDF/Stellungnahmen-Gruenbuch/150226-fraunhofer-iwes-energiesystemtechnik_property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf(2015).
- [95] Eurostat, Eurostat renewable energy statistics explained, http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics, Online, retrieved June 2017.
- [96] Sustainable Energy for All 2013–2014: Global Tracking Framework, Tech. rep., World Bank and International Energy Agency (2014). <http://dx.doi.org/10.1596/978-1-4648-0200-3>.
- [97] Staffell I, Brett D, Brandon N, Hawkes A. A review of domestic heat pumps. Energy Environ Sci 2012;5:9291–306. <http://dx.doi.org/10.1039/C2EE22653G>.
- [98] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems, Energy 48 (1) (2012) 160–168, 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environmental Systems, SDEWES 2011. <https://doi.org/10.1016/j.energy.2012.07.063>.
- [99] Lund H, Werner S, Wilshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th generation district heating (4gdh). Energy 2014;68:1–11. <http://dx.doi.org/10.1016/j.energy.2014.02.089>.
- [100] Connolly D, Lund H, Mathiesen B, Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. <http://dx.doi.org/10.1016/j.enpol.2013.10.035>.
- [101] Energy balances, <http://ec.europa.eu/eurostat/web/energy/data/energy-balances>; 2017.
- [102] van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. Clim Change 2011;109(1):5. <http://dx.doi.org/10.1007/s10584-011-0148-z>.
- [103] Schellnhuber HJ, Rahmstorf S, Winkelmann R. Why the right climate target was agreed in Paris. Nat Clim Change 2016;6:649. <http://dx.doi.org/10.1038/nclimate3013>.
- [104] Creutzig F, Agoston P, Goldschmidt JC, Luderer G, Nemet G, Pietzcker RC. The underestimated potential of solar energy to mitigate climate change, Nature Energy 2. <http://dx.doi.org/10.1038/nenergy.2017.140>.
- [105] Gerhardt N, Scholz A, Sandau F, Hahn H. Interaktion EE-Strom, Wärme und Verkehr, Tech. rep., Fraunhofer IWES (2015). http://www.energiesystemtechnik.iwes.fraunhofer.de/de/projekte/suche/2015/interaktion_strom_waerme_verkehr.html.
- [106] Carolyn Fischer and Evan Herrnstadt and Richard Morgenstern, Understanding Errors in EIA Projections of Energy Demand, Tech. rep. (2008). <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.480.6720&rep=rep1&type=pdf>.
- [107] Martin St. C, Lundquist J, Handschy M. Variability of interconnected wind plants: correlation length and its dependence on variability time scale. Environ Res Lett 2015;10:044004. <http://dx.doi.org/10.1088/1748-9326/10/4/044004>.
- [108] Nørgård PBE, Giebel G, Holttinen H, Søder L, Petteiteig A. WILMAR: Fluctuations and predictability of wind and hydropower: Deliverable 2.1, Tech. rep., Forskningscenter Risø (2004). URL http://orbit.dtu.dk/files/7711241/ris_r_1443.pdf.
- [109] Holttinen H, Kiviluoma J, Estanqueiro A, Gómez-Lázaro E, Rawn B, Dobschinski J, Meibom P, Lannoye E, Aigner T, Wan YH, Milligan M. Variability of load and net load in case of large scale distributed wind power. In: 10th Wind Integration Workshop, Aarhus, 2011. https://www.ieawind.org/task_25/PDF/W1W/WIWAarhus_Task%202025%20Variability%20paper%20final.pdf.

- [110] Ernst B. Analysis of wind power ancillary services characteristics with German 250-MW wind data. Tech. rep., National Renewable Energy Laboratory; 1999. <<http://dx.doi.org/10.2172/752651>>.
- [111] Ernst B, Bischof-Niemz T, van Heerden R, Mushwana C. Balancing wind energy within the South African power system. In: 15th Wind Integration Workshop, Vienna; 2016.
- [112] Deane J, Drayton G, Gallachóir BO. The impact of sub-hourly modelling in power systems with significant levels of renewable generation. *Appl Energy* 2014;113:152–8. <http://dx.doi.org/10.1016/j.apenergy.2013.07.027>.
- [113] Troy N, Flynn D, O'Malley M, The importance of sub-hourly modeling with a high penetration of wind generation. In: 2012 IEEE Power and Energy Society General Meeting, 2012, pp. 1–6. <<https://doi.org/10.1109/PESGM.2012.6345631>>.
- [114] O'Dwyer C, Flynn D. Using energy storage to manage high net load variability at sub-hourly time-scales. *IEEE Trans Power Syst* 2015;30(4):2139–48. <http://dx.doi.org/10.1109/TPWRS.2014.2356232>.
- [115] Dimoukas I, Amelin M, Levihn F. District heating system operation in power systems with high share of wind power. *J Mod Power Syst Clean Energy* 2017;5(6):850–62. <http://dx.doi.org/10.1007/s40565-017-0344-6>.
- [116] Pfenninger S. Dealing with multiple decades of hourly wind and PV time series in energy models: a comparison of methods to reduce time resolution and the planning implications of inter-annual variability. *Appl Energy* 2017;197:1–13. <http://dx.doi.org/10.1016/j.apenergy.2017.03.051>.
- [117] Schröder A, Kunz F, Meiss J, Mendelevitch R, von Hirschhausen C. Current and prospective costs of electricity generation until 2050, Data Documentation, DIW 68, Deutsches Institut für Wirtschaftsforschung (DIW), Berlin, <<http://hdl.handle.net/10419/80348>>, [Accessed July 2016]; 2013.
- [118] Stellungnahme zum fünften Monitoring-Bericht der Bundesregierung für das Berichtsjahr 2015, Tech. rep., Expertenkommission zum Monitoring-Prozess 'Energie der Zukunft'; 2016. URL <<https://www.bmwi.de/Redaktion/DE/Downloads/V/fuenfter-monitoring-bericht-energie-der-zukunft-stellungnahme.pdf>>.
- [119] Gerhardt N, Böttger D, Trost T, Scholz A, Pape C, Gerlach A-K, Härtel P, Ganal I. Analyse eines europäischen 95%-Klimazielszenarios über mehrere Wetterjahre, Tech. rep., Fraunhofer IWES; 2017. <http://www.energieversorgung-elektromobilitaet.de/includes/reports/Auswertung_7Wetterjahre_95Prozent_FraunhoferIWES.pdf>.
- [120] Roehrkasten S, Schaeuble D, Helgenberger S. Secure and sustainable power generation in a water-constrained world, IASS <<https://doi.org/10.2312/iass.2015.023>>.
- [121] Ueckerdt F, Hirth L, Luderer G, Edenhofer O. System LCOE: what are the costs of variable renewables? *Energy* 2013;63:61–75. <http://dx.doi.org/10.1016/j.energy.2013.10.072>.
- [122] Hirth L, Ueckerdt F, Edenhofer O. Integration costs revisited - An economic framework for wind and solar variability. *Renew Energy* 2015;74:925–39. <http://dx.doi.org/10.1016/j.renene.2014.08.065>.
- [123] Hess D, Wetzel M, Cao K-K. Representing node-internal transmission and distribution grids in energy system models. *Renew Energy* 2018;119:874–90. <http://dx.doi.org/10.1016/j.renene.2017.10.041>.
- [124] Integration of Renewable Energy in Europe, Tech. rep., Imperial College, NERA, DNV GL, <https://ec.europa.eu/energy/sites/ener/files/documents/201406_report_renewables_integration_europe.pdf>; 2014.
- [125] Ackermann T, Martensen N, Brown T, et al., Verteilnetzstudie Rheinland-Pfalz; 2014. <<https://www.oeko.de/oekodoc/1885/2014-008-de.pdf>>.
- [126] Brown T, Schierhorn P, Tröster E, Ackermann T. Optimising the European transmission system for 77% renewable electricity by 2030. *IET Renew Power Gener* 2016;10(1):3–9. <http://dx.doi.org/10.1049/iet-rpg.2015.0135>.
- [127] Tröster E, Kuwahata R, Ackermann T. European grid study 2030/2050, Tech. rep., Energynautics GmbH; 2011.
- [128] Deutsche Energie-Agentur, DENA-Verteilnetzstudie; 2012. <<http://www.dena.de/publikationen/energiesysteme>>.
- [129] Becker S, Rodriguez R, Andresen G, Schramm S, Greiner M. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. *Energy* 2014;64:404–18. <http://dx.doi.org/10.1016/j.energy.2013.10.010>.
- [130] ACER, ACER Market Monitoring Report 2016, Tech. rep.; 2017. <http://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202016%20-%20ELECTRICITY.pdf>.
- [131] Amprión, Pressemitteilung: Generator wird zum Motor, <https://www.amprion.net/Presse/Presse-Detailseite_2667.html>; 2012.
- [132] Uijlings W, System Service Provision: An independent view on the likely costs incurred by potential System Service Providers in delivering additional and enhanced System Services, Tech. rep., DNV KEMA; 2012.
- [133] Deutsche Energie-Agentur, Momentanreserve 2030: Bedarf und Erbringung von Momentanreserve 2030; 2016. URL <https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9142_Studie_Momentanreserve_2030.pdf>.
- [134] TenneT, TenneT gestaltet die Energiewende in Bayern: 360 Tonnen schwerer Generator erreicht Umspannwerk Bergheimfeld West; 2015. URL <<https://www.tennet.eu/de/news/news/tennet-gestaltet-die-energiewende-in-bayern-360-tonnen-schwerer-generator-erreicht-umspannwerk-berg/>>.
- [135] Siemens, The stable way: Synchronous condenser solutions; 2014. <https://w3.usa.siemens.com/smartgrid/us/en/events/Documents/IEEE%202016/TS_Synchronous_Condenser.pdf>.
- [136] Managing a High Penetration of Renewables - A Tasmanian Case Study, Tech. rep., Hydro Tasmania and TasNetworks (Aug 2016).
- [137] Orths A, Eriksen PB. The future has come: the 100% res driven power system is reality, *Revue de l'Electricité et de l'Electronique* 5. <<http://dx.doi.org/10.23723/1301:2016-5/17783>>.
- [138] Danish Electrical Grid Independent of Centralised Power Plants for 41 Days; 2018. <<https://stateofgreen.com/en/profiles/state-of-green/news/danish-electrical-grid-independent-of-centralised-power-plants-for-41-days>>.
- [139] Miller NW. Keeping it together: transient stability in a world of wind and solar generation. *IEEE Power Energy Mag* 2015;13(6):31–9. <http://dx.doi.org/10.1109/MPE.2015.2461332>.
- [140] Miller NW, Leonardi B, D'Aquila R, Clark K, Tech. rep., NREL (Nov 2015). [link]. <<http://www.nrel.gov/docs/fy16osti/64822.pdf>>.
- [141] Urdal H, Ierna R, Zhu J, Ivanov C, Dahresobh A, Rostom D. System strength considerations in a converter dominated power system. *IET Renew Power Gener* 2015;9(7):10–7. <http://dx.doi.org/10.1049/iet-rpg.2014.0199>.
- [142] Kueck J, Kirby B, Rizy T, Li F, Fall N. Reactive power from distributed energy. *Electr J* 2006;19(10):27–38. <http://dx.doi.org/10.1016/j.tej.2006.10.007>.
- [143] Igbinovia FO, Fandi G, Müller Z, vec J, Tlustý J. Cost implication and reactive power generating potential of the synchronous condenser. In: 2016 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG); 2016, pp. 1–6. <<http://dx.doi.org/10.1109/IGBSG.2016.7539450>>.
- [144] Zukünftige Bereitstellung von Blindleistung und anderen Maßnahmen für die Netzsicherheit, Tech. rep., INA, OTH; 2016.
- [145] Company GE, Synchronous Condensers for Transmission Systems, <http://www.ercot.com/content/meetings/rpg/keydocs/2013/1115/GE_Condensers_Ercot_presentation_11-15-13.pdf>; 2013.
- [146] Kroposki B, Johnson B, Zhang Y, Gevorgian V, Denholm P, Hodge BM, et al. Achieving a 100% renewable grid: operating electric power systems with extremely high levels of variable renewable energy. *IEEE Power Energy Mag* 2017;15(2):61–73. <http://dx.doi.org/10.1109/MPE.2016.2637122>.
- [147] Milligan M, Frew B, Kirby B, Schuerger M, Clark K, Lew D, et al. Alternatives no more: wind and solar power are mainstays of a clean, reliable, affordable grid. *IEEE Power Energy Mag* 2015;13(6):78–87. <http://dx.doi.org/10.1109/MPE.2015.2462311>.
- [148] Ackermann T, Martensen N, Brown T, Schierhorn P-P, Boshell F, Gafaro F, Ayuso M. Scaling Up Variable Renewable Power: The Role of Grid Codes, Tech. rep., International Renewable Energy Agency (IRENA); 2016. <http://www.irena.org/DocumentDownloads/Publications/IRENA_Grid_Codes_2016.pdf>.
- [149] MacDowell J, Dutta S, Richwine M, Achilles S, Miller N. Serving the future: advanced wind generation technology supports ancillary services. *IEEE Power Energy Mag* 2015;13(6):22–30. <http://dx.doi.org/10.1109/MPE.2015.2461331>.
- [150] RoCoF Alternative & Complementary Solutions Project: Phase 2 Study Report, Tech. rep., EirGrid, SONI; 2016. <<http://www.eirgridgroup.com/site-files/library/EirGrid/RoCoF-Alternative-Solutions-Project-Phase-2-Report-Final.pdf>>.
- [151] Ierna R, Zhu J, Roscoe AJ, Yu M, Dysko A, Booth CD, Urdal H. Effects of VSM convertor control on penetration limits of non-synchronous generation in the GB power system. In: 15th Wind Integration Workshop, 2016, this paper was presented at the 15th Wind Integration Workshop and published in the workshop's proceedings. <<http://strathprints.strath.ac.uk/58052/>>.
- [152] Roscoe AJ, Yu M, Ierna R, Zhu J, Dyško A, Urdal H, Booth C. A VSM (virtual synchronous machine) convertor control model suitable for RMS studies for resolving system operator/owner challenges. In: 15th Wind Integration Workshop, 2016, this paper was presented at the 15th Wind Integration Workshop and published in the workshop's proceedings. <<http://strathprints.strath.ac.uk/58053/>>.
- [153] Chen Y, Hesse R, Turschner D, Beck HP. Improving the grid power quality using virtual synchronous machines. In: 2011 International Conference on Power Engineering, Energy and Electrical Drives; 2011. p. 1–6. <<https://doi.org/10.1109/PowerEng.2011.6036498>>.
- [154] Karapanos V, de Haan S, Zwetsloot K. Real time simulation of a power system with VSG hardware in the loop. In: IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society; 2011, p. 3748–3754 <<https://doi.org/10.1109/IECON.2011.6119919>>.
- [155] Zhong QC, Weiss G. Synchronverters: inverters that mimic synchronous generators. *IEEE Trans Ind Electron* 2011;58(4):1259–67. <http://dx.doi.org/10.1109/TIE.2010.2048839>.
- [156] Torres M, Lopes L. Virtual synchronous generator: a control strategy to improve dynamic frequency control in autonomous power systems. *Energy Power Eng* 2013;5(2A):32–8. <http://dx.doi.org/10.4236/epe.2013.52A005>.
- [157] Bevrani H, Ise T, Miura Y. Virtual synchronous generators: a survey and new perspectives. *Int J Electr Power Energy Syst* 2014;54:244–54. <http://dx.doi.org/10.1016/j.ijepes.2013.07.009>.
- [158] Jouini T, Arghir C, Dörfler F. Grid-Friendly Matching of Synchronous Machines by Tapping into the DC Storage IFAC-Pap, 49, 22; 2016 192–197, 6th IFAC Workshop on Distributed Estimation and Control in Networked Systems NECSYS 2016. <<https://doi.org/10.1016/j.ifacol.2016.10.395>>].
- [159] Sinha M, Dörfler F, Johnson BB, Dhople SV. Uncovering droop control laws embedded within the nonlinear dynamics of van der pol oscillators. *IEEE Trans Control Netw Syst* 2017;4(2):347–58. <http://dx.doi.org/10.1109/TCNS.2015.2503558>.
- [160] Technology Brief: Renewable Energy Integration in Power Grids, Tech. rep., IRENA, IEA-ETSAP; 2015.
- [161] dena-Studie Systemdienstleistungen 2030, Tech. rep., DENA, online at <<https://www.dena.de/themen-projekte/projekte/energiesysteme/dena-studie-systemdienstleistungen-2030/>>; 2014.
- [162] Kombikraftwerk 2: Abschlussbericht, Tech. rep., Fraunhofer IWES and others (August 2014).
- [163] BNetzA, BKartA, Monitoringbericht 2016; 2016. URL <<https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen>

- Institutionen/DatenaustauschundMonitoring/Monitoring/Monitoringberichte/Monitoring_Berichte_node.html).
- [164] WEMAG, WEMAG-Batteriespeicher testet erfolgreich Schwarzstart nach Blackout; 2017. URL <<https://www.wemag.com/aktuelles-presse/wemag-batteriespeicher-testet-erfolgreich-schwarzstart-nach-blackout>>.
- [165] News ES, California battery's black start capability hailed as 'major accomplishment in the energy industry'; 2017. URL <<https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-i>>.
- [166] Uranium 2016: Resources, Production and Demand, Tech. rep., Nuclear Energy Agency and International Atomic Energy Agency; 2016.
- [167] Abbott D. Is nuclear power globally scalable? Proc IEEE 2011;99(10):1611–7. <http://dx.doi.org/10.1109/JPROC.2011.2161806>.
- [168] Key world energy statistics 2016, Tech. rep., International Energy Agency; 2016. URL <<http://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf>>.
- [169] Perez R, Perez M. A fundamental look at supply side energy reserves for the planet, IEA SHC. <<https://www.iea-shc.org/data/sites/1/publications/2015-11-A-Fundamental-Look-at-Supply-Side-Energy-Reserves-for-the-Planet.pdf>>.
- [170] Verbruggen A. Renewable and nuclear power: a common future? Energy Policy 2008;36(11):4036–47. <http://dx.doi.org/10.1016/j.enpol.2008.06.024>. [transition towards Sustainable Energy Systems].
- [171] Hamacher T, Huber M, Dorfner J, Schaber K, Bradshaw AM. Nuclear fusion and renewable energy forms: Are they compatible?, Fusion Engineering and Design 88 (6) (2013) 657–660, proceedings of the 27th Symposium On Fusion Technology (SOFT-27); Liège, Belgium, September 24–28, 2012. <<https://doi.org/10.1016/j.fusengdes.2013.01.074>>.
- [172] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems, Energies 10 (4). <<https://doi.org/10.3390/en10040578>>.
- [173] South Australia turns on Tesla's 100MW battery; Dec 2017. <<https://www.theguardian.com/australia-news/2017/dec/01/south-australia-turns-on-teslas-100mw-battery-history-in-the-making>>.
- [174] Batteries perform many different functions on the power grid; Jan 2018. <<https://www.eia.gov/todayinenergy/detail.php?id=34432>>.
- [175] Gougar H, Bari R, Kim T, Sowinski TE, Worrall A. Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications, Tech. rep., Idaho National Laboratory; 2015. <<https://indigitallibrary.inl.gov/sites/sti/sti/6721146.pdf>>.
- [176] Cochran TB, Feiveson HA, Mian Z, Ramana MV, Schneider M, von Hippel FN. It's time to give up on breeder reactors. Bull At Sci 2010;66(3):50–6. <http://dx.doi.org/10.2968/066003007>.
- [177] J. Green, The slow death of fast reactors, Nuclear Monitor (4587). <<https://www.wiseinternational.org/nuclear-monitor/831/slow-death-fast-reactors>>.
- [178] A roadmap to the realisation of fusion energy, Tech. rep., EFDA; 2012.
- [179] Summary for Policy Makers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx J. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2014. <<https://www.ipcc.ch/report/ar5/wg3/>>.
- [180] Nykvist B, Nilsson M. Rapidly falling costs of battery packs for electric vehicles. Nat Clim Change 2015;7:329–32. <http://dx.doi.org/10.1038/nclimate2564>.
- [181] Schmidt O, Hawkes A, Gambhir A, Staffell I. The future cost of electrical energy storage based on experience rates, Nat Energy 2 (17110). <<https://doi.org/10.1038/nenergy.2017.110>>.
- [182] Kittner N, Lill F, Kammen DM. Energy storage deployment and innovation for the clean energy transition, Nat Energy 2 (17125). <<https://doi.org/10.1038/nenergy.2017.125>>.
- [183] Afanasyeva S, Breyer C, Engelhard M. Impact of battery cost on the economics of hybrid photovoltaic power plants, Energy Procedia 99 (2016) 157–173, 0th International Renewable Energy Storage Conference, IRES 2016, 15–17 March 2016, Düsseldorf, Germany. <<https://doi.org/10.1016/j.egypro.2016.10.107>>.
- [184] Deign J. Xcel Attracts 'Unprecedented' Low Prices for Solar and Wind Paired With Storage; 2018. URL <<https://www.greentechmedia.com/articles/read/record-low-solar-plus-storage-price-in-xcel-solicitation>>.
- [185] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36. <http://dx.doi.org/10.1016/j.apenergy.2014.09.081>.
- [186] Götz M, Lefebvre J, Mörs F, Koch AM, Graf F, Bajohr S, et al. Renewable Power-to-Gas: a technological and economic review. Renew Energy 2016;85:1371–90. <http://dx.doi.org/10.1016/j.renene.2015.07.066>.
- [187] Rönsch S, Schneider J, Matthischke S, Schlüter M, Götz M, Lefebvre J, et al. Review on methanation - From fundamentals to current projects. Fuel 2016;166:276–96. <http://dx.doi.org/10.1016/j.fuel.2015.10.111>.
- [188] The Fuel Cell Industry Review 2016, Tech. rep., E4tech; 2016.
- [189] Power-to-Gas with High Efficiency; 2018. <http://www.helmeth.eu/images/joomlapiates/documents/PI_2018_009_Power%20to%20Gas%20with%20High%20Efficiency.pdf>.
- [190] Lund H, Østergaard P, Connolly D, Ridjan I, Mathiesen B, Hvelplund F, Thellufsen J, Sorknaes P. Energy Storage and Smart Energy Systems, International Journal of Sustainable Energy Planning and Management 11 (0). <<https://doi.org/10.5278/ijsepm.2016.11.2>>.
- [191] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renew Power Gener 2009;3(2):190–204. <http://dx.doi.org/10.1049/iet-rpg:20080049>.
- [192] Europe GI, Gas storage data, <<https://agsi.gie.eu/>>.
- [193] Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, et al. Bioenergy and Climate Change mitigation: an assessment. GCB Bioenergy 2015;7(5):916–44. <http://dx.doi.org/10.1111/gcbb.12205>.
- [194] Lindfeldt EG, Saxe M, Magnusson M, Mohseni F. Strategies for a road transport system based on renewable resources - The case of an import-independent Sweden in 2025. Appl Energy 2010;87(6):1836–45. <http://dx.doi.org/10.1016/j.apenergy.2010.02.011>.
- [195] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. <http://dx.doi.org/10.1016/j.apenergy.2015.01.013>. [Supplement C].
- [196] Pires J, Martins F, Alvim-Ferraz M, Simões M. Recent developments on carbon capture and storage: an overview. Chem Eng Res Des 2011;89(9):1446–60. <http://dx.doi.org/10.1016/j.cherd.2011.01.028> [Special Issue on Carbon Capture & Storage].
- [197] Boot-Handford ME, Abanades JC, Anthony EJ, Blunt MJ, Brandani S, Mac Dowell N, et al. Carbon capture and storage update. Energy Environ Sci 2014;7:130–89. <http://dx.doi.org/10.1039/C3EE42350F>.
- [198] Leung DY, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev 2014;39:426–43. <http://dx.doi.org/10.1016/j.rser.2014.07.093>.
- [199] McLaren D. A comparative global assessment of potential negative emissions technologies. Process Saf Environ Prot 2012;90(6):489–500. <http://dx.doi.org/10.1016/j.psep.2012.10.005> [Special Issue: Negative emissions technology].
- [200] Seigo SL, Dohle S, Siegrist M. Public perception of carbon capture and storage (ccs): a review. Renew Sustain Energy Rev 2014;38:848–63. <http://dx.doi.org/10.1016/j.rser.2014.07.017>.
- [201] Lund H, Mathiesen BV. The role of carbon capture and storage in a future sustainable energy system, Energy (2012) 44 (1) 469–476, integration and Energy System Engineering, European Symposium on Computer-Aided Process Engineering 2011. <<https://doi.org/10.1016/j.energy.2012.06.002>>.
- [202] Fasihi M, Bogdanov D, Breyer C. Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia (2016) 99 243–268, 10th International Renewable Energy Storage Conference, IRES 2016, 15–17 March 2016, Düsseldorf, Germany. <<https://doi.org/10.1016/j.egypro.2016.10.115>>.
- [203] Fasihi M, Bogdanov D, Breyer C. Long-term hydrocarbon trade options for the maghreb region and europe/renewable energy based synthetic fuels for a net zero emissions world, Sustainability 9 (2). <<https://doi.org/10.3390/su9020306>>.
- [204] Keith DW. Why capture co2 from the atmosphere? Science 2009;325(5948):1654–5. <http://dx.doi.org/10.1126/science.1175680>.
- [205] Williamson P. Emissions reduction: Scrutinize CO₂ removal methods. Nature 2016;530:153–5. <http://dx.doi.org/10.1038/530153a>.
- [206] Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, et al. Betting on negative emissions. Nat Clim Change 2014;4:850. <http://dx.doi.org/10.1038/nclimate2392>. [EP].
- [207] Schlessner C-F, Rogelj J, Schaeffer M, Lissner T, Licker R, Fischer EM, et al. Science and policy characteristics of the Paris Agreement temperature goal. Nat Clim Change 2016;6:827. <http://dx.doi.org/10.1038/nclimate3096>. [EP –, perspective].
- [208] van Vuuren DP, Hof AF, van Sluiseveld MAE, Riahi K. Open discussion of negative emissions is urgently needed. Nat Energy 2017;2(12):902–4. <http://dx.doi.org/10.1038/s41560-017-0055-2>.
- [209] Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber HJ. A roadmap for rapid decarbonization. Science 2017;355(6331):1269–71. <http://dx.doi.org/10.1126/science.aah3443>.
- [210] Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson RB, Cowie A, Krieger E, van Vuuren DP, Rogelj J, Ciais P, Milne J, Canadell JG, McCollum D, Peters G, Andrew R, Krey V, Shrestha G, Friedlingstein P, Gasser T, Grubler A, Heidug WK, Jonas M, Jones CD, Kraxner F, Littleton E, Lowe J, Moreira JR, Nakicenovic N, Obersteiner M, Patwardhan A, Rogner M, Rubin E, Sharifi A, Torvanger A, Yamagata Y, Edmonds J, Yongsung C. Biophysical and economic limits to negative CO₂ emissions, Nat Clim Change 6, review Article. <<http://dx.doi.org/10.1038/nclimate2870>>.
- [211] Anderson K, Peters G. The trouble with negative emissions. Science 2016;354(6309):182–3. <http://dx.doi.org/10.1126/science.aah4567>. [arXiv:<http://science.sciencemag.org/content/354/6309/182.full.pdf>].
- [212] Vaughan NE, Gough C. Expert assessment concludes negative emissions scenarios may not deliver. Environ Res Lett 2016;11(9):095003. <http://dx.doi.org/10.1088/1748-9326/11/9/095003>.
- [213] Special Eurobarometer 459 Report: Climate Change; 2017. <<https://doi.org/10.2834/92702>>.
- [214] Ørsted Green Energy Barometer; 2017. <<https://orsted.com/en/Barometer>>.
- [215] Die Akzeptanz für Erneuerbaren Energien im Spiegel von Umfragen in Industriestaaten; 2016. URL <https://www.unendlich-viel-energie.de/media/file/426.AEE_RK29_Internationale_Akzeptanzumfragen_Mrz16.pdf>.
- [216] Maruyama Y, Nishikido M, Iida T. The rise of community wind power in Japan: enhanced acceptance through social innovation. Energy Policy 2007;35(5):2761–9. <http://dx.doi.org/10.1016/j.enpol.2006.12.010>.
- [217] Jobert A, Laborgne P, Mimler S. Local acceptance of wind energy: factors of success identified in French and German case studies. Energy Policy 2007;35(5):2751–60. <http://dx.doi.org/10.1016/j.enpol.2006.12.005>.
- [218] Enevoldsen P, Sovacool BK. Examining the social acceptance of wind energy: practical guidelines for onshore wind project development in France. Renew

- Sustain Energy Rev 2016;53:178–84. <http://dx.doi.org/10.1016/j.rser.2015.08.041>.
- [219] Schlachtberger D, Brown T, Schäfer M, Schramm S, Greiner M. Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints. <<https://arxiv.org/abs/1803.09711>>.
- [220] Cohen JJ, Reichl J, Schmidthaler M. Re-focussing research efforts on the public acceptance of energy infrastructure: a critical review. Energy 2014;76:4–9. <http://dx.doi.org/10.1016/j.energy.2013.12.056>.
- [221] Galvin R. Trouble at the end of the line: local activism and social acceptance in low-carbon electricity transmission in Lower Franconia, Germany. Energy Res Social Sci 2018;38:114–26. <http://dx.doi.org/10.1016/j.erss.2018.01.022>.
- [222] Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: is energy research lagging behind? Energy Policy 2017;101:211–5. <http://dx.doi.org/10.1016/j.enpol.2016.11.046>.
- [223] Pfenninger S, Hirth L, Schlecht I, Schmid E, Wiese F, Brown T, et al. Opening the black box of energy modelling: strategies and lessons learned. Energy Strategy Rev 2018;19:63–71. <http://dx.doi.org/10.1016/j.esr.2017.12.002>.
- [224] Child M, Koskinen O, Linnanen L, Breyer C. Sustainability guardrails for energy scenarios of the global energy transition. Renew Sustain Energy Rev 2018;91:321–34. <http://dx.doi.org/10.1016/j.rser.2018.03.079>.
- [225] Renewable Power Generation Costs in 2017, Tech. rep., International Renewable Energy Agency (IRENA); 2018. <http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf>.
- [226] Joskow PL. Comparing the costs of intermittent and dispatchable electricity generating technologies. Am Econ Rev 2011;101(3):238–41. <http://dx.doi.org/10.1257/aer.101.3.238>.
- [227] Jacobson MZ. Review of solutions to global warming, air pollution, and energy security. Energy Environ Sci 2009;2:148–73. <http://dx.doi.org/10.1039/B809990C>.
- [228] Verbruggen A, Laes E, Lemmens S. Assessment of the actual sustainability of nuclear fission power. Renew Sustain Energy Rev 2014;32:16–28. <http://dx.doi.org/10.1016/j.rser.2014.01.008>.
- [229] Tokelau becomes the world's first 100% solar powered country, press Release (Nov 2012). <<http://dx.doi.org/10.1016/j.egypro.2016.10.107>>. <<https://www.sma.de/en/newsroom/current-news/news-details/news/3943-tokelau-becomes-the-worlds-first-100-solar-powered-country.html>>.
- [230] Black System South Australia 28 September 2016 - Final Report, Tech. rep., Australian Energy Market Operator (AEMO); March 2017. URL <<https://www.aemo.com.au/Media-Centre/AEMO-publishes-final-report-into-the-South-Australian-state-wide-power-outage>>.