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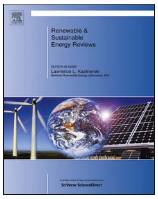

Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems

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ABSTRACT

An effective response to climate change demands rapid replacement of fossil carbon energy sources. This must occur concurrently with an ongoing rise in total global energy consumption. While many modelled scenarios have been published claiming to show that a 100% renewable electricity system is achievable, there is no empirical or historical evidence that demonstrates that such systems are in fact feasible. Of the studies published to date, 24 have forecast regional, national or global energy requirements at sufficient detail to be considered potentially credible. We critically review these studies using four novel feasibility criteria for reliable electricity systems needed to meet electricity demand this century. These criteria are: (1) consistency with mainstream energy-demand forecasts; (2) simulating supply to meet demand reliably at hourly, half-hourly, and five-minute timescales, with resilience to extreme climate events; (3) identifying necessary transmission and distribution requirements; and (4) maintaining the provision of essential ancillary services. Evaluated against these objective criteria, none of the 24 studies provides convincing evidence that these basic feasibility criteria can be met. Of a maximum possible unweighted feasibility score of seven, the highest score for any one study was four. Eight of 24 scenarios (33%) provided no form of system simulation. Twelve (50%) relied on unrealistic forecasts of energy demand. While four studies (17%; all regional) articulated transmission requirements, only two scenarios—drawn from the same study—addressed ancillary-service requirements. In addition to feasibility issues, the heavy reliance on exploitation of hydroelectricity and biomass raises concerns regarding environmental sustainability and social justice. Strong empirical evidence of feasibility must be demonstrated for any study that attempts to construct or model a low-carbon energy future based on any combination of low-carbon technology. On the basis of this review, efforts to date seem to have substantially underestimated the challenge and delayed the identification and implementation of effective and comprehensive decarbonization pathways.

1. Introduction

The recent warming of the Earth's climate is unequivocal [1,2]. Over the 20 years to 2015, atmospheric concentration of carbon dioxide has risen from around 360 ppm (ppm) to over 400 ppm; emissions of carbon dioxide from fossil fuels have grown from approximately 6.4 Gt C year^{-1} in 1995 to around 9.8 Gt C year^{-1} in 2013 [3]. Global average temperature rise has continued, with 2016 confirmed as the warmest year on record. Thermal coal production increased for 14 consecutive years to 2013 before recording a slight decline, with a net increase of approximately 3 billion tonnes of production per year since 1999 [4].

Inexpensive and abundant energy remains crucial for economic development; the relationship between per-capita energy consumption and the United Nations Human Development Index is “undeniable” [5]. But there seems little prospect of decreasing energy consumption globally this century, especially with > 10% of the global population in extreme poverty [6]. With the fate of modern society and global environments at stake, effective action on climate change demands credible, evidence-based plans for energy systems that (i) almost wholly avoid the exploitation of fossil carbon sources, and (ii) are scalable to the growing energy demands of approximately nine to ten billion people by mid-century, and perhaps over 12 billion by the end of the century [7]. This process logically begins with displacing coal, gas and oil in electricity generation, but must eventually expand to eliminate nearly all fossil hydrocarbon used in industrial and residential heat, personal and commercial transportation, and most other energy-related services.

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Much academic, governmental and non-governmental effort has focused on developing energy scenarios devoted exclusively to energy technologies classed as ‘renewable’ (mainly hydroelectricity, biomass, wind, solar, wave and geothermal), often with the explicit exclusion of nuclear power and fossil fuels with carbon capture and storage [8–28]. These imposed choices automatically foreclose potentially essential technologies. In this paper, we argue that the burden of proof for such a consequential decision is high and lies with the proponents of such plans. If certain pathways are excluded *a priori*, then such exclusions should be fully justified and the alternatives proven. This is rarely the case.

There is a near-total lack of historical evidence for the technical feasibility of 100% renewable-electricity systems operating at regional or larger scales. The only developed-nation today with electricity from 100% renewable sources is Iceland [29], thanks to a unique endowment of shallow geothermal aquifers, abundant hydropower, and a population of only 0.3 million people. Other European nations lauded for their efforts in renewable energy deployment produce greenhouse emissions from electricity at rates close to the EU-27 average (468, 365 and 442 g CO_2-e kWh^{-1} for Denmark, Germany and EU-27, respectively) [29].

Scenarios for 100% renewable electricity (and energy) have nevertheless proven influential as a platform for advocacy on the development of energy policy [30–32]. Despite this, there has been only limited structured review of this literature to test for fundamental technical feasibility. A narrative review of 23 studies in 2012 provided a useful diagnosis of common features and gaps in the peer-reviewed literature on 100% renewable systems [33]. That review identified extensive deficiencies in the evidence, highlighting in particular the lack of attention paid to the necessary transmission/distribution networks, and provisions of ancillary services. In assessing the feasibility of these studies however, feasibility itself was not defined, and no firm conclusions were drawn regarding the most basic questions that responsible policy making requires: (i) can such a system work? and (ii) what evidence is required to describe such a system in sufficient detail such that elements like time, cost, and environmental implications can be estimated accurately? IPCC Working Group III, in examining the potential contribution of renewable energy to future climate-change mitigation, examined 164 scenarios from 16 different large-scale models [34]. However, the IPCC did not examine explicitly the feasibility of the various renewable-energy systems considered [34].

Repeated critiques of individual studies by Trainer [35–37] have highlighted feasibility deficiencies, including the reliance on only single years of data to determine the necessary generating capacity, and not accounting for worst-known meteorological conditions. A critique by Gilbraith et al. [38] identified insufficient analysis of the “technical, economic and social feasibility” of a 100% renewables proposal focused on New York State [18]. Another recent assessment has highlighted serious and extensive methodological errors and deficiencies in a 100%-renewable plan for the continental United States [39]. Loftus et al. [40] examined global decarbonization scenarios (encompassing all energy use, not only electricity), including several 100%-renewable analyses. Their review highlighted several deficiencies in the latter, including assumptions of unprecedented rates of decline in energy intensity. However, their review did not consider national- or regional-level studies, nor did it attend closely to issues of electricity reliability [35–39,41–43].

Policy makers are therefore handicapped regarding the credibility of this literature —there is no empirical basis to understand the evidence behind propositions of 100%-renewable electricity (or energy) for global-, regional- or national-scale scenarios. Consequently, there is a risk that policy formation for climate-change mitigation will be based more on considerations of publicity and popular opinion than on evidence of effectiveness, impacts, or feasibility.

Here we provide a first step in remedying this problem. We present the results of a comprehensive review seeking evidence that the electricity requirements of modern economies can be met through 100% renewable-energy sources. We describe the method we used to identify the relevant scenarios, define the concept of *feasibility*, and describe and justify our choice of assessment criteria. We discuss the results of the assessment in terms of the strength of the evidence for technical feasibility of 100% renewable-electricity systems, and outline some of the major environmental and human development implications of these proposed pathways. Our intention is to provide policy makers and researchers with a framework to make balanced and logical decisions on low-carbon electricity production.

2. Methods

We identified published scenarios that have attempted to address the challenge of providing electricity supply entirely from renewable sources. We applied the following screening criteria for this literature search: (i) Scenarios had to be published after 2006: we applied this cut-off date to weight selections towards literature that was representative of the current state of knowledge; (ii) Scenarios must propose electricity supply to be from at least 95% renewable sources (through some combination of hydroelectricity, biomass, wind, solar, geothermal or wave energy); (iii) For spatial scale, scenarios must consider large-scale demand areas such as the whole globe, whole nations, or covering extensive regions within large nations (so excluding scenarios for single towns, small islands, counties, cantons and the like); (iv) Scenarios were required to forecast to the year 2050 or earlier. If scenarios extended beyond 2050, but still allowed scores to be determined based on 2050 milestones, we included the scenario and scored it against the 2050 outcome.

We were principally concerned with evidence for the strict technical feasibility of proposed 100%-renewable electricity systems. We were not seeking to establish the viability of the proposed systems. These terms are frequently used interchangeably. We use *viability* as a subordinate concept to *feasibility*. We define *feasible* as ‘possible within the constraints of the physical universe’, so a demonstration of feasibility requires that evidence is presented that a proposed system will work with current or near-current technology at a specified reliability. Note that our use of *feasible* refers to the whole electricity system, not merely the individual items of technology, such as a solar panel or a wind turbine. *Viable* means that the system is not only feasible, but also realistic within the socio-economic constraints of society [40]. Thus, unless something is first established as feasible, there is no point in assessing its viability (*sensu* [44]).

Our definitions are not unique; *feasibility* has been used elsewhere to refer to technical characteristics of the energy system under assessment [45,46], and Dalton et al. [44] explicitly distinguished between solutions that are “technically feasible” but not considered “economically viable”. This distinction is not applied universally. Several other studies confound these terms or have used them semi-interchangeably [47–50]. For example, while Loftus et al. 40] acknowledged the physical barriers of feasibility, their use of the term extended beyond what they called “hard physical constraints” [40]. Our study is based on the lower hurdle only. We require only evidence for feasibility, i.e., that the system will work.

Even so, our use of *feasible* requires four subsidiary criteria so that it can be workable when applied to a whole electricity network. Our goal is to distil many of the issues raised by previous critical examinations [33,38] into a well-defined set of criteria. Below we describe our four subsidiary feasibility criteria.

2.1. Criterion 1: The electricity demand to which supply will be matched must be projected realistically over the future time interval of interest

Total global energy consumption, consisting of both electrical and non-electrical energy end-use, is projected to grow to at least 2100

[51,52]. Population growth is expected to continue at least to the end of the century [7,53,54]. Nearly all of the expected population growth — around 2.4 billion people relative to today (range 1.4–3.5 billion) [55] — will occur in Africa, Asia and the Middle East [7,54]. These growth trends contain such momentum that the range of possible mid-century outcomes is insensitive even to major interventions in fertility policy, or widespread catastrophe [7,55,56]. This population growth will occur at the same time as growth in per-capita income, which is strongly correlated with per-capita energy consumption in the early stages of modern development [57].

Growth is also anticipated specifically for electricity consumption. The International Energy Agency estimates that in 2016, > 1.2 billion people had no access to electricity [58]. Electricity supplies an increasing share of the world's total energy demand and is the world's fastest growing form of delivered energy [59]. Projected ‘electrification’ of energy use in countries outside the Organisation for Economic Co-operation and Development (OECD) is higher (3.6% year^{-1}) than in OECD countries (1.1% year^{-1}) [59], but different models make a wide range of forecasts.

An effective climate change response requires provision of electricity to avoid the exploitation of fossil fuels. Substitutes will also be required for non-electric energy services traditionally met by fossil fuels [11,16,27,60–65]. Today, fossil-fuel sources account for about 80% of primary energy and two thirds of final energy [66]. This reflects not only the availability, but also the great utility of hydrocarbon fuels in a variety of services including transportation and industrial process heat [67,68]. To achieve deep climate-mitigation outcomes, these energy services must be provided in ways that minimize the use of fossil carbon sources. Electrification of energy services via non-carbon-based electricity generation offers one pathway towards that outcome [51]. However, other energy-intensive pathways, such as the production of synthetic hydrocarbons [68] or ammonia [69–71], are also likely to be required to achieve the required stabilization of atmospheric carbon dioxide while meeting demand for versatile energy services.

Given these issues, any future global scenario that presents static or reduced demand in either primary energy or electricity is unrealistic, and is inconsistent with almost all other future energy projections. Such an outcome would be at odds with the increase in global population, ongoing economic development for the non-OECD majority, and the firmly established link between industrialization and increased energy consumption. The inevitability of increased primary energy consumption holds, even after accounting for projected rates of decline in energy intensity (primary energy GDP^{-1}) — rates that are expected to be more than the average rate of change for the last 40 years (−0.8% year^{-1}) [40]. For example, the most extreme (Level 1) mitigation scenarios in the US Climate Change Science Program report show primary energy increases of 0.26%, 0.62% and 0.85% yr^{-1} over 2010–2050 for the IGSM, MERGE and MiniCAM models, respectively, compared with (and much less than) the corresponding rates of gross domestic product change (2.80%, 2.35% and 2.28% yr^{-1}, respectively). While the implied reductions in energy intensity are large, primary energy consumption will still increase. Electrification results (electric primary energy/total primary energy) show how complex this parameter is. For the IGSM from 2010 to 2050, electrification is predicted to decrease (from 0.43 to 0.37), while electrification increases in the other two models, from 0.38 to 0.54 in MERGE, and from 0.41 to 0.52 in MiniCAM. Scenarios that project electricity demand under the assumption of extreme increases in electrification might imply unrealistic energy transition pathways that are inconsistent with the mainstream literature [51].

So for scenarios to be feasible, they must be consistent with: (i) the range of primary energy projections in the mainstream literature for that region, and (ii) complementary projections in total electricity consumption. Electricity-demand scenarios that are inconsistent with the above represent low-probability outcomes. Effective climate-change mitigation under scenarios that diverge from the above would call for total reinvention of *both* supply *and* demand of energy. Proposed supply systems for such scenarios therefore represent policy pathways with a high potential for failure.

2.2. Criterion 2: The proposed supply of electricity must be simulated/calculated to be capable of meeting the real-time demand for electricity for any given year, together with an additional back-up margin, to within regulated reliability limits, in all plausible climatic conditions

An electrical power system must provide reliable electricity to its customers as economically as possible [72,73]. Cepin [72] stated that power-system reliability depends on both adequacy and security. *Adequacy* refers to the existence of sufficient generation for the electric power system to satisfy consumer demand at any time, and *security* describes the ability of the system to respond to multiple types of disturbance in the quality of power supply [74]. These concepts together define a reliability standard, which prescribes the required service as a percentage of customer demand that must be served over a given period of time (e.g., 1 year). High reliability (> 99.9%) is a common requirement of modern electricity supply (e.g., 99.98% service of customer demand every year for the Pennsylvania, New Jersey, Maryland (PJM) network in the United States, and 99.998% for the Australian National Electricity Market). Electricity supply must vary dynamically to ensure instantaneous matching with demand [73]. For this reason, generation that is constant (i.e., available at all times [baseload]) and/or fully dispatchable (able to be called-up or withdrawn at any time in response to demand changes) is deemed essential for system reliability.

The increasing penetration of variable, climate-dependent sources of generation that are largely uncorrelated with demand, such as wind and solar generation, provides additional challenges for managing system reliability [75–79]. Such generators can have high reliability in terms of being in working order, yet they have low and intermittent availability of the resource itself [72]. Furthermore, system-wide reliability cannot be determined based on ‘typical’ weather conditions [36], but must instead account for present and predicted variability in the resource over foreseeable time scales, from < 1 minute to decadal. Atypical conditions that are extreme, yet credible (e.g., based on historical precedent or realistic future projections), must be identified, both for each generation type in isolation and in combination (e.g., severely drought-impacted hydro-electric output in winter combined with coincident low solar and wind output).

Any proposed supply system must therefore demonstrate that the proposed supply will meet any foreseeable demand in real time at a defined reliability standard and with a sufficient reserve margin for unscheduled outages like breakdowns. It must do so in a way that fully accounts for the limited and intermittent availability of most renewable resources and the potential for extreme climate conditions that are outside the historical record. As per Criterion 1, this reliability must be demonstrated as achievable for the full range of plausible future energy demand.

2.3. Criterion 3: Any transmission requirements for newly installed capacity and/or growth in supply must be described and mapped to demonstrate delivery of generated electricity to the user network such that supply meets both projected demand and reliability standards

Transmission networks transport electricity from generators to distribution networks [80], which in turn transport electricity to customers. To achieve high penetration of renewable energy, augmented transmission networks are vital [81–86]. Credible characterization of the necessary enhanced transmission network is essential for establishing the feasibility of any high-penetration renewable electricity system.

2.4. Criterion 4: The proposed system must show how critical ancillary services will be provided to ensure power quality and the reliable operation of the network, including distribution requirements

Ancillary services are a physical requirement of any electrical system and have been necessary since the development of reticulated power [87]. The availability of ancillary services can be compromised by high penetration of renewable energy sources. For example in Germany, the determined implementation of the *Energiewende* strategy has triggered an examination of how ancillary services will be retained. Unresolved challenges, particularly in system-restart requirements, have been identified to 2033, even in a scenario that maintains 72 GW (28% of total installed capacity) of fossil-fuel-powered, synchronous generators, in a network that is connected to greater Europe [88]. Such challenges at 100% penetration of renewables remain largely unexamined and unresolved.

We discuss two examples of ancillary service requirements:

2.4.1. Frequency control ancillary services

At any point in time, the frequency of the alternating-current electrical system must be maintained close to the prescribed standard (typically 50 or 60 cycles per second [Hz] within a normal operating band of ± 0.1 Hz). In practice, the frequency varies due to changes in electrical load on the system. Changes in frequency arise from the small, instantaneous and ongoing variation in load that occurs due to consumer behavior (e.g., turning lights on and off), to larger changes in demand occurring in the normal course of a day. Instantaneous frequency control is typically provided by the inertia of 'synchronous' generators, where electricity is generated through turbines spinning in unison at close to the regulated standard. However, increased wind and solar penetration, with asynchronous generation of electricity, displaces traditional synchronous generators from the market [89].

For example, in the Australian National Electricity Market, the provision of all frequency-control ancillary services comes from bids to the market by 116 connected generating units (a mixture of coal, gas and hydro-electric power stations) [90]. No wind or solar generators are registered bidders for these services. The increase of intermittent renewable generation is already leading to a scarcity of support services in the network and an increasing risk of breaching reliability standards. Modeling the potential withdrawal of coal-fired generation to meet Australia's COP-21 commitments suggests this situation could be exacerbated in the future [91]. In September 2016, the loss of transmission lines in South Australia during a major storm caused disturbances triggering the departure of 445 MW of wind generation. Without adequate synchronous generation, the rate of change of frequency exceeded prescribed limits, resulting in total power loss to all 1.7 million residents, all business and all industry in the state [92]. The estimated economic impact of this event was AU$367 million [93].

2.4.2. Network control ancillary services: voltage control

Voltage must be managed to within specified tolerances for insulation and safety equipment [87,94]. Voltage management is affected by the expansion of generation that is connected to an electrical-distribution network, known as 'embedded generation' [95]. The impact of embedded generation has been transformed by the rapid uptake of small-scale solar photovoltaic systems [95]. As a consequence, voltage control at distribution level has become a concern in markets with high penetration of solar photovoltaics [95–103].

Projected 100%-renewable electricity systems are incomplete in the absence of evidence that essential, regulated ancillary services will be maintained. This is particularly relevant for 100% renewable-supply systems that propose high reliance on asynchronous wind generation and embedded, asynchronous solar photovoltaic generation.

2.5. Scoring

With our four feasibility criteria we can assign scores for each individual study. We assigned each of Criteria 1, 3 and 4 a maximum score of one. Studies fully meeting an individual criterion scored one and we combined scores for each of these three criteria without weighting. We gave studies not meeting a criterion a score of zero. If efforts to address a criterion stood out among studies, yet still did not address the criterion fully, we gave the study a score of 0.5.

We subdivided Criterion 2 into four parts because different scenarios simulate system reliability over different time scales. We gave a score of one to scenarios simulating supply to the hour; an additional score of one to those simulating to the half-hour, and another score of one to scenarios simulating to the five-minute interval. Finally, we gave another score of one to scenarios that specifically attempted to account for, and adequately addressed, the impact of extreme climate events. Our emphasis on Criterion 2 (higher relative weighting, with a maximum score =4) is justified based on the following: (i) demand-supply matching is one of the most challenging aspects of electricity provision [75–78]; (ii) the cost of meeting higher reliabilities is non-linear (i.e., increasing reliability toward 100% imparts exponentially rising costs, with diminishing returns on loss-of-load probability reductions); and (iii) maintaining reliability under extreme climate conditions that have no historical precedent further exacerbates the challenge. Thus, the maximum possible score for any scenario was seven.

3. Results

Based on our criteria, none of the 100% renewable-electricity studies we examined provided a convincing demonstration of feasibility. Of the 24 studies we assessed, the maximum score accrued was four out of a possible seven for Mason et al. [9,104]. Four scenarios scored zero (i.e., they did not meet a single feasibility criterion). Eight of the 24 scenarios did not do any form of integrated simulation to verify the reliability of the proposed renewable electricity system. Twelve of the 24 relied on unrealistic energy-demand scenarios, either by assuming unrealistic reductions in total primary energy and/or by making assumptions of extreme increases in electrification. Only four of the studies articulated the necessary transmission requirements for the system to operate, and only two scenarios, from the same authors [8], partially addressed how ancillary services might be maintained in modified electricity-supply systems. No studies addressed the distribution-level infrastructure that would be required to accommodate increased embedded generation, leaving a gap in the evidence relating to ancillary services and overall system reliability.

3.1. Energy demand

Our review revealed that among the 100% renewable-energy studies examined, many assumed reductions in primary energy. This is conceptually unrealistic, and at odds with most of the literature. To show how widely each proposed global renewable energy scenario diverges from 'mainstream projections', we compared energy demand in the scenarios that considered the whole globe to the primary energy data from the following sources: the IPCC Special Report on Emission Scenarios [105], the US Climate Change Science Program (an inter-agency effort from the U.S. Government) [51], and the World Energy Technology Outlook of the European Commission [106]. We plotted 28 demand scenarios from these three organizations in 10-year steps from 2000 (where available) to 2050 (Fig. 2). This set of 28 included scenarios with strong mitigation of greenhouse-gas emissions in response to climate change. We also plotted actual (observed) annual global primary energy data from 1990 from the BP Statistical Review of World Energy [107]. We calculated the median of all 28 scenarios in ten-year steps from 2000. Primary energy consumption in 2050 for the

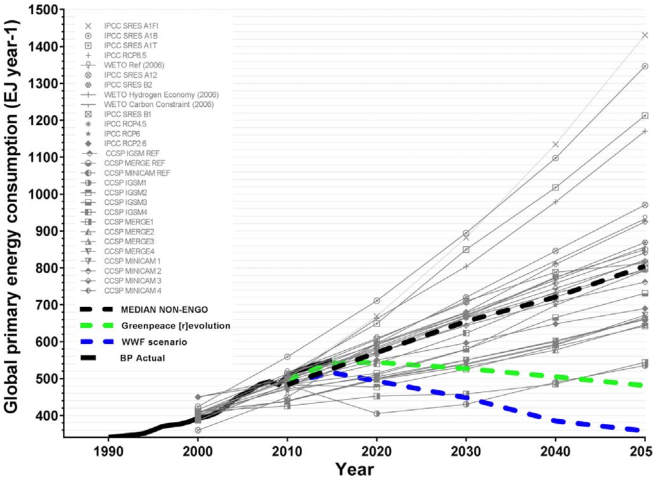

Fig. 1. Comparison of scenarios for global primary energy from the Intergovernmental Panel on Climate Change (IPCC), the Climate Change Science Program (CCSP), the World Energy Technology Organisation (WETO), the BP Statistical Review, Greenpeace and the World Wildlife Fund (WWF). Sources: US Energy Information Administration (EIA) [59]; Intergovernmental Panel on Climate Change [105]; Jeffries et al. [108] Teske et al. [15]; European Commission [106], Van Vuuren et al. [109]. All WETO values are converted from million tonnes oil-equivalent. All EIA values are converted from quadrillion British Thermal Units. Greenpeace values are converted from petajoules. All WWF values were published as final energy only and are converted from final energy to primary energy based on the ratio of primary to final energy provided in the Greenpeace scenario.

scenarios ranges from 535 EJ for the US Climate Change Science Program IGSM Level 1 scenario (1.2% below the actual primary energy consumption figure for 2014) to 1431 EJ (165% above 2014 actual primary energy). The median is 805 EJ (+49% above 2014). Twenty-three of the 28 scenarios projected global primary energy to between 600 and 1000 EJ in the year 2050. These 28 scenarios provide a reasonable spectrum of credible possibilities within which realistic 100%-renewable scenarios should lie (Fig. 1).

The two global scenarios from environmental non-governmental organizations (WWF and Greenpeace) assumed that total (global) primary energy consumption in 2050 would be less than primary energy consumption in their respective baseline years (481 EJ, or only 97% of the 2009 baseline for the Greenpeace scenario; and 358 EJ, or only 74% of the 2010 baseline for the WWF scenario) (Fig. 2). These assumptions are clearly unrealistic. Human population will grow by about 3 billion compared with the baseline years. Even in the baseline years, approximately 2.4 billion people live in energy poverty [110]. To rely on contraction in total primary energy in 2050 compared to today, by as much as 30% in the case of the WWF scenario, is therefore implausible. Several other national and regional scenarios were based on similarly unrealistic assumptions relating to steep reductions in primary energy (Fig. 2). Additional analysis from Lund et al. [111] contends that the magnitude of energy demand must be adjusted to the realistic amount of supply from renewable sources. We contend the opposite is true; supply solutions must be scalable to realistic projections of future demand.

A few scenarios [27,60,112,113] attempted to maintain *final* energy demand at values consistent with the mainstream literature. These scenarios assumed up to 100% transition of whole-of-economy energy to either direct electrification or electrolytic hydrogen production, with reliance on flexibility of demand and/or 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). The speculative storage assumptions used in these scenarios, as for the earlier primary energy assumptions, are inconsistent with the literature on future energy, so these scenarios represent low-probability outcomes. They also prematurely foreclose on the application of several potential technology pathways, such as synthetic fuels [68,114] or second-generation biofuels for transportation energy, and high-temperature nuclear reactors for industrial heat applications (or electricity generation) [115].

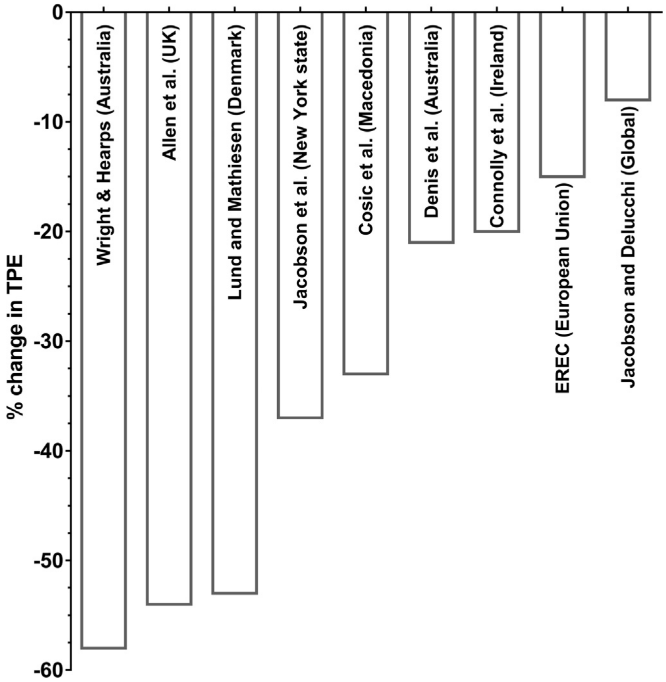

Fig. 2. Summary of percentage changes in Total Primary Energy (TPE) from baseline years across nine scenarios of 100% renewable energy. Baseline years vary among scenarios [11,16,19,24–28,38].

3.2. System simulations

The absence of whole-system simulations from nine of the reviewed studies suggests that many authors and organizations have either not grasped or not tackled explicitly the challenge of ensuring reliable supply from variable sources. For example, WWF assumes that by 2050 the share of energy from variable renewable sources could increase to 60% via all of the following: (i) grid-capacity improvements, (ii) demand-side management, (iii) storage, and (iv) conversion of energy excesses into storable hydrogen [108]. This suite of assumptions for managing a system dominated by supply-driven sources is largely repeated in the Greenpeace scenario (Teske et al. [15]). In neither case is evidence from system simulation provided for how this might occur.

Jacobson et al. [24,113,116] also proposed supply systems without doing simulations, instead referencing other studies to assert that system reliability is possible [8,117,118]. Jacobson et al. [24,113,116] did not apply simulation processes to their own, different proposed systems, nor did they address the uncertainties, challenges and limitations articulated in their supporting references or related critiques [35–38,42,43]. A recent critique highlights these and other errors in the methodologies of Jacobson and co-authors [39].

Of the 16 scenarios that provided simulations, only two simulated to intervals of < 1 hour and only two tested against historically low renewable-energy conditions. Historical testing is useful in general, but such tests do not address the high variability of output from renewable resources, let alone the attendant uncertainties associated with future climatic changes. Because of these issues, the system-simulation approaches applied so far mostly cannot demonstrate the feasibility and reliability of 100% renewable energy systems. Additionally, several of the simulations [8,20,27,116,119] assumed reliance on electricity-generation technologies, such as wave, tidal or enhanced dry rock geothermal, that are yet to be established on any comparable scale anywhere in the world, yet they are assumed to provide dispatchable and baseload roles in the simulations. Our framework applies no penalty against these technology assumptions; however, it further highlights the challenges that must be overcome to ensure reliability.

The only study we reviewed that simulated below half-hourly reliability (i.e., 30 min) [112] offers a system simulation for the continental United States. The results show a *perfect* match between supply and demand based on a renewable-energy scenario that assumed (i) expansion in the use of thermal stored energy (ii) total electrification of the United States' whole-of-economy energy needs, (iii) nation-wide dependence on underground thermal-energy storage for space and water heating based on a system that has not yet been commissioned, and (iv) flexibility in demand ranging from 50% to 95% across different energy sectors, including some industrial applications (see Supplementary Material for further discussion). As such, the scenario is unrealistic, violating the first criterion. Such work calls into question whether energy system simulations are valid when the system under simulation bears little resemblance to that in operation today, or one likely to be achieved in the foreseeable future.

3.3. Large, dispatchable supply

Most of the studies that did system simulations [8,14,16,19,20,27,60,75,104] included high proportions of dispatchable-generation sources for the provision of a reliable electricity system. Those scenarios exploited two intrinsically 'stored' resources in particular: hydro-electricity and biomass. Mason et al. [9,104] simulated 75–78% of generated electricity coming from dispatchable sources of expanded, unconstrained hydro-electricity and geothermal. For New Zealand, with large endowments of hydro and geothermal resources and a small population (4.5 million people), a 100%-renewable electricity system might be possible at reasonable cost, provided the consequences of unconstrained hydro ramping (i.e., the change in power flow from one time unit to the next) are deemed acceptable for the operations of the plant and the hydrology of the waterways [9,104].

The Mason and colleagues' studies reinforce the notion that integration of variable renewable energy sources into existing grids can be cost-effective up to penetrations of around 20%, after which integration costs escalate rapidly [120,121]. An upper threshold to economically rational amounts of wind generation capacity is also found in simulations for the United Kingdom [27]. Any further installed wind-generating capacity makes little difference in meeting electricity demand in times of low wind supply. While the cost-effective threshold for integration of variable renewable electricity will vary among grids, 100%-renewable studies such as these reinforce that penetration thresholds exist and that alternative dispatchable generation supplies are required to meet the balance of supply [9,27,104].

In other scenarios where high penetration of hydro power was not possible, biomass typically filled the need for fully dispatchable supply [8,11,16,19,27,75,122]. Jacobson and Delucchi [24] excluded the use of biomass globally, citing irreconcilable concerns relating to air pollution, land use and water use. However, other studies have found biomass to be essential to ensure system reliability, providing between 2% and 70% of the electricity supplied under 100%-renewable scenarios (Fig. 3).

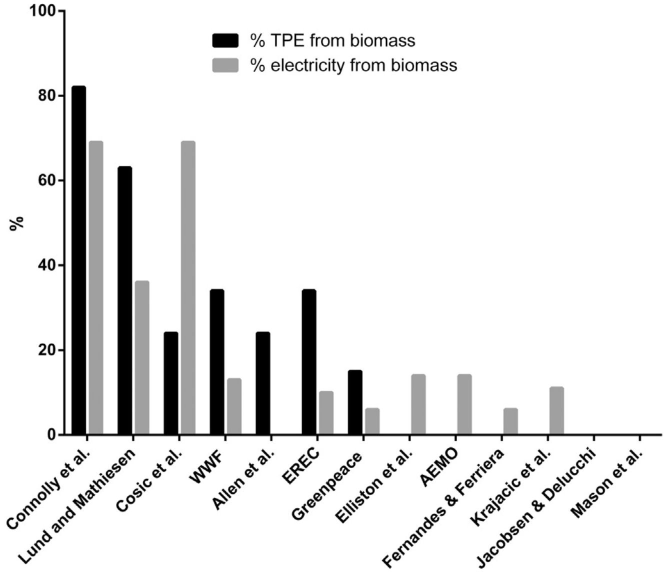

Fig. 3. Percentage contribution of biomass to total primary energy (TPE) (for scenarios covering all energy) and to electricity production other selected scenarios [8,11,15,16,19,20,24,26,27,75,104,108,119].

3.4. Solar shows promise in Australia, but with limitations

Scenarios for Australia drew heavily on solar-thermal technologies with energy storage, and solar photovoltaics. Elliston et al. [75] claimed to meet the high reliability standard of Australia's National Electricity Market of 99.998% on a cost-optimized basis, with 46% of generation from onshore wind and 20% from solar photovoltaic (with no storage). The scenario simulated hourly supply for a single year based on demand for the year 2010. That study did not consider demand variation on < 1-hr time scales and in terms of representativeness, is limited by using a single simulation year (both common problems; see Table 1). There is ample evidence for conditions with sustained, coincident low output from both wind and solar resources in Australia [42]. Such conditions might converge with drought-constrained hydroelectric output in the future. Solar photovoltaic output varies on timescales of minutes, with large changes in output occurring on sub-hourly timescales [123]. Simulation to the one-hour timescale only will therefore not account for these rapid fluctuations. Finally, an assessment based on a single year's current demand and meteorological record underestimates the system-wide reliability requirements in all years in a nation where electricity demand is forecast to grow by 30% to 2050 [124]. The subsequent attempted costing of this system is therefore unrepresentative of the future range of possibilities.

The Australian Energy Market Operator Ltd. [8] generated 2050-based supply-systems with conventional baseload profiles using biomass and geothermal energy as continually available sources of generation. Low-cost, inflexible solar photovoltaics were deployed to reach between 22% and 37% of installed capacity. We generously awarded these scenarios a mark as realistic in demand and a mark for simulation to the hourly timescale. To achieve reliability of supply, Australian Energy Market Operator Ltd. [8] assumed that between 5% and 10% of demand in any hour is "flexible". Unfortunately "flexible" was not defined, how the demand was to be controlled was not discussed, and achieving this flexibility was not costed. In the absence of this assumed "flexible" demand, and based on values shown in the cited report, the simulation would likely have unmet demand on every single day. The system would not, therefore, be feasible according to our minimum criteria.

3.5. Ancillary services largely ignored

The report from Australian Energy Market Operator Ltd. [8] is the only study in the published large-scale scenario literature to acknowledge the importance of maintaining ancillary services through the wholesale system redesign demanded by 100% renewable electricity. The other 22 studies make no reference to these challenges. The review from Australian Energy Market Operator found that the operational issues should be manageable. However, they also cautioned that such a system is at or beyond globally known capabilities and this demands further assessment [8]. Furthermore, none of the studies we reviewed considered any of the challenges that will be faced in redesigning distribution networks to accommodate greater embedded generation, offering no robust way of assessing the associated costs.

Table 1
Summary of scoring against feasibility criteria for twenty-four 100% renewable energy scenarios. 'Coverage' refers to the spatial/geographic area of each scenario. 'Total' means the aggregated score for the scenario across all criteria with a maximum possible score of 7. Criteria are defined in Methods. For concision, the 'Reliability' column aggregates all four potential scores for reliability into a single score. An expanded table is available in the Supplementary Material.

		Criterion				
Study	Coverage	I (Demand)	II (Reliability)	III (Transmission)	IV (Ancillary)	Total
Mason et al. [9,104]	New Zealand	1	2	1	0	4
Australian Energy Market Operator (1) [8]	Australia (NEM–only)	1	1	1	0.5	3.5
Australian Energy Market Operator (2) [8]	Australia (NEM–only)	1	1	1	0.5	3.5
Jacobson et al. [112]	Contiguous USA	0	3	0	0	3
Wright and Hearps [60]	Australia (total)	0	2	1	0	3
Fthenakis et al. [133]	USA	0	2	0	0	2
Allen et al. [27]	Britain	0	2	0	0	2
Connolly et al. [19]	Ireland	1	1	0	0	2
Fernandes and Ferreira [119]	Portugal	1	1	0	0	2
Krajacic et al. [20]	Portugal	1	1	0	0	2
Esteban et al. [17]	Japan	1	1	0	0	2
Budischak et al. [118]	PJM Interconnection	1	1	0	0	2
Elliston et al. [22]	Australia (NEM–only)	0	1	0	0.5	1.5
Lund and Mathiesen [16]	Denmark	0	1	0	0	1
Cosic et al. [11]	Macedonia	0	1	0	0	1
Elliston et al. [75]	Australia (NEM–only)	0	1	0	0	1
Jacobsen et al. [18]	New York State	1	0	0	0	1
Price Waterhouse Coopers [10]	Europe and North Africa	1	0	0	0	1
European Renewable Energy Council [26]	European Union 27	1	0	0	0	1
ClimateWorks [116]	Australia	1	0	0	0	1
World Wildlife Fund [108]	Global	0	0	0	0	0
Jacobsen and Delucchi [24,25]	Global	0	0	0	0	0
Jacobson et al. [113]	California	0	0	0	0	0
Greenpeace (Teske et al.) [15]	Global	0	0	0	0	0

4. Discussion

Our review of the 100%-renewable-scenario literature raises substantial concerns. The widespread assumptions of deep cuts in primary energy consumption defy historical experience, are generally inconsistent with realistic projections, and would likely raise problems for developing countries in meeting goals of poverty alleviation. Loftus et al. [40] found that scenarios with a decline in total primary energy consumption from 2009 to 2050 required annual declines in energy intensity (primary energy consumption GDP^{-1}) of 3.4–3.7% yr^{-1}, which is approximately twice the most rapid rates observed at the global scale over the last four decades. The US Climate Change Science Program scenarios shed further light on energy-intensity requirements. If primary energy were not to increase, the energy intensities would have to decrease by 2.72%, 2.29% and 2.06% yr^{-1}, respectively, with even larger rates of increase if primary energy were to decrease from 2010 to 2050 (as in the WWF and Greenpeace scenarios).

Whether these estimated required rates of decline in energy intensity are possible is a complex question. Our view is that they are not. The large decline in the IGSM Level 1 case is atypical and depends on other assumptions made in that model. But this misses the essential point that economic growth and poverty reduction in developing countries is crucially dependent on energy availability. A reduction in primary energy is an unlikely pathway to achieve these humanitarian goals. To move beyond subsistence economies, developing nations must accumulate the necessary infrastructure materially concentrated around cement and steel. That energy-intensive process likely brings with it a minimum threshold of energy intensity for development [57]. Across a collation of 20 separately modelled scenarios of primary energy for both India and China, Blanford et al. [125] found a range of energy-growth pathways from approximately +50 to +200% from 2005 to 2030. None of those scenarios analyzed for these two countries — with a combined population of almost 2.5 billion people — suggested static or reduced primary energy consumption [125].

Many, or possibly all, of the changes assumed to decrease the energy intensity of economies in the scenarios that assumed falling primary energy demand might have individual elements of realism. However, in applying so many assumptions to deliver changes far beyond historical precedents, the failure in any or several of these assumptions regarding energy efficiency, electrification or flexible load would nullify the proposed supply system. As such, these systems present a fragile pathway, being conceived to power scenarios that do not exist and likely never will. The evidence from these studies for the proposition of 100% renewable electricity must therefore be heavily discounted, modified or discarded.

Our review also found that reliability is usually only simulated to the hour or half-hour in modelled scenarios. A common assumption is that advances in storage technologies will resolve issues of reliability both at sub-hourly timescales and in situations of low availability of renewable resources that can occur seasonally. Yet in the 24 scenarios we examined, 23 either already relied directly on expanded storage technology, or they described an implicit reliance on such technologies without simulation support (see Supplementary Material). Despite these storage assumptions, only five of the 24 studies demonstrated sub-hourly reliability. A high-penetration renewable scenario for California developed by Hart and Jacobson [126] suggested that moving to 100% generation from renewables would require a lower bound storage capacity of 65% of the peak demand to decouple most real-time generation from real-time demand. The authors describe this as a "significant paradigm shift in the electric power sector". Achieving such a paradigm shift is an unresolved challenge, one that Hart and Jacobson claim will require a willingness to transform not only a region's generating fleet, but also the controls, regulations and markets that dictate how that fleet is operated. It behooves policy makers to interrogate such pathways carefully and critically, and to ask the question of whether more mature, dispatchable clean energy technologies should be rejected *a priori* at the cost of uncertainty and upheaval required by 100%-renewable systems.

It is reasonable to assume a greater range of cost-effective options in energy storage will be available in the future. Such solutions will undoubtedly assist in achieving reliability standards in systems with greater penetration of variable renewable generation. However, whether such breakthroughs will enable the (as yet unknown) scale of storage and associated paradigm shift required for 100% renewable remains unknown and is largely unaddressed in the literature (see additional discussion in Supplementary Material). To bet the future on such breakthroughs is arguably risky and it is pertinent for policy makers to recall that dependence on storage is entirely an artefact of deliberately constraining the options for dispatchable low-carbon generation [127,128]. In optimal systems for reliable, decarbonized electricity systems that have included generic, dispatchable zero-carbon generation as well as variable renewable generation, the supply provided by storage is just 2–10% [128].

Not accounting for the full range of variability of renewable energy resources is another area of vulnerability. The year-to-year variability of inflows that ultimately determine hydro-electric output is well-known — the minimum annual US output over 1990–2010 was 23% lower than mean output for the same period [129]. The range of capacity factors for Hydro Portugal varied from 11.8% to 43.2% over 13 years to 2009 [20]. Recent drought has reduced California's hydro-electric output by more than half [130]. Record-low dam levels in Tasmania coincided with the failure of network interconnection and triggered an energy crisis for that state in 2015–2016 [131]. Extreme droughts are also projected to impact hydroelectric output negatively in the Zambezi River Basin [132]. Yet there has been limited or no effort, with the exception of studies by Mason et al. [9,104] and Fthenakis et al. [133], to identify and resolve renewable-energy conditions that are not 'typical', but are ultimately inevitable in a system that is relied on every year. Ensuring stable supply and reliability against all plausible outcomes in renewable energy availability, not only for hydro-electricity, but also for wind, solar and commercial biomass, will raise costs and complexity through the need for additional capacity that will be redundant in most years. Such costs are obscured unless the impacts of worst-case conditions are expressly identified and quantified.

Resource variability is not the only concern regarding hydro-electricity. The widespread potential disruption to rivers and associated habitats from hydro-electric dams are well documented, particularly for the rivers and forests of the Amazon [134–137]. Proposed hydro-electric developments in the Amazon will be major drivers of disruption to connectivity of habitat and deforestation [138]. Proposed developments will also lead to displacement of indigenous populations [139].

Perhaps our most concerning finding relates to the dependence of 100% renewable scenarios on biomass (see Fig. 3). The British scenario [27] is a typical example; even with the assumption of a 54% reduction in primary energy consumption, biomass requires 4.1 million ha of land to be committed to the growing of grasses, short-rotation forestry and coppice crops (17% of UK land area) [27]. Lund and Mathiesen [16] described how Denmark would need to reorganize farming from wheat to corn to produce the requisite biomass, in a scenario of 53% reduction in primary energy consumption from the baseline year. For Ireland, Connolly et al. [19] calculated a biomass requirement that was 60% of the total potential biomass resource in Ireland. Crawford et al. [140] suggested that short-rotation and coppice crops, coupled to an extensive and logistically challenging fuel-distribution infrastructure, would be required to meet energy requirements. Turner et al. [21] proposed trucking and burning Australia's agricultural residue, and then trucking the residual ash back to avoid long-term nutrient depletion. The WWF scenario [108] demanded up to 250 million ha for biomass production for energy, along with another 4.5 billion m^3 of biomass from existing production forests to meet a scenario of an absolute reduction in primary energy from today.

The demand-reduction assumptions in most of the scenarios considered here, when combined with their dependence on hydro-electricity and biomass, suggest that 100% renewable electricity is likely to be achievable only in a low-energy, high-environmental-impact future, where an increasing area of land is recruited into the service of providing energy from diffuse sources. The realization of 100% renewable electricity (and energy more broadly) appears diametrically opposed to other critical sustainability issues such as eradication of poverty, land conservation and reduced ecological footprints, reduction in air pollution, preservation of biodiversity, and social justice for indigenous people [139].

The remaining feasibility gaps lie in the largely ignored, yet essential requirements for expanded transmission and enhanced distribution systems, both to transport electricity from more sources over greater distances, and to maintain stable system operations. Fürsch et al. [81] suggested that a cost-optimized transmission network to meet a target of 80% renewables in Europe by 2050 would demand an additional 228,000 km of transmission grid extensions, a +76% addition compared to the base network. However, this is an underestimate because they applied a "typical day" approach to assess the availability of the renewable-energy resources instead of using full year or multi-year hourly or half-hourly data. Rodríguez et al. [83] concluded that to obtain 98% of the potential benefit of grid integration for renewables would require long-distance interconnector capacities that are 5.7 times larger than current capacities. Becker et al. [141] found that an optimal four-fold increase in today's transmission capacity would need to be installed in the thirty years from 2020 to 2050. An expansion of that scale is no mere detail to be ignored, as it has been in Elliston et al. [75], all work led by Jacobson [18,24,25,32,112,113], the global proposals from major environmental NGOs [15,108] and many more of the studies we reviewed. Transmission lines are acknowledged as slow projects, taking 5–10 years on average to construct, projects that are vulnerable to social objection that may force even more delay [82]. In one case, a transnational interconnection took more than 30 years from planning to completion [142].

Recent work [143] demonstrates the importance of power-flow modeling done at the necessary scales. In that study, where the necessary transmission network was identified and the power flows were modelled, the system in question required 100 GWe of nuclear generation (delivering 16% of supply) and 461 GWe of gas (delivering 21% of supply). In the absence of such baseload and dispatchable contributions, the expanded transmission requirements will evidently present technical, economic and social challenges that are largely unexamined in the 100% renewables literature. Policy makers must be aware of this gap.

Nonetheless, of the four criteria we propose, transmission networks could arguably be regarded as more a matter of *viability* than *feasibility*; the individual requirement of long-distance interconnection is well-known and understood. Rescoring all the studies excluding this criterion (effectively granting all the assumptions of a copperplate network), feasibility is still not met completely by any study (see additional Table in Supplementary Material).

The same grace cannot be granted for maintaining sufficient synchronous generation, voltage requirements and ensuring robust system-restart capabilities in 100% renewable systems with high production from variable and asynchronous sources. The state of research into how variable renewable sources such as wind can contribute actively to providing frequency control services is nascent [144–146]. There is a much research examining the role of batteries in frequency control, indicating growing understanding of the potential applications, prototype large grid-connected projects, and aggregation of distributed-storage systems via novel technology platforms [147–149]. However, we found nothing approaching a clear understanding of the scale of intervention that might be required for maintaining these services in 100% renewable electricity systems in large markets [150]. As well as the direct use of batteries or modified wind turbines, maintaining stability could require interventions that include payments for minimum synchronous generation to remain online, development of new markets in ancillary services, network augmentation, and even the mandated curtailing of supply from wind and photovoltaics in some supply situations [97,101–103]. Others have suggested that changes in market operations will be required to accommodate energy sources that are euphemistically described as "flexible" [151].

A practical portfolio of solutions to these challenge lies beyond current operational knowledge [8,88]. In Germany where penetration of solar photovoltaic systems is the highest in the world, voltage overloading is leading to grid-reinforcement requirements expected to cost €21–27 billion [E-bridge consulting cited in 96]. Potential partial solutions include intelligent operation of distributed energy storage (i.e., batteries) [101,102], grid reinforcement [101], active power curtailment (i.e., preventing export from photovoltaics to the feeder, representing a loss of income to the owner of the photovoltaics) [101], and active and reactive power control from the photovoltaic unit itself, demanding more advanced inverters [96,99,101]. It is axiomatic that these requirements add to the uncertainty surrounding 100% renewable pathways as we depart from well-known and understood electricity systems into novel approaches that rely on reinvented networks with greater complexity. It seems likely that current research and applications will boost the potential role for variable renewable energy sources. However, compelling evidence for the feasibility of 100% renewable electricity systems in relation to this criterion is absent.

5. Limitations of our framework

The scoring system we developed and applied emphasizes the importance of simulating supply to meet demand. In turn, this underscores the issue of achieving reliability with electricity-generation systems that vary over time. With our simple scoring system, some specific item scores might be unjustified when assessed more holistically — specifically if there are major deficiencies in other areas. For example, some studies have done system simulations (earning a score between 1-4 depending on the time-scale of the simulation), but have made unrealistic assumptions in setting up the simulation. We did not penalize these cases. The work of Jacobson et al. [112] is an example of this because it depends strongly on extraordinary assumptions relating to electrification, energy storage and flexibility in demand. Although this work scored 3 for a fine-grained timescale simulation, the results of such a simulation are likely to be meaningless because the underlying assumptions are unrealistic. There is potential for a more useful framework to be developed that reflects these interdependencies.

Under our framework, a study can achieve relatively low scores, which might suggest it lacks breadth of coverage of the feasibility criteria. Yet the study itself can be meritorious for its quality in areas it has specifically chosen to address. We highlight the work of Elliston et al. [75] as one such example, because it provides valuable insights in several areas and explores useful assessment methods. Finally, the criteria of ancillary services will be of varying importance depending on the proposed mix of technologies. For example, approximately 80% of the proposed renewable generation for New Zealand comes from dispatchable, synchronous hydro and geothermal, with $<20\%$ of supply from wind and no embedded solar generation [9,104]. Such a mix provides some certainty at the outset in terms of system reliability and power quality.

6. Conclusions

Our assessment of studies proposing 100% renewable-electricity systems reveals that in all individual cases and across the aggregated evidence, the case for feasibility is inadequate for the formation of responsible policy directed at responding to climate change. Addressing the identified gaps will likely yield improved technologies and market structures that facilitate greater uptake of renewable energy, but they might also show even more strongly that a broader mix of non-fossil energy technologies is necessary. To date, efforts to assess the viability of 100% renewable systems, taking into account aspects such as financial cost, social acceptance, pace of roll-out, land use, and materials consumption, have substantially underestimated the challenge of excising fossil fuels from our energy supplies. This desire to push the 100%-renewable ideal without critical evaluation has ironically delayed the identification and implementation of effective and comprehensive decarbonization pathways. We argue that the early exclusion of other forms of technology from plans to decarbonize the global electricity supply is unsupportable, and arguably reckless.

For the developing world, important progress in human development would be threatened under scenarios applying unrealistic assumptions regarding the scale of energy demand, assumptions that lack historical precedent and fall outside all mainstream forecasts. Other outcomes in sustainability, social justice and social cohesion will also be threatened by pursuing maximal exploitation of high-impact sources like hydro-electricity and biomass, plus expanded transmission networks. The unsubstantiated premise that renewable energy systems alone can solve challenge of climate change risks a repeat of the failure of decades past. The climate change problem is so severe that we cannot afford to eliminate *a priori* any carbon-free technologies.

Our sobering results show that a 100% renewable electricity supply would, at the very least, demand a reinvention of the entire electricity supply-and-demand system to enable renewable supplies to approach the reliability of current systems. This would move humanity away from known, understood and operationally successful systems into uncertain futures with many dependencies for success and unanswered challenges in basic feasibility.

Uniting the alleviation of poverty with a successful climate-change response in our energy and electricity systems should be an international goal. This is likely to require revolutionary changes in the way we grow food, manage land, occupy homes and buildings, demand electricity, and otherwise live our lives. Such changes will require more, not less energy. It would be irresponsible to restrict our options to renewable energy technologies alone. The reality is that 100% renewable electricity systems do not satisfy many of the characteristics of an urgent response to climate change: highest certainty and lowest risk-of-failure pathways, safeguarding human development outcomes, having the potential for high consensus and low resistance, and giving the most benefit at the lowest cost.

A change in approach by both researchers and policy makers is therefore required. It behooves all governments and institutions to seek optimized blends of all available low-carbon technologies, with each technology rationally exploited for its respective strengths to pursue clean, low-carbon electricity-generation systems that are scalable to the demands of 10 billion people or more. Only by doing so can we hope to break the energy paradox of the last twenty years and permit human development to continue apace while rapidly reducing greenhouse gas emissions from electricity generation and other demands for energy. Anything less is an abrogation of our responsibilities to both the present and the future.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.03.114.

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