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

B.P. Heard[a,*], B.W. Brook[b], T.M.L. Wigley[a,c], C.J.A. Bradshaw[d]

[a] University of Adelaide, Adelaide, South Australia 5005, Australia
[b] University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia
[c] National Center for Atmospheric Research, Boulder, CO 80301, USA
[d] Flinders University, GPO Box 2100, South Australia 5001, Australia

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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.

* Corresponding author.

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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