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

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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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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