Energy descent as a post-carbon transition scenario: how 'knowledge humility' reshapes energy futures for post-normal times

Joshua Floyd[1], Samuel Alexander[1], Manfred Lenzen[2], Patrick Moriarty[3], Graham Palmer[4], Sangeetha Chandra-Shekeran[1], Barney Foran[5], and Lorenz Keyßer[6]

[1] Melbourne Sustainable Society Institute, University of Melbourne, Australia
[2] School of Physics, Faculty of Science, University of Sydney, Australia
[3] Department of Design, Monash University, Australia
[4] Mechanical and Aerospace Engineering, Monash University, Australia
[5] Institute of Land, Water, and Society, Charles Sturt University, Australia
[6] Department of Environmental Systems Science, Institute for Environmental Decisions, ETH Zurich, Switzerland

Cite as: Floyd, J., Alexander, S., Lenzen, M., Moriarty, P., Palmer, G., Chandra-Shekeran, S., Foran, B, Keyßer, L. (2020). Energy descent as a post-carbon transition scenario: how 'knowledge humility' reshapes energy futures for post-normal times. *Futures*. doi: https://doi.org/10.1016/j.futures.2020.102565.

Abstract: Many studies have concluded that the current global economy can transition from fossil fuels to be powered entirely by renewable energy. While supporting such transition, we critique analysis purporting to conclusively demonstrate feasibility. Deep uncertainties remain about whether renewables can maintain, let alone grow, the range and scale of energy services presently provided by fossil fuels. The more optimistic renewable energy studies rely upon assumptions that may be theoretically or technically plausible, but which remain highly uncertain when real-world practicalities are accounted for. This places investigation of energy-society futures squarely in the domain of post-normal science, implying the need for greater 'knowledge humility' when framing and interpreting the findings from quantitative modelling exercises conducted to investigate energy futures. Greater appreciation for the limits of what we can know via such techniques reveals 'energy descent' as a plausible post-carbon scenario. Given the fundamental dependence of all economic activity on availability of energy in appropriate forms at sufficient rates, profound changes to dominant modes of production and consumption may be required, a view marginalised when more techno-optimistic futures are assumed. Viewing this situation through the lens of 'post-normal times' opens avenues for response that can better support societies in navigating viable futures.

Keywords: energy descent, energy-society futures, energy transition, post-normal science, quantitative modelling, knowledge humility

1. Introduction

Transcending fossil fuels by initiating a swift decarbonisation of the global economy is one of the defining challenges of the 21st century. The most prominent factor necessitating this shift is climate change (and its related impacts), driven primarily by greenhouse gas (GHG) emissions for which fossil fuel combustion is the leading source (IPCC, 2018). Alongside this driver, the geological inevitability of fossil fuel depletion, with its potential to disrupt economies due to the increasing costs of maintaining anticipated energy supply rates, is relevant on a similar timeframe (Mohr et al., 2015; Wang et al., 2017).

In light of the transition imperative's urgency and the high-stakes implications for sociopolitical stability, the extent to which alternative energy sources can reprise the physical economic roles of incumbent primary sources demands close and thorough investigation (Moriarty & Honnery, 2016, 2019). Will alternatives – specifically renewables and/or nuclear energy – be able to replace, in an economically and energetically affordable (let alone equitable) way, the fossil energy sources of today's complex and globalised industrial civilization? Might a transition to post-carbon energy systems ('a post-carbon transition') imply fundamental discontinuities or step changes beyond present cultural, social and political-economic arrangements, rather than incremental techno-economic adjustments along a relatively smooth trajectory?

Today, more than thirty years after the IPCC was established, fossil energy sources still make up 84% of global commercial primary energy supply, and global emissions continue to rise (BP, 2019), suggesting that transcending fossil fuels may be harder and more problematic than some optimistic studies suggest (see, e.g., Jacobson et al., 2011, 2017a). Assessing the theoretical performance of systems comprising alternative energy technologies in the abstract, via quantitative modelling exercises that consider historically unprecedented developments unfolding decades into the future, cannot hope to address the full spectrum of questions relevant to establishing the practically realizable potential for such systems (Lenzen et al., 2016). Given the rate and scale of economic change required to minimise climate risks (i.e. net-zero emissions by 2050 or sooner), in navigating the terrain ahead we should expect that knowledge systems and practices established to deal with past and even current change processes will at best provide partial guidance, and at worst be misguiding.

In light of this, we believe that there is much insight to be gained by locating the investigation of energy-society futures squarely within the domain of post-normal science (Friedrichs, 2011). That is, we are dealing with situations that accord fully with Funtowicz & Ravetz's (1993) original characterization of 'post-normality' in terms of uncertain facts, disputed values, high stakes, and urgent decisions. At the same time, the arguments we present in this paper are not limited to such framing. Even if energy-society futures are considered from a viewpoint of normal science and policy formulation, the case we make has direct relevance.

This paper assumes that transitioning to 100% renewable energy supply is an urgent and appropriate goal for humankind. However, informed by and consistent with the cautions from the post-normal perspective (Saltelli, 2019; Saltelli & Funtowicz, 2014; Ravetz, 1998; Funtowicz & Ravetz, 1993), we present a critical and somewhat sobering assessment of the potential for quantitative analytical approaches to provide conclusive answers about whether renewable energy conversions can meet in full the demands for work, heat transfer, lighting and data manipulation made by today's globalised and growth-orientated world economy (Alexander & Floyd, 2018). Reflecting an implicit positivist orientation, the findings of model-based energy and sustainability transition studies are frequently presented as if they relate directly to a 'real world' that a model is purported to represent, rather than relating to a 'model world' (McDowall & Geels, 2017; Ramirez et al. 2019). Even where correspondence between findings and 'model world' rather than 'real world' is strictly observed by study authors, such correspondence is often neglected in third party interpretation and reporting. This gives rise to what we see as a dangerously misleading optimism. While the post-normal framing directly challenges the grounds for such optimism, we emphasise once more that the case we set out is relevant even under the presumption of normalcy.

In this paper we show that energy transition modelling exercises are necessarily based on myriad complex and often controversial assumptions that necessitate the interpretation of their findings strictly in relation to the model as an abstract representation of a real world as understood by the modeler. Any conclusions drawn from such studies should be presented and applied with due acknowledgement of the deep uncertainties and limitations inherent therein.

When the range of uncertainties and controversies is given due weight, we argue that a position of 'knowledge humility' is called for when assessing and developing scenarios and policies for a post-carbon transition (Amara, 1975; Sardar, 2010; Fazey et al., 2018; Jasanoff, 2018; McDowall & Geels, 2017; Ramirez et al., 2019; Sovacool & Brown, 2015). A disposition of knowledge humility entails reflexivity with respect to the epistemological foundations and commitments that inform transition-oriented decision making and action. Here the response to the dilemma of uncertainty and ignorance is not to deny it or seek to eliminate it, but to learn to live with it through reflexive governance (Voß, Bauknecht, & Kemp, 2006).

Our review of the evidence and arguments suggests it is highly plausible that the transition to post-carbon energy sources and technologies implies reducing demand for energy services, per-capita and perhaps overall, below the levels of energy services enabled by existing fossil fuel-dominated global energy supply. While this statement is subject to the same circumspection that we argue should apply to contrary findings, we contend that such futures, which are presently marginalized (Laugs & Moll, 2017), should be elevated from a peripheral concern to one that actively shapes the ways in which actors engage in energy transition praxis. The case for this is sufficiently plausible that in the energy-intensive developed regions of the world, a post-carbon transition should include policy making and planning for what can be called 'energy descent' (see Odum and Odum, 2008; Holmgren, 2012); or, to use the terminology previously introduced to *Futures* by Friedrichs (2011), 'peak energy' (i.e. futures characterised by significantly reduced energy supply). This would mean planning for and managing major supply reductions in coming decades, not just 'greening' existing supply (Moriarty & Honnery, 2008, 2012a). This has profound implications for the basic social and political-economic formations that underpin our current modes of production and consumption.

The uncertainty attending energy-society futures, and the knowledge humility it demands, supports the case for adopting an anticipatory stance that is open to energy descent. Energy is a critical factor in economic production, but appreciation for the significance of this is weak within orthodox economics (Keen & Ayres, 2019). Reduced overall availability of energy services implies economic degrowth, or downsizing of economies in terms of physical production (Sakai et al., 2018). This view diverges from mainstream green growth aspirations that involve 'decoupling' GDP from physical production, and physical production from energy and other resource use, enabled by technological efficiency gains and greater emphasis on services (Hatfield-Dodds et al., 2015). Evidence continues to mount that decoupling is incapable of meeting green growth expectations (Hickel & Kallis, 2019; Parrique et al., 2019; Bithas & Kalimeris, 2018). Furthermore, empirical studies cast doubt on the intuitively appealing idea that orienting economies towards services and ICT-mediated activity will reduce their energy intensity (Fix, 2019; Palmer, 2017a; Parrique et al., 2019). On the other hand, the case for reduced economic growth allowing much more rapid decarbonisation is strongly supported (Foran, 2011; Victor, 2012; Le Quéré et al., 2018).

Before beginning our assessment of renewable energy's physical and economic prospects, a brief note on nuclear power is required to delimit the scope of the present analysis. We appreciate that nuclear energy will play an important role in global energy systems for many decades ahead. Whether its share of total final energy supply increases modestly (Froggart, 2015), or perhaps even declines as old plants are decommissioned faster than new plants are brought on-line, nuclear energy's persistence contributes only marginally to the question of energy descent plausibility and does not fundamentally alter our conclusions. We justify this on the pragmatic ground that, regardless of their relative techno-economic and environmental merits, considered globally, renewable energy sources seem to have achieved a large advantage over nuclear energy in terms of social and political support.

Given the extent to which renewable energy dominates visions of post-carbon futures, and the associated weight of research effort that it receives, it seems reasonable to focus attention on this prospectively dominant share of total supply. Nonetheless, the broad arguments that we make about the relationship between quantitative modelling and knowledge pertaining to plausible futures apply also to visions of alternative futures in which the relative contributions of nuclear and renewable sources are reversed. On this basis, the primary focus in this paper is the question of whether existing energy service expectations in the developed industrial economies can be satisfied primarily – and as close as possible to 'entirely' – via renewable sources.

2. Making sense of model-based feasibility assessments: a map is not the territory

Many distinct forms of social organization reliant entirely on renewable energy flows have persisted over prolonged periods throughout human history (Smil, 2017). But renewable energy (hereafter 'RE') feasibility research overwhelmingly has a narrower focus. In essence, it asks whether currently commercial and close-to-market RE conversion technologies (especially wind turbines and solar PV) can support industrial, growth-oriented societies and economies functionally equivalent to those in place today.

In response to this research question two polarised perspectives dominate, holding that current renewable technologies absolutely can or absolutely cannot provide the scope and scale of energy services currently provided by fossil fuels (see e.g. Hansen et al., (2019) for a survey of perspectives; for a sense of the long history of polarisation in relation to energy futures, see Thompson, 1984). There is a broad middle-ground, though, who support the transition to renewable energy to whatever extent is possible, and who at the same time regard the nature of future energy systems – and, often, the forms of economy and society that they enable – as open questions. The following critical inquiry seeks to deepen the understanding of an area that is presently, and will remain for some time at the very least, subject to major uncertainties.

When findings from any conceptual modelling exercise are claimed to prove feasibility (or non-feasibility) of transition to 100% RE, careful critical interpretation is obviously required. Many such studies have been conducted to date (see Elliston et al., 2014; Jacobson et al., 2018; Lenzen et al., 2016; Wiseman et al., 2013) and, when they are published by government organisations or in prestigious scientific journals, accepting the conclusions at face value has social legitimacy. As Loftus et al. (2015) and Heuberger & MacDowell (2018) argue, media outlets may report on the findings of such studies without critical insight and necessary nuance. Indeed, given the complexity of the issues under consideration, it can require considerable expertise to interpret the findings of such studies.

Decision makers relying on such studies may be inclined to assume that the peer-review process provides sufficient assurance of authority (Pfenninger, 2017) and that the latest modelling exercise demonstrates a transition to 100% RE faces no insurmountable technical, economic or practical barriers – and, moreover, that the engineering challenges confronting such an undertaking are all resolvable. Perhaps the most pervasive assumption is that of economic growth (Stern 2013). The large-scale models used for the climate mitigation scenarios summarised by the IPCC simply assume a baseline economic growth forecast. Compounded over the 21st century, the annual growth projections result in a three to eight-fold increase in global per-capita income by 2100 regardless of biophysical constraints (Palmer 2018).

But such models and the findings derived from them cannot be validated against real-world outcomes, because those outcomes relate to situations decades in the future (Ravetz, 1998; DeCarolis et al., 2012; Heuberger & MacDowell, 2018; Nelder & Koomey, 2016). This is not to say that such forward-looking models cannot be valid. High quality energy-economy models are routinely based on 20-50 years of actual past performance data and must replicate historical behaviour accurately to be considered robust (see for instance, Turner et al., 2011; Roberts et al., 2018). It is also possible to have high degrees of confidence in relation to overall mass and energy balances, given the very well established physical and engineering principles on which energy conversion processes are based. If the underlying energy-economy structural relationships that have prevailed in the past are accurately represented in a model, and if these do in fact remain sufficiently unaffected by the transition process that the model seeks to investigate, then model-based findings can provide plausible forward views.

However, establishing whether or not the evolution of real-world behaviour will remain within the performance envelope bounded by the model structure is not a question that can be answered from within the model environment itself. All models are conceived and implemented within superordinate, encompassing and exogenous contexts that are necessarily external to the model itself. These contexts are by definition fixed for the purpose of the modelling exercise – the model cannot respond to or influence them. There is a boundary beyond which the model cannot 'see', because those aspects of the real world are not endogenized. In the real world though, these superordinate contexts are always subject to potential change, possibly under the influence of changes originating from processes that are included in the model itself. Futures-oriented model-making necessarily and unavoidably entails judgements by the modellers about what is and is not relevant, which means that all such models are subject to a degree of irreducible uncertainty (Voros, 2007; Saltelli & Funtowicz, 2014).

Furthermore (and this is more philosophically mundane but of great practical significance), modelling outcomes are a function of the assumptions on which models are constructed, and different assumptions can lead to disparate and conflicting conclusions (see, e.g., Jacobson, et al., 2017a; Clack et al., 2017; Heard et al., 2017; Brown et al., 2018; Diesendorf & Elliston, 2018). As such, any model-derived knowledge is relative to a model's limited context and assumptions, and not the actual situation within which the envisaged change process would need to be realised in practice (Grunwald, 2011). What is assumed to be relevant for a particular model is a function, in part, of the modeller's worldview, and worldviews give rise to perspectives that are unavoidably partial (Checkland & Poulter, 2006; Hodges & Dewar, 1992; McDowall & Geels, 2017; Valentine et al., 2017).

The real world always holds unforeseen complexities and obstacles in store, and it is very difficult to 'out-smart' it when grappling with a situation of the size and complexity entailed by rapid global transformation of humanity's tightly coupled economy-energy systems (Jefferson, 2014; Cherp et al, 2018). In this respect, the management of 'energy systems' and their transitions is better understood not as a technological or even techno-economic challenge, but as a complex of interacting challenges that are essentially socio-technical in character (Büscher, Schippl, & Sumpf, 2019). Each of the myriad social dimensions involved in energy transition processes has potential to feedback upon other dimensions. There is simply no 'technological world' that can be said to stand alone from its social contexts for analytical purposes.

If a single key assumption in a feasibility study turns out to be flawed, the entire conclusion can be called into question (Saltelli & Funtowicz, 2014). The socio-technical character of energy transition amplifies this basic vulnerability, due to the diversity of interactions across the multiple dimensions of the social world that are implicated in the associated change processes. If many or all of the assumptions are dubious, then the uncertainty or implausibility of the conclusions compounds (Keepin, 1984). When serious critics examine high-profile models that claim to prove feasibility for transition to 100% RE over territories ranging from regional to global scale, they typically find that these exercises are informed by many uncertainties and contestable assumptions (Clack et al., 2017; Heard et al., 2017; Capellán-Pérez et al., 2017), even if they do not remain unanswered (Jacobson et al., 2017b; Brown et al., 2018; Diesendorf & Elliston, 2018). It follows that 'real-world' inferences extrapolated from such research should be viewed as speculative at best and dangerously misleading at worst.

Modelling exercises of this nature certainly play an important role in the scoping process for any large-scale engineering initiative. But transition of energy systems globally away from fossil fuels represents an engineering undertaking of utterly unprecedented scale (Smil, 2010). Conceptual modelling is only the first step in figuring out what might be possible in practice, and what efforts might be involved in realising such a vision. Its utility lies in its ability to interact with, and inform, practical implementation steps, including the design, construction, operational management and maintenance activities of engineers, experience that can then provide feedback to improve subsequent modelling efforts, in a process of continuous action learning. The actual engineering practice of building plant and infrastructure, and then operating it over extended periods, is, however, absolutely essential to this learning. It is in the strictest sense 'learning by doing'. Knowing and doing are inseparable here: certainty can only be claimed with respect to what has been done and shown to be effective in practice. Even then, the application of knowledge developed in one context to another demands that a great deal of care be taken in understanding the equivalence of those contexts.

In light of the socio-technical character of energy transition, the need for an action learning orientation extends beyond the engineering domain into transition governance more broadly. The uncertainties faced call for governance that is reflexive with respect to the knowledge foundations informing decisions and actions. We should expect the knowledge that informs governance to be informed in turn by the decisions and actions taken, in a process of continuous and open-ended learning (Grunwald, 2004).

The preliminary message here is that the status of claims based on conceptual modelling exercises alone – that is, where these relate to initiatives that have never before been attempted and for which there is no equivalent precedent – are best treated with a healthy dose of critical scepticism. This reveals as problematic any truth claims made by studies purporting to demonstrate the feasibility of a 100% RE transition. The interests of sound public policy and decision making require that this message be taken seriously. Notably in the financial sector, where uncertainty with respect to future developments entails significant and immediate monetary costs, this is not a controversial matter (Anthony & Coram, 2019). In important respects, success in the realm of finance reflects skill in assessing the robustness of knowledge about possible futures. Taking a leaf out of the financiers' book may serve other investigators of energy-society futures well.

3. Fully replacing fossil fuels with renewable energy: challenges to definitive feasibility analysis

The analysis below presents a range of feasibility issues that we maintain cannot be answered by analytical and quantitative modelling methods with the confidence they are often assumed to provide (DeCarolis et al., 2012; Loftus et al., 2015). When these feasibility issues are considered in aggregate, uncertainty is compounded about the viability of RE sources and conversion technologies to fully or directly replace the magnitude and nature of energy services provided by fossil fuels. Viewed as a whole, the post-normal character of energy-society futures within the context of transition away from fossil fuels is, we contend, readily apparent.

The case we make recognizes that in a world powered entirely by RE, the primary energy required to provide final energy services of the magnitude used in the non-energy economic sectors today will almost certainly reduce significantly.[1] Most final energy services today are provided via thermal conversions which necessarily make only a portion of the primary energy in fuels available as work, dispersing the balance as waste heat. It is therefore likely that current global primary energy use significantly overstates the scale of the supply task for scenarios where electricity from non-thermal energy conversions (including wind, PV and hydro) is the principal energy carrier.

Current global final energy use is a better guide to future primary energy requirements. In a future fully-electrified world, the portion of this comprising transport fuels could also be expected to reduce significantly, due to the current reliance on thermal conversions for transport work. On the other hand, if transport remains significantly reliant on alternative liquid and gaseous fuels, and hence on thermal energy conversions, the difference may be smaller. A further unknown relates to the potential cost reductions for energy services resulting from the higher efficiency of electrical energy conversions, with consequential possibility of rebound effects driving primary energy consumption up again, e.g. electric vehicles being used more frequently than their internal combustion engine counterparts (Parrique et al., 2019, Hickel & Kallis, 2019). This illustrates the deep uncertainties that energy transition presents.

A basic limitation encountered in applying prospective analytical techniques (Voros, 2006) to an issue such as global shift in the means by which energy is distributed is that implementing the proposed changes would fundamentally alter important contextual assumptions that the analysis itself relies upon (Voros, 2007; Scher & Koomey, 2011; Hodges & Dewar, 1992). A particularly important aspect of systemic feedback challenge relates to the question of how the global energy sector's own demand for energy services might change in the transition to a fully electrified or 100% RE-powered world (Palmer & Floyd, 2017; Palmer, 2017b; King & van den Bergh, 2018). As we discuss below, there is reason to expect that the scale of the energy services required for energy supply will increase significantly (Bardi & Sgouridis, 2017).

We acknowledge that the issues discussed below are complex and that space does not permit comprehensive treatment. Nevertheless, by reviewing a broad range of diverse challenges and limitations of RE it is hoped more energy transition advocates come to recognize that replacing fossil fuels with RE may be harder than some optimistic modelling studies suggest, from which we hope increased knowledge humility flows.

3.1. 'Theoretical potential' is not 'practically realisable potential'

---

[1] In stating this, we adopt the International Energy Agency's convention, based on the UN's 'International Recommendations for Energy Statistics', of defining 'primary energy' at the point where 'the energy source becomes a "marketable product"'; see Millard & Quadrelli, 2017; see also Palmer & Floyd, 2017 for discussion of the distinction between the 'energy harvested' and 'energy harvestable' concepts for defining primary energy, both of which are employed in life-cycle assessment.

The scale of solar energy's theoretical potential is vast (Moriarty & Honnery, 2012b). However, this metric diverts attention from a more important question: what is the *practically realisable potential* of solar energy, after accounting for the full range of factors affecting its conversion to energy forms useful to human societies (de Castro et al., 2013)?

In considering the potential for RE, there is a series of unavoidable 'discounts' applied to the earth energy flows that act as the primary sources from which human use is derived (Moriarty & Honnery, 2016). The naturally occurring energy flows that are accessible must then be converted via techniques for which the useful outputs entail inherent reductions relative to the inputs. This technical potential is governed by fundamental physical relations that are not subject to human influence, and is also mediated by practical technology-specific constraints.

The wider array of renewable energy sources without doubt holds promising potential (Jacobson et al., 2017a). But the proportion of RE's theoretical potential that can be realised in practice, once the broad spectrum of geographical, technical, engineering, environmental, economic and socio-political factors is taken into account, is far less certain – though certainly orders of magnitude less than theoretical potential in absolute scale (Moriarty & Honnery, 2016). The practically realisable potential for RE is ultimately dependent on engineered systems. But engineers design systems within limits that pay little heed to abstract ideas about theoretical maxima. Engineers work with, but ultimately within, the performance characteristics, properties and availability of materials; the bounds of manufacturing techniques; the bounds of established transport, handling, and logistics infrastructures and institutions; the bounds of operability, maintainability and control; and so on.

Beyond this, the practical challenges of engineering systems for capturing, converting and distributing energy must be tackled within complex and encompassing socio-political contexts. This raises a raft of further questions. Will politicians be prepared to drive a renewables transition? Will vested interests (continue to) get in the way? Will cultural values adapt to accommodate higher energy prices and the behavior changes those prices prompt or require? Will rural communities object to wind farms on aesthetic grounds? Will environmental groups object to large-scale RE projects that threaten biodiversity? There are myriad socio-political, economic and engineering reasons why the practically realisable potential of renewables will remain a fraction only of even conservative estimates for the technical potential (Heuberger & MacDowell, 2018).

The foundational point, then, is that policy-making and planning processes should not treat the best-case scenarios for technical potential, let alone the much larger theoretical potential, as models for plausible futures – since these almost certainly will not be realised (see, e.g. de Castro & Capellán-Perez, 2018; Jefferson, 2014; Gans et al., 2012; Miller et al., 2011).

3.2. Variability, base-load, dispatchability and cost

When considering the prospects for transition to renewably powered economies, the variable electricity supply provided by PV and wind (variable renewable energy, or VRE) looms large as the principal challenge that must be confronted (Rai et al., 2019). This contributes to what is sometimes referred to as the 'base-load problem'.

We recognize here that increasing VRE penetration implies a shift away from the past base-load dominated operating regime, and that old assumptions about this will not hold in the future. Nonetheless, there are significant techno-economic and related path dependencies to which the transition process is subject by virtue of the historical fact of base-load and the ways in which it has helped shape the present situation. Current demand patterns have typically developed to suit the supply-side characteristics of thermal generation systems biased towards continuous, steady-state operation. Such base-load oriented demand patterns are subject to significant structural 'lock-in', due to the myriad social and economic habits and expectations that the availability of base-load power has given rise to (Yakubovich et al, 2005). As such, there is a basic structural requirement, in the short term at the very least, that replacements for conventional steam-turbine thermal power generation provide, in the aggregate, equivalent dispatchability characteristics. Grids highly reliant on generation sources that, by their very nature, cannot be considered as having the dispatchability characteristics of fossil fuel-powered generators therefore face what can be characterised in common parlance as the 'base-load problem'.

The dispatchability problems that arise for grid systems dependent on variable primary energy sources are more general, though, than the requirement to meet base-load demand. For instance, winter peaking grids, where demand is highest during winter evenings when the sun is not shining, present a particular challenge (Palzer & Henning, 2014; van der Wiel et al., 2019; Trainer, 2013). A proposed response to this issue is to distribute renewable electricity generation capacity sufficiently widely and then transmit that electricity to where it is needed. For example, Europe could import electricity from the Sahara, as the Desertec project envisioned (Samus et al., 2013). The strategy of geographically diversifying across regions or national borders is important for utilising variable renewables. At the same time, greater dependence on long distance, undersea and trans-national electricity flows opens the way to novel security risks and governance challenges, increasing the divergence between envisaged future energy systems and historical experience (Ralph & Hancock 2019). Further, this strategy requires replicating generation and transmission capacity across multiple regions. For instance, Lenzen et al. (2016) found that meeting 2016 electricity demand in Australia from RE sources would require increasing supply infrastructure by a factor of approximately 5, with levelised cost of electricity around 0.15-0.20 AU$/kWh. Exploiting opportunities to shift demand load out of peak periods can reduce the cost, but for those options studied to date the reductions implied are only 0.055 AU$/kWh (Ali, Lenzen & Huang, 2018) and 0.028 AU$/kWh (Ali, Lenzen & Tyedmer, 2019) respectively. During periods of favourable weather conditions, supply will exceed immediate demand, and so grid operation and market dynamics can be expected to depart significantly from historical behaviour. Grid operators and market participants can also be expected to adapt to these new conditions, for instance via novel load shifting regimes and related demand management techniques. Exactly how these might unfold though, and what their second-order economic, political and social consequences might be, are open questions that will ultimately only be resolved through building and operating actual systems.

The challenge presented by RE variability can also be addressed via integration of storage technologies into electricity supply systems (Blakers et al., 2018). We note in this respect that the very promising cost declines for wind and PV electricity reflect the cost of supplying that electricity at the margins of existing grid systems. Here, the ability of grid systems to meet demand is underwritten by dispatchable capacity mainly reliant on fossil fuels. If the intermediate storage required to make intermittent RE sources similarly dispatchable is included (i.e. pumped hydro storage (PHS), batteries, hydrogen and similar) then the economics may change dramatically. The economics of grid-connected PV (or wind) when integrated with fossil fuel dispatchable capacity may be very different from PV (or wind) with sufficient storage to meet demand whenever it occurs (Jenkins & Thernstrom 2017).

Future energy systems will involve the coordination of a wide diversity and increased number of VRE sources on shorter time intervals than the past (Rai et al., 2019). Intermediate energy storage is one part only of this picture, and subject to local conditions will be complemented by stock-based supply in the form of dispatchable thermal generation powered by bio-fuels. The challenge, however, is largely defined by the required buffering or storage scale. Even if significant weather anomalies occur only infrequently, it is these statistical outliers that determine the performance criteria for which supply systems must be designed. Perspectives on the quantity of storage required currently rely on quantitative modelling that cannot yet be calibrated against large-scale field performance. Findings are dependent on starting assumptions, and these can diverge very significantly (Palmer 2017b; Palmer & Floyd, 2020). One study for RE electricity supply in Australia reported a PHS requirement of 450 GWh or 19 hours average demand (Blakers et al., 2017; see also Trainer, 2019a). At the other extreme, a study for Germany covering electricity and heating found that 45 days full load storage via synthetic gas would be required (Palzer & Henning, 2014). A study for 100% RE electricity in Texas found a requirement of approximately 14 days storage capacity (Preston, 2015).

Distributed storage will take on an important role for supporting network stability, but this relates primarily to short term buffering rather than multi-day or multi-week storage. The practical benefits for grid management currently being realised as a consequence of battery technology and manufacturing developments relate to a class of problems quite distinct from the far larger challenge of long-term energy storage at a systemic scale. Furthermore, large scale consumer-side battery storage will have safety, maintenance and disposal implications that are yet to play out. The rapid reduction in price for lithium ion batteries is clearly improving the economics of electricity buffering, in both grid-connected and off-grid situations. But the current deployment rate is remarkable relative to the small existing installed base, rather than in relation to the macro-level physical economics of a global transition in all energy supply. The global market for lithium-ion batteries in 2018, for all uses, was 210 GWh, with roughly 1,000 GWh of installed capacity (Austrade 2018). For comparison, the current capacity of the European gas network is 1,131,000 GWh (GIE, 2018).

Concentrated solar power (CSP) offers a further option that can help address the challenges associated with variable irradiance, when coupled with molten salt thermal storage and/or via hybridization by coupling with auxiliary boilers fired with conventional fuels or biomass (Lenzen et al. 2016). The economics of CSP also continue to improve (Mir-Artigues et al., 2019). Recent analysis of field data indicates, however, that actual performance of CSP plants is significantly below design and theoretical expectations (de Castro & Capellán-Pérez, 2018; Yousefzadeh & Lenzen, 2019). This illustrates how the anticipatory problem faced in closing the gap between theoretical and practically realizable RE potential is not ameliorated even by focusing on commercially available technology options.

A further challenge in this respect, especially when considering feasibility questions at global scale, is that local context has a major bearing on the prospects for different renewable sources and conversion technologies in different regions (Heuberger & MacDowell, 2018). For example, most of Norway's electricity comes from hydroelectricity, a vastly different situation to the world considered as a whole. Iceland's hydro and geothermal resources make its situation similarly unique. The prospects for PV electricity are far more favourable in Australia than in the UK, Canada or Japan, which is a function not only of local irradiance, but of implications of local irradiance for the relationship between supply and demand power densities (Smil, 2015). From a global and systemic perspective, this supports the plausibility that powering societies with 100% RE will be costlier and more difficult than typically assumed, and in turn provides grounds for preparing and planning for reduced energy supply (by managing demand) rather than merely trying to ‘green’ existing, or even growing, supply.

There are important nuances here. The economic arrangements that currently prevail globally entail what could be viewed as enormous waste. For instance, Australians spend AU$24 billion annually (AU$1300 per capita) on gambling. Diverting expenditure from gambling and other activities detrimental to health towards zero-carbon energy supply represents a compellingly straightforward net societal benefit. It seems likely that the financial cost of RE transition, viewed from a more technocratic perspective in isolation, will be affordable. The question that we pose here though is what the systemic socio-economic consequences might be of the fundamental restructuring this implies, given the actual political contexts within which such change would need to occur. For instance, historical evidence suggests a significant correlation between expenditure on energy as a proportion of GDP and economic recession (Hall & Klitgaard, 2011). This appears to be a function of marginal changes in cost share, rather than a question of affordability in the conventional sense of expenditure exceeding income.

Regardless of this though, reducing overall demand must make the cost of transition lower, and therefore the scale of the financing task must become comparatively smaller. Here again, energy descent provides avenues to mitigate obstacles. That said, we would anticipate major shifts in the means by which financing is achieved under energy descent conditions, especially if this entails more general economic degrowth not just ‘no growth’ stabilization (see e.g., Jackson & Victor, 2015). So, this financing question (which cannot be addressed herein) should not necessarily be viewed through the lens of the finance mechanisms currently employed for RE deployment.

3.3. Electricity is only a minor share of global final energy

The storage challenge gets comparatively easier as electricity demand reduces, and becomes more flexible through load shifting. On the other hand, it is significantly compounded when the task expands from decarbonizing electricity via RE, to decarbonizing all global energy use.

Transport presents a particular conundrum. The key RE technologies of solar, wind and hydro produce electricity but electricity comprises between 18% and 40% of global energy use, depending on the stage of the transformation process and energy accounting methodology. As a share of ‘World total final consumption by fuel’ reported by IEA (2018, p.16), electricity comprised 18.8% in 2016, having risen from 9.4% in 1973. Measured in terms of primary energy use, electricity production accounts for roughly 40% (Palmer & Floyd, 2017).

There is currently a clear trend towards greater electrification of final energy use. As noted earlier though, the extent to which electrification can reduce primary energy demand for transport is highly uncertain. Heavy haulage presents a formidable challenge (Friedemann, 2016). For many transport tasks in this and the aviation spheres, electrification will require energy intensive electricity-to-synfuel processes.

There are many industrial processes that rely on fossilized carbon and hydrocarbons either as fuels, chemical reactants or both, and for which electrification is not a practical option. Examples include ammonia production (for fertilizers), and iron ore reduction. The task of satisfying electricity demand from predominantly intermittent renewable sources is difficult and expensive even when this is a minor share of the global final energy supply task (Trainer, 2018). The magnitude of the challenge amplifies if all or almost all energy demand is to be met with electricity from a similar mix of sources.

Solving this liquid fuel problem appears to be the greatest challenge to creating post-carbon societies in the present mould (Sims et al. 2014, section 8.3). The realisation of a long-touted 'hydrogen economy', whether in parallel with the current petroleum system or replacing it, certainly seems to have significant potential for mitigating the scale of this liquid fuel problem, nonetheless the challenges to this remain formidable (Palmer & Floyd, 2020; Staffell et al., 2019).

3.4. Biofuels?

If the transition to a post-carbon civilisation hinges primarily on addressing the liquid fuels challenge, and if electrification alone is unable to decarbonize a growing and diversifying fleet of transport vehicles, then could biofuels offer a solution (Robertson et al., 2017)? Considered globally, the primary obstacle to scaling up biofuels is the land and resources (or, in the case of algal biofuels, impacts on marine environment) needed to do so (Mediavilla et al., 2013). Global population is approaching eight billion people, many of whom today live in conditions of material deprivation (Hickel, 2017), trending to exceed eleven billion by the end of the century. Food security is already a serious problem today and will only become more challenging with population growth and climate destabilisation (Bowles, Alexander, and Hadjikakou, 2019). Available arable land is finite. The more land and resources dedicated to biofuels, the less there is for food production, or for biomass for materials such as lumber and pulp (Moriarty & Honnery, 2018). There is also the risk that expanding biofuel production will drive yet more deforestation (IPBES, 2019; IPCC, 2018).

A further limitation of biofuels is their typically low energy return on (energy) investment (EROI) – generally less than 5:1 and, for corn ethanol in the United States, close to 1:1 (Murphy et al., 2011). In comparison, Murphy (2014) found the EROI for petroleum at point of acquisition to be in the range 10-20:1. More recently, Brockway et al. (2019) have found aggregate EROI for all final energy carriers from fossil fuels, at the point of entry to the economy, to be 6:1.[2] While this closes the gap between conventional energy carriers and biofuels, biofuels are clearly in the zone of minimum energetic viability (Murphy et al., 2011). Moriarty & Honnery (2019) have considered the case of biodiesel replacing oil-based diesel in the production and transport of bioenergy. If, say, the EROIs for conventional diesel and biodiesel are 10.0 and 2.0 respectively, it is clear that the *overall* EROI for bioenergy will fall as biodiesel replaces fossil fuel diesel.

With 2018 global biofuel production only 2% of annual world oil production (BP, 2019), the prospects for significant scale-up seem remote. Biofuels are sure to play important niche roles in post-carbon societies, but the overall scale of the contribution, at least on a global scale, is likely to be very limited relative to liquid fuel use today. On the other hand, biofuels can clearly have great technical and economic potential in particular contexts. Foran has studied the potential for

---

2 We also note in relation to Brockway et al.'s finding that Raugei (2019) cautions against practices of the type that must be employed in arriving at an aggregate global EROI figure for all energy carriers. Aggregating energy carriers implicitly treats them as interchangeable, or capable of substituting for one another. In some instances this may be possible, but only with requisite changes to supply chains and end-use energy conversion devices. In other instances though, substitution may not be practically possible, even via changes to physical plant and equipment.

bio-methanol use in Australia very extensively, finding much higher EROI values of around 8:1 for the entire fuel cycle (Foran, 2009, 2011).

Again, the questions that we raise with this paper relate to the contexts that lie beyond techno-economic analysis, for instance the political implications of major shifts in land use, and the potential for resource use (including land and water) problem shifting (Alexander, Rutherford, & Floyd, 2018; Van den Bergh et al., 2015). Similar issues can be raised concerning bioenergy with carbon capture and storage (BECCS), which features centrally as a negative emission technology in IPCC climate mitigation scenarios (IPCC, 2018; Palmer, 2018; Minx et al., 2018).

3.5. Renewable technologies rely on fossil fuels

Currently the availability of RE interception and conversion technologies – their manufacture, deployment, operation, maintenance and end-of-life management – is inextricably dependent on the fossil fuels that it's hoped they will replace. This has led some investigators to characterise wind and solar electricity as fossil fuel 'extenders' rather than replacements (Tverberg, 2011).

By adding energy (with zero operational fuel input) at the margins of an electricity grid system, RE generators reduce the average fuel input per unit of electricity delivered by the grid system as a whole. But the renewable generators remain reliant on the existing grid to give value to the electrical energy that they contribute (Palmer, 2014). Beyond this system operability issue, the situation ramifies on taking into account the myriad ways that fossil fuels enable the supply chains through which wind turbines and PV equipment come to be deployed in the first place.

For the foreseeable future the deployment of RE infrastructure will remain locked via innumerable path dependencies to fossil-fuelled industrial production and distribution systems. It is theoretically conceivable that in the future all the processes involved in RE supply system production – including mining, manufacture and transport – can be powered by renewably generated electricity. But this is subject to a wide range of engineering, economic and institutional challenges. It will not be possible to anticipate many of the consequences of confronting these.

This is no argument against as rapid a deployment of RE technology as humanity can mobilise. Instead, it is a further argument for anticipating societies that require as little energy as possible to flourish, rather than assuming that energy-intensive societies can simply transition to RE technologies without difficulty or disruption.

3.6. Energy return on investment

The implications of energy return on investment (EROI) for RE transition feasibility is a vexed and often highly contentious area of inquiry (Moriarty & Honnery, 2012b, 2016, 2019). The EROI for an energy supply technology is highly context specific, and it is not possible to arrive at definitive assessments of EROI for any one RE source that apply to all situations (Palmer & Floyd, 2017). Nonetheless, some general observations can be made about EROI of wind and PV electricity relative to incumbent energy sources, and how this relates to questions about the forms that future societies may take.

Firstly, it is axiomatic that adding energy storage, increased transmission and distribution, and redundant supply capacity to existing systems entails significant energy costs and hence reduces EROI at the overall system level (Palmer & Floyd, 2017). Additionally, at higher grid penetrations the EROI of RE decreases, since the most productive spaces get used first (Dupont et al., 2018; Moriarty & Honnery, 2012b). This can be mitigated only to the extent that technology change and efficiency improvements offset these increasing system-level energy costs. Secondly, to the extent that RE systems remain dependent on a globally integrated industrial economy dependent on fossil fuels (see subsection 3.5 above), then declining EROI of fossil fuels will feed through into declining EROI of these systems.

Following from this, a question arises as to what declining EROI implies for the viability of consumption- and growth-oriented industrial economies (Hall et al., 2014; Lambert et al., 2014). As EROI declines, the proportion of total available energy services that must be directed towards the overall economy's energy supply sub-system increases. If overall supply of energy services cannot expand fast enough to compensate, then this implies reducing energy service availability for all other economic activity enabled by the energy sub-system. In such a situation, the strong dependence of economic activity on sufficient energy services implies a contraction in the rest of the physical economy (Ayres & Voudouris, 2014).

A situation such as this would be exacerbated in the transition phase to RE, as the energy investment in transitioning supply systems to renewable sources represents an additional drain on available energy services. The required energy investment rate is particularly sensitive to the rate of transition (Honnery & Moriarty, 2011; Kessides & Wade, 2011; Neumeyer & Goldston, 2016; Carbajales-Dale et al., 2014; Capellán-Pérez et al., 2019; Carbajales-Dale, 2019). Wind and PV electricity supply systems require nearly all of their energy investment up front, before they deliver useful outputs, increasing the sensitivity to transition rate. The higher the transition rate, the greater the diversion of energy services from the rest of the economy to the energy sector.

Attention at this point often turns to the question of the minimum EROI required to support societies functionally equivalent to today's (Hall et al., 2009; Brandt, 2017; Capellán-Pérez et al., 2019; Raugei, 2019). Brandt (2017), for instance, finds that below 5:1, energy available for discretionary purposes declines rapidly. Views vary on precisely where this threshold might lie for any given society. What can be stated clearly, however, is that in order to remain viable in energetic terms, any social form ultimately requires that forms of energy services appropriate to support its basic 'economic metabolism' be available when and where required *at sufficient rates*. In principle, so long as the energy sector delivers more energy over its lifecycle than it uses for that task (i.e. EROI > 1), then viability is dependent on having sufficient power availability at any given instant in time. But EROI is specifically defined over the full lifecycle of an asset. Even if a supply system comprises assets with EROI much greater than 1 over their operating lives, the power return ratio (the rate of energy return over the rate at which energy is used to provide the return) (King et al., 2015) for the system as a whole at a given instant in time can be far lower, even less than one.

Ultimately, the viability of a society from an energy perspective depends on its ability to meet the ongoing costs (financial, environmental, material and energetic) of providing sufficient power at any given point in time. Energy-focused lifecycle assessment is clearly essential for understanding the long-term prospects of any social form, and hence for assessing the feasibility of transitions to 100% RE. But at the whole-of-society level for which such assessment must be conducted, it is power return ratios that are most directly relevant (King et al., 2015).

Transition from fossil fuelled societies to societies powered by 100% RE, at least on the multi-decadal timeframes that are typically discussed by proponents, will most likely constrain the energy available to non-energy supply economic sectors (Capellán-Pérez et al., 2019). To enable such transition, economies and the societies that they support will need to adapt accordingly.

3.7. Power density

The spatial intensity of energy use is often overlooked in assessing the prospects for renewably powered societies, but is critically important. This spatial intensity is most readily measured via power density, typically the rate of energy use or supply per unit of horizontal land area occupied by the systems involved (Smil, 2015).

While the power densities achieved by incumbent supply systems typically exceed the power densities at which energy is used in urban industrial societies, for RE this relationship between power density of supply and use is reversed. In fact with power densities ranging from roughly 1 W/m^2 (electricity out) for wind to a few tens of watts per square metre for PV (averaged over a year), RE supply power density is orders of magnitude lower than peak usage rates for industrial plants and high-rise buildings (often greater than 1000 W/m^2), and lower even than average rates over city centres (in the order of 500 W/m^2) (Smil, 2015). Even energy use power densities averaged over entire city areas (including low-density suburbs) can be several times higher than maximum power densities for best-case PV supply. More recent estimates for supply-side power densities of onshore wind and PV derived from large numbers of geographically diverse actual installations are considerably lower even than Smil's estimates above: 0.5 W/m^2 and 5.4 W/m^2 respectively (Miller & Keith, 2018).

Consequently, a transition to energy systems dominated by renewable sources will see a shift from energy supply occupying much smaller areas than those over which it is used, to one in which human settlements depend on hinterlands many times their size to capture and concentrate the energy that they rely on (Smil, 2015). Without vast reductions in power density of energy use, there is essentially no prospect that urban densification and local energy self-sufficiency will coexist. Such self-sufficiency will be possible only where demand expectations are reduced, and density of habitation is sufficiently low. Where local climate conditions are favourable, suburban population densities probably represent the upper limit for household or neighbourhood energy self-sufficiency.

This presents a major challenge in light of the ongoing urban densification trajectory (Burger et al, 2019). A shift to energy supply dominated by RE will also mean high reliance on utility-scale systems, and an increased rather than decreased reliance on grid interconnectivity, though with major changes in grid architecture. While this is clearly the direction that electricity grids are heading in any case (Rai et al., 2019), widespread shift towards greater local energy self-sufficiency would also require reversal in densification of settlements. This infers major implications for settlement forms and governing institutions. Fundamental indeterminacy in relation to the specifics of these forms and institutions, and the second-order consequences of such changes, is therefore implied. Again, however, the disruptions entailed would be significantly ameliorated by energy demand reductions realised through coordinated social change processes (Trainer, 2019b).

3.8. Energy system transitions are slow and complicated

The experience of accelerating technological change, particularly in relation to computing and information technology, but also in the renewable energy area itself, drives a widespread perception that a transition to 100% RE can occur on a timeframe of a few decades (Jacobson et al., 2017a). Some proponents even tout the plausibility of achieving this in a single decade (e.g. Gore, 2008). Such hopes are strongly at odds with the record of historical energy transitions (Grubler et al., 2016, Smil, 2010; Smil, 2014; Smil, 2016).

The concept of 'energy transition' can be defined in different ways, and can refer to energy supply, end-use converters, and prime movers (Sovacool 2016). There are many context-specific examples of rapid development in the historical record, including nuclear electricity in France, flex-fuel vehicles in Brazil, and combined heat and power in Denmark. However, if a transition is measured from the time an energy system or technology occupies a 1% global share, up until reaching a significant share, such as 25%, the timeframe is of the order of many decades up to longer than a century.

Furthermore, none have involved the scope and scale of change involved in shifting *en masse* to renewable energy. This is because past transitions, even with the large-scale expansion of coal use, have tended to involve expansion of total supply by adding new energy sources to the existing base, rather than substituting incumbent sources with alternatives. For RE to replace rather than just extend fossil fuels, fossil-fuelled supply capacity will need to be retired as RE capacity is rolled out. This is a far more institutionally, infrastructurally and logistically complex challenge than expanding existing capacity by adding RE at the margins of the fossil-fuelled system.

As we have noted, rapid transition can have significant implications for energy service availability for the rest of the economy. Retiring existing assets in parallel exacerbates this.

3.9. Two meta-factors

In addition to the eight points just discussed, we highlight two 'meta-factors' that constrain the potential for humanity to do via RE what it currently does via its incumbent energy systems. Firstly, RE technology is dependent on a wide range of mineral resources for which a major transition effort will have significant implications for overall demand (Jefferies, 2015). This can be expected to drive environmental and resource use 'problem shifting', whereby addressing one set of challenges leads to new problems in other areas (van den Bergh et al., 2015, Parrique et al. 2019). The increased engineering and economic effort to meet new demand implies major costs, measurable in financial, environmental and resource terms.

The second 'meta-factor' enters the picture here. If such a transition is long, difficult and expensive, then systems of human organisation and their environments will evolve together accordingly in a manner that conserves their mutual adaptation. Whatever forms this takes will very likely entail reduced availability of, and hence demand for, energy services and so energy will be intercepted from the environment and converted to forms useful to human systems at rates far lower than for incumbent sources.

4. Conclusion: a call for knowledge humility in response to post-normal times

Here we have attempted to set out a cumulative case (albeit in summary form) demonstrating why quantitative analytical methods cannot definitively demonstrate that industrialised societies functionally equivalent to those familiar today can be powered entirely (or almost so) via RE. However, as we have argued throughout, unpacking this question of renewable energy's capacity to meet humanity's demand for energy services depends also and significantly on the level of that demand. Here we need to consider what is required, in terms of energy services, to live in the ways that humans are content to live – which is a highly vexed and contested issue.

The nature of the envisaged transition means that we are entering entirely unexplored territory, and the pathways that we walk into existence are subject to inherent, irreducible uncertainty. It is impossible to know up front just how these pathways will unfold, the full range of challenges that will be encountered along the way, and where the novel responses to them will take us. As such, there is very good reason to think that the situations that emerge will be very different from the expectations created by any model constructed or plan conceived today. It seems prudent to conclude that global-scale transition away from fossil fuels leads humanity into the post-normal realm of 'unthought future(s)' (Sardar & Sweeney, 2016).

Here actors will do better to anticipate complex, uncertain and chaotic conditions as typical, rather than extreme outliers. The perspectives on energy-society futures that are most influential today typically remain grounded in Sardar and Sweeney's (2016) 'extended present'. Unanticipated developments are treated as perturbations away from the historical conditions of order and equilibrium – stable conditions towards which systems can be expected to return via the interventions of orthodox governance institutions. The analysis presented here implies that this stance is no longer tenable. Uncertainty of the nature now faced demands new governance approaches that embody learning and reflexivity as the basis for guiding action (Grunwald, 2004; Voß, Bauknecht, & Kemp, 2006).

Consistent with such a conclusion, we believe that the situation we have outlined here infers the need for a high degree of 'knowledge humility' in approaching energy transition questions. The prospects for viable futures will be greatly assisted by acknowledging that even the best available evidence today leaves many questions open and in need of continued inquiry. This case for humility can only be emphasised further when one looks at the real world to see how slowly the renewable energy transition has advanced in recent decades. The world knew enough about fossil fuels and climate change in 1988 to establish the IPCC, but in the last thirty years, very modest progress has been made on the post-carbon transition. Wind, solar and geothermal together provided merely between 1.7% (IEA, 2018) and 4.1% (BP, 2019) of global primary energy supply depending on energy accounting convention. A transition to 100% renewable energy is likely going to be more difficult, slower and almost certainly more expensive than is typically thought to be the case.

We believe that such an assessment holds regardless of whether the challenge is framed in post-normal terms. Even if transition is viewed through the prism of normalcy—a matter of incrementally applying established science and technological understanding with no major further-order implications for wider social contexts—then a situation is still faced in which relying upon a 'normal' change trajectory leads to extraordinary climate impacts. While knowledge humility is a disposition suited especially well to post-normal times, it will also support more judicious policy and action where prevailing conditions are perceived as normal.

The greater the demand for energy services, the lower the likelihood that RE can meet that demand. As demand expectations decrease, the likelihood increases. The fundamental practical point, with respect to energy-intensive societies, is that it would be better to organise and prepare for reduced energy demand (i.e. energy descent), because the less energy we need, the more readily any transition to 100% RE will be realised. This is so, even as the particular forms of the societies and political-economies to which such transitions give expression become increasingly difficult to envision where thinking is constrained by past experience – where, as Ramirez et al. (2019, p. 76) discuss, drawing on Kahneman and Klein's (2009) work on expert judgement, “those with the most experience will not necessarily make the wisest decisions”. And in light of this, the distributive question of how to equitably share the RE that is available in any post-carbon society only strengthens the case for preparing for energy descent futures.

Within these circumstances, humility becomes more than a precautionary support to better quality policy and planning. Following Sardar (2010), alongside the virtues of modesty and accountability, it forms part of an adaptive value set that may support human societies in navigating as-yet unknown pathways to live well in the face of post-normal dilemmas.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

Alexander, S., & Floyd, J. (2018). *Carbon civilisation and the energy descent future: Life beyond this brief anomaly*. Melbourne: Simplicity Institute.

Alexander, S., Rutherford, J., & Floyd, J. (2018). A critique of the Australian National Outlook decoupling strategy: A ‘limits to growth’ perspective. *Ecological Economics, 145*, 10-17. doi: https://doi.org/10.1016/j.ecolecon.2017.08.014.

Ali, S. M. H., Lenzen, M., & Huang, J. (2018). Shifting air-conditioner load in residential buildings: benefits for low-carbon integrated power grids. *IET Renewable Power Generation, 12*(11), 1314-1323. https://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2017.0859 doi:10.1049/iet-rpg.2017.0859 Accessed 10 September 2019.

Ali, S. M. H., Lenzen, M., & Tyedmers, E. (2019). Optimizing 100%-renewable grids through shifting residential water-heater load. *International Journal of Energy Research, 43*(4), 1479-1493. doi: 10.1002/er.4416.

Amara, R. (1975). Some observations on the interaction of technology and society. *Futures, 7*(6), 515-517. doi: https://doi.org/10.1016/0016-3287(75)90006-3.

Anthony, S., & Coram, A. (2019). *Modernising electricity sectors: a guide to long-run investment decisions*: Industry Super Australia.

Ayres, R., & Voudouris, V. (2014). The economic growth enigma: Capital, labour and useful energy? *Energy Policy, 64*(0), 16-28. doi: http://dx.doi.org/10.1016/j.enpol.2013.06.001.

Austrade. (2018). The lithium-ion battery value chain: New economy opportunities for Australia. Canberra: Commonwealth of Australia.

Bardi, U., & Sgouridis, S. (2017). In support of a physics-based energy transition planning: Sowing our future energy needs. *BioPhysical Economics and Resource Quality, 2*(4), 14. doi: 10.1007/s41247-017-0031-2.

Bithas, K., & Kalimeris, P. (2018). Unmasking decoupling: Redefining the Resource Intensity of the Economy. *Science of The Total Environment, 619–620*, 338-351. doi: https://doi.org/10.1016/j.scitotenv.2017.11.061.

Blakers, A., Lu, B., & Stocks, M. (2017). 100% renewable electricity in Australia. *Energy, 133*(Supplement C), 471-482. doi: https://doi.org/10.1016/j.energy.2017.05.168.

Blakers, A., Lu, B., Stocks, M., Anderson, K., & Nadolny, A. (2018, 10-15 June 2018). *Pumped hydro energy storage to support 100% renewable electricity.* Paper presented at the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC).

Bowles, N., Alexander, S., & Hadjikakou, M. (2019). The livestock sector and planetary boundaries: A 'limits to growth' perspective with dietary implications. *Ecological Economics, 160*, 128-136. doi: https://doi.org/10.1016/j.ecolecon.2019.01.033.

BP. (2019). BP statistical review of world energy 2019. London: BP.

Brandt, A. R. (2017). How does energy resource depletion affect prosperity? Mathematics of a minimum Energy Return on Investment (EROI). *BioPhysical Economics and Resource Quality, 2*(1), 2. doi: 10.1007/s41247-017-0019-y.

Brockway, P. E., Owen, A., Brand-Correa, L. I., & Hardt, L. (2019). Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nature Energy, 4*(7), 612-621. doi: 10.1038/s41560-019-0425-z.

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renewable and Sustainable Energy Reviews, 92*, 834-847. doi: https://doi.org/10.1016/j.rser.2018.04.113.

Burger, P., Frecè, J., Scherrer, Y., & Daub, C.-H. (2014). Strategies for sustainability: Institutional and organisational challenges. *Sustainability, 6*(11), 8342-8347.

Büscher, C., Schippl, J., & Sumpf, P. (Eds.). (2019). *Energy as a sociotechnical problem: an interdisciplinary perspective on control, change, and action in energy transitions*. New York: Routledge.

Capellán-Pérez, I., de Castro, C., & Arto, I. (2017). Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. *Renewable and Sustainable Energy Reviews, 77*, 760-782. doi: https://doi.org/10.1016/j.rser.2017.03.137.

Capellán-Pérez, I., de Castro, C., & Miguel González, L. J. (2019). Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies. *Energy Strategy Reviews, 26*, 100399. doi: https://doi.org/10.1016/j.esr.2019.100399.

Carbajales-Dale, M. (2019). When is EROI Not EROI? *BioPhysical Economics and Resource Quality, 4*(4), 16. doi: 10.1007/s41247-019-0065-8.

Carbajales-Dale, M., Barnhart, C. J., & Benson, S. M. (2014). Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. [10.1039/C3EE42125B]. *Energy & Environmental Science, 7*(5), 1538-1544. doi: 10.1039/c3ee42125b.

Checkland, P. B., & Poulter, J. (2006). *Learning for action: A short definitive account of Soft Systems Methodology, and its use for practitioners, teachers and students*. London: John Wiley & Sons.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research & Social Science, 37*, 175-190. doi: https://doi.org/10.1016/j.erss.2017.09.015.

Clack, C. T. M., Qvist, S. A., Apt, J., Bazilian, M., Brandt, A. R., Caldeira, K., . . . Whitacre, J. F. (2017). Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences*. doi: 10.1073/pnas.1610381114.

de Castro, C., & Capellán-Pérez, I. (2018). Concentrated solar power: Actual performance and foreseeable future in high penetration scenarios of renewable energies. *BioPhysical Economics and Resource Quality, 3*(3), 14. doi: 10.1007/s41247-018-0043-6.

de Castro, C., Mediavilla, M., Miguel, L. J., & Frechoso, F. (2013). Global solar electric potential: A review of their technical and sustainable limits. *Renewable and Sustainable Energy Reviews, 28*(0), 824-835. doi: http://dx.doi.org/10.1016/j.rser.2013.08.040.

DeCarolis, J. F., Hunter, K., & Sreepathi, S. (2012). The case for repeatable analysis with energy economy optimization models. *Energy Economics, 34*(6), 1845-1853. doi: https://doi.org/10.1016/j.eneco.2012.07.004.

Diesendorf, M., & Elliston, B. (2018). The feasibility of 100% renewable electricity systems: A response to critics. *Renewable and Sustainable Energy Reviews, 93*, 318-330. doi: https://doi.org/10.1016/j.rser.2018.05.042.

Dupont, E., Koppelaar, R., & Jeanmart, H. (2018). Global available wind energy with physical and energy return on investment constraints. *Applied Energy, 209*, 322-338. doi: https://doi.org/10.1016/j.apenergy.2017.09.085.

Elliston, B., MacGill, I., & Diesendorf, M. (2014). Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market. *Renewable Energy, 66*(0), 196-204. doi: http://dx.doi.org/10.1016/j.renene.2013.12.010.

Fazey, I., Schäpke, N., Caniglia, G., Patterson, J., Hultman, J., van Mierlo, B., . . . Wyborn, C. (2018). Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. *Energy Research & Social Science, 40*, 54-70. doi: https://doi.org/10.1016/j.erss.2017.11.026.

Fix, B. (2019). Dematerialization through services: Evaluating the evidence. *BioPhysical Economics and Resource Quality, 4*(2), 6. doi: 10.1007/s41247-019-0054-y.

Foran, B. (2009). Powerful choices: transition to a biofuel economy in Australia. http://lwa.gov.au/products/pn30178. Accessed 19 September 2019.

Foran, B. (2011). Low carbon transition options for Australia. *Ecological Modelling, 223*(1), 72-80. doi: https://doi.org/10.1016/j.ecolmodel.2011.05.008.

Friedemann, A. J. (2016). *When trucks stop running: Energy and the future of transportation*. New York: Springer.

Friedrichs, J. (2011). Peak energy and climate change: The double bind of post-normal science. *Futures, 43*(4), 469-477. doi: https://doi.org/10.1016/j.futures.2010.12.004.

Froggatt, A., & Schneider, M. (2015). Nuclear power versus renewable energy — A trend analysis. *Proceedings of the IEEE, 103*(4), 487-490. doi: 10.1109/jproc.2015.2414485.

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures, 25*(7), 739-755. doi: https://doi.org/10.1016/0016-3287(93)90022-L.

Gans, F., Miller, L. M., & Kleidon, A. (2012). The problem of the second wind turbine--a note on a common but flawed wind power estimation method. *Earth System Dynamics, 3*(1), 79-86. doi: http://dx.doi.org/10.5194/esd-3-79-2012.

GIE. (2018). Existing gas storage capacity in Europe exceeded 1 petawatthour in 2018, shrinked against 2016. https://www.gie.eu/events/email/download/2018/GIEPRSTORMAP2018.pdf. Accessed 5 January 2020.

Gore, A. (2008). Al Gore's Speech On Renewable Energy. https://www.npr.org/templates/story/story.php?storyId=92638501. Accessed 7 June 2020.

Grubler, A., Wilson, C., & Nemet, G. (2016). Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. *Energy Research & Social Science, 22*, 18-25. doi: https://doi.org/10.1016/j.erss.2016.08.015.

Grunwald, A. (2004). Strategic knowledge for sustainable development: the need for reflexivity and learning at the interface between science and society. *International Journal of Foresight and Innovation Policy*, 1(1/2), 150-167. doi: 10.1504/IJFIP.2004.004619.

Grunwald, A. (2011). Energy futures: Diversity and the need for assessment. *Futures, 43*(8), 820-830. doi: https://doi.org/10.1016/j.futures.2011.05.024.

Hall, C. A. S., Balogh, S., & Murphy, D. J. R. (2009). What is the minimum EROI that a sustainable society must have? *Energies, 2*(1), 25-47.

Hall, C. A. S., & Klitgaard, K. A. (2011). *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. New York: Springer.

Hall, C. A. S., Lambert, J. G., & Balogh, S. B. (2014). EROI of different fuels and the implications for society. *Energy Policy, 64*(0), 141-152. doi: http://dx.doi.org/10.1016/j.enpol.2013.05.049.

Hansen, K., Breyer, C., & Lund, H. (2019). Status and perspectives on 100% renewable energy systems. *Energy, 175*, 471-480. doi: https://doi.org/10.1016/j.energy.2019.03.092.

Hatfield-Dodds, S., Schandl, H., Adams, P. D., Baynes, T. M., Brinsmead, T. S., Bryan, B. A., . . . Wonhas, A. (2015). Australia is 'free to choose' economic growth and falling environmental pressures. *Nature, 527*(7576), 49-53. doi: 10.1038/nature16065 http://www.nature.com/nature/journal/v527/n7576/abs/nature16065.html#supplementary-information. Accessed 10 September 2019.

Heard, B. P., Brook, B. W., Wigley, T. M. L., & Bradshaw, C. J. A. (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews, 76*, 1122-1133. doi: http://dx.doi.org/10.1016/j.rser.2017.03.114.

Heuberger, C. F., & Mac Dowell, N. (2018). Real-world challenges with a rapid transition to 100% renewable power systems. *Joule* 2(3): 367-370. doi: https://doi.org/10.1016/j.joule.2018.02.002.

Hickel, J. (2017). *The divide: a brief guide to global inequality and its solutions*: New York: Random House.

Hickel, J., & Kallis, G. (2019). Is green growth possible? *New Political Economy*, 1-18. doi: 10.1080/13563467.2019.1598964.

Hodges, J. S., & Dewar, J. A. (1992). *Is it you or your model talking?: a framework for model validation*. Santa Monica, CA: Rand.

Holmgren, D. (2012). Retrofitting the suburbs for the energy descent future. *Simplicity Institute Report 12i*, 1-8.

Honnery, D., & Moriarty, P. (2011). Energy availability problems with rapid deployment of wind-hydrogen systems. *International Journal of Hydrogen Energy, 36*(5), 3283-3289. doi: https://doi.org/10.1016/j.ijhydene.2010.12.023.

IEA. (2018). *World Energy Outlook*. Paris: International Energy Agency.

IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In E. S. Brondizio, J. Settele, S. Díaz & H. T. Ngo (Eds.). Bonn, Germany: IPBES Secretariat.

IPCC. (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia,

C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor & T. Waterfield (Eds.).

Jackson, T., & Victor, P. A. (2015). Does credit create a 'growth imperative'? A quasi-stationary economy with interest-bearing debt. *Ecological Economics, 120*, 32-48. doi: https://doi.org/10.1016/j.ecolecon.2015.09.009.

Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy, 39*(3), 1154-1169. doi: http://dx.doi.org/10.1016/j.enpol.2010.11.040.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A. F., Goodman, S. C., Chapman, W. E., Cameron, M. A., . . . Yachanin, A. S. (2017). 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. *Joule, 1*(1), 108-121. doi: https://doi.org/10.1016/j.joule.2017.07.005.

Jacobson, M. Z., Delucchi, M. A., Cameron, M. A., & Frew, B. A. (2017). The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims. *Proceedings of the National Academy of Sciences, 114*(26), E5021-E5023. doi: 10.1073/pnas.1708069114.

Jacobson, M. Z., Delucchi, M. A., Cameron, M. A., & Mathiesen, B. V. (2018). Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. *Renewable Energy, 123*, 236-248. doi: https://doi.org/10.1016/j.renene.2018.02.009.

Jasanoff, S. (2018). Just transitions: A humble approach to global energy futures. *Energy Research & Social Science, 35*, 11-14. doi: https://doi.org/10.1016/j.erss.2017.11.025.

Jefferson, M. (2014). Closing the gap between energy research and modelling, the social sciences, and modern realities. *Energy Research & Social Science, 4*, 42-52. doi: https://doi.org/10.1016/j.erss.2014.08.006.

Jeffries, E. (2015). Coming clean. *Nature Climate Change, 5*, 93. doi: 10.1038/nclimate2504.

Jenkins, J., & Thernstrom, S. (2017). Deep decarbonization of the electric power sector insights from recent literature: Energy Innovation Reform Project.

Kahneman, D., & Klein, G. (2009). Conditions for intuitive expertise: A failure to disagree. *American Psychologist, 64*(6), 515-526. doi: 10.1037/a0016755.

Keen, S., Ayres, R. U., & Standish, R. (2019). A note on the role of energy in production. *Ecological Economics, 157*, 40-46. doi: https://doi.org/10.1016/j.ecolecon.2018.11.002.

Keepin, B. (1984). A technical appraisal of the IIASA energy scenarios. *Policy Sciences, 17*(3), 199-276. doi: 10.1007/bf00138708.

Kessides, I. N., & Wade, D. C. (2011). Deriving an improved dynamic EROI to provide better information for energy planners. *Sustainability, 3*(12), 2339-2357. doi: https://doi.org/10.3390/su3122339.

King, C., Maxwell, J., & Donovan, A. (2015). Comparing world economic and net energy metrics, Part 1: Single technology and commodity perspective. *Energies, 8*(11), 12949-12974.

King, L. C., & van den Bergh, J. C. J. M. (2018). Implications of net energy-return-on-investment for a low-carbon energy transition. *Nature Energy, 3*(4), 334-340. doi: 10.1038/s41560-018-0116-1.

Lambert, J. G., Hall, C. A. S., Balogh, S., Gupta, A., & Arnold, M. (2014). Energy, EROI and quality of life. *Energy Policy, 64*(0), 153-167. doi: http://dx.doi.org/10.1016/j.enpol.2013.07.001.

Laugs, G. A. H., & Moll, H. C. (2017). A review of the bandwidth and environmental discourses of future energy scenarios: Shades of green and gray. *Renewable and Sustainable Energy Reviews, 67*, 520-530. doi: https://doi.org/10.1016/j.rser.2016.09.053.

Le Quéré, C., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., . . . van Vuuren, D. P. (2019). Drivers of declining CO2 emissions in 18 developed economies. *Nature Climate Change, 9*(3), 213-217. doi: 10.1038/s41558-019-0419-7.

Lenzen, M., McBain, B., Trainer, T., Jütte, S., Rey-Lescure, O., & Huang, J. (2016). Simulating low-carbon electricity supply for Australia. *Applied Energy, 179*, 553-564. doi: http://dx.doi.org/10.1016/j.apenergy.2016.06.151.

Loftus, P. J., Cohen, A. M., Long, J. C. S., & Jenkins, J. D. (2015). A critical review of global decarbonization scenarios: what do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change, 6*(1), 93-112. doi: 10.1002/wcc.324.

McDowall, W., & Geels, F. W. (2017). Ten challenges for computer models in transitions research: Commentary on Holtz et al. *Environmental Innovation and Societal Transitions, 22*, 41-49. doi: https://doi.org/10.1016/j.eist.2016.07.001.

Mediavilla, M., de Castro, C., Capellán, I., Javier Miguel, L., Arto, I., & Frechoso, F. (2013). The transition towards renewable energies: Physical limits and temporal conditions. *Energy Policy, 52*(0), 297-311. doi: http://dx.doi.org/10.1016/j.enpol.2012.09.033.

Millard, D., & Quadrelli, R. (2017, 4 September). Commentary: Understanding and using the Energy Balance. https://www.iea.org/newsroom/news/2017/september/commentary-understanding-and-using-the-energy-balance.html. Accessed 19 September 2019.

Miller, L. M., Gans, F., & Kleidon, A. (2011). Estimating maximum global land surface wind power extractability and associated climatic consequences. *Earth System Dynamics, 2*(1), 1-12. doi: http://dx.doi.org/10.5194/esd-2-1-2011.

Miller, L. M., & Keith, D. W. (2018). Climatic impacts of wind power. *Joule 2*(12): 2618-2632. doi: https://doi.org/10.1016/j.joule.2018.09.009.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., . . . del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters, 13*(6), 063001. doi: 10.1088/1748-9326/aabf9b.

Mir-Artigues, P., del Río, P., & Caldés, N. (2019). Economics of Concentrating Solar Power Generation. In P. Mir-Artigues, P. del Río & N. Caldés (Eds.), *The economics and policy of concentrating solar power generation* (pp. 85-134). Cham: Springer International Publishing.

Mohr, S. H., Wang, J., Ellem, G., Ward, J., & Giurco, D. (2015). Projection of world fossil fuels by country. *Fuel, 141*, 120-135. doi: https://doi.org/10.1016/j.fuel.2014.10.030.

Moriarty, P., & Honnery, D. (2008). Low-mobility: The future of transport. *Futures, 40*(10), 865-872. doi: https://doi.org/10.1016/j.futures.2008.07.021.

Moriarty, P., & Honnery, D. (2012a). Preparing for a low-energy future. *Futures, 44*(10), 883-892. doi: http://dx.doi.org/10.1016/j.futures.2012.08.002.

Moriarty, P., & Honnery, D. (2012b). What is the global potential for renewable energy? *Renewable and Sustainable Energy Reviews, 16*(1), 244-252. doi: http://dx.doi.org/10.1016/j.rser.2011.07.151.

Moriarty, P., & Honnery, D. (2016). Can renewable energy power the future? *Energy Policy, 93*, 3-7. doi: http://dx.doi.org/10.1016/j.enpol.2016.02.051.

Moriarty, P., & Honnery, D. (2018). Energy policy and economics under climate change. *AIMS Energy, 6*(2), 272-290. doi: http://dx.doi.org/10.3934/energy.2018.2.272.

Moriarty, P., & Honnery, D. (2019). Ecosystem maintenance energy and the need for a green EROI. *Energy Policy, 131*, 229-234. doi: https://doi.org/10.1016/j.enpol.2019.05.006.

Moriarty, P., Yan, X., & Wang, S. J. (2019). Liquid biofuels: not a long-term transport solution. *Energy Procedia, 158*, 3265-3270. doi: https://doi.org/10.1016/j.egypro.2019.01.986.

Murphy, D. J. (2014). The implications of the declining energy return on investment of oil production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372*(2006). doi: 10.1098/rsta.2013.0126.

Murphy, D. J., Hall, C. A. S., & Powers, B. (2011). New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. [journal article]. *Environment, Development and Sustainability, 13*(1), 179-202. doi: 10.1007/s10668-010-9255-7.

Nelder, C., & Koomey, J. (2016). Episode #23: Facts and falsehoods in energy transition. *The Energy Transition Show*. Retrieved 19 September, 2019, from https://xenetwork.org/ets/episodes/episode-23-facts-and-falsehoods-in-energy-transition/#more-256.

Neumeyer, C., & Goldston, R. (2016). Dynamic EROI assessment of the IPCC 21st century electricity production scenario. *Sustainability, 8*(5), 421. doi: https://doi.org/10.3390/su8050421.

Odum, H. T., & Odum, E. C. (2008). *A prosperous way down: principles and policies*. Boulder: University Press of Colorado.

Palmer, G. (2014). *Energy in Australia: Peak oil, solar power, and Asia's economic growth*. New York: Springer.

Palmer, G. (2017a). Energetic implications of a post-industrial information economy: The case study of Australia. *BioPhysical Economics and Resource Quality, 2*(2), 5. doi: 10.1007/s41247-017-0021-4.

Palmer, G. (2017b). A framework for incorporating EROI into electrical storage. *BioPhysical Economics and Resource Quality, 2*(2), 6. doi: 10.1007/s41247-017-0022-3.

Palmer, G. (2018). A biophysical perspective of IPCC integrated energy modelling. *Energies, 11*(4), 839. doi: https://doi.org/10.3390/en11040839.

Palmer, G., & Floyd, J. (2017). An exploration of divergence in EPBT and EROI for solar photovoltaics. *BioPhysical Economics and Resource Quality, 2*(4), 15. doi: https://doi.org/10.1007/s41247-017-0033-0.

Palmer, G., & Floyd, J. (2020). *Energy Storage and Civilization: A Systems Approach*. New York: Springer.

Palzer, A., & Henning, H.-M. (2014). 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. *Renewable and Sustainable Energy Reviews, 30*, 1019-1034. doi: http://dx.doi.org/10.1016/j.rser.2013.11.032.

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., & Spangenberg, J. H. (2019). Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability: European Environmental Bureau.

Pfenninger, S. (2017). Energy scientists must show their workings. *Nature News, 542*(7642), 393. doi: https://doi.org/10.1038/542393a.

Preston, G. (2015, 16 June 2015). 100% solar and wind power simulation for ERCOT Retrieved 6 September, 2019, from http://egpreston.com/100percentrenewables.pd.

Rai, A., Esplin, R., Nunn, O., & Nelson, T. (2019). The times they are a changin': Current and future trends in electricity demand and supply. *The Electricity Journal, 32*(6), 24-32. doi: https://doi.org/10.1016/j.tej.2019.05.017.

Ralph, N., & Hancock, L. (2019). Energy security, transnational politics, and renewable electricity exports in Australia and Southeast Asia. *Energy Research & Social Science, 49*, 233-240. doi: https://doi.org/10.1016/j.erss.2018.10.023.

Ramirez, R., Ravetz, J., Sharpe, B., & Varley, L. (2019). We need to talk (more wisely) about wisdom: A set of conversations about wisdom, science, and futures. *Futures*. doi: https://doi.org/10.1016/j.futures.2019.02.002.

Raugei, M. (2019). Net energy analysis must not compare apples and oranges. *Nature Energy, 4*(2), 86-88. doi: 10.1038/s41560-019-0327-0.

Ravetz, J. (1998). The Emperor's new models? *Impact Assessment and Project Appraisal, 16*(2), 79-80. doi: 10.1080/14615517.1998.10590191.

Roberts, S. H., Foran, B. D., Axon, C. J., Warr, B. S., & Goddard, N. H. (2018). Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom. *Applied Energy, 228*, 409-425. doi: https://doi.org/10.1016/j.apenergy.2018.06.078.

Robertson, G. P., Hamilton, S. K., Barham, B. L., Dale, B. E., Izaurralde, R. C., Jackson, R. D., . . . Tiedje, J. M. (2017). Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science, 356*(6345), eaal2324. doi: 10.1126/science.aal2324.

Sakai, M., Brockway, P. E., Barrett, J. R., & Taylor, P. G. (2018). Thermodynamic efficiency gains and their role as a key ‘engine of economic growth’. *Energies, 12*(1), 110.

Saltelli, A. (2019). A short comment on statistical versus mathematical modelling. *Nature Communications, 10*(1), 3870. doi: 10.1038/s41467-019-11865-8.

Saltelli, A., & Funtowicz, S. (2014). When all models are wrong. *Issues in Science and Technology, 30*(2), 79-85.

Samus, T., Lang, B., & Rohn, H. (2013). Assessing the natural resource use and the resource efficiency potential of the Desertec concept. *Solar Energy, 87*, 176-183. doi: https://doi.org/10.1016/j.solener.2012.10.011.

Sardar, Z. (2010). Welcome to postnormal times. *Futures, 42*(5), 435-444. doi: https://doi.org/10.1016/j.futures.2009.11.028.

Sardar, Z., & Sweeney, J. A. (2016). The three tomorrows of postnormal times. *Futures, 75*, 1-13. doi: https://doi.org/10.1016/j.futures.2015.10.004.

Scher, I., & Koomey, J. G. (2011). Is accurate forecasting of economic systems possible? *Climatic Change, 104*(3), 473-479. doi: 10.1007/s10584-010-9945-z.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D’agosto, M., Dimitriu, D., . . . Lah, O. (2014). Transport climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al. *Cambridge and New York: Cambridge University Press. Available at: http://www. ipcc. ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter8. pdf*.

Smil, V. (2010). *Energy transitions: History, requirements, prospects*. Santa Barbara: Praeger.

Smil, V. (2014). The long slow rise of solar and wind. *Scientific American, 310*(1), 52-57.

Smil, V. (2015). *Power density: A key to understanding energy sources and uses*. Cambridge, Massachusetts: The MIT Press.

Smil, V. (2016). Examining energy transitions: A dozen insights based on performance. *Energy Research & Social Science, 22*, 194-197. doi: https://doi.org/10.1016/j.erss.2016.08.017.

Smil, V. (2017). *Energy and civilization: A history*. Cambridge, Massachusetts: MIT Press.

Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science, 13*, 202-215. doi: https://doi.org/10.1016/j.erss.2015.12.020.

Sovacool, B. K., & Brown, M. A. (2015). Deconstructing facts and frames in energy research: Maxims for evaluating contentious problems. *Energy Policy, 86*, 36-42. doi: https://doi.org/10.1016/j.enpol.2015.06.020.

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., . . . Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. [10.1039/C8EE01157E]. *Energy & Environmental Science, 12*(2), 463-491. doi: 10.1039/c8ee01157e.

Stern, N. (2013). The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature, 51*(3), 838-859. doi: 10.1257/jel.51.3.838.

Thompson, M. (1984). Among the energy tribes: A cultural framework for the analysis and design of energy policy. *Policy Sciences, 17*(3), 321-339. doi: 10.1007/bf00138710.

Trainer, T. (2013). Limits to solar thermal energy set by intermittency and low DNI: Implications from meteorological data. *Energy Policy, 63*(0), 910-917. doi: http://dx.doi.org/10.1016/j.enpol.2013.07.065.

Trainer, T. (2018). Estimating the EROI of whole systems for 100% renewable electricity supply capable of dealing with intermittency. *Energy Policy, 119*, 648-653. doi: https://doi.org/10.1016/j.enpol.2018.04.045.

Trainer, T. (2019a). Remaking settlements for sustainability: the Simpler Way. *Journal of Political Ecology, 26*(1). doi: https://doi.org/10.2458/v26i1.22972.

Trainer, T. (2019b). Some questions concerning the Blakers et al. case that pumped hydro storage can enable 100% electricity supply. *Energy Policy, 128*, 470-475. doi: https://doi.org/10.1016/j.enpol.2018.12.063.

Turner, G. M., Hoffman, R., McInnis, B. C., Poldy, F., & Foran, B. (2011). A tool for strategic biophysical assessment of a national economy – The Australian stocks and flows framework. *Environmental Modelling & Software, 26*(9), 1134-1149. doi: http://dx.doi.org/10.1016/j.envsoft.2011.03.007.

Tverberg, G. (2011). Clean energy won't save the world! https://ourfiniteworld.com/2011/01/26/clean-energy-wont-save-the-world/. Accessed 5 January 2020.

Valentine, S. V., Sovacool, B. K., & Brown, M. A. (2017). Frame envy in energy policy ideology: A social constructivist framework for wicked energy problems. *Energy Policy, 109*, 623-630. doi: https://doi.org/10.1016/j.enpol.2017.07.028.

van den Bergh, J., Folke, C., Polasky, S., Scheffer, M., & Steffen, W. (2015). What if solar energy becomes really cheap? A thought experiment on environmental problem shifting. *Current Opinion in Environmental Sustainability, 14*, 170-179. doi: https://doi.org/10.1016/j.cosust.2015.05.007.

van der Wiel, K., Stoop, L. P., van Zuijlen, B. R. H., Blackport, R., van den Broek, M. A., & Selten, F. M. (2019). Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall. *Renewable and Sustainable Energy Reviews, 111*, 261-275. doi: https://doi.org/10.1016/j.rser.2019.04.065.

Victor, P. A. (2012). Growth, degrowth and climate change: A scenario analysis. *Ecological Economics, 84*, 206-212. doi: https://doi.org/10.1016/j.ecolecon.2011.04.013.

Voros, J. (2006). Introducing a classification framework for prospective methods. *Foresight, 8*(2), 43-56. doi: doi:10.1108/14636680610656174.

Voros, J. (2007). On the philosophical foundations of futures research. In P. van der Duin (Ed.), *Knowing tomorrow? How science deals with the future* (pp. 69-90). Delft, The Netherlands: Eburon.

Voß, J.-P., Bauknecht, D., & Kemp, R. (Eds.). (2006). *Reflexive governance for sustainable development*. Cheltenham: Edward Elgar.

Wang, J., Feng, L., Tang, X., Bentley, Y., & Höök, M. (2017). The implications of fossil fuel supply constraints on climate change projections: A supply-side analysis. *Futures, 86*, 58-72. doi: http://dx.doi.org/10.1016/j.futures.2016.04.007.

Wiseman, J., Edwards, T., & Luckins, K. (2013). Post carbon pathways: A meta-analysis of 18 large-scale post carbon economy transition strategies. *Environmental Innovation and Societal Transitions, 8*, 76-93. doi: https://doi.org/10.1016/j.eist.2013.04.001.

Yakubovich, V., Granovetter, M., & Mcguire, P. (2005). Electric charges: The social construction of rate systems. [journal article]. *Theory and Society, 34*(5), 579-612. doi: 10.1007/s11186-005-4198-y.

Yousefzadeh, M., & Lenzen, M. (2019). Performance of concentrating solar power plants in a whole-of-grid context. *Renewable and Sustainable Energy Reviews, 114*, 109342. doi: https://doi.org/10.1016/j.rser.2019.109342.