Investigating energy-society futures for post-normal times: a review of approaches

Draft working paper
Text last revised 17 August 2020
PDF created 22 August 2022

Joshua Floyd

Abstract

The physical characteristics of the energy sources harnessed by human societies are deeply intertwined with day-to-day forms of social organization and lived practices. There is a range of views about whether the transition from fossil fuels to lower- and zero-carbon energy sources can occur without disrupting fundamental social forms and processes. Despite this, dominant approaches to planning and managing future energy system developments rely heavily on quantitative computer-based modelling which generally assumes that established social and economic arrangements will continue over the period modelled. In this paper we review a range of perspectives that challenge this assumption of structural continuity, highlighting the wide band of uncertainty surrounding our energy futures. We present a heuristic map that characterizes the energy-society investigation landscape and classifies its key approaches. We discuss approaches to investigating energy futures that respond to the high levels of uncertainty entailed. The study presents investigators of energy-society futures with an expanded tool-kit, bringing previously marginalized future narratives into view. It offers planners and policy-makers charged with high-stakes, high-uncertainty, and urgent decision making a wider range of potential pathways to explore. More critical interpretation of findings based on analytical approaches in general, and quantitative modelling in particular, will bring into focus a broader range of plausible energy futures which in turn will change the way we envision and plan for energy transitions.

1. Introduction

The physical characteristics of the energy sources harnessed by human societies are deeply intertwined with and embedded in the day-to-day forms of social organization and lived practices that have emerged historically (Smil, 2017). In order to remain viable, any form of social organisation therefore relies on the ongoing availability of appropriate energy forms at sufficient rates. For all societies, it follows that planning and managing future energy system developments is of vital importance (Grunwald, 2011). This is especially so for contemporary fossil fuel-dependent societies, where the industrial effort directed towards maintaining necessary energy flows represents humanity's largest scale technical endeavour (Tainter & Patzek, 2012). Today, the urgent need to transition from these to lower- and zero-carbon energy sources greatly amplifies the challenge entailed in the planning and management task.

A defining characteristic of this challenge is the need to conceptually pre-figure and anticipate system behaviours—and the complex trajectories of change connecting them with the present—that will play out over a temporal scale extending many decades into the future. The capacity of planning and management institutions for such foresight has major implications for the outcomes of the transition task.

The dominant approaches to planning and managing future energy system developments rely heavily on quantitative computer-based modelling which generally assumes that established social and economic arrangements will continue over the period modelled. The very act of creating a quantitative model – that is, representing a situation, as observed and understood by the modeller, algorithmically – entails the definition of that situation in terms of a fixed set of parametric relationships. That is, it assumes structural constancy. Even if the situation being modelled involves structural change *as a characteristic of that situation*, the model structure to represent that change will be constant. Quantitative models must, by definition, assume structural constancy at some level, in order to proceed (DeCarolis, Hunter, & Sreepathi, 2012; Hodges & Dewar, 1992; Scher & Koomey, 2011). This is the case regardless of whether a model is deterministic or stochastic. Quantitative models can deal with parametric uncertainty, but not ultimately with structural uncertainty, when it is recognised that there must always be structural contexts beyond the structure represented in and by the model. The contexts beyond the model are by definition treated as fixed. Any act of modelling a situation quantitatively therefore entails an implicit assumption of structural constancy beyond the model boundary. The validity of the model outputs depends (among other considerations) on the adequacy of this assumption.

In relation to energy-society modelling, this is not presented as a criticism *per se*. Such modelling is overwhelmingly employed for managing the stability and security of incumbent societal arrangements at some macro-level, via incremental change at the micro-scale, in terms of the detailed elements that produce the macro-level behaviour. We argue that this is necessary and important, but it is not sufficient, in light of vulnerability of incumbent structures to breakdown (environmental, economic, political) (Homer-Dixon et al., 2015). Understanding how to manage within the operating envelope of incumbent systems is a different task to understanding the limits of those systems – to finding the edges of the envelope where incumbent structures fail or are no longer relevant, and new structures must arise to replace them.

The predicament that now demands wholesale transformation of the energy foundations for human societies can readily be cast as an existential crisis. The welfare of humankind and of many species beyond is at stake. This places the investigation of energy-society futures squarely within the domain of post-normal science (Friedrichs, 2011; Floyd et al., forthcoming). 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. Such a situation presents an urgent imperative for the development of prospective practices that are specifically suited to such conditions.

In seeking ways to reach beyond the limits implied by analytical approaches that anchor thinking within the envelope of structural constancy, we look to the futures studies field for guidance. The futures field offers broad perspectives for surveying and making sense of futures-oriented investigation in general (Amara, 1974, 1981; Bell, 1997; Inayatullah, 1990; R. A. Slaughter, 1999, 2004; Tapio & Hietanen, 2002), including investigation that is explicitly focused on energy-society relations (Grunwald, 2011).

With this as context, we frame this study as a review of *approaches to investigating energy-society futures*, recognising from the outset that this encompasses broader and richer territory than is implied by the quantitative modelling emphasis in mainstream energy development and transition research, and even by the more heterogeneous *analytical* emphasis in other research areas, such as those related to socio-technical transitions, and narrative scenario development. Further, in order both to bring the terrain that this encompasses into sufficiently comprehensive view, and to make sense of it such that the findings might usefully inform improved prospective thinking, we set the study within a broader and more domain-general context of *prospective inquiry* grounded in thinking and practice drawn from the futures field. We use this framing to present a heuristic map characterising the energy-society investigation landscape and classifying its key approaches. By visually representing the diversity of approaches, we hope to present investigators with an expanded palette of options for envisaging energy-society futures and a means of situating their own favoured ways of sense-making within a wider landscape, and to encourage expanded openness to alternative views and sense-making. This stands to bring highly consequential but presently marginalized futures into view, offering planners and policy-makers charged with high-stakes, high-uncertainty decision making a wider range of potential pathways to explore.

A standout theme of the review is a diversity of voices calling for epistemic humility in relation to what we know, and what we *can* know, about energy-society futures decades in advance. Considered collectively, these voices point towards a shift in emphasis from relatively discrete techniques and approaches for generating specific knowledge about closely defined research questions, to placing such questions and their related techniques within processes of inquiry and action in ways that are more sensitive to the limits of human knowing. We consider what this implies for the practices by which human societies navigate their futures, including the ways in which views of plausible and probable futures interact with ideas of the possible and preferable. In closing, we propose some guiding principles for investigative practice and process that is pragmatically oriented, in the philosophical sense, towards participatory, socially-oriented learning and action.

2. Futures inquiry: investigating possible, plausible, probable, and preferable futures

There has always been much at stake for the knowledge-making endeavours charged with formal oversight of energy-society futures. It is of no surprise that this was an early application area for scientifically-oriented national planning initiatives emerging in the wake of the second world war (Hoffman & Wood, 1976). Bell (1997) identifies such initiatives as some of the early formal expressions of futures studies, a field of inquiry and practice emerging at that time that broadly encompasses the interests and motivations apparent within the territory canvassed by the present review.

Within the futures studies field, methodology and process for the development of future-oriented knowledge are explicit subjects of investigation. Bell (1997) identifies the field's distinctive contribution as 'prospective thinking'. Rigorous, critical investigation is directed towards the ways in which socially legitimate forward views and 'images of the future' are constructed to inform decision-making and action. Futures studies is therefore, according to Bell (1997, p. 181), expressly 'an action science'.

A broad spectrum of 'prospective approaches' is recognized within future studies (Voros, 2006). While various typologies for classifying approaches have been proposed, Amara's (1974, 1981) differentiation between goals, premises and methodologies for futures inquiry on the basis of their relationship to *possible*, *probable* and *preferable futures* is widely recognized as providing a sound foundation for delineating the field's investigative scope (Tapio & Hietanen, 2002). The possible realm is explored through forming perceptions and images; the probable, through systematic, analytically-driven study of alternatives regarded by investigators as likely; and the preferable, through surfacing and expressing preferences for particular pathways in order to guide action in their pursuit (Amara, 1981). More recently, Voros (2003) introduced the category of *plausible futures*, relating to questions of what could conceivably happen, given current understanding of how the world works. For our purposes, this can be viewed as closely related to and encompassing Amara's probable futures category. That is, the probable can be treated as a subset of the plausible (Urueña, 2019).

Voros (2006) also identifies two distinct modes of prospective thinking, evolutionary and revolutionary. The former is associated with relatively continuous change trajectories developing forward from the present, while the latter is associated with discontinuous and disruptive change processes. According to Voros, investigation of plausible and probable futures typically aligns with the evolutionary mode, whereas investigation of possible and preferable futures aligns with the revolutionary mode.

Here we have adopted these conceptual distinctions between futurists' interests and their means for pursuing them as the basis for developing a maximally comprehensive view of futures investigation in general, from the perspective of the futures studies field. We use this as a heuristic to locate the particular approaches to investigating energy-society futures canvassed in the review, building up a picture of how investigative attention and effort is distributed and where it is concentrated, and hence revealing where certain forms of knowledge and modes of inquiry are privileged, and conversely, where others are marginalized.

The heuristic is shown schematically in Figure 1. Drawing on Amara and Voros, the figure includes typical profiles for groups working in each of the futures domains, and of the tools that they employ for doing so. We present possible, plausible-probable, and preferable futures not as mutually exclusive, where a focus on one would preclude consideration of the others. Rather, these are adjacent regions of a whole, and the differences are often a matter of relative emphasis. To illustrate this, we include in the figure a number of prominent approaches to thinking about energy-society futures that in our interpretation seem to span between regions. The examples were identified on the basis of their wider public influence beyond the technical and academic literature, and are intended to evoke with the reader a sense of how we have used the heuristic to make sense of the territory traversed. For example, investigation grounded in biophysical economics often employs a strongly analytical approach to highlight dangers (and opportunities), drawing attention to possible alternative futures. The ways we locate the examples are intended as propositions only. Others may have different interpretations; the heuristic is intended to support conversation and learning, not for setting rigid positions.

A contention we hold is that more comprehensive perspectives are better than less comprehensive perspectives. Under-representation or marginalization of certain futures perspectives relative to others has potentially adverse consequences for the prospects of societies confronting major transitions. Both the public interest and sound policy decisions will be better served by understanding where the perspectival gaps lie, and understanding what might be done to fill them. Filling the gaps is an important first step, but beyond this lies the question of how perspectives can be brought together to support comprehensive understanding and coordinated social action. It seems self-evident to us that an undertaking as complex and ambitious as the global transition away from fossil fuels demands the most effective integration of perspectives that can be achieved.

From its post-second world war origins, the futures studies field was oriented towards predictive forecasting, generally taking the future as an object to be revealed through empirical approaches grounded in positivism (Bell, 1997; Martin, 2010; Voros, 2006). As the limitations and social consequences of this orientation became apparent, increasing attention was directed towards the cultural, psychological and philosophical dimensions of futures inquiry. What it is that people do individually and collectively when they investigate futures, and how they both think about futures, and think about investigating futures, became principal loci of inquiry for the field. This is seen in the expansion of research beyond prospective methodology and process, to examine questions related to ontological, epistemological and axiological premises. Some notable developments in this respect are the 'French school' or *la prospective* (Godet, 1986), critical futures studies (Inayatullah, 1990; R. Slaughter, 1982), integral futures (R. A. Slaughter, 2004), and most recently the post-normal times discourse drawing on insights from post-normal science (Funtowicz & Ravetz, 1993; Sardar, 2010; Sardar & Sweeney, 2016). This is a sample only; for more comprehensive coverage of this history, including important contributions that pre-date those listed here, see Bell (1997) and Voros (2006, 2007).

A theme discernable amongst these developments is appreciation for participatory process as essential to high quality inquiry under post-normal conditions of high uncertainty and high decision stakes. Such conditions imply that we cannot know in the present with any certainty what the outcomes of successful transition away from fossil fuels will entail in practice for future societies. The transition process implies unprecedented techno-economic transformations, implying in turn the possible creation of entirely new social realities. Voros (2007) identifies Heron and Reason's (1997) *participatory paradigm* as a basis for futures inquiry that is particularly suited to such conditions and human needs. The participatory paradigm was introduced as an extension to Guba and Lincoln's (1994) prior schema of *positivism*, *post-positivism*, *critical theory*, and *constructivism* to encompass the range of basic belief systems guiding investigators, at least within western research initiatives. Voros (2007) provides a detailed characterization and comparison of the five paradigms in the context of futures inquiry. For present purposes, the features of the participatory paradigm that identify it as especially relevant for thinking about energy-society futures investigation in the context of a global post-carbon transition include: an explicit aim of human flourishing, and the intrinsic valuing of such flourishing with a balance of autonomy, cooperation, and hierarchy as a self-sufficient end; the primacy of practical knowing within a broader inclusion of diverse legitimate knowledges including direct experience, and critical subjectivity; a view of reality as co-created through participation in collaborative action-inquiry; knowledge accumulation as necessarily occurring within communities of inquiry embedded in communities of practice; and the regard of values as intrinsic to inquiry (Heron & Reason, 1997; Voros, 2007).

These considerations inform a key contention that on our interpretation is well-supported by the review findings: that in order for energy transition praxis to be as effective as possible in guiding the development of viable pathways for human societies, it should be organized along similar lines to those that motivate and organize participatory action research. That is, it should recognize and include diverse ways of knowing and forms of knowledge, from what is termed in post-normal science the ‘extended peer community’, with the effect of democratizing transition praxis (Funtowicz & Ravetz, 1993; Ravetz, 2004). At the same time, this should be grounded in and informed by experiential knowledge relating to what works in ‘real world’ human situations, and the diverse ways of knowing should be coordinated towards the development of action-oriented practical knowledge. The ultimate basis for evaluating energy-society futures investigation efforts should be their contribution to coordinating social action in support of human flourishing. These ideas are incorporated into Figure 1. The review findings supporting their inclusion will be pointed out as we proceed.

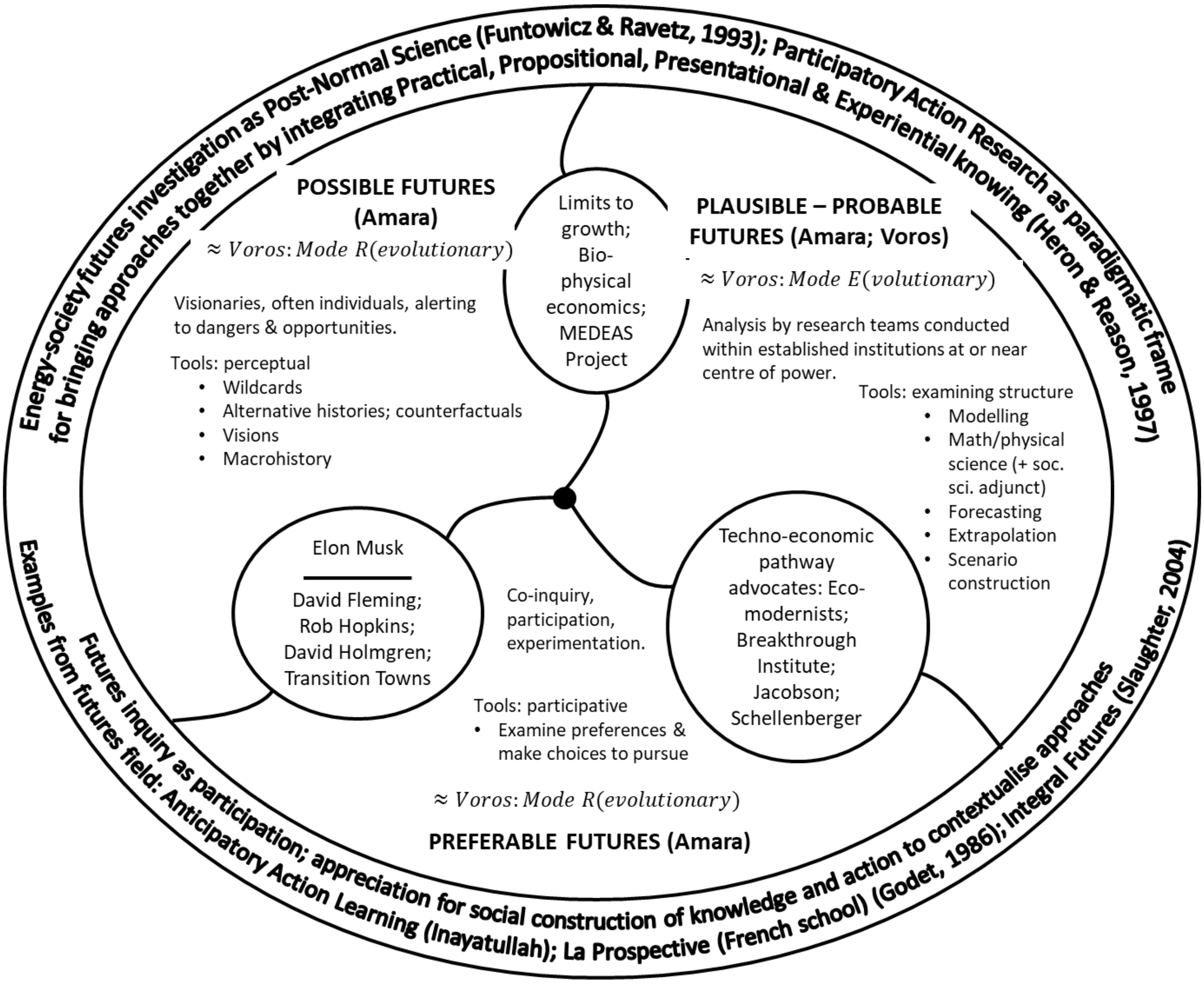

Figure 1: A sense-making heuristic informed by the futures studies field, for approaches to investigating energy-society futures. Sources for ‘boundary spanning’ examples: (Meadows, Randers, & Meadows, 2005); (Capellán-Pérez et al., 2020); (Vance, 2015); (Fleming, 2016); (Holmgren, 2009); (Hopkins, 2019); (Jacobson, Delucchi, Cameron, & Mathiesen, 2018); Ecomodernist Manifesto https://www.ecomodernism.org/; Michael Schellenberger TED talk https://www.ted.com/talks/michael_shellenberger_how_fear_of_nuclear_power_is_hurting_the_environment.

3. Predominance of analytical approaches: probable and plausible futures

The stand-out finding from the review when considered through the heuristic of Figure 1 is the predominance of analytical approaches located squarely within the plausible-probable domain. To a degree this could be read as a consequence of the review approach: we surveyed literature published mainly in academic journals and largely conducted by teams located in research institutes, mostly university-based (this article's reference list includes the full set of sources considered). Exceptions to this include several of the 'boundary spanning' examples mentioned in the previous section and shown in Figure 1. In the case of those spanning the plausible-probable boundaries their public prominence affords them in our view a status as more than just analytical findings about plausibility or probability.

The analytical approaches identified are mapped in overview in Figure 2. We identified four broad 'families' of analytical approaches, classified as (1) Orthodox quantitative modelling; (2) Heterodox quantitative modelling; (3) Socio-technical transitions modelling; and (4) Scenario analysis. Each of the families encompasses multiple sub-categories. The map highlights key landscape features, to be examined more closely as we proceed. In the remainder of the review we will give closest attention to families (1) and (2), and so for these we have proposed general descriptions for the sub-categories identified, each grouping together many particular instances that will nevertheless differ in implementation detail (see Figure 2 for descriptions). For family (3) we have drawn on the comprehensive review of socio-technical energy transition models by Li et al. (2015), listing the specific approaches that they identify and treating this as sufficiently complete for the purpose of this review. For family (4) we identified two broad modes of use: (i) to inform quantitative modelling or (ii) informed by quantitative modelling. This distinction seems to relate to the breadth of possible futures that a set of scenario narratives addresses, and hence is relevant to our concern with bringing marginalized futures into view.

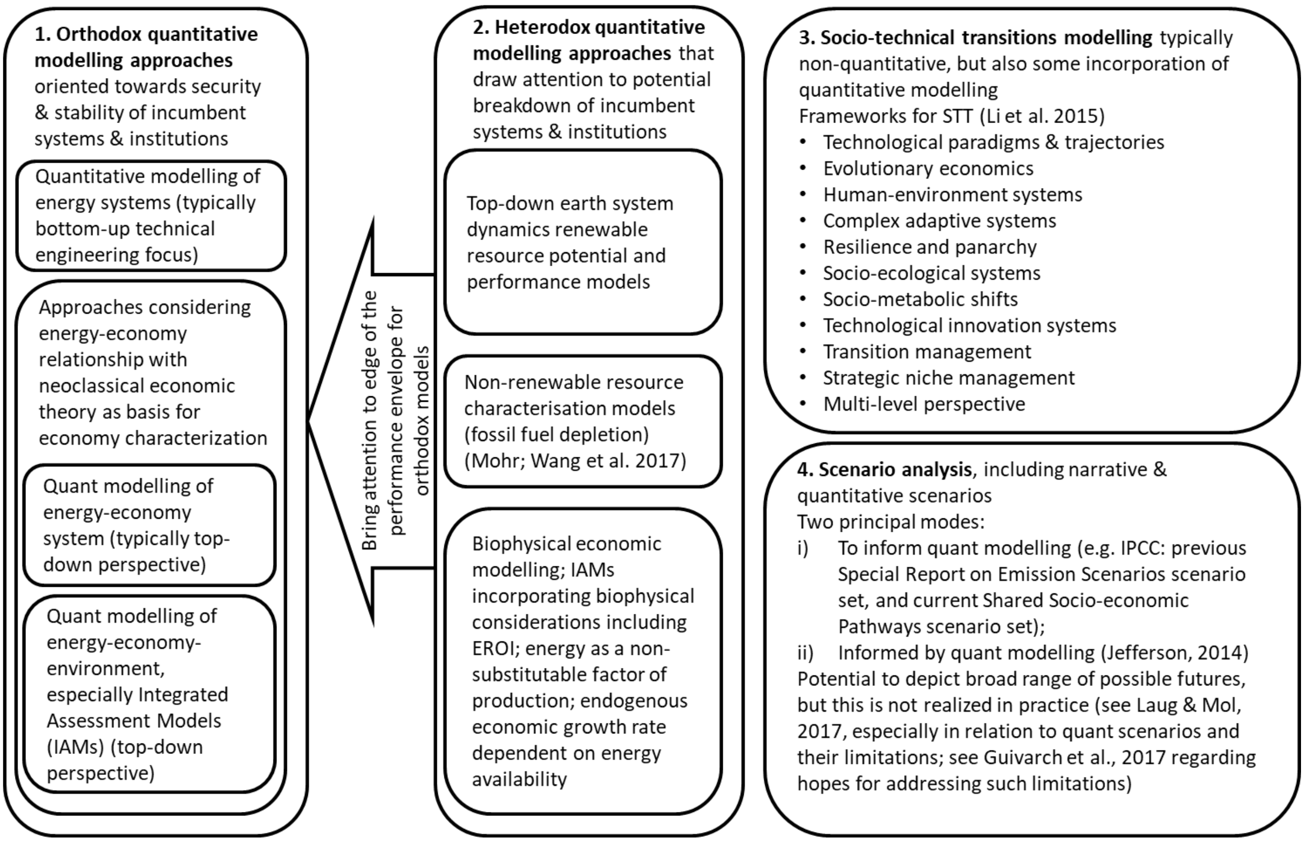

Figure 2: Overview map of analytical approaches to investigate plausible-probable energy-society futures.

While we found that analytical approaches in general dominate the investigation landscape, within this domain itself there is a similarly strong weighting towards quantitative modelling techniques. A further distinction can be drawn between orthodox techniques (family (1) in Figure 2) and heterodox techniques (family (2)). Investigation approaches falling in the orthodox quantitative modelling category comprise a significant majority of all approaches, and instances of the application of approaches, identified in the review. As such, the overall picture emerging from the review is one in which orthodox quantitative modelling is afforded a special status as the pathway to legitimate knowledge. In turn, this privileged position confers on such techniques great power to shape collective understandings of the energy-society futures open to our societies. The significance of this is reflected in the weight of attention we will give in the subsequent sections to families (1) and (2), though we will also discuss findings related to others. The reason that we give particular attention to family (2), the heterodox approaches, is that these can be viewed on the whole as 'expanding the boundaries' on orthodox approaches while sharing with them a common basis for claims to *methodological* legitimacy, and as such offer the most direct route for bringing a broader range of futures into view.

Subsequent sections comprise synopses, notes and sources (including excerpts from sources of special relevance). While the text is in draft form only, the overall case made can be considered complete i.e. the document sets out the full case that I intended to make.

4. Quantitative energy modelling: a very brief history

History of quant here

In this section we present a high-level overview of the review findings, sketching out a heuristic map of the territory revealed, and highlighting key features that will be explored in more depth. Chief amongst these is the dominant role of quantitative modelling techniques specifically, and analytical approaches more generally, in research relating to energy-society futures. The implication of their ubiquity and influence for anticipating and responding to futures structurally discontinuous with the present emerges as a principal theme of the review.

Given the prominence of quantitative techniques, we devote this and the subsequent section to brief overview of their history and identification of the particular approaches in widespread use. We then survey commentary on their limitations, drawing on a range of critical perspectives including many from within the energy modelling field itself.

> **Surveying energy-society futures investigation: a domain dominated by analytical approaches focused on probable, and to a lesser extent, plausible, futures. Overview of the range of approaches and techniques identified in the survey. Presented as a 'heuristic map' of the energy-society investigation territory.**

- Exploration of societies' energy contexts – typically through the lens of energy supply and demand, whether in relative isolation or integrated, is a major focus of governments, research bodies, corporations and increasingly, civil society organisations. See Amara's probable futures focus, the domain of analytical approaches.
- Even within this *analytical* dominance, quantitative modelling dominates.

- A broader range of approaches to prospective/anticipatory exploration of energy systems is evident in the literature, encompassing a variety of quantitative and qualitative methodologies. Even so, analytical methods prevail.
- This range includes especially: Socio Technical Transitions analysis; analysis methodologies addressing and incorporating biophysical economic limits. A heuristic for making sense of the breadth of approaches is presented in tabular form [and as a mind map - to be developed, but seems this would be a valuable complement to the table that could better represent associations between different approaches].
- Given their orientation towards 'maintaining continuity of recent historical and present trend trajectories', conventional models used for energy system management and planning by mainstream agencies are typically not oriented towards understanding the full range of societal futures that humanity may face.

History of quantitative energy modelling: historical basis for the probable and plausible futures orientation

- Since the 1950s, quantitative accounting approaches have formed the mainstay of energy system analysis.(Hoffman & Wood, 1976) Especially from the 1970s, this work has been dominated by computer-based modelling techniques with a prospective or anticipatory orientation.
- Conventional modelling techniques used by mainstream agencies necessarily "model for socio-economic continuity": focus on energy needs to maintain industrial market economies along the lines that function today: "Look to the centre". Not a criticism: institutions must be so-oriented.

Sources:

(Hoffman & Wood, 1976) HOFFMAN, K. C. & WOOD, D. O. (1976) Energy System Modeling and Forecasting. *Annual Review of Energy,* 1, 1, 423-453.

> Cited in Bhattacharya and Timilsina. History of energy modelling. Very clear, simple categorisation of energy models. Recognises relevance and importance of energy investment and return. Recognises relevance of energy supply constraints for economic growth forecasts.

(Pfenninger et al., 2018) Pfenninger, S., Hirth, L., Schlecht, I., Schmid, E., Wiese, F., Brown, T., . . . Wingenbach, C. (2018). Opening the black box of energy modelling: Strategies and lessons learned. *Energy Strategy Reviews, 19*, 63-71. doi: https://doi.org/10.1016/j.esr.2017.12.002

(Herbst, Toro, Reitze, & Jochem, 2012) Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. [journal article]. *Swiss Journal of Economics and Statistics, 148*(2), 111-135. doi: 10.1007/bf03399363

> Very good brief introduction to history of energy modelling. Traces top-down to 1950s, and bottom-up to 1970s oil crises.

(Bhattacharyya & Timilsina, 2010) BHATTACHARYYA, S. C. & TIMILSINA, G. R. (2010) A review of energy system models. *International Journal of Energy Sector Management,* 4, 4, 494-518.

5. Survey and mapping of dominant energy-society futures investigation approaches

A high-level review of the dominant *quantitative energy modelling* approaches

Sources:

(Hoffman & Wood, 1976)HOFFMAN, K. C. & WOOD, D. O. (1976) Energy System Modeling and Forecasting. *Annual Review of Energy,* 1, 1, 423-453.

> The models or forecasts that are included are best characterized by the coverage of various fuel supplies and demand for them and by the methodology employed. Thus, the scope of the models reviewed includes addressing the supply and/or demand for specific energy forms such as natural gas and electricity, analysis of interfuel substitution and competition in a more complete energy system framework, and analysis of the interrelationships between energy, the economy, and the environment.
> Energy system models are employed for both normative or descriptive analysis and predictive purposes. In normative analysis, the primary objective is to measure the impact on the system of changing some element or process that is an exogenous, or independent, event in the model. Predictive models are used to forecast energy supply and/or demand and attendant effects over a particular time horizon. Most models have both normative and predictive capability, and a partition of models into these classes can be misleading. Whenever such a classification is used here; it is intended only to identify the primary objective of the model.
> …
> Energy system models are developed and applied in a wide variety of energy planning and policymaking activities. Before we review specific models, it is useful to classify the types of planning functions and the requirements that must be imposed upon models if they are to be useful in supporting these planning activities.
> Ayres (I) provides a useful classification of modes and levels of planning. He defines three levels of planning: policy planning, strategic planning, and tactical or operational planning. Policy planning involves the formulation of goals or objectives and may be accomplished with little regard to technology as long as technical factors do not constrain the selection among alternative goals. Strategic planning concentrates on the development of a set of alternative paths to the desired goals and generally includes the establishment of criteria by which alternative strategies may be evaluated and ranked. Lastly, tactical planning deals with the determination of the steps necessary to implement a particular strategy.
> Energy system models provide support at all three planning levels, for regulatory [page break] agencies; for industrial planning; for planning, management, and evaluation of R&D programs; and for national energy policy and strategy planning. The objectives of these planning activities and the requirements imposed upon the models are discussed below.
> …
>
> The energy models are discussed in several groups according to their scope, and they range from supply-oriented models of a single fuel to models encompassing the overall energy system coupled to the economy. The four major groups of models and forecasts reviewed here are
>
> > 1. sectoral models. covering the supply or demand for specific fuels or energy forms,
> > 2. industry market models. which include both supply and demand relationships for individual or related fuels,
> > 3. energy system models. which encompass supply and demand relationships for all energy sources,

4. energy/economic models. which model the relationships between the energy system and the overall economy.

No single categorization of energy models can represent all of the important characteristics; this classification is intended to highlight the scope of particular models.

(Van Beeck, 1999)Van Beeck, N. (1999). Classificaiton of energy models: Tilburg University & Eindhoven University of Technology. Technical Report FEW-777. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.43.8055&rep=rep1&type=pdf

(Pfenninger, Hawkes, & Keirstead, 2014)Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi: https://doi.org/10.1016/j.rser.2014.02.003

Table 2. The four model groups.

Model family	Examples	Primary focus
Energy system optimization models	MARKAL, TIMES, MESSAGE, OSeMOSYS	Normative scenarios
Energy system simulation models	LEAP, NEMS, PRIMES	Forecasts, predictions
Power systems and electricity market models	WASP, PLEXOS, ELMOD, EMCAS	Operational decisions, business planning
Qualitative and mixed-methods scenarios	DECC 2050 pathways, Stabilization wedges	Narrative scenarios

(Hall & Buckley, 2016)Hall, L. M. H., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy, 169*, 607-628. doi: https://doi.org/10.1016/j.apenergy.2016.02.044

Comprehensive UK-focused review of quantitative energy systems models; proposed categorisation framework.

(Ringkjøb, Haugan, & Solbrekke, 2018)Ringkjøb, H.-K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews, 96*, 440-459. doi: https://doi.org/10.1016/j.rser.2018.08.002

Uses model categorisation from Despres et al. (2015)

(Crespo del Granado, van Nieuwkoop, Kardakos, & Schaffner, 2018) Crespo del Granado, P., van Nieuwkoop, R. H., Kardakos, E. G., & Schaffner, C. (2018). Modelling the energy transition: A nexus of energy system and economic models. *Energy Strategy Reviews, 20*, 229-235. Doi: https://doi.org/10.1016/j.esr.2018.03.004

To analyse different decarbonization pathways for the energy system, existing models have traditionally focused on specific energy sectors, adopted specific research perspectives, assessed only certain technologies, or studied isolated components and factors of the energy system. However, few efforts have been undertaken to successfully model a broader picture of the energy-economic system. In this conceptual paper, we propose linking top-down and bottom-up models to represent: distributed generation and demand, operations of electricity grids, infrastructure investments and generation dispatch, and macroeconomic interactions. We review existing work on modelling the different dimensions of the energy transition to understand why models tend to focus on certain features or parts of the energy system. We then discuss methodologies for linking different type of models.

(Després, Hadjsaid, Criqui, & Noirot, 2015) Després, J., Hadjsaid, N., Criqui, P., & Noirot, I. (2015). Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. *Energy, 80*, 486-495. doi: https://doi.org/10.1016/j.energy.2014.12.005

Table 1. The main classifications of energy models.

	Bottom-up	**Hybrid**	**Top-down**
Optimization	Sectoral optimization: MARKAL[a]	MERGE[b]	Optimal growth pathway: DICE[c]
Simulation	Recursive sectoral simulation: POLES[d]	Imaclim	Recursive general equilibrium: GREEN[e]

[a] Market Allocation.
[b] Model for Estimating the Regional and Global Effects of greenhouse gas reductions.
[c] Dynamic Integrated Climate-Economy.
[d] Prospective Outlook on Long-term Energy Systems.
[e] General Equilibrium Environmental model.

(Hedenus, Johansson, & Lindgren, 2013) Hedenus, F., Johansson, D. & Lindgren, K. A critical assessment of Energy-economy-climate models for policy analysis. *Journal of Applied Economics and Business Research* **3**, 118-132, (2013).

(Gargiulo & Gallachóir, 2013) Gargiulo, M. & Gallachóir, B. Ó. Long-term energy models: Principles, characteristics, focus, and limitations. *Wiley Interdisciplinary Reviews: Energy and Environment* **2**, 158-177, (2013).

(Jebaraj & Iniyan, 2006) Jebaraj, S. & Iniyan, S. A review of energy models. *Renewable and Sustainable Energy Reviews* **10**, 281-311, (2006).

(Herbst et al., 2012) Herbst, A., Toro, F., Reitze, F. & Jochem, E. Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics* **148**, 111-135, (2012).

Very clear and concise overview of bottom-up techno-economic and top-down macro-economic models, discussing hard-linking to produce hybrid models. Very good brief introduction to history of energy modelling. Traces top-down to 1950s, and bottom-up to 1970s oil crises.

(Lopion, Markewitz, Robinius, & Stolten, 2018) Lopion, P., Markewitz, P., Robinius, M. & Stolten, D. A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews* **96**, 156-166, (2018).

(Debnath & Mourshed, 2018) Debnath, K. B., & Mourshed, M. (2018). Challenges and gaps for energy planning models in the developing-world context. *Nature Energy, 3*(3), 172-184. doi: 10.1038/s41560-018-0095-2

(Bhattacharyya & Timilsina, 2010) BHATTACHARYYA, S. C. & TIMILSINA, G. R. (2010) A review of energy system models. *International Journal of Energy Sector Management,* 4, 4, 494-518.

Developing country focus; Detailed history of energy system models

(Suganthi & Samuel, 2012) SUGANTHI, L. & SAMUEL, A. A. (2012) Energy models for demand forecasting—A review. *Renewable and Sustainable Energy Reviews,* 16, 2, 1223-1240.

Debnath and Mourshed claim that this article misclassifies top-down and bottom-up modelling approaches.

(Subramanian, Gundersen, & Adams, 2018) SUBRAMANIAN, A. S. R., GUNDERSEN, T. & ADAMS, T. A. (2018) Modeling and Simulation of Energy Systems: A Review. *Processes,* 6, 12, 238.

(Urban, Benders, & Moll, 2007) URBAN, F., BENDERS, R. M. J. & MOLL, H. C. (2007) Modelling energy systems for developing countries. *Energy Policy,* 35, 6, 3473-3482

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

(Loftus, Cohen, Long, & Jenkins, 2015) 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

1. *Top–down, scenario-based back-casting* methods
2. *Top–down integrated assessment modeling* approaches
3. *Bottom–up energy systems modeling* approaches
4. *Bottom–up technical or techno-economic assessments*

Note that this taxonomy distinguishes scenarios based on the *method* of scenario construction, rather than the *purpose* for which that scenario is constructed. Irrespective of method, scenarios can be constructed for a variety of purposes, including, identifying the least-cost pathway to accomplish a specific CO_2 stabilization target, exploring the technical feasibility or economic cost of certain pathways, describing the expected results of policies, or exploring the sensitivity of scenario results to specific key assumptions. Where possible, we therefore also note the intent for which the scenarios were constructed (see Table 1).

(Hafner, Anger-Kraavi, Monasterolo, & Jones, 2020) Hafner, S., Anger-Kraavi, A., Monasterolo, I., & Jones, A. (2020). Emergence of New Economics Energy Transition Models: A Review. *Ecological Economics, 177*, 106779. doi: https://doi.org/10.1016/j.ecolecon.2020.106779.

Well-known academic and non-academic institutions call for a new approach in economics able to capture features of modern economies including, but not limited to, complexity, non-equilibrium and uncertainty. In this paper, we provide a systematic review of ecological macroeconomic models that are suitable for the investigation of low-carbon energy transitions and assess them based on the features considered desirable for a new approach in economics. We draw two main conclusions:

firstly, the knowledge base and structure of these existing ecological macroeconomic models are relevant, alongside other types of models, for the creation of a new approach in economics. Secondly, the reviewed models are policy relevant, especially in the context of the complexity and urgency of rapid energy transitions, where increasingly policymakers require economic models able to capture real-world characteristics. However, further improvements are needed to these models and future research should focus on i) assuring comparability of models' results and their policy insights, ii) incorporation of the relationships between macroeconomics, finance and sustainability and iii) the institutionalization of a new approach in economics.

6. Critiques and limits of quantitative modelling, especially highlighting uncertainty

Sources:

(Haikola, Hansson, & Fridahl, 2019) Haikola, S., Hansson, A., & Fridahl, M. (2019). Map-makers and navigators of politicised terrain: Expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures, 114*, 102472. doi: https://doi.org/10.1016/j.futures.2019.102472.

(Saltelli, 2016) Saltelli, A. (2016). Climate costing is politics not science. *Nature, 532*(7598), 177-177. doi: 10.1038/532177a.

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

(Saltelli & Funtowicz, 2014) Saltelli, A., & Funtowicz, S. (2014). When All Models Are Wrong. *Issues in Science and Technology, 30*(2), 79-85.

(Pfenninger, 2017b) Pfenninger, S. Energy scientists must show their workings. *Nature News* **542**, 393, (2017).

(Nature Energy Editorial, 2017) Business as unusual. (2017). [Editorial]. *Nature Energy, 2*, 17150. doi: 10.1038/nenergy.2017.150

(Strachan, Fais, & Daly, 2016) Strachan, N., Fais, B. & Daly, H. Reinventing the energy modelling–policy interface. *Nature Energy* **1**, 16012, (2016).

(Morgan & Keith, 2008) Morgan, M. G. & Keith, D. W. Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change* **90**, 189-215, (2008).

(Bardi, 2013) Bardi, U. (2013). Mind Sized World Models. *Sustainability, 5*(3), 896-911. doi: https://doi.org/10.3390/su5030896

(Iyer & Edmonds, 2018) Iyer, G., & Edmonds, J. (2018). Interpreting energy scenarios. *Nature Energy, 3*(5), 357-358. doi: 10.1038/s41560-018-0145-9

(Heuberger & Mac Dowell, 2018) Heuberger, C. F., & Mac Dowell, N. (2018). Real-World Challenges with a Rapid Transition to 100% Renewable Power Systems. *Joule*. doi: https://doi.org/10.1016/j.joule.2018.02.002

(DeCarolis et al., 2012) 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

> Very strong insider critique of energy-economy optimisation modelling. Structural constancy discussed as part of basis for critique.
>
> "EEO model-based insights cannot be validated through comparison to real world outcomes. As a result, modelers are left without credible metrics to assess a model's ability to deliver reliable insight"

(Pindyck, 2017) Pindyck, R. S. (2017). The Use and Misuse of Models for Climate Policy. *Review of Environmental Economics and Policy, 11*(1), 100-114. doi: 10.1093/reep/rew012

> Devastating critique of IAMs, and of quantitative modelling in general. LTG (World3) comes in for a particularly scathing critique – though I don't think grounds for that particular critique are well informed (author assumes perfect and infinite substitutability of resources without blinking an eye).
>
> "we don't even know the correct functional forms for some of the key relationships. This is particularly a problem when it comes to the damage function"
>
> "what really matters for the SCC is the likelihood and possible impact of a catastrophic climate outcome: a much larger than expected temperature increase and/or a much larger than expected reduction in GDP caused by even a moderate temperature increase. IAMs, however, simply cannot account for catastrophic outcomes."

(Larkin, Kuriakose, Sharmina, & Anderson, 2018) Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy, 18*(6), 690-714. doi: 10.1080/14693062.2017.1346498

(Peters, 2017) Peters, Glenn (2017), 'The trouble with negative emissions', Presentation to IPCC Expert Meeting on Scenarios (Addis Ababa, 26/04/2017), viewed 16 November 2018 at https://www.ipcc-wg3.ac.uk/Presentations/ExpertMeeting/Session2/4_Peters_IPCC_20170425.pdf

> "Value simple(r) models and alternative approaches
> The solution to IAM "problems", is not more complex IAMs…"

(Vaughan & Gough, 2016) Vaughan, N. E. & Gough, C. Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters* **11**, 095003, (2016).

(Pfenninger et al., 2014) Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi: https://doi.org/10.1016/j.rser.2014.02.003

(Li, 2017) Li, F. G. N. (2017). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews, 15*, 57-71. doi: https://doi.org/10.1016/j.esr.2017.01.002

(DeCarolis et al., 2017) DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., . . . Zeyringer, M. (2017). Formalizing best practice for energy system optimization modelling. *Applied Energy, 194*, 184-198. doi: https://doi.org/10.1016/j.apenergy.2017.03.001

(Trutnevyte, 2016) Trutnevyte, E. (2016). Does cost optimization approximate the real-world energy transition? *Energy, 106*, 182-193. doi: https://doi.org/10.1016/j.energy.2016.03.038

(Geels, Berkhout, & van Vuuren, 2016) Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. [Perspective]. *Nature Climate Change, 6*, 576. doi: 10.1038/nclimate2980

On limits of mathematical modelling (IAMs specifically though, rather than bottom-up cost optimisation energy system models); also considers in detail relationship between analytical approaches and differing philosophies of science.

(Turnheim et al., 2015) Turnheim, B. *et al.* Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change* **35**, 239-253, (2015).

(McDowall & Geels, 2017) 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

(Jefferson, 2014) 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

(Nelder & Koomey, 2016) Nelder, Chris and Koomey, Jonathan (2016), 'Facts and falsehoods in energy transition', The Energy Transition Show podcast, episode #23, 10 August, https://xenetwork.org/ets/episodes/episode-23-facts-and-falsehoods-in-energy-transition/#more-256, viewed 13 November 2018

(DeCarolis, 2011) DeCarolis, J. F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics, 33*(2), 145-152. doi: https://doi.org/10.1016/j.eneco.2010.05.002

(Li & Strachan, 2017) Li, F. G. N., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions, 24*, 106-129. doi: https://doi.org/10.1016/j.eist.2016.08.002

(Yue et al., 2018) Yue, X. *et al.* A review of approaches to uncertainty assessment in energy system optimization models. *Energy Strategy Reviews* **21**, 204-217, (2018).

(Pye et al., 2018) Pye, S. *et al.* Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. *Energy Research & Social Science* **46**, 332-344, (2018).

(Jasanoff, 2018) Jasanoff, S. Just transitions: A humble approach to global energy futures. *Energy Research & Social Science* **35**, 11-14, (2018).

(Moallemi & Malekpour, 2018) Moallemi, E. A. & Malekpour, S. A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science* **35**, 205-216, (2018).

(Hulme, 2012) Hulme, M. (2012). How climate models gain and exercise authority *The Social Life of Climate Change Models* (pp. 40-54): Routledge.

7. The structural constancy assumption in quantitative models

In this section, we home in on a specific assumption inherent in quantitative modelling, that of structural constancy and the necessity of commitment to a structural regime that provides empirical legitimacy to the analysis being conducted. We consider how such influence can often be seen also in socio-technical transitions approaches, even if in that realm it is not necessarily an inherent entailment of the approaches employed.

Structural constancy assumption/dependence in quantitative models.

- "Structural constancy (DeCarolis et al., 2012; Hodges & Dewar, 1992; Scher & Koomey, 2011) assumption necessary to build models" therefore models are oriented towards questions of how to maintain energy security to support current arrangements (global population of 7.6 billion and rising), while maintaining habitable climate.
- But the situations with which the futures field deals, and with which energy-society futures investigations are concerned, are not subject to structural constancy, and are hence not predictable (that the future is not predictable does not mean that it is not possible to make predictions that turn out to be correct). Further, these situations are only represented partially by techno-economic perspectives (or for that matter by socio-political, political-economic, geographical etc perspectives). That is, they are not reducible to disciplinary (even inter- or cross-disciplinary) characterisations. The situations of interest are whole or complete only in and of themselves. Any conceptual treatment of such situations must necessarily be incomplete, and hence can only produce *certain* knowledge relative to the conceptual treatment *itself* as a phenomenon. All statements about what is known via any such perspective must therefore be statements relative to the conceptual treatment, and not relative to the 'real world' situation that such treatment purports to represent.

Sources:

(Nelder & Koomey, 2016) Nelder, Chris and Koomey, Jonathan (2016), 'Facts and falsehoods in energy transition', The Energy Transition Show podcast, episode #23, 10 August, https://xenetwork.org/ets/episodes/episode-23-facts-and-falsehoods-in-energy-transition/#more-256, viewed 13 November 2018

(Scher & Koomey, 2011) Scher, I. & Koomey, J. G. Is accurate forecasting of economic systems possible? *Climatic Change* **104**, 473-479, (2011)

(DeCarolis et al., 2012) 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

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

> "It is possible to validate a model when the situation being modeled satisfies four prerequisites:
>
> - The situation must be observable and measureable.
> - The situation must exhibit constancy of structure in time.
> - The situation must exhibit constancy across variations in conditions not specified in the model.
> - The situation must permit the collection of ample data.
>
> …
>
> If a model is unvalidated or unvalidatable, it may not be used to predict, but that does not mean it is useless. There are at least seven distinct nonpredictive uses for models:
>
> 1. As a bookkeeping device, to condense masses of data or to provide a means of incentive to improve data quality;
> 2. As an aid in selling an idea of which the model is but an illustration;
> 3. As a training aid, to induce a particular behaviour;
> 4. As part of an automatic management system whose efficacy is not evaluated by using the model as if it were a true representation;
> 5. As an aid to communication, e.g., in teaching or in operating organizations;
> 6. As a vehicle for a fortiori arguments; and
> 7. As an aid to thinking and hypothesizing, e.g., as a stimulus to intuition in applied research or in training or as a decision aide in operating organizations.

(Van Beeck, 1999) Van Beeck, N. (1999). Classification of energy models: Tilburg University & Eindhoven University of Technology.

> p.11: So, as Hourcade et. al. summarize (1996, 281), in general top-down models can only be used "if historical development patterns and relationships among key underlying variables hold constant for the projection period" i.e., there is no discontinuity in historical patterns. Bottom-up models, on the other hand, are suited only "if there are no important feedbacks between the structural evolution of a particular sector in a strategy and the overall development pattern" i.e., if interactions between the energy sector and the other sectors are negligible.
>
> Citing (Hourcade, Haites, & Barker, 1996): Hourcade, J. C., Haites, E., & Barker, T. (1996). Contribution of Working Group III to the Second Assessment Report of the IPCC. Estimating the cost of mitigating greenhouse gases. In J. P. Bruce, H. Lee & E. F. Haites (Eds.), *Climate change 1995: economic and social dimensions of climate change* (pp. 263-296). Cambridge: Cambridge University Press.

8. Perspectives showing the problems with assuming structural constancy

Armed with an appreciation for structural constancy assumptions and their implications, we then shift focus again to review a wide range of sources that challenge the plausibility that such constancy will prevail over the course of large-scale transitions to zero- and low-carbon

energy sources. We give additional attention to literature on resource limits that are generally ignored by mainstream approaches to investigating energy-society futures. As further weight to the arguments here relating to the dangers of failing to think more broadly about energy futures, we briefly survey a number of areas that are considered far from settled even from within the realm of mainstream energy modelling practice.

This amounts in our view to a clear case that, at best, the jury must be considered still out on whether post-transition futures can reasonably be envisaged as the resultants of trajectories of change continuous with the present and recent past. If so, then where to from here, and how to proceed?

Challenging the structural constancy assumption for the major energy transition required in response to climate change and depletion of conventional energy sources ("investigative approaches seeking the edges of the conventional socio-economic behaviour envelope and looking beyond"). Includes discussion of the limitations of conventional quantitative modelling due to: omission of biophysical economic considerations (endogenous dependence of growth on energy availability); neglect of possibility of degrowth; limits of neoclassical economic theory assumptions; differences in physical characteristics of energy sources; de-growth economic perspectives

Sources:

(Feola, 2019) Feola, G. (2019). Capitalism in sustainability transitions research: Time for a critical turn? *Environmental Innovation and Societal Transitions*. doi: https://doi.org/10.1016/j.eist.2019.02.005

> Sustainability transition research (STR) has failed to engage in any significant analyses or critiques of capitalism. This article argues that capitalism is not a 'landscape' factor, but rather permeates the workings of socio-technical systems in ways that must be recognised both for elaborating rigorous accounts of transition trajectories and for enhancing the capacity of STR to support future societal sustainability transitions. This argument is developed specifically in relation to the three challenges of STR: the analysis of the actual sustainability of sustainability transitions, the application of transition theory to cases in the Global South, and the move towards a forward-looking STR. The article identifies three main implications of this argument with respect to interdisciplinarity, the validity of current theoretical frameworks, and the practice of STR. Ultimately, the article invites STR scholars to be more openly reflexive not only about possible theoretical biases, but also regarding their own roles in society.

(Safarzyńska & van den Bergh, 2017b) Safarzyńska, K., & van den Bergh, J. C. J. M. (2017). Integrated crisis-energy policy: Macro-evolutionary modelling of technology, finance and energy interactions. *Technological Forecasting and Social Change, 114*, 119-137. doi: https://doi.org/10.1016/j.techfore.2016.07.033

> Addressing four persistent problems, namely human-induced environmental change, financial instability, inequality and unemployment has now become an urgent necessity. To better grasp complex interactions between technological, financial and energy systems, we

propose a formal behavioral-evolutionary macroeconomic model. It describes the coevolution of four populations, namely of heterogeneous consumers, producers, power plants and banks, interacting through interconnected networks. We examine how decisions by all these economic agents affect financial stability, the direction of technological change and energy use. The approach generates non-trivial, even surprising insights, such as that brand loyalty, captured by a network externality on the demand side, can increase the likelihood of bankruptcies of banks. Cascades of such bankruptcies are found to be more likely under greater income inequalities and higher electricity prices. We employ the model to assess macroeconomic impacts of sustainability policies along three dimensions: environmental effectiveness, financial stability and socio-economic consequences.

(Safarzyńska & van den Bergh, 2017a) Safarzyńska, K., & van den Bergh, J. C. J. M. (2017). Financial stability at risk due to investing rapidly in renewable energy. *Energy Policy, 108*, 12-20. doi: https://doi.org/10.1016/j.enpol.2017.05.042

We present novel insights about effective energy policies using an agent-based model. The model describes relevant feedback mechanisms between technological evolution, the interbank market and the electricity sector. Analysis with it shows that energy policies affect interbank connectivity and hence the likelihood of cascades of bank failures. This effect has not been studied before in the literature. In particular, we find that investments in renewable energy reduce interbank connectivity, increasing the probability of bank failures, while raising taxes on energy has an opposite effect. Increasing the share of renewable energy in electricity production initially increases the price of electricity, and thus improves profits and the ability to re-pay debts of incumbent power plants. However, when the share of renewable energy increases too quickly, financial stability may be at stake as the burden of financing investments in renewable energy offsets the improved profitability of existing power stations. All in all, this study provides a unique and novel perspective on the relationship between renewable energy investments and financial stability.

From introduction:

Policymakers concerned with sustainability transitions need models capturing feedback mechanisms between different sub-systems of the economy, so that they can simultaneously assess economic, social and environmental performance of anticipated public policies and strategies. But current studies tend to examine climate change, financial instability or inequality without considering their complicated interrelationships. As a result, they are incapable of identifying indirect effects of sustainability policies in social, financial and economic realms. Hence they may overestimate the effectiveness of various policies, particularly by overlooking potential effects of policies directed at one sub-systems on other sub-systems. The proposed new approach avoids this deficiency by accounting for interactions between financial, energy and social subsystems.

(Ayres, Van den Bergh, Lindenberger, & Warr, 2013) Ayres, R. U., Van den Bergh, J. C. J. M., Lindenberger, D., & Warr, B. (2013). The Underestimated Contribution of Energy to Economic Growth: INSEAD.

Standard economic theory regards capital and labour as the main factors of production that satisfy the “cost-share theorem”. This paper argues that when a third factor, namely energy, is added physical constraints on substitution among the factors arise. We show that energy is a much more important factor of production than its small cost share may indicate. This

implies that continued economic growth along the historical trend cannot safely be assumed, notably in view of considerably higher energy prices in the future due to peak oil and climate policy.

(Ayres, Campbell, et al., 2013) Ayres, R. U., Campbell, C. J., Casten, T. R., Horne, P. J., Kümmel, R., Laitner, J. A., . . . von Weiszäcker, E. U. (2013). Sustainability transition and economic growth enigma: Money or energy? *Environmental Innovation and Societal Transitions, 9*, 8-12. doi: https://doi.org/10.1016/j.eist.2013.09.002

The complex relationship between economic growth, job creation, peak oil and climate change is discussed. This starts from seven facts and leads to five propositions to deal with the consequences of these facts. The overall message is that global economic policy should be redirected, that we need a better understanding of the reasons for the current economic malaise, that "peak oil" remains a concern (despite shale "fracking"), and that climate change is a relevant economic issue demanding a serious response. There is probably only one strategy that has a chance of reversing the present "death spiral" of the global economy and simultaneously reducing the risk of catastrophic climate change. That path requires major investments in energy efficiency and renewable energy technologies in the near and medium term. The investments must be attractive to long-run (20–30 year) investors (pension funds, insurance companies) and probably take the form of securitized, resource-based bonds.

(Davis, 2018) Davis, S. J. (2018). Predicting unpredictability. *Nature Energy, 3*(4), 257-258. doi: 10.1038/s41560-018-0127-y

(Sherwin, Henrion, & Azevedo, 2018) Sherwin, E. D., Henrion, M., & Azevedo, I. M. L. (2018). Estimation of the year-on-year volatility and the unpredictability of the United States energy system. *Nature Energy, 3*(4), 341-346. doi: 10.1038/s41560-018-0121-4

(Markard, 2018) Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy, 3*(8), 628-633. doi: 10.1038/s41560-018-0171-7

(King & van den Bergh, 2018) 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

But see also qualifications in the article from Raugei below:

(Raugei, 2019) Raugei, M. Net energy analysis must not compare apples and oranges. *Nature Energy* **4**, 86-88, (2019).

(Tainter, 1988) Tainter, J. A. *The Collapse of Complex Societies*. (Cambridge University Press, 1988).

(Tainter, 2011) Tainter, J. A. (2011). Energy, complexity, and sustainability: A historical perspective. *Environmental Innovation and Societal Transitions, 1*(1), 89-95. doi: http://dx.doi.org/10.1016/j.eist.2010.12.001

(Bardi, Falsini, & Perissi, 2019) Bardi, U., Falsini, S., & Perissi, I. (2019). Toward a General Theory of Societal Collapse: A Biophysical Examination of Tainter's Model of the Diminishing Returns of

Complexity. *BioPhysical Economics and Resource Quality, 4*(1), 3. doi: 10.1007/s41247-018-0049-0.

(Bardi, Falsini, & Perissi, 2018) Bardi, U., Falsini, S., & Perissi, I. (2018). Toward a General Theory of Societal Collapse. A Biophysical Examination of Tainter's Model of the Diminishing Returns of Complexity. https://export.arxiv.org/abs/1810.07056

(Sakai, Brockway, Barrett, & Taylor, 2018) Sakai, M., Brockway, P. E., Barrett, J. R. & Taylor, P. G. Thermodynamic Efficiency Gains and their Role as a Key 'Engine of Economic Growth'. *Energies* **12**, 110, (2018).

(Hirth, Ueckerdt, & Edenhofer, 2014) Hirth, L., Ueckerdt, F. & Edenhofer, O. Why Wind is Not Coal: On the Economics of Electricity. *FEEM Working Paper No. 39 2014*. Report No. FEEM Working Paper No. 39 2014, (Fondazione Eni Enrico Mattei, Milan, Italy, 2014) https://www.feem.it/en/publications/feem-working-papers-note-di-lavoro-series/why-wind-is-not-coal-on-the-economics-of-electricity/

> The economics of electricity is shaped by its physics. A well know example is the non-storability of electricity that causes its price to fluctuate widely. More generally, physical constraints cause electricity to be a heterogeneous good along three dimensions - time, space, and lead-time. Consequently, different generation technologies, such as coal and wind power, produce different economic goods that have a different marginal economic value. Welfare maximization or competitiveness analyses that ignore heterogeneity deliver biased estimates. This paper provides an analytical welfare-economic framework that accounts for heterogeneity for unbiased assessments of power generators. The framework offers a rigorous interpretation of commonly used cost indicators such as 'levelized electricity costs' and 'grid parity'. Heterogeneity is relevant for all generators, but especially for variable renewables such as wind and solar power. We propose a definition of 'variability', derive the opportunity costs of variability, and link that concept to the 'integration cost' literature. A literature review shows that variability can reduce the value of wind power by 20-50%. Thus it is crucial that economic analysis accounts for the physics of electricity.

(Palmer, 2018) Palmer, G. (2018). A Biophysical Perspective of IPCC Integrated Energy Modelling. *Energies, 11*(4), 839. doi: https://doi.org/10.3390/en11040839

(Palmer & Floyd, 2017) Palmer, G. & Floyd, J. An Exploration of Divergence in EPBT and EROI for Solar Photovoltaics. *BioPhysical Economics and Resource Quality* **2**, 15, (2017).

(Kuhnhenn, 2018) Kuhnhenn, K (2018), 'Economic growth in mitigation scenarios: A blind spot in climate science: Global scenarios from a growth-critical perspective', Heinrich Böll Foundation, December, accessed 7 December 2018 at https://www.boell.de/sites/default/files/endf2_kuhnhenn_growth_in_mitigation_scenarios.pdf?dimension1=division_oen

(Järvensivu et al., 2018) Järvensivu, P., Toivanen, T., Vadén, T., Lähde, V., Majava, A., & Eronen, J. T. (2018). Governance of economic transition: a scientific background document for the UN Global Sustainable Development Report 2019. Helsinki, Finland: BIOS Research Unit. Accessed 16 November 2018 at https://bios.fi/bios-governance_of_economic_transition.pdf

supports the contention that modelling based on orthodox neoclassical economic theory will not be capable of identifying or dealing with crisis conditions, especially those arising due to biophysical 'limits to growth'. Argues instead for Post-Keynesian economics as basis for political-economic governance.

(Hardt & O'Neill, 2017) Hardt, L., & O'Neill, D. W. (2017). Ecological Macroeconomic Models: Assessing Current Developments. *Ecological Economics, 134*, 198-211. doi: https://doi.org/10.1016/j.ecolecon.2016.12.027

Excellent, detailed overview of the strengths, weaknesses and challenges of various **marcoeconomic** (i.e. **not energy-centric or specific**) modelling approaches, applied to questions of post-growth economics i.e. models designed for "addressing post-growth policy themes". Key take away for us is that exploring post-growth requires the development of new classes of quantitative models i.e. this structural potential cannot simply be "plugged in" or "added on" to orthodox macroeconomic models that assume or are designed in the context of continuous economic growth. These ecological macroeconomic models could presumably be incorporated into IAM practice, but for IAM to deal with post-growth questions, the macroeconomic modelling approach needs comprehensive overhaul. It's not clear that a single macroeconomic modelling approach could handle the shift from growth to post-growth.

(D. W. O'Neill, Fanning, Lamb, & Steinberger, 2018) O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability, 1*(2), 88-95. doi: 10.1038/s41893-018-0021-4

(Brandt, 2017) Brandt, A. R. (2017). How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). [journal article]. *BioPhysical Economics and Resource Quality, 2*(1), 2. doi: 10.1007/s41247-017-0019-y

(Sgouridis, Csala, & Bardi, 2016) Sgouridis, S., Csala, D., & Bardi, U. (2016). The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environmental Research Letters, 11*(9), 094009. doi: 10.1088/1748-9326/11/9/094009

(Sers & Victor, 2018) Sers, M. R., & Victor, P. A. (2018). The Energy-emissions Trap. *Ecological Economics, 151*, 10-21. doi: https://doi.org/10.1016/j.ecolecon.2018.04.004

(Rye & Jackson, 2018) Rye, C. D., & Jackson, T. (2018). A review of EROEI-dynamics energy-transition models. *Energy Policy, 122*, 260-272. doi: https://doi.org/10.1016/j.enpol.2018.06.041

(Vandeventer, Cattaneo, & Zografos, 2019) Vandeventer, J. S., Cattaneo, C., & Zografos, C. (2019). A Degrowth Transition: Pathways for the Degrowth Niche to Replace the Capitalist-Growth Regime. *Ecological Economics, 156*, 272-286. doi: https://doi.org/10.1016/j.ecolecon.2018.10.002

(Dupont, Koppelaar, & Jeanmart, 2018) 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.

We use a grid-cell approach to assess the theoretical wind potential in all geographic locations by considering technological and land-use constraints. An analysis is then performed where the Energy Return on Investment (EROI) of the wind potential is evaluated. Finally, a top-down limitation on kinetic energy available in the atmospheric boundary layer is imposed.

With these constraints wind farm designs are optimized in order to maximize the net energy flux. We find that the global wind potential is substantially lower than previously established when both physical limits and a high cut-off EROI > 10 is applied. Several countries' potentials are below what is needed according to 100% renewable energy studies.

(Capellán-Pérez et al., 2018) Capellán-Pérez, I., de blas sanz, I., Nieto, J., Miguel, L., Mediavilla, M., Carpintero, Ó., . . . Parrado Hernando, G. (2018). *MEDEAS-World: a new IAM framework integrating biophysical and socioeconomic constraints*. https://www.researchgate.net/publication/329483306_MEDEAS-World_a_new_IAM_framework_integrating_biophysical_and_socioeconomic_constraints

(Capellán-Pérez, de Castro, & Miguel González, 2019) 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.

A novel methodology is developed to dynamically assess the energy and material investments required over time to achieve the transition from fossil fuels to renewable energy sources in the electricity sector. The obtained results indicate that a fast transition achieving a 100% renewable electric system globally by 2060 consistent with the Green Growth narrative could decrease the EROI of the energy system from current ~12:1 to ~3:1 by the mid-century, stabilizing thereafter at ~5:1. These EROI levels are well below the thresholds identified in the literature required to sustain industrial complex societies. Moreover, this transition could drive a substantial re-materialization of the economy, exacerbating risk availability in the future for some minerals. Hence, the results obtained put into question the consistence and viability of the Green Growth narrative.

(Capellán-Pérez et al., 2020) Capellán-Pérez, I., de Blas, I., Nieto, J., de Castro, C., Miguel, L. J., Carpintero, Ó., . . . Álvarez-Antelo, D. (2020). MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. [10.1039/C9EE02627D]. *Energy & Environmental Science*. doi: 10.1039/c9ee02627d.

A diversity of integrated assessment models (IAMs) coexists due to the different approaches developed to deal with the complex interactions, high uncertainties and knowledge gaps within the environment and human societies. This paper describes the open-source MEDEAS modeling framework, which has been developed with the aim of informing decision-making to achieve the transition to sustainable energy systems with a focus on biophysical, economic, social and technological restrictions and tackling some of the limitations identified in the current IAMs. MEDEAS models include the following relevant characteristics: representation of biophysical constraints to energy availability; modeling of the mineral and energy investments for the energy transition, allowing a dynamic assessment of the potential mineral scarcities and computation of the net energy available to society; consistent representation of climate change damages with climate assessments by natural scientists; integration of detailed sectoral economic structure (input–output

analysis) within a system dynamics approach; energy shifts driven by physical scarcity; and a rich set of socioeconomic and environmental impact indicators. The potentialities and novel insights that this framework brings are illustrated by the simulation of four variants of current trends with the MEDEAS-world model: the consideration of alternative plausible assumptions and methods, combined with the feedback-rich structure of the model, reveal dynamics and implications absent in classical models. Our results suggest that the continuation of current trends will drive significant biophysical scarcities and impacts which will most likely derive in regionalization (priority to security concerns and trade barriers), conflict, and ultimately, a severe global crisis which may lead to the collapse of our modern civilization. Despite depicting a much more worrying future than conventional projections of current trends, we however believe it is a more realistic counterfactual scenario that will allow the design of improved alternative sustainable pathways in future work.

(de Castro & Capellán-Pérez, 2020) Standard, Point of Use, and Extended Energy Return on Energy Invested (EROI) from Comprehensive Material Requirements of Present Global Wind, Solar, and Hydro Power Technologies. *Energies, 13*(12), 3036.

Whether renewable energy sources (RES) will provide sufficient energy surplus to entirely power complex modern societies is under discussion. We contribute to this debate by estimating the current global average energy return on energy invested (EROI) for the five RES technologies with the highest potential of electricity generation from the comprehensive and internally consistent estimations of their material requirements at three distinct energy system boundaries: standard farm-gate (EROIst), final at consumer point-of-use (EROIfinal), and extended (including indirect investments, EROIext). EROIst levels found fall within the respective literature ranges. Expanding the boundaries closer to the system level, we find that only large hydroelectricity would currently have a high EROIext ~ 6.5:1, while the rest of variable RES would be below 3:1: onshore wind (2.9:1), offshore wind (2.3:1), solar Photovoltaic (PV) (1.8:1), and solar Concentrated Solar Power (CSP) (<1:1). These results indicate that, very likely, the global average EROIext levels of variable RES are currently below those of fossil fuel-fired electricity. It remains unknown if technological improvements will be able to compensate for factors, which will become increasingly important as the variable RES scale-up. Hence, without dynamically accounting for the evolution of the EROI of the system, the viability of sustainable energy systems cannot be ensured, especially for modern societies pursuing continuous economic growth.

(Solé et al., 2020) Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., . . . Theofilidi, M. (2020). Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. *Renewable and Sustainable Energy Reviews, 132*, 110105. doi: https://doi.org/10.1016/j.rser.2020.110105.

This paper reviews different approaches to modelling the energy transition towards a zero carbon economy. It identifies a number of limitations in current approaches such as a lack of consideration of out-of-equilibrium situations (like an energy transition) and non-linear feedbacks. To tackle those issues, the new open source integrated assessment model *pymedeas* is introduced, which allows the exploration of the design and planning of appropriate strategies and policies for decarbonizing the energy sector at World and EU level. The main novelty of the new open-source model is that it addresses the energy transition by considering biophysical limits, availability of raw materials, and climate change impacts. This paper showcases the model capabilities through several simulation experiments to explore alternative pathways for the renewable transition. In the selected scenarios of this work, future shortage of fossil fuels is found to be the most influential factor of the simulations system evolution. Changes in efficiency and climate change damages are also important determinants influencing model outcomes.

(Nieto, Carpintero, Lobejón, & Miguel, 2020) Nieto, J., Carpintero, Ó., Lobejón, L. F., & Miguel, L. J. (2020). An ecological macroeconomics model: The energy transition in the EU. *Energy Policy, 145*, 111726. doi: https://doi.org/10.1016/j.enpol.2020.111726.

The Energy Roadmap 2050 (ER2050) is committed to achieve the European Union's emissions mitigation goals by reducing energy use and a transition to renewables. The macroeconomic impacts of the Ref16 and 'EUCO' scenarios of this strategy have been reported to entail an absolute decoupling between GDP growth and energy use. The aim of this paper is assessing the ER2050 targets with a novel modelling methodology based on Post-Keynesian Economics, i.e. demand-led economic growth and Ecological Economics, i.e. taking into account absolute biophysical (energy availability) constrains to economic growth. Thus, this article presents the Economy module of the Integrated Assessment Model MEDEAS-Europe, combining System Dynamics and Input-Output analysis, and evaluates the ER2050 targets under different scenarios regarding primary income distribution, foreign trade, labour productivity, industrial policy and working time reduction. Our results show that GDP growth and employment creation may be halted due to energy scarcity if the ER2050 targets are met even considering great energy efficiency gains. In addition, the renewables share would increase enough to reduce the energy imports dependency, but not sufficiently to meet the emissions targets. Only a Post-Growth scenario would be able to meet the climate goals and maintain the level of employment.

(de Blas, Mediavilla, Capellán-Pérez, & Duce, 2020) de Blas, I., Mediavilla, M., Capellán-Pérez, I., & Duce, C. (2020). The limits of transport decarbonization under the current growth paradigm. *Energy Strategy Reviews, 32*, 100543. doi: https://doi.org/10.1016/j.esr.2020.100543.

•Transportation is the sector most difficult to decarbonize.
•Technological change alone cannot achieve ambitious GHG reductions.
•Transport decarbonization can only be achieved with a strong reduction in demand.
•Strategic minerals are a serious limit to the expansion of electric vehicles.
•MEDEAS-W model shows the limits and rebound effects of transport electrification.

(Samsó, de Blas, Perissi, Martelloni, & Solé, 2020) Samsó, R., de Blas, I., Perissi, I., Martelloni, G., & Solé, J. (2020). Scenario analysis and sensitivity exploration of the MEDEAS Europe energy-

economy-environment model. *Energy Strategy Reviews*, 100582. doi: https://doi.org/10.1016/j.esr.2020.100582.

Seems to focus only on parametric uncertainty. In relation to structural uncertainty vs parametric uncertainty, cites: J. DeCarolis, H. Daly, P. Dodds, I. Keppo, F. Li, W. McDowall, S. Pye, N. Strachan, E. Trutnevyte, W. Usher, M. Winning, S. Yeh, M. Zeyringer, Formalizing best practice for energy system optimization modelling, Appl. Energy, 194 (2017), pp. 184-198, 10.1016/j.apenergy.2017.03.001

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

This paper outlines some very real issues with the use of energy return on investment (EROI) for comparing different energy delivery pathways, particularly when directly comparing EROI calculated at the scale of a single energy facility (as a ratio of full lifetime energy transfers) with that calculated at the scale of a geographical region or industry (as a ratio of annual energy flows). While these two ratios may converge, it is only under a very specific set of circumstances. The aim of this paper is to outline this issue in detail and provide some specific examples of the difference between these two ratios for the global wind and photovoltaics industries.

(Gaël Giraud & Kahraman, 2014; G. Giraud, Mc Isaac, Bovari, & Zatsepina, 2016) Giraud, G., Mc Isaac, F., Bovari, E., & Zatsepina, E. (2016). Coping with the Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming *AFD Research Papers*, No. 2016-29, August. https://www.afd.fr/en/coping-collapse-stock-flow-consistent-monetary-macrodynamics-global-warming-updated-version-dated-july-2017

(Gaël Giraud & Kahraman, 2014) Giraud, G. & Kahraman, Z. *How Dependent is Growth from Primary Energy? The Dependency ratio of Energy in 33 Countries (1970-2011)* (2014). https://halshs.archives-ouvertes.fr/halshs-01151590

(Homer-Dixon et al., 2015) Homer-Dixon, T., Walker, B., Biggs, R., Crépin, A.-S., Folke, C., Lambin, E. F., . . . Troell, M. (2015). Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society, 20*(3). doi: 10.5751/es-07681-200306

(Motesharrei, Rivas, & Kalnay, 2014) Motesharrei, S., Rivas, J., & Kalnay, E. (2014). Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics, 101*, 90-102. doi: https://doi.org/10.1016/j.ecolecon.2014.02.014

(Sherwood, Ditta, Haney, Haarsma, & Carbajales-Dale, 2017) Sherwood, J., Ditta, A., Haney, B., Haarsma, L. & Carbajales-Dale, M. Resource Criticality in Modern Economies: Agent-Based Model Demonstrates Vulnerabilities from Technological Interdependence. *BioPhysical Economics and Resource Quality* **2**, 9, (2017).

This paper presents an economic modeling framework that demonstrates ways that advanced economies can be susceptible to severe collapse and lengthy recovery scenarios, even in the presence of extraordinarily high levels of economic output. The

industrial revolution produced great leaps in material well-being in large part through harnessing the power of fossil fuels and incorporating natural resources with highly specific properties into manufacturing processes. This extraordinary material wealth, however, has come with a hidden cost. The same technology and resource-dependence that produces high levels of output can also create latent vulnerabilities within the system (Graedel et al. 2015a, b; Chen and Graedel 2015). A seemingly small disruption in the complex network of resource and technological interdependencies can lead to an unexpected cascading collapse in productivity and severe drop in societal well-being. When hidden system vulnerabilities exist, historical patterns of smooth, exponential growth in economic output are not necessarily the best predictors of the future. Production may suffer a sudden collapse and lengthy recovery period unlike anything experienced before (Stern 1997).

As levels of resource criticality and technological interdependence have increased in recent decades, traditional macroeconomic models have begun to show signs of wear.

…

This alternative framework demonstrates that potentially devastating macroeconomic outcomes are indeed possible when the simplifying assumptions used in traditional macroeconomic models are removed. These potential vulnerabilities are not taken seriously as real possibilities because the assumptions that undergird traditional economic models do not allow for them.

Collapse and recovery scenarios are explicitly ruled out in Solow growth models and other traditional modeling frameworks. These models assume and require that macroeconomic outcomes follow a smooth trajectory, modeled best by a twice differentiable function (Solow 2007). The seemingly innocuous assumption of smooth growth results from four underlying assumptions detailed in "Where are Resources in Macro-Economic Growth Models?"

8.1 Resource limit perspectives further undermine the structural constancy assumption

(Related to 8 above) energy resource limits (renewable or fossil) are generally neglected in conventional quantitative modelling, and discounted in analytical approaches to investigating energy-society futures more generally

- Biophysical methodologies include especially: systems-based renewable resource characterization (whereby influence of resource exploitation on resource availability is taken into account); extension of factors of production in economic models to include energy, so that relationship between economic growth and energy use is endogenised; energy return on investment analysis.

Sources:

(Capellán-Pérez, de Castro, & Arto, 2017) Capellán-Pérez, I., de Castro, C. & Arto, I. 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, (2017) (Capellán-Pérez, Mediavilla, de Castro, Carpintero, & Miguel, 2014) Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó. & Miguel, L. J. Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy* **77**, 641-666, (2014)

(Mediavilla et al., 2013) 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.

(Mohr, Wang, Ellem, Ward, & Giurco, 2015) Mohr, S. H., Wang, J., Ellem, G., Ward, J. & Giurco, D. Projection of world fossil fuels by country. *Fuel* **141**, 120-135, (2015).

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

(L. M. Miller, Gans, & Kleidon, 2011a) Miller, L. M., Gans, F., & Kleidon, A. (2011a). 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

(L. M. Miller, Gans, & Kleidon, 2011b) Miller, L. M., Gans, F., & Kleidon, A. (2011b). Jet stream wind power as a renewable energy resource: little power, big impacts. *Earth System Dynamics, 2*(2), 201-212. doi: http://dx.doi.org/10.5194/esd-2-201-2011

(Gans, Miller, & Kleidon, 2012) 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

(L. M. Miller et al., 2015) Miller, L. M., Brunsell, N. A., Mechem, D. B., Gans, F., Monaghan, A. J., Vautard, R., . . . Kleidon, A. (2015). Two methods for estimating limits to large-scale wind power generation. *Proceedings of the National Academy of Sciences, 112*(36), 11169-11174. doi: 10.1073/pnas.1408251112

(Adams & Keith, 2013) Adams, A. S., & Keith, D. W. (2013). Are global wind power resource estimates overstated? *Environmental Research Letters, 8*(1), 015021. doi: http://dx.doi.org/10.1088/1748-9326/8/1/015021

(Moriarty & Honnery, 2012) Moriarty, P., & Honnery, D. (2012). 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 & Honnery, 2016) 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

(Lee M. Miller & David W. Keith, 2018) Miller, L. M., & Keith, D. W. (2018a). Climatic Impacts of Wind Power. *Joule*. doi: https://doi.org/10.1016/j.joule.2018.09.009

(Lee M. Miller & David W Keith, 2018) Miller, L. M., & Keith, D. W. (2018b). Observation-based solar and wind power capacity factors and power densities. *Environmental Research Letters, 13*(10), 104008. https://doi.org/10.1088/1748-9326/aae102

(de Castro & Capellán-Pérez, 2018) de Castro, C. & Capellán-Pérez, I. Concentrated Solar Power: Actual Performance and Foreseeable Future in High Penetration Scenarios of Renewable Energies. *BioPhysical Economics and Resource Quality* **3**, 14, (2018).

(de Castro, Carpintero, Frechoso, Mediavilla, & de Miguel, 2014) de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M. & de Miguel, L. J. A top-down approach to assess physical and ecological limits of biofuels. *Energy* **64**, 506-512, (2014).

(de Castro, Mediavilla, Miguel, & Frechoso, 2011) de Castro, C., Mediavilla, M., Miguel, L. J. & Frechoso, F. Global wind power potential: Physical and technological limits. *Energy Policy* **39**, 6677-6682, (2011).

(de Castro, Mediavilla, Miguel, & Frechoso, 2013) de Castro, C., Mediavilla, M., Miguel, L. J. & Frechoso, F. Global solar electric potential: A review of their technical and sustainable limits. *Renewable and Sustainable Energy Reviews* **28**, 824-835, (2013).

(Dupont et al., 2018) 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.

(Dupont, Koppelaar, & Jeanmart, 2020) Dupont, E., Koppelaar, R., & Jeanmart, H. (2020). Global available solar energy under physical and energy return on investment constraints. *Applied Energy, 257*, 113968. doi: https://doi.org/10.1016/j.apenergy.2019.113968.

(Kis, Pandya, & Koppelaar, 2018) Kis, Z., Pandya, N., & Koppelaar, R. H. E. M. (2018). Electricity generation technologies: Comparison of materials use, energy return on investment, jobs creation and CO2 emissions reduction. *Energy Policy, 120*, 144-157. doi: https://doi.org/10.1016/j.enpol.2018.05.033.

8.2 Many areas of conventional techno-economic analysis are not settled

(Further related to 8 above) Even within conventional analytical approaches, there are many areas relevant to techno-economic analysis that cannot be considered as settled

Sources:

(de Blas et al., 2020) de Blas, I., Mediavilla, M., Capellán-Pérez, I., & Duce, C. (2020). The limits of transport decarbonization under the current growth paradigm. *Energy Strategy Reviews, 32*, 100543. doi: https://doi.org/10.1016/j.esr.2020.100543.

(Gross, Hanna, Gambhir, Heptonstall, & Speirs, 2018) Gross, R., Hanna, R., Gambhir, A., Heptonstall, P., & Speirs, J. (2018). How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. *Energy Policy, 123*, 682-699. doi: https://doi.org/10.1016/j.enpol.2018.08.061.

(Antonakakis, Chatziantoniou, & Filis, 2017) Antonakakis, N., Chatziantoniou, I. & Filis, G. Energy consumption, CO2 emissions, and economic growth: An ethical dilemma. *Renewable and Sustainable Energy Reviews* **68**, 808-824, (2017).

(Sovacool, 2016) Sovacool, B. K. How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science* **13**, 202-215, (2016).

(Smil, 2016) Smil, V. Examining energy transitions: A dozen insights based on performance. *Energy Research & Social Science* **22**, 194-197, (2016).

(Sovacool & Geels, 2016) Sovacool, B. K. & Geels, F. W. Further reflections on the temporality of energy transitions: A response to critics. *Energy Research & Social Science* **22**, 232-237, (2016).

(Loftus et al., 2015) 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

> We find that all of the scenarios envision historically unprecedented improvements in energy intensity, while normalized low-carbon capacity deployment rates are broadly consistent with historical experience. Three scenarios that constrain the available portfolio of low-carbon options by excluding some technologies (nuclear and carbon capture and storage) *a priori* are outliers, requiring much faster low-carbon capacity deployment and energy intensity improvements. Finally, all of the studies present comparatively little detail on strategies to decarbonize the industrial and transportation sectors, and most give superficial treatment to relevant constraints on energy system transformations. To be reliable guides for policymaking, scenarios such as these need to be supplemented by more detailed analyses realistically addressing the key constraints on energy system transformation.

> these studies tend to only superficially address the key technical, economic, infrastructural, and societal factors that may constrain a rapid energy system transition or how such constraints can be plausibly overcome. We recognize that detailed treatment of these factors is beyond the scope and purpose of many of these studies, which are intended to address at a relatively high-level the scope and pace of energy system transformation required under different assumptions or to suggest the portfolio of technologies necessary to decarbonize the energy sector. However, this point may be lost on lay audiences and the media through which these studies are reported. To be reliable guides for policymaking, these types of scenarios clearly need to be supplemented by more detailed analyses addressing the key constraints on energy system transformation, including technological readiness, economic costs, infrastructure and operational issues, and societal acceptability with respect to each of the relevant technology pathways.

(Pfenninger, 2017a) Pfenninger, S. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. *Applied Energy* **197**, 1-13, (2017).

there is no one-size-fits-all approach to the problem of time step reduction, but heuristic approaches appear promising. In addition, the 25 years of time series demonstrate considerable inter-year variability in wind and PV power output. This further complicates the problem of time detail in energy models as it suggests long time series are necessary. Model results with high shares of PV and wind generation using a single or few years of data are likely unreliable. Better modeling and planning methods are required to determine robust scenarios with high shares of variable renewables.

(Collins, Deane, Ó Gallachóir, Pfenninger, & Staffell, 2018) Collins, S., Deane, P., Ó Gallachóir, B., Pfenninger, S. & Staffell, I. Impacts of Inter-annual Wind and Solar Variations on the European Power System. *Joule*, (2018).

(Collins et al., 2017) Collins, S. *et al.* Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renewable and Sustainable Energy Reviews* **76**, 839-856, (2017).

Long term integrated energy systems models are useful in improving our understanding of decarbonisation but they struggle to take account of short term variations in the power system associated with increased variable renewable energy penetration. This can oversimplify the ability of power systems to accommodate variable renewables and result in mistaken signals regarding the levels of flexibility required in power systems. Capturing power system impacts of variability within integrated energy system models is challenging due to temporal and technical simplifying assumptions needed to make such models computationally manageable.

(Pfenninger & Staffell, 2016) Pfenninger, S. & Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **114**, 1251-1265, (2016).

Solar PV is rapidly growing globally, creating difficult questions around how to efficiently integrate it into national electricity grids. Its time-varying power output is difficult to model credibly because it depends on complex and variable weather systems, leading to difficulty in understanding its potential and limitations.

(van der Wiel et al., 2019) 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

(Jenkins & Thernstrom, 2017) Jenkins, J. D., & Thernstrom, S. (2017). Deep Decarbonization of the Electric Power Sector: Insights from Recent Literature: Energy Innovation Reform Project. https://www.innovationreform.org/wp-content/uploads/2018/02/EIRP-Deep-Decarb-Lit-Review-Jenkins-Thernstrom-March-2017.pdf.

Good on uncertainties with respect to storage under high VRE penetration. Basically supports findings of Clack et al. re: Jacobson.

9. Socio-technical transitions approaches to investigating energy transitions

In this section we expand the field of view to also take in socio-technical transitions (STT) approaches to investigating energy futures. The STT literature displays a far more heterodox and philosophically reflexive approach to engaging with societal futures than is evident in the literature relating generally to planning and management of 'energy-society systems'. We consider how these approaches relate to quantitative modelling, in terms of major differences, but also shared attributes brought into view by our more general futures studies sense-making frame. Within the STT literature, we find significant pointers towards investigative approaches better suited to engaging with the post-normal character of the energy transition dilemma.

STT views are concordant with the outlook from the futures field

Energy futures investigation from a philosophy of science, knowledge practices or epistemological view point: perspectives from within the energy-society futures investigation domain that are concordant with the outlook from the broader futures field.

Sources:

(McDowall & Geels, 2017) 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

> p. 46: "3.3. Challenge 9: Different philosophies of science and the limitations of positivism"
>
> Another fundamental challenge for modellers relates to the variety of philosophies of science and research styles. Many models (especially in economics and system analysis) are rooted in a positivist philosophy of science, which assumes an independent objective world, with deterministic relations between variables that should be investigated with quantitative methods, experiments and model simulations (Table 1). Many scholars have discussed the limitations of positivism for understanding social change (e.g. Danermark et al., 2002, Sayer, 1992, Flyvbjerg, 2001, Kagan, 2009). Scholars have therefore developed other philosophies of science, based on different assumptions of the nature of reality, epistemology and methodology (Table 1). Since societal transitions are complex processes, we suggest they can fruitfully be studied through different approaches and philosophies of science. The MLP, for instance, works from a critical realist approach, assuming a layered reality and aiming to identify causal mechanisms and patterns in transitions, which are studied as longitudinal event chains (e.g. Geels, 2005). Transition scholars working from other scientific styles have focused on asking normative questions, emancipating silenced voices, opening up debates to show multiplicity or hidden power structures (Genus and Coles, 2008, Stirling, 2008, Leach et al., 2010).
>
> The philosophical position of Holtz et al. (2015) is somewhat ambivalent in our view. On the one hand, system dynamics and agent-based modellers have traditionally argued either that their approaches do not necessarily adhere to a particular philosophical position (Lane,

2001), or that critical realism is an appropriate philosophical underpinning for such simulation (Mingers, 2000, Miller, 2015). This latter view is echoed in the transitions field by Papachristos and Adamides (2016), who explicitly advocate simulation modelling based on critical realist assumptions. On the other hand, we suggest that Holtz et al. (2015) display many features characteristic of positivism, such as a tendency to conflate causality with generality, an emphasis on experimentation and formalization; and an abstraction from specific contexts. Perhaps this ambivalence reflects the diversity of positions within the transition modelling community. In any case, our intention is to highlight that positivism is not the only scientific approach, to draw attention to some of postivism's underlying assumptions and associated blind spots, and to highlight the value of both plural approaches and critical reflection on such foundational assumptions. We suggest that there is value in further reflection on the underlying philosophical assumptions associated with the various modelling approaches, and how these assumptions relate to the transitions field.

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

"a review of why social constructivism has a significant role to play in building consensus and enhancing understanding between competing energy policy perspectives"

"Constructivism posits that human beings "construct" understanding through a recursive process that involves comparing experiences (including interactions with others) with existing beliefs (Piaget, 1951). Social constructivism represents a subfield wherein scholars believe that worldviews are largely constructed through interactions with others. Under the social constructivist paradigm, the process of confirmation or disconfirmation of worldviews emerges as central to learning and sense making (Jonassen, 1999). Individuals acquire information or experiential knowledge through interactive cues (peer groups, schools, books, media etc.) and then over time, the aggregate body of cues serve to confirm or disconfirm understanding (Tam, 2000). This thus distinguishes constructivism or constructivist approaches from others summarized in Table 1 such as positivism, critical realism, and relativism (Geels et al., 2016)."

"Energy evangelism: Energy is such a heated topic that the outcome can become a matter of religious or political faith - downgrading or ignoring opposing information."

(Geels et al., 2016) Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. [Perspective]. *Nature Climate Change, 6*, 576. doi: 10.1038/nclimate2980

- The socio-technical transitions (STT) literature offers a highly relevant source of alternative thinking and approaches to explore in seeking better ways to engage with the post-normal character of the energy transition dilemma. The STT literature displays a far more heterodox and philosophically reflexive approach to engaging with societal futures than is evident in the literature relating generally to planning and management of 'energy-society systems'.

Nonetheless, the treatment of macro-structural considerations as largely exogenous plays a similar role to the reliance on structural continuity and structural constancy in quantitative modelling. For instance, this diverts attention away from considering how envisaged transitions could plausibly influence their own enabling contexts in ways that are self-limiting. Alternative futures involving macro-scale structural discontinuities tend therefore to be granted a more peripheral status as 'probabilistic outliers', rather than as more central analytical concerns. The implications of this for the treatment of alternative futures are evident in the way that Turnheim et al. (Turnheim et al., 2015) take integrated assessment modelling as self-sufficient for defining the range of energy-society futures that are 'envisionable' or 'worth envisioning' for analytic purposes. This in turn treats such futures as practically realisable by default (even if neither pathways to such futures nor the specific details of their manifestation are pre-determined), therefore assuming that there are transition pathways from the present involving relatively continuous, incremental change by which desired later states can be realised. That is, incumbent actual-world structures are taken to have sufficient scope for modification and adjustment for the envisaged transitions to be navigated under collective human agency.

- Further, and arguably more significantly, the analytical approaches employed in relation to such efforts rely on structural constancy for their legitimacy and reliability: analysis is unavoidably grounded in structural contexts that lie beyond the boundary of analysis itself, and that are therefore necessarily assumed as given. The knowledge products of analysis are always products-in-context, and so the applicability of those products to new situations is unavoidably dependent on the degree of constancy of those contexts. As such, there are 'horizons' beyond which analyses relating to historical transition pathways and present behaviour cannot adequately see on their own.
- In light of this, we make the observation that the introduction of STT analysis approaches cannot 'correct' for what mainstream quantitative analysis struggles to do on its own terms, namely to understand its own quantitative analytical limits, and especially, to seek out the edge of the performance envelope for incumbent techno-economic and political-economic systems. More is called for here, beyond the otherwise very important contributions of methodological pluralism for informing and guiding effective transition action.
- The socio-technical transitions (STT) literature displays a far more heterodox and philosophically reflexive approach to engaging with societal futures than is evident in the literature relating generally to planning and management of 'energy-society systems'. In fact, quantitative modelling can be viewed here as a relative late-comer, having to make the case for its inclusion alongside more established qualitative approaches (Holtz et al., 2015; Köhler et al., 2018; McDowall & Geels, 2017; Papachristos, 2018). Interdisciplinarity, transdisciplinarity and methodological pluralism are notable themes discussed in the Sustainability Transitions Research Network's recently updated research agenda (Köhler et al., 2019). A commitment to methodological pluralism is evident in recent work that proposes a bridging approach to integrate the respective strengths of quantitative and qualitative analytical approaches (Geels, Berkhout, & van Vuuren, 2016; Turnheim et al., 2015; van Sluisveld et al., 2018).
- Nevertheless, within the STT literature, while there is recognition of alternative futures involving macro-level structural discontinuities as plausible (J. C. J. M. van den Bergh, Truffer, & Kallis, 2011), these are more commonly treated as relatively slow-moving

independent or exogenous influences originating beyond the scope of the analysis itself. This can be considered, for instance, in terms of the multi-level perspective's heuristic of niche, regime and landscape. In this approach, the analytical emphasis is on plausible alternatives at the niche level, as drivers of disruption shaping longer-term evolutionary change of socio-technical regimes. This occurs within the context of shifts in the relatively slow-moving socio-technical landscape that destabilise the existing regime, but that are explicitly regarded as technology-external (Geels, 2002). It is only once a new sociotechnical regime is established that its influence on the landscape level might come into play (Geels, 2002). Examples of landscape factors described in the MLP literature include 'oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems' (Geels, 2002, p. 1260); and 'factors that change over the very long term, such as climate or topography; rapid external shocks, such as wars or drought; or long- term changes in a certain direction, such as demography (Vandeventer, Cattaneo, & Zografos, 2019, pp. 273-274).

- STT analysis tends to be employed in support of the conventional focus of established modelling techniques, and hybrid approaches have recently been proposed by originators of the best known and most influential of the STT approach to energy-society futures, the MLP.
- But Vandeventer et al effectively extent the structural constancy critique as it applies to quantitative modelling to the MLP as the dominant socio-technical transition investigation approach.

Sources:

(Li et al., 2015)Li, F. G. N., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change, 100*, 290-305. doi: https://doi.org/10.1016/j.techfore.2015.07.017

(Timma, Blumberga, Bazbauers, & Blumberga, 2017)Timma, L., Blumberga, A., Bazbauers, G., & Blumberga, D. (2017). Novel tools to study socio-technical transitions in energy systems. *Energy Procedia, 128*, 418-422. doi: https://doi.org/10.1016/j.egypro.2017.09.048

(van Sluisveld et al., 2018)van Sluisveld, M. A. E., Hof, A. F., Carrara, S., Geels, F. W., Nilsson, M., Rogge, K., . . . van Vuuren, D. P. (2018). Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technological Forecasting and Social Change*. doi: https://doi.org/10.1016/j.techfore.2017.10.024

(Li & Strachan, 2017)Li, F. G. N., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions, 24*, 106-129. doi: https://doi.org/10.1016/j.eist.2016.08.002

(Bolton & Foxon, 2015)Bolton, R. & Foxon, T. J. Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. *Technological Forecasting and Social Change* **90, Part B**, 538-550, (2015).

(Rosenbloom, Haley, & Meadowcroft, 2018)Rosenbloom, D., Haley, B. & Meadowcroft, J. Critical choices and the politics of decarbonization pathways: Exploring branching points surrounding low-carbon transitions in Canadian electricity systems. *Energy Research & Social Science* **37**, 22-36, (2018).

(Geels et al., 2016) Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. [Perspective]. *Nature Climate Change, 6*, 576. doi: 10.1038/nclimate2980

(Turnheim et al., 2015) Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., & van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change, 35*, 239-253. doi: https://doi.org/10.1016/j.gloenvcha.2015.08.010

(Papachristos, 2018) Papachristos, G. (2018). System dynamics modelling and simulation for sociotechnical transitions research. *Environmental Innovation and Societal Transitions*. doi: https://doi.org/10.1016/j.eist.2018.10.001

(Köhler et al., 2018) Köhler, J., de Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G., & Chappin, E. (2018). Modelling Sustainability Transitions: An Assessment of Approaches and Challenges. *Journal of Artificial Societies and Social Simulation, 21*(1), 8. doi: 10.18564/jasss.3629

10. Narrative scenario approaches to investigating energy futures

In this section we give closer attention to narrative scenario approaches to energy-society futures investigation, considering both strengths and limitations, again framed from our future studies perspective. There are clear lessons that can be drawn upon in this area, but no clear solutions to an emerging picture of futures characterised by limits to human knowing ranging from deep uncertainties to fundamental ignorance.

Narrative scenario approaches to investigating energy futures; critiques of narrative scenarios. What role for these analytical approaches in opening to broader narratives on energy futures?

- Narrative scenario generation is an analytical prospective technique originating in the futures studies field that departs from the dominant emphasis on quantitative modelling, and that, amongst the analytical techniques focused on probable and plausible futures, has perhaps the best potential to deal with novel, divergent and discontinuous energy-society futures, from within the analytical realm itself. However, in order to do so effectively, openness to other realms of inquiry is necessary.
- With respect to scenario-related approaches to prospective inquiry, it is important to distinguish between use of quantitative models to *generate* scenarios, and use of models *within* narrative scenarios to elaborate features quantitatively.
- The use of 'bounded purpose' and issue-specific quantitative models within narrative scenario approaches offers a way to address the 'structural constancy' limitation of

computer modelling techniques to open mainstream thinking to a broader range of plausible energy-society futures.

Sources:

(Thomas J. Chermack, 2005) Chermack, T. J. Studying scenario planning: Theory, research suggestions, and hypotheses. *Technological Forecasting and Social Change* **72**, 59-73, (2005).

(T. J. Chermack & van der Merwe, 2003) Chermack, T. J. & van der Merwe, L. The role of constructivist learning in scenario planning. *Futures* **35**, 445-460, (2003).

(Pfenninger et al., 2014) Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi: https://doi.org/10.1016/j.rser.2014.02.003

(Jefferson, 2014) 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

(Dator, 2014) Dator, J. (2014). “New beginnings” within a new normal for the four futures. *Foresight, 16*(6), 486-511. doi: 10.1108/FS-09-2013-0046

Narrative scenarios including energy and climate within ‘Holy Trinity, Plus One’; scenario method is widely used and explicitly accounts for crisis potential.

(Morgan & Keith, 2008) Morgan, M. G. & Keith, D. W. Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change* **90**, 189-215, (2008).

Excellent history of narrative scenarios, and critique of their too-narrow views of plausible futures.

(Nikoleris, Stripple, & Tenngart, 2017) Nikoleris, A., Stripple, J. & Tenngart, P. Narrating climate futures: shared socioeconomic pathways and literary fiction. *Climatic Change* **143**, 307-319, (2017).

(C. A. Miller, O’Leary, Graffy, Stechel, & Dirks, 2015) Miller, C. A., O’Leary, J., Graffy, E., Stechel, E. B., & Dirks, G. (2015). Narrative futures and the governance of energy transitions. *Futures, 70*, 65-74. doi: https://doi.org/10.1016/j.futures.2014.12.001

(Mahony, 2014) Mahony, T. O. (2014). Integrated scenarios for energy: A methodology for the short term. *Futures, 55*, 41-57. doi: https://doi.org/10.1016/j.futures.2013.11.002

(Hughes & Strachan, 2010) Hughes, N., & Strachan, N. (2010). Methodological review of UK and international low carbon scenarios. *Energy Policy, 38*(10), 6056-6065. doi: https://doi.org/10.1016/j.enpol.2010.05.061

(Fortes, Alvarenga, Seixas, & Rodrigues, 2015) Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and

energy modeling. *Technological Forecasting and Social Change, 91*, 161-178. doi: https://doi.org/10.1016/j.techfore.2014.02.006

(Robertson et al., 2017) Robertson, E., O'Grady, Á., Barton, J., Galloway, S., Emmanuel-Yusuf, D., Leach, M., . . . Foxon, T. (2017). Reconciling qualitative storylines and quantitative descriptions: An iterative approach. *Technological Forecasting and Social Change, 118*, 293-306. doi: https://doi.org/10.1016/j.techfore.2017.02.030

(Söderholm, Hildingsson, Johansson, Khan, & Wilhelmsson, 2011) Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., & Wilhelmsson, F. (2011). Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. *Futures, 43*(10), 1105-1116. doi: https://doi.org/10.1016/j.futures.2011.07.009

(Laugs & Moll, 2017) 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

> The global energy supply system is characterized by a complex coupling of technical, social, economic and political factors. The result of this characterization is that the global energy system is inherently slow to react on external as well as internal stimuli [41]. Changes in the periphery of energy may take (very) long to become apparent on a global scale. Correct modeling of energy systems would take the associated complexity into account. Since the vast majority of recently published energy scenarios are associated with modeling exercises, those scenarios would – or perhaps, should – reflect certain inertia. The exception to this may be backcasting scenarios, which take a point in the future and draw backwards from there. Such an approach would inevitably have to allow some degree of flexibility with regard to the ability or inability of the current energy system to react to changing environments. The composition of the set of scenarios investigated during this research confirms this notion: the few scenarios that suggest futures distinct from variations on current developments are typically backcasting scenarios.
>
> Typically, the more a scenario is a radical departure from current trends and developments, the more difficult it becomes to adequately outline the required changes in peripheral variables, and thus to set such variables in a model, and eventually to produce credible quantitative data [42]. We may therefore argue that quantitative future energy scenarios that are the result of a modeling exercise are inherently limited by the realistic spectrum of different states of the world that define the scenario’s context. The focus of this research on quantitative data thus precludes to some extent scenarios that represent a strong departure from current trends and developments, unlikely futures, or perhaps controversial visions of future energy system development pathways. As such, the absence of extreme ‘outlier’ scenarios in the set of scenarios analyzed is a logical consequence of the focus of this research. However, the focus of this research on quantitative data only partially accounts for the rather subtle differences between (the clusters of) scenarios investigated.
>
> …
>
> Although extreme incarnations of Cornucopian and Malthusian discourses define two

> ends of a scale, manifestations of those discourses often represent moderate of hybrid versions from the middle of the scale. The separation between the two discourses is usually not very explicit and the two world views may, in moderation, overlap [42]. Although moderate Cornucopian and Malthusian world views may both agree with interventions to alter future prospects, the Cornucopian world view appears to be largely underrepresented in the realm of future energy scenarios. Some scholars have argued that under- or overrepresentation of particular world views skews the outlook on energy futures and hampers a full view on the range of possibilities [43]. They point out that analysis of past projections compared with subsequent realities indicates that Cornucopian perspectives on future energy pathways were closer to eventual reality than Malthusian perspectives.

(Grubler et al., 2018) Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* **3**, 515-527, (2018).

(Guivarch, Lempert, & Trutnevyte, 2017) Guivarch, C., Lempert, R., & Trutnevyte, E. (2017). Scenario techniques for energy and environmental research: An overview of recent developments to broaden the capacity to deal with complexity and uncertainty. *Environmental Modelling & Software, 97*, 201-210. doi: https://doi.org/10.1016/j.envsoft.2017.07.017

> "Obviously, scenarios approaches will always have limitations, either because there is a tendency to ignore unpleasant or politically unpopular futures, or because scenarios developers would be subject to overconfidence or lack of imagination, or else because the underlying model structures used convey their own limitations and biases."

(Trutnevyte et al., 2014) Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., & Robertson, E. (2014). Linking a storyline with multiple models: A cross-scale study of the UK power system transition. *Technological Forecasting and Social Change, 89*, 26-42. doi: https://doi.org/10.1016/j.techfore.2014.08.018

(Nakicenovic, Lempert, & Janetos, 2014) Nakicenovic, N., Lempert, R. J., & Janetos, A. C. (2014). A Framework for the Development of New Socio-economic Scenarios for Climate Change Research: Introductory Essay. [journal article]. *Climatic Change, 122*(3), 351-361. doi: 10.1007/s10584-013-0982-2

(B. C. O'Neill et al., 2014) O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., . . . van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. [journal article]. *Climatic Change, 122*(3), 387-400. doi: 10.1007/s10584-013-0905-2

(B. C. O'Neill et al., 2017) O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169-180. doi: https://doi.org/10.1016/j.gloenvcha.2015.01.004

(Riahi et al., 2017) Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153-168. doi: https://doi.org/10.1016/j.gloenvcha.2016.05.009

(Kok, Pedde, Gramberger, Harrison, & Holman, 2019) Kok, K., Pedde, S., Gramberger, M., Harrison, P. A. & Holman, I. P. New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. *Regional Environmental Change* **19**, 643-654, (2019).

(Pargman et al., 2017) Pargman, D. *et al.* What if there had only been half the oil? Rewriting history to envision the consequences of peak oil. *Energy Research & Social Science* **31**, 170-178, (2017).

(Moallemi & Malekpour, 2018) Moallemi, E. A. & Malekpour, S. A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science* **35**, 205-216, (2018).

(Voros, 2009) Voros, J. Morphological prospection: profiling the shapes of things to come. *Foresight* **11**, 4-20, (2009).

Ward, J et al. (2019), 'Should 'degrowth' narratives be considered alongside the SSPs?', conference poster, Forum on Scenarios for Climate and Societal Futures 2019, Denver, March 11-13. "Do we have a blind spot to scenarios that don't involve growth?"

11. What is the nature of the work done by analytical and quantitative approaches to energy-society investigation?

At this juncture, we pause to reflect on what a sense-making framework grounded in a wide view of legitimate knowledge creation paradigms might imply about the work that analytical and quantitative energy-society investigation approaches do in socio-politically complex industrial societies. Can this framework shed light on why it is that approaches emerging from and representative of particular paradigms continue to carry such weight, and clearly do so much societally-legitimate and productive work, despite their necessary and inherent partiality? Here we propose the view that these approaches continue to be so successful and influential for reasons other than their power for generating useful and reliable knowledge (functions that they clearly also fulfil). We draw on a developmental systems perspective to discuss the role that they play in supporting viable social systems—systems that, as a consequence of their ongoing viability, in turn confer legitimacy on these very approaches. We contrast this role in supporting viability with the more outwardly apparent role that such approaches play in delivering optimal social systems, and question whether this goal of optimality is in fact realizable in practice, as distinct from acting as a normative value for identifying preferred futures and coordinating social action in the present.

The work that analytical and quantitative energy-society investigation approaches do in socio-politically complex industrial societies. Viability not optimality and conservation of adaptation between social entities and their environments.

- A key insight has also come to light around the success criteria for quantitative investigation approaches including forecasting, and why the ultimate accuracy of those methods has little bearing on their institutional legitimacy. The poor track record for long term forecasts does little to undermine the status of forecasting, because despite the "rationalist" story that's told about how and why technocratic societies do what they do, there is always an informal pragmatism operating in the background that's where the "real game" is playing out. From a point of view grounded in pragmatism, it is the sufficiency of decisions made and actions taken in the present, informed by the quant input, that matters. What constitutes 'sufficiency' is a pragmatic question -- it's about whether a social entity remains viable, not about whether the values of a set of characteristic quantitative parameters were accurately anticipated.
- It doesn't matter whether an analytical technique accurately anticipates in the present a situation that is realised at some later time. What matters is the utility of that technique for producing knowledge that contributes to the effective coordination of social action.
- Here, 'effective coordination' relates to the evaluative criterion not of 'optimality', but of 'viability'. Any entity that maintains viability through conservation of adaptation is subject to continuous change – there is no fixed, essential identity that is unchanging moment to moment. What is conserved is the network of relationships and processes that produce the conditions necessary for the network's ongoing trajectory of differentiation from and integration with the environment for which it is adapted and with which it is structurally coupled as both entity and environment undergo mutually influencing evolutionary drift. As such, there is no fixed evaluative reference condition for assessing optimality of fit between entity and environment.
- Quantitative forecasting and optimization techniques play such a central in the investigation of energy-society futures because the social forms that their practice seeks to conserve happen to be forms within which technical, rationalist-empiricist, quantitative knowledges are especially esteemed and valued. That is, the practice of such techniques as the basis for planning and managing the continuity of such social forms is itself necessary for the ongoing production of those social forms.
- Forecasting: conventional success criterion assumed to be *accuracy of prediction*; success can be considered though in relation to how a forecasting initiative – or any approach to exploring futures – contributes to ongoing viability, as social entities conserve adaptation with their environments.
- More generally, quantitative futures investigation methods are means of coordinating social action in order to maintain ongoing conservation of adaptation between social entity and environment; viability not optimality as criterion for success. To remain viable is to continue to produce the conditions that enable an entity's ongoing trajectory of differentiation from and integration with its environment. Quantitative modelling techniques especially, but analytical techniques more generally, are the institutionally legitimate means for informing decisions and actions by which modern social systems conserve adaptation to the environments with which they are structurally coupled in evolutionary drift. These techniques are privileged and prioritised, because the social systems that are seeking to maintain ongoing viability are systems in which the knowledge produced by these techniques is regarded as being of pre-eminent value. Part of what such societies seek to maintain as structurally constant or continuous is the reliability and hence legitimacy of knowledge produced by quantitative techniques for investigating futures, which in turn depends on structural constancy for its reliability.

Sources:

(Wynne, 1984) Wynne, B. (1984). The institutional context of science, models, and policy: The IIASA energy study. [journal article]. *Policy Sciences, 17*(3), 277-320. doi: 10.1007/bf00138709

> This article is a complement to Keepin's technical analysis of the energy models and scenarios in the IIASA global energy study, Energy in a Finite World. It analyses the role of formal global energy models in the scenarios and policy conclusions as described in the IIASA Energy System Program's (ESP) own statements. It finds inconsistencies which have confused external audiences, including modelers, as to the importance of properties of formal models in generating authority for policy conclusions. The analysis finds two contradictory images of scientific authority pervading the ESP's published accounts. This article argues that models are more symbolic vehicles for gaining authority than objective technical frameworks. Whilst this is in principle legitimate, it means that the internal processes (and not just the products) of modeling projects are a legitimate subject of public evaluation. Due attention must therefore be paid to the quality and disclosure of such processes. The institutional process of analysis reflects a particular policy style itself and constrains what policies are even conceivable. Claims to scientific analysis and definition of policy problems are themselves symptomatic of a policy framework which is biased at a deeper level than that of specific prescriptions.

(Grunwald, 2011) 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

> Providing much more insight into the cognitive and normative structure of energy futures is required for allowing a more transparent and deliberative societal debate about future energy systems.
>
> due to the enormous number of energy futures (see Section 2) such as scenarios and the huge spread in what they assume about future energy systems, the problem of arbitrariness arises. The diversity of energy futures threatens any possibility for orientation, and could lead to disorientation instead of helping more rational decision-making. This diversity also opens the door for ideologies using energy futures such as scenarios for transporting particular interests, often hidden behind model-based simulations claiming objectivity.
>
> The main theses to be developed in this paper are:
>
> a. futures in general and energy futures in particular are social constructs and thus inevitable parts of the respective present time
> b. the diversity of energy futures cannot be resolved by an optimizing procedure which sometimes is expected to provide the "one best" future scenario
> c. the popular decision-making mode, that energy futures should enable decision-makers to simply "derive" the adequate decision or at least to give orientation does not work in the naïve sense
> d. instead, energy futures can contribute to decision-making in a much more sophisticated and complex way via democratic debate and deliberation
> e. in order to exploit this potential an epistemological scrutiny and enlightenment is needed for uncovering the "ingredients", the premises and presuppositions, the knowledge but also the hopes, assumptions, biases and concerns included in the energy futures as well as possible hidden interests.

3.1. Futures as social constructs

> Futures do not exist per se, they are not discovered and they do not arise of their own accord. On the contrary, futures are "made" and linguistically constructed in a more or less complex manner (or are linguistically explicable, e.g. in the case of mathematical equations or diagrams). The design of futures is purposive action, especially to provide orientation (Fig. 2) and against the background of specific limiting conditions. Futures, whether they are forecasts, scenarios, plans, programs, or speculative fears or expectations, are "produced" using a whole range of ingredients such as the available knowledge, value judgements or suppositions. The common reference to "scenario building" emphasizes this construction process.
>
> …
>
> even scientifically produced futures such as model-based scenarios are social constructs… The frequent situation that the basic models used by the institutions providing energy scenarios are not public but are part of the business model of the institutions in a competitive field [24], [25] is a serious obstacle to a transparent debate about the resulting energy scenarios.
>
> …
>
> the quality of energy futures cannot be assessed by looking at the predicted or projected substantial future developments. Rather, any quality assessment has to accept that energy futures are social constructs and are part of the present time. Quality therefore only can mean procedural quality looking at the *process* of construction and at the "*ingredients*" having been used in that process. Quality assessment of energy futures means scrutiny and assessment of the quality of the inputs and of their composition. It consists of a critical reconstruction of the genesis of the energy futures [24], [25].
>
> It is the interplay between construction of energy futures and their scrutiny and assessment (Fig. 4) which can be used as a medium of *learning* about our own positions, biases, hopes, fears and expectations and our pictures of future society and humankind which are necessarily involved in our pictures of future energy supply.

(Ehrenfeld & Hoffman, 2013) Ehrenfeld, J. R., & Hoffman, A. J. (2013). *Flourishing: A Frank Conversation About Sustainability*. Stanford: Stanford University Press.

> On philosophical pragmatism: By developing an experiential viewpoint from which to understand our world, we find the truth in practice through a continuing inquiry process, and apply it to underpin and explain our successful actions. Truth is then manifest in outcomes that work as desired. Pragmatism is a way of acting deliberately and consciously within the partial truths of scientific analysis, always watching the results and adjusting to maintain the course toward the ends being sought. We seek truth by continually inquiring, experimenting, and acting until we arrive at the end we envisioned…(p. 103)

12. Approaches to exploring energy futures from social sciencies

In this section, using the broader prospective outlook provided by the futures field as our guide, we look beyond the analytical approaches surveyed to this point, to take in a range of other approaches from within the social sciences and humanities. This starts to address some of the gaps revealed by the futures field's encompassing paradigmatic view.

Social scientific approaches to exploring energy futures that go beyond the analytical focus

- Beyond the analytical focus on probable and plausible futures, there are the realms of the possible and preferable. Here, the broader social sciences and political and cultural domains of knowledge and practice draw attention to a wider range of narratives about energy futures.

Sources:

(Pereira, Sitas, Ravera, Jimenez-Aceituno, & Merrie, 2019) Pereira, L., Sitas, N., Ravera, F., Jimenez-Aceituno, A., & Merrie, A. (2019). Building capacities for transformative change towards sustainability: Imagination in Intergovernmental Science-Policy Scenario Processes. Elementa Science of the Anthropocene, 7(1), 35. doi: http://doi.org/10.1525/elementa.374

> Scenario development has been recognized as a potential method to explore future change and stimulate a reflective process that can contribute to more informed decision-making. The assessment process under IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) has however shown that the current predominantly biophysical and economic models and scenario processes for exploring the future of biodiversity, ecosystem services and their contributions to human wellbeing are insufficient to capture the complexity and context-specific nature of the problems facing these sectors. Several important challenges have been identified that require a more in-depth analysis of where more imaginative scenario efforts can be undertaken to address this gap. In this paper, we identify six key characteristics necessary for scenario processes: adaptability across diverse contexts, inclusion of diverse knowledge and value systems, legitimate stakeholder engagement that foregrounds the role of power and politics, an ability to grapple with uncertainty, individual and collective thinking mechanisms and relevance to policy making. We compared four cases of imaginative, arts-based scenario processes that each offer aspects of meeting these criteria. These approaches emphasise the importance of engaging the imagination of those involved in a process and harnessing it as a tool for identifying and conceptualising more transformative future trajectories. Drawing on the existing literature, we argue that there is value in fostering more inclusive and creative participatory processes that acknowledge the importance of understanding multiple value systems and relationships in order to reimagine a more inclusive and just future. Based on this, we reflect on future research to understand the transformative role that imagination can play in altering and enhancing knowledge-making for global assessments, including IPBES. We conclude that creative scenario co-development processes that promote imagination and create an opening for more empathetic responses should be considered as complementary tools within the suite of methodologies used for future IPBES scenario development.

(Tidwell & Tidwell, 2018) Tidwell, J. H., & Tidwell, A. S. D. (2018). Energy ideals, visions, narratives, and rhetoric: Examining sociotechnical imaginaries theory and methodology in energy research. *Energy Research & Social Science, 39*, 103-107. doi: https://doi.org/10.1016/j.erss.2017.11.005

as we reflect back on the journal to date, and the larger body of literature in Science and Technology Studies, Anthropology, History, English and a myriad of other disciplines concerned with the role of energy in constituting that problematic condition we call "modernity," is it enough to simply acknowledge there are humans *in* energy systems? More to the point, is the project of energy social science research fundamentally concerned with the views of individuals in specific social, political, and institutional contexts or with the larger norms, values, and systems of morality that, exercised through existent social and political infrastructures, dominate daily life?

(Nilsson, Nilsson, Hildingsson, Stripple, & Eikeland, 2011) Nilsson, M., Nilsson, L. J., Hildingsson, R., Stripple, J., & Eikeland, P. O. (2011). The missing link: Bringing institutions and politics into energy future studies. *Futures, 43*(10), 1117-1128. doi: https://doi.org/10.1016/j.futures.2011.07.010

(Van Poeck, Östman, & Block, 2018) Van Poeck, K., Östman, L. & Block, T. Opening up the black box of learning-by-doing in sustainability transitions. *Environmental Innovation and Societal Transitions*, (2018).

(Moezzi, Janda, & Rotmann, 2017) Moezzi, M., Janda, K. B. & Rotmann, S. Using stories, narratives, and storytelling in energy and climate change research. *Energy Research & Social Science* **31**, 1-10, (2017).

(Raven, 2017) Raven, P. G. Telling tomorrows: Science fiction as an energy futures research tool. *Energy Research & Social Science* **31**, 164-169, (2017).

> This paper makes a case for the utility of prose science fiction both as a methodological tool of representation and portrayal for energy futures research which meets these criteria, and as a storehouse of tools and strategies for the critique of energy futures.

(Burke & Stephens, 2018) Burke, M. J. & Stephens, J. C. Political power and renewable energy futures: A critical review. *Energy Research & Social Science* **35**, 78-93, (2018).

(Delina & Janetos, 2018) Delina, L. & Janetos, A. Cosmopolitan, dynamic, and contested energy futures: Navigating the pluralities and polarities in the energy systems of tomorrow. *Energy Research & Social Science* **35**, 1-10, (2018).

> Each of us has their own visions, imaginations, dreams, predictions, anticipations, fabulations, and fantasies, even nightmares, with what the futures of energy may, can, and ought to look like (see for example Volume 31 in this journal on narratives including those by Moessi et al. [27] and Raven [9]) as well as in other outlets (in *Futures*, for example, about 1466 energy-related articles have explicitly mentioned the sense of futurity in their titles). Individually or collectively, it seems our fascination with the future is not easily satiated. We envisage what could be 'the' feasible, 'the' probable, 'the' plausible, and 'the' preferable futures for ourselves, our households, our communities, and our nations. We base these visions on our experiences, expertise, and biases, using different lenses—both fictional and logical. In short, these futures of energy are cultural, political, and economic—not just

technological—and are exceedingly and inarguably value-laden. While there's nothing new in this claim (see [28]; cf. [29]), this acknowledgment and understanding opens up new challenges both in ways 'energy' is conceptually, theoretically, and empirically examined and studied, and practically in terms of designing and implementing new policy, market, and governance infrastructures, and interventions to meet the needs and ends of these highly-contested futures (cf. [10], [6]).

(Stirling, 2014) Stirling, A. Transforming power: Social science and the politics of energy choices. *Energy Research & Social Science* **1**, 83-95, (2014).

The roles of social science in interdisciplinary energy research, are not just about the social complexities encountered in pursuing goals driven primarily by natural science or engineering. Social research also assists in framing priorities, questions and options for these other disciplines – in turn informing its own driving aims and those of society more widely.

(Pargman et al., 2017) Pargman, D. *et al.* What if there had only been half the oil? Rewriting history to envision the consequences of peak oil. *Energy Research & Social Science* **31**, 170-178, (2017).

Janda and Topouzi [42] argue that researchers always "*communicate with and through stories*" and noted psychologist Jerome Bruner stated that narratives ("stories, excuses, *myths*, reasons for doing and not doing") are the basis for how we perceive the world and how we communicate those perceptions ([43], p. 4). Narratives are, from this perspective, much more than a mere tool that is used to inform and entertain. They are instead an "instrument of mind in the *construction of reality*" ([43], p. 6), an organizing principle and a mental data structure that we use to collectively describe, define and *constitute* our reality. Simply put, the stories we tell ourselves about the world (about what matters, what doesn't matter, what is true, what is false, etc.) play a significant role in how we regard our world, and by extension, the decisions we make, the policies we endorse and the actions we undertake.

The implication is that speculative approaches, such as the allohistorical narrative we present here, don't exist only in an isolated "realm of fantasy" − they arise from our current understandings of the world and they can serve as a critical lens on our assumptions about the world. We can understand this kind of intellectual work as a form of *defamiliarization,* "*a literary device that compels the reader to examine their automated perceptions of that which is so familiar that it seems natural and so unquestionable*" (Bell et al. [61], p. 151). Speculative methods such as allohistorical narratives can foreground and illuminate hidden biases while simultaneously proposing alternative modes of thinking.

(Popa, Guillermin, & Dedeurwaerdere, 2015) Popa, F., Guillermin, M. & Dedeurwaerdere, T. A pragmatist approach to transdisciplinarity in sustainability research: From complex systems theory to reflexive science. *Futures* **65**, 45-56, (2015).

The main conclusion of the analysis is the need to combine conventional consensus-oriented deliberative approaches to reflexivity with more open-ended, action-oriented transformative approaches.

In particular, solving sustainability problems involves decisions on values that require civic participation and the building of social legitimacy for proposed transition pathways to sustainable societies. Therefore, both scientists and policy makers have called for re-conceptualizing the role of experts, practitioners and citizens in the production and use of scientific knowledge [2], [3].

(Isoaho & Karhunmaa, 2019) Isoaho, K., & Karhunmaa, K. (2019). A critical review of discursive approaches in energy transitions. *Energy Policy, 128*, 930-942. doi: https://doi.org/10.1016/j.enpol.2019.01.043

13. Humility and the participatory paradigm in energy futures investigation: how to proceed for post-normal times?

Perspectives relevant to intellectual humility. From a focus on techniques, to placing techniques within process that is sensitive to the limits of human knowing. What this implies for the practices by which human societies navigate their futures. Also, the ways in which views of plausible and probable futures interact with ideas of the possible and preferable; implications for investigative practice and process.

- End on knowledge humility point. Implications of treating human knowledge systems not as means of codifying absolute truth, but as the basis for coordinating social action as humans negotiate the demands of living well together in the face of increasingly pressing socio-ecological dilemmas. See Sovacool & Brown (2015), 'Deconstructing facts and frames in energy research: Maxims for evaluating contentious problems', *Energy Policy*
- A shift from *techniques* for investigating the future to *processes* for making sense of and enacting futures. From forecasting to anticipatory action learning (Inayatullah, Voros); and to foresight and *la prospective* (Godet, Berger, Martin). Techniques are contextualised within processes, and it is via process that the integration and synthesis of diverse knowledge practices can be realised beneficially. See McDowall and Geels(?) caution against attempts to integrate techniques grounded in different philosophical orientations; call for respecting plurality of knowledges.
- Participatory paradigm (epistemology) as basis for anticipatory action learning – see Inayatullah, also discussed by Ramos and by Floyd (Floyd, 2012).

Sources:

(Sovacool & Brown, 2015) 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

(Fazey et al., 2018) 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

Very significant article in relation to research approach under conditions of high uncertainty. Call for reflexivity supports our case for modelling that does not assume energy abundance from the outset.

(Li, 2017) Li, F. G. N. (2017). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews, 15*, 57-71. doi: https://doi.org/10.1016/j.esr.2017.01.002

(Sovacool & Geels, 2016) Sovacool, B. K., & Geels, F. W. (2016). Further reflections on the temporality of energy transitions: A response to critics. *Energy Research & Social Science, 22*, 232-237. doi: https://doi.org/10.1016/j.erss.2016.08.013

Particularly useful for consideration of how different knowledges founded on different philosophical premises affect what is seen (both by investigators, and by interpreters of their reported findings).

(McDowall & Geels, 2017) 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

(Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018) 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

See especially introduction and literature review, for overview of knowledge & disciplinary domains relevant to energy transition inquiry, and relationship between energy, low-carbon & sustainability transitions. See also list of journals considered relevant in lit review.

(Castree et al., 2014) Castree, N. *et al.* Changing the intellectual climate. *Nature Climate Change* **4**, 763, (2014).

"Interdisciplinary dialogue, we suggest, should engender plural representations of Earth's present and future that are reflective of divergent human values and aspirations. In turn, this might insure publics and decision-makers against overly narrow conceptions of what is possible and desirable as they consider the profound questions raised by global environmental change."

(Jasanoff, 2018) Jasanoff, S. Just transitions: A humble approach to global energy futures. *Energy Research & Social Science* **35**, 11-14, (2018).

Without asking hard, *scientific* questions about the sources and limits of what we know, we cannot become truly enlightened in our efforts transform our entrenched patterns of energy use.

The questions demanding answers should not be posed from a position of scientific exceptionalism. It would be a mistake to think that science alone can stand apart from the commitments, biases, and imperfections that mark all other human enterprises. The national and international institutions that guide global energy policy, including even the highly respected Intergovernmental Panel on Climate Change (IPCC), would do well to recognize how their findings are marked by particular histories of knowledge production that brightly illuminate some puzzles while leaving others shadowed [7]. Under these

> circumstances the choice of how to characterize the world is never divorced from values. Values are inextricably woven into the production of facts, not only in the topics we choose to study but in the means with which we do so. Making those values explicit is an essential step toward producing transformative solutions for a global society.
>
> Expert knowledge, coupled to state regulatory authority, produces abstract problem framings at the transnational level that lay subjects within nations rarely have the opportunity to question or protest. Paternalistic assumptions guide the choice of solutions that seem plausible to higher echelons of authority, even when disconnected from the ways people actually live and behave.

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

> In assessing what constitutes wisdom for the future, our conversation suggests it is important to acknowledge and address the crises science is currently undergoing. This includes practices which embrace uncertainty, ignorance and complexity. We discuss three approaches which can be deployed, alone or together, to that effect. They are scenario planning as a tool to contemplate multiple possibilities and navigate the future; Post-Normal Science as a theory for understanding uncertainty; and hosting and supporting more meaningful and more courageous conversations.
>
> …
>
> I would argue that one more key trait is required: humility. While a specialist may know all in their field, a wise person with a future lens must accept what they do not know in order to be able to ask the right questions. As my co-author Jerry wisely once articulated, understanding the boundaries of knowledge, where ignorance starts, is important as the knowledge itself (Ravetz, 1986). Humility means acceptance of the limitations of our knowledge and the possibility of failure. It is only then that we will truly learn the lessons to make us wise.

(Amara, 1975) Amara, R. Some observations on the interaction of technology and society. *Futures* **7**, 515-517, (1975).

> To avoid either of these extremes, we need to develop a strategy for the next decade that permits us to do the following :
>
> - to place the greatest emphasis on monitoring technology as it develops and in situ; achieving this objective requires a broad programme of experimentation, assessment, and indicator design.
> - to increase greatly the level of public participation and involvement in technology assessment; the major issues are political and social, not technological, and thus the interplay of values and preferences is paramount for effective social choice.
> - to approach the understanding of technology and society with both “nerve” and humility, undertaking a wise exploration of technological alternatives with a keen sense of the limits of the tools of forecasting, planning, and analysis.

Adams, A. S., & Keith, D. W. (2013). Are global wind power resource estimates overstated? *Environmental Research Letters, 8*(1), 015021. doi: http://dx.doi.org/10.1088/1748-9326/8/1/015021.
Amara, R. (1974). The futures field: Functions, forms, and critical issues. *Futures, 6*(4), 289-301. doi: https://doi.org/10.1016/0016-3287(74)90072-X.
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.
Amara, R. (1981). The futures field: Searching for definitions and boundaries. *The Futurist*(February), 25-29.
Antonakakis, N., Chatziantoniou, I., & Filis, G. (2017). Energy consumption, CO2 emissions, and economic growth: An ethical dilemma. *Renewable and Sustainable Energy Reviews, 68*, 808-824. doi: https://doi.org/10.1016/j.rser.2016.09.105.
Ayres, R. U., Campbell, C. J., Casten, T. R., Horne, P. J., Kümmel, R., Laitner, J. A., . . . von Weiszäcker, E. U. (2013). Sustainability transition and economic growth enigma: Money or energy? *Environmental Innovation and Societal Transitions, 9*, 8-12. doi: https://doi.org/10.1016/j.eist.2013.09.002.
Ayres, R. U., Van den Bergh, J. C. J. M., Lindenberger, D., & Warr, B. (2013). The Underestimated Contribution of Energy to Economic Growth: INSEAD.
Bardi, U. (2013). Mind Sized World Models. *Sustainability, 5*(3), 896-911. doi: https://doi.org/10.3390/su5030896.
Bardi, U., Falsini, S., & Perissi, I. (2018). Toward a General Theory of Societal Collapse. A Biophysical Examination of Tainter s Model of the Diminishing Returns of Complexity.
Bardi, U., Falsini, S., & Perissi, I. (2019). Toward a General Theory of Societal Collapse: A Biophysical Examination of Tainter's Model of the Diminishing Returns of Complexity. *BioPhysical Economics and Resource Quality, 4*(1), 3. doi: 10.1007/s41247-018-0049-0.
Bell, W. (1997). *Foundations of futures studies: human science for a new era, Volume 1: history, purposes, knowledge* (Vol. 1). New Brunswick: Transaction Publishers.
Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management, 4*(4), 494-518. doi: doi:10.1108/17506221011092742.
Bolton, R., & Foxon, T. J. (2015). Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. *Technological Forecasting and Social Change, 90, Part B*, 538-550. doi: http://dx.doi.org/10.1016/j.techfore.2014.02.017.
Brandt, A. R. (2017). How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). [journal article]. *BioPhysical Economics and Resource Quality, 2*(1), 2. doi: 10.1007/s41247-017-0019-y.
Burke, M. J., & Stephens, J. C. (2018). Political power and renewable energy futures: A critical review. *Energy Research & Social Science, 35*, 78-93. doi: https://doi.org/10.1016/j.erss.2017.10.018.
Capellán-Pérez, I., de Blas, I., Nieto, J., de Castro, C., Miguel, L. J., Carpintero, Ó., . . . Álvarez-Antelo, D. (2020). MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. [10.1039/C9EE02627D]. *Energy & Environmental Science*. doi: 10.1039/c9ee02627d.
Capellán-Pérez, I., de blas sanz, I., Nieto, J., Miguel, L., Mediavilla, M., Carpintero, Ó., . . . Parrado Hernando, G. (2018). *MEDEAS-World: a new IAM framework integrating biophysical and socioeconomic constraints*. Paper presented at the Eleventh Annual Meeting of the IAMC (Integrated Assessment Modeling Consortium), Seville, Spain.

https://www.researchgate.net/publication/329483306_MEDEAS-World_a_new_IAM_framework_integrating_biophysical_and_socioeconomic_constraints.
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.
Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó., & Miguel, L. J. (2014). Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy, 77*(0), 641-666. doi: http://dx.doi.org/10.1016/j.energy.2014.09.063.
Carbajales-Dale, M. (2019). When is EROI Not EROI? [journal article]. *BioPhysical Economics and Resource Quality, 4*(4), 16. doi: 10.1007/s41247-019-0065-8.
Castree, N., Adams, W. M., Barry, J., Brockington, D., Büscher, B., Corbera, E., . . . Wynne, B. (2014). Changing the intellectual climate. [Perspective]. *Nature Climate Change, 4*, 763. doi: 10.1038/nclimate2339.
Chermack, T. J. (2005). Studying scenario planning: Theory, research suggestions, and hypotheses. *Technological Forecasting and Social Change, 72*(1), 59-73. doi: https://doi.org/10.1016/j.techfore.2003.11.003.
Chermack, T. J., & van der Merwe, L. (2003). The role of constructivist learning in scenario planning. *Futures, 35*(5), 445-460. doi: https://doi.org/10.1016/S0016-3287(02)00091-5.
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.
Collins, S., Deane, J. P., Poncelet, K., Panos, E., Pietzcker, R. C., Delarue, E., & Ó Gallachóir, Brian P. (2017). Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renewable and Sustainable Energy Reviews, 76*, 839-856. doi: https://doi.org/10.1016/j.rser.2017.03.090.
Collins, S., Deane, P., Ó Gallachóir, B., Pfenninger, S., & Staffell, I. (2018). Impacts of Inter-annual Wind and Solar Variations on the European Power System. *Joule*. doi: https://doi.org/10.1016/j.joule.2018.06.020.
Crespo del Granado, P., van Nieuwkoop, R. H., Kardakos, E. G., & Schaffner, C. (2018). Modelling the energy transition: A nexus of energy system and economic models. *Energy Strategy Reviews, 20*, 229-235. doi: https://doi.org/10.1016/j.esr.2018.03.004.
Dator, J. (2014). "New beginnings" within a new normal for the four futures. *Foresight, 16*(6), 486-511. doi: 10.1108/FS-09-2013-0046.
Davis, S. J. (2018). Predicting unpredictability. *Nature Energy, 3*(4), 257-258. doi: 10.1038/s41560-018-0127-y.
de Blas, I., Mediavilla, M., Capellán-Pérez, I., & Duce, C. (2020). The limits of transport decarbonization under the current growth paradigm. *Energy Strategy Reviews, 32*, 100543. doi: https://doi.org/10.1016/j.esr.2020.100543.
de Castro, C., & Capellán-Pérez, I. (2018). Concentrated Solar Power: Actual Performance and Foreseeable Future in High Penetration Scenarios of Renewable Energies. [journal article]. *BioPhysical Economics and Resource Quality, 3*(3), 14. doi: 10.1007/s41247-018-0043-6.
de Castro, C., & Capellán-Pérez, I. (2020). Standard, Point of Use, and Extended Energy Return on Energy Invested (EROI) from Comprehensive Material Requirements of Present Global Wind, Solar, and Hydro Power Technologies. *Energies, 13*(12), 3036.

de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M., & de Miguel, L. J. (2014). A top-down approach to assess physical and ecological limits of biofuels. *Energy, 64*(0), 506-512. doi: http://dx.doi.org/10.1016/j.energy.2013.10.049.
de Castro, C., Mediavilla, M., Miguel, L. J., & Frechoso, F. (2011). Global wind power potential: Physical and technological limits. *Energy Policy, 39*(10), 6677-6682. doi: http://dx.doi.org/10.1016/j.enpol.2011.06.027.
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.
Debnath, K. B., & Mourshed, M. (2018). Challenges and gaps for energy planning models in the developing-world context. *Nature Energy, 3*(3), 172-184. doi: 10.1038/s41560-018-0095-2.
DeCarolis, J. F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics, 33*(2), 145-152. doi: https://doi.org/10.1016/j.eneco.2010.05.002.
DeCarolis, J. F., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., . . . Zeyringer, M. (2017). Formalizing best practice for energy system optimization modelling. *Applied Energy, 194*, 184-198. doi: https://doi.org/10.1016/j.apenergy.2017.03.001.
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.
Delina, L., & Janetos, A. (2018). Cosmopolitan, dynamic, and contested energy futures: Navigating the pluralities and polarities in the energy systems of tomorrow. *Energy Research & Social Science, 35*, 1-10. doi: https://doi.org/10.1016/j.erss.2017.11.031.
Després, J., Hadjsaid, N., Criqui, P., & Noirot, I. (2015). Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. *Energy, 80*, 486-495. doi: https://doi.org/10.1016/j.energy.2014.12.005.
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.
Dupont, E., Koppelaar, R., & Jeanmart, H. (2020). Global available solar energy under physical and energy return on investment constraints. *Applied Energy, 257*, 113968. doi: https://doi.org/10.1016/j.apenergy.2019.113968.
Ehrenfeld, J. R., & Hoffman, A. J. (2013). *Flourishing: A Frank Conversation About Sustainability*. Stanford: Stanford University Press.
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.
Feola, G. (2019). Capitalism in sustainability transitions research: Time for a critical turn? *Environmental Innovation and Societal Transitions*. doi: https://doi.org/10.1016/j.eist.2019.02.005.
Fleming, D. (2016). *Lean Logic: A Dictionary for the Future and How to Survive It*. White River Junction, VT: Chelsea Green Publishing.
Floyd, J. (2012). Action research and integral futures studies: A path to embodied foresight. *Futures, 44*(10), 870-882. doi: http://dx.doi.org/10.1016/j.futures.2012.09.001.
Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. *Technological Forecasting and Social Change, 91*, 161-178. doi: https://doi.org/10.1016/j.techfore.2014.02.006.
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.

Gargiulo, M., & Gallachóir, B. Ó. (2013). Long-term energy models: Principles, characteristics, focus, and limitations. *Wiley Interdisciplinary Reviews: Energy and Environment, 2*(2), 158-177. doi: doi:10.1002/wene.62.

Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. [Perspective]. *Nature Climate Change, 6*, 576. doi: 10.1038/nclimate2980.

Giraud, G., & Kahraman, Z. (2014). *How Dependent is Growth from Primary Energy? The Dependency ratio of Energy in 33 Countries (1970-2011)*. Documents de travail du Centre d'Economie de la Sorbonne 2014.97 - ISSN : 1955-611X. Retrieved from https://halshs.archives-ouvertes.fr/halshs-01151590.

Giraud, G., Mc Isaac, F., Bovari, E., & Zatsepina, E. (2016). Coping with the Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming *AFD Research Papers*.

Godet, M. (1986). Introduction to la prospective: Seven key ideas and one scenario method. *Futures, 18*(2), 134-157. doi: https://doi.org/10.1016/0016-3287(86)90094-7.

Gross, R., Hanna, R., Gambhir, A., Heptonstall, P., & Speirs, J. (2018). How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. *Energy Policy, 123*, 682-699. doi: https://doi.org/10.1016/j.enpol.2018.08.061.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515-527. doi: 10.1038/s41560-018-0172-6.

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.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 105-117). London: Sage.

Guivarch, C., Lempert, R., & Trutnevyte, E. (2017). Scenario techniques for energy and environmental research: An overview of recent developments to broaden the capacity to deal with complexity and uncertainty. *Environmental Modelling & Software, 97*, 201-210. doi: https://doi.org/10.1016/j.envsoft.2017.07.017.

Hafner, S., Anger-Kraavi, A., Monasterolo, I., & Jones, A. (2020). Emergence of New Economics Energy Transition Models: A Review. *Ecological Economics, 177*, 106779. doi: https://doi.org/10.1016/j.ecolecon.2020.106779.

Haikola, S., Hansson, A., & Fridahl, M. (2019). Map-makers and navigators of politicised terrain: Expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage. *Futures, 114*, 102472. doi: https://doi.org/10.1016/j.futures.2019.102472.

Hall, L. M. H., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy, 169*, 607-628. doi: https://doi.org/10.1016/j.apenergy.2016.02.044.

Hardt, L., & O'Neill, D. W. (2017). Ecological Macroeconomic Models: Assessing Current Developments. *Ecological Economics, 134*, 198-211. doi: https://doi.org/10.1016/j.ecolecon.2016.12.027.

Hedenus, F., Johansson, D., & Lindgren, K. (2013). A critical assessment of Energy-economy-climate models for policy analysis. *Journal of Applied Economics and Business Research, 3*(2), 118-132.

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. [journal article]. *Swiss Journal of Economics and Statistics, 148*(2), 111-135. doi: 10.1007/bf03399363.

Heron, J., & Reason, P. (1997). A participatory inquiry paradigm. *Qualitative Inquiry, 3*(3), 274-295.

Heuberger, C. F., & Mac Dowell, N. (2018). Real-World Challenges with a Rapid Transition to 100% Renewable Power Systems. *Joule*. doi: https://doi.org/10.1016/j.joule.2018.02.002.

Hirth, L., Ueckerdt, F., & Edenhofer, O. (2014). Why Wind is Not Coal: On the Economics of Electricity. *FEEM Working Paper No. 39 2014*. In G. Sammarco (Ed.), *Energy: Resources and Markets*. Milan, Italy: Fondazione Eni Enrico Mattei.

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

Hoffman, K. C., & Wood, D. O. (1976). Energy System Modeling and Forecasting. *Annual Review of Energy, 1*(1), 423-453. doi: 10.1146/annurev.eg.01.110176.002231.

Holmgren, D. (2009). *Future Scenarios: How Communities Can Respond to Peak Oil and Climate Change*. White River Jct, Vermont: Chelsea Green Publishing.

Homer-Dixon, T., Walker, B., Biggs, R., Crépin, A.-S., Folke, C., Lambin, E. F., . . . Troell, M. (2015). Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society, 20*(3). doi: 10.5751/es-07681-200306.

Hopkins, R. (2019). *From What Is to What If: Unleashing the Power of Imagination to Create the Future We Want*. White River Junction: Chelsea Green Publishing.

Hourcade, J. C., Haites, E., & Barker, T. (1996). Contribution of Working Group III to the Second Assessment Report of the IPCC. Estimating the cost of mitigating greenhouse gases. In J. P. Bruce, H. Lee & E. F. Haites (Eds.), *Climate change 1995: economic and social dimensions of climate change* (pp. 263-296). Cambridge: Cambridge University Press.

Hughes, N., & Strachan, N. (2010). Methodological review of UK and international low carbon scenarios. *Energy Policy, 38*(10), 6056-6065. doi: https://doi.org/10.1016/j.enpol.2010.05.061.

Hulme, M. (2012). How climate models gain and exercise authority *The Social Life of Climate Change Models* (pp. 40-54): Routledge.

Inayatullah, S. (1990). Deconstructing and reconstructing the future: Predictive, cultural and critical epistemologies. *Futures, 22*(2), 115-141. doi: https://doi.org/10.1016/0016-3287(90)90077-U.

Isoaho, K., & Karhunmaa, K. (2019). A critical review of discursive approaches in energy transitions. *Energy Policy, 128*, 930-942. doi: https://doi.org/10.1016/j.enpol.2019.01.043.

Iyer, G., & Edmonds, J. (2018). Interpreting energy scenarios. *Nature Energy, 3*(5), 357-358. doi: 10.1038/s41560-018-0145-9.

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.

Järvensivu, P., Toivanen, T., Vadén, T., Lähde, V., Majava, A., & Eronen, J. T. (2018). Governance of economic transition: a scientific background document for the UN Global Sustainable Development Report 2019. Helsinki, Finland: BIOS Research Unit.

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.

Jebaraj, S., & Iniyan, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews, 10*(4), 281-311. doi: https://doi.org/10.1016/j.rser.2004.09.004.

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.

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

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.
Kis, Z., Pandya, N., & Koppelaar, R. H. E. M. (2018). Electricity generation technologies: Comparison of materials use, energy return on investment, jobs creation and CO2 emissions reduction. *Energy Policy, 120*, 144-157. doi: https://doi.org/10.1016/j.enpol.2018.05.033.
Köhler, J., de Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G., & Chappin, E. (2018). Modelling Sustainability Transitions: An Assessment of Approaches and Challenges. *Journal of Artificial Societies and Social Simulation, 21*(1), 8. doi: 10.18564/jasss.3629.
Kok, K., Pedde, S., Gramberger, M., Harrison, P. A., & Holman, I. P. (2019). New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. [journal article]. *Regional Environmental Change, 19*(3), 643-654. doi: 10.1007/s10113-018-1400-0.
Kuhnhenn, K. (2018). A blind spot in climate science: Global scenarios from a growth-critical perspective: Heinrich Böll Foundation.
Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy, 18*(6), 690-714. doi: 10.1080/14693062.2017.1346498.
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.
Li, F. G. N. (2017). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews, 15*, 57-71. doi: https://doi.org/10.1016/j.esr.2017.01.002.
Li, F. G. N., & Strachan, N. (2017). Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions, 24*, 106-129. doi: https://doi.org/10.1016/j.eist.2016.08.002.
Li, F. G. N., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change, 100*, 290-305. doi: https://doi.org/10.1016/j.techfore.2015.07.017.
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.
Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews, 96*, 156-166. doi: https://doi.org/10.1016/j.rser.2018.07.045.
Mahony, T. O. (2014). Integrated scenarios for energy: A methodology for the short term. *Futures, 55*, 41-57. doi: https://doi.org/10.1016/j.futures.2013.11.002.
Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy, 3*(8), 628-633. doi: 10.1038/s41560-018-0171-7.
Martin, B. R. (2010). The origins of the concept of 'foresight' in science and technology: An insider's perspective. *Technological Forecasting and Social Change, 77*(9), 1438-1447. doi: https://doi.org/10.1016/j.techfore.2010.06.009.
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.
Meadows, D., Randers, J., & Meadows, D. (2005). *Limits to Growth: the 30-Year Update*. London: Earthscan.
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.

Miller, C. A., O'Leary, J., Graffy, E., Stechel, E. B., & Dirks, G. (2015). Narrative futures and the governance of energy transitions. *Futures, 70*, 65-74. doi: https://doi.org/10.1016/j.futures.2014.12.001.

Miller, L. M., Brunsell, N. A., Mechem, D. B., Gans, F., Monaghan, A. J., Vautard, R., . . . Kleidon, A. (2015). Two methods for estimating limits to large-scale wind power generation. *Proceedings of the National Academy of Sciences, 112*(36), 11169-11174. doi: 10.1073/pnas.1408251112.

Miller, L. M., Gans, F., & Kleidon, A. (2011a). 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., Gans, F., & Kleidon, A. (2011b). Jet stream wind power as a renewable energy resource: little power, big impacts. *Earth System Dynamics, 2*(2), 201-212. doi: http://dx.doi.org/10.5194/esd-2-201-2011.

Miller, L. M., & Keith, D. W. (2018). Climatic Impacts of Wind Power. *Joule*. doi: https://doi.org/10.1016/j.joule.2018.09.009.

Miller, L. M., & Keith, D. W. (2018). Observation-based solar and wind power capacity factors and power densities. *Environmental Research Letters, 13*(10), 104008. doi: https://doi.org/10.1088/1748-9326/aae102.

Moallemi, E. A., & Malekpour, S. (2018). A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science, 35*, 205-216. doi: https://doi.org/10.1016/j.erss.2017.10.022.

Moezzi, M., Janda, K. B., & Rotmann, S. (2017). Using stories, narratives, and storytelling in energy and climate change research. *Energy Research & Social Science, 31*, 1-10. doi: https://doi.org/10.1016/j.erss.2017.06.034.

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.

Morgan, M. G., & Keith, D. W. (2008). Improving the way we think about projecting future energy use and emissions of carbon dioxide. [journal article]. *Climatic Change, 90*(3), 189-215. doi: 10.1007/s10584-008-9458-1.

Moriarty, P., & Honnery, D. (2012). 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.

Motesharrei, S., Rivas, J., & Kalnay, E. (2014). Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics, 101*, 90-102. doi: https://doi.org/10.1016/j.ecolecon.2014.02.014.

Nakicenovic, N., Lempert, R. J., & Janetos, A. C. (2014). A Framework for the Development of New Socio-economic Scenarios for Climate Change Research: Introductory Essay. [journal article]. *Climatic Change, 122*(3), 351-361. doi: 10.1007/s10584-013-0982-2.

Nature Energy Editorial. (2017). Business as unusual. [Editorial]. *Nature Energy, 2*, 17150. doi: 10.1038/nenergy.2017.150.

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.

Nieto, J., Carpintero, Ó., Lobejón, L. F., & Miguel, L. J. (2020). An ecological macroeconomics model: The energy transition in the EU. *Energy Policy, 145*, 111726. doi: https://doi.org/10.1016/j.enpol.2020.111726.

Nikoleris, A., Stripple, J., & Tenngart, P. (2017). Narrating climate futures: shared socioeconomic pathways and literary fiction. *Climatic Change, 143*(3), 307-319. doi: 10.1007/s10584-017-2020-2.
Nilsson, M., Nilsson, L. J., Hildingsson, R., Stripple, J., & Eikeland, P. O. (2011). The missing link: Bringing institutions and politics into energy future studies. *Futures, 43*(10), 1117-1128. doi: https://doi.org/10.1016/j.futures.2011.07.010.
O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169-180. doi: https://doi.org/10.1016/j.gloenvcha.2015.01.004.
O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., . . . van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. [journal article]. *Climatic Change, 122*(3), 387-400. doi: 10.1007/s10584-013-0905-2.
O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability, 1*(2), 88-95. doi: 10.1038/s41893-018-0021-4.
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.
Papachristos, G. (2018). System dynamics modelling and simulation for sociotechnical transitions research. *Environmental Innovation and Societal Transitions*. doi: https://doi.org/10.1016/j.eist.2018.10.001.
Pargman, D., Eriksson, E., Höök, M., Tanenbaum, J., Pufal, M., & Wangel, J. (2017). What if there had only been half the oil? Rewriting history to envision the consequences of peak oil. *Energy Research & Social Science, 31*, 170-178. doi: https://doi.org/10.1016/j.erss.2017.06.007.
Pereira, L., Sitas, N., Ravera, F., Jimenez-Aceituno, A., & Merrie, A. (2019). Building capacities for transformative change towards sustainability: Imagination in Intergovernmental Science-Policy Scenario Processes. *Elementa Science of the Anthropocene, 7*(1), 35. doi: http://doi.org/10.1525/elementa.374.
Peters, G. (2017). *The trouble with negative emissions*. Paper presented at the IPCC Experty Meeting on Scenarios, Addis Ababa. https://www.ipcc-wg3.ac.uk/Presentations/ExpertMeeting/Session2/4_Peters_IPCC_20170425.pdf.
Pfenninger, S. (2017a). Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. *Applied Energy, 197*, 1-13. doi: https://doi.org/10.1016/j.apenergy.2017.03.051.
Pfenninger, S. (2017b). Energy scientists must show their workings. *Nature News, 542*(7642), 393. doi: https://doi.org/10.1038/542393a.
Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi: https://doi.org/10.1016/j.rser.2014.02.003.
Pfenninger, S., Hirth, L., Schlecht, I., Schmid, E., Wiese, F., Brown, T., . . . Wingenbach, C. (2018). Opening the black box of energy modelling: Strategies and lessons learned. *Energy Strategy Reviews, 19*, 63-71. doi: https://doi.org/10.1016/j.esr.2017.12.002.
Pfenninger, S., & Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy, 114*, 1251-1265. doi: https://doi.org/10.1016/j.energy.2016.08.060.
Pindyck, R. S. (2017). The Use and Misuse of Models for Climate Policy. *Review of Environmental Economics and Policy, 11*(1), 100-114. doi: 10.1093/reep/rew012.

Popa, F., Guillermin, M., & Dedeurwaerdere, T. (2015). A pragmatist approach to transdisciplinarity in sustainability research: From complex systems theory to reflexive science. *Futures, 65*, 45-56. doi: https://doi.org/10.1016/j.futures.2014.02.002.
Pye, S., Li, F. G. N., Petersen, A., Broad, O., McDowall, W., Price, J., & Usher, W. (2018). Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. *Energy Research & Social Science, 46*, 332-344. doi: https://doi.org/10.1016/j.erss.2018.07.028.
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.
Raven, P. G. (2017). Telling tomorrows: Science fiction as an energy futures research tool. *Energy Research & Social Science, 31*, 164-169. doi: https://doi.org/10.1016/j.erss.2017.05.034.
Ravetz, J. (2004). The post-normal science of precaution. *Futures, 36*(3), 347-357. doi: https://doi.org/10.1016/S0016-3287(03)00160-5.
Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153-168. doi: https://doi.org/10.1016/j.gloenvcha.2016.05.009.
Ringkjøb, H.-K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews, 96*, 440-459. doi: https://doi.org/10.1016/j.rser.2018.08.002.
Robertson, E., O'Grady, Á., Barton, J., Galloway, S., Emmanuel-Yusuf, D., Leach, M., . . . Foxon, T. (2017). Reconciling qualitative storylines and quantitative descriptions: An iterative approach. *Technological Forecasting and Social Change, 118*, 293-306. doi: https://doi.org/10.1016/j.techfore.2017.02.030.
Rosenbloom, D., Haley, B., & Meadowcroft, J. (2018). Critical choices and the politics of decarbonization pathways: Exploring branching points surrounding low-carbon transitions in Canadian electricity systems. *Energy Research & Social Science, 37*, 22-36. doi: https://doi.org/10.1016/j.erss.2017.09.022.
Rye, C. D., & Jackson, T. (2018). A review of EROEI-dynamics energy-transition models. *Energy Policy, 122*, 260-272. doi: https://doi.org/10.1016/j.enpol.2018.06.041.
Safarzyńska, K., & van den Bergh, J. C. J. M. (2017a). Financial stability at risk due to investing rapidly in renewable energy. *Energy Policy, 108*, 12-20. doi: https://doi.org/10.1016/j.enpol.2017.05.042.
Safarzyńska, K., & van den Bergh, J. C. J. M. (2017b). Integrated crisis-energy policy: Macro-evolutionary modelling of technology, finance and energy interactions. *Technological Forecasting and Social Change, 114*, 119-137. doi: https://doi.org/10.1016/j.techfore.2016.07.033.
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. (2016). Climate costing is politics not science. *Nature, 532*(7598), 177-177. doi: 10.1038/532177a.
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.
Samsó, R., de Blas, I., Perissi, I., Martelloni, G., & Solé, J. (2020). Scenario analysis and sensitivity exploration of the MEDEAS Europe energy-economy-environment model. *Energy Strategy Reviews*, 100582. doi: https://doi.org/10.1016/j.esr.2020.100582.

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.
Sers, M. R., & Victor, P. A. (2018). The Energy-emissions Trap. *Ecological Economics, 151*, 10-21. doi: https://doi.org/10.1016/j.ecolecon.2018.04.004.
Sgouridis, S., Csala, D., & Bardi, U. (2016). The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environmental Research Letters, 11*(9), 094009. doi: 10.1088/1748-9326/11/9/094009.
Sherwin, E. D., Henrion, M., & Azevedo, I. M. L. (2018). Estimation of the year-on-year volatility and the unpredictability of the United States energy system. *Nature Energy, 3*(4), 341-346. doi: 10.1038/s41560-018-0121-4.
Sherwood, J., Ditta, A., Haney, B., Haarsma, L., & Carbajales-Dale, M. (2017). Resource Criticality in Modern Economies: Agent-Based Model Demonstrates Vulnerabilities from Technological Interdependence. [journal article]. *BioPhysical Economics and Resource Quality, 2*(3), 9. doi: 10.1007/s41247-017-0026-z.
Slaughter, R. (1982). *Critical Futures Studies and Curriculum Renewal.* PhD dissertation, University of Lancaster, Britain.
Slaughter, R. A. (1999). *Futures for the third millenium: Enabling the forward view*. St Leonards: Prospect Media.
Slaughter, R. A. (2004). *Futures beyond dystopia: Creating social foresight*. London: RoutledgeFalmer.
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* (Revised ed.). Cambridge, Massachusetts: MIT Press.
Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., & Wilhelmsson, F. (2011). Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. *Futures, 43*(10), 1105-1116. doi: https://doi.org/10.1016/j.futures.2011.07.009.
Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., . . . Theofilidi, M. (2020). Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. *Renewable and Sustainable Energy Reviews, 132*, 110105. doi: https://doi.org/10.1016/j.rser.2020.110105.
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.
Sovacool, B. K., & Geels, F. W. (2016). Further reflections on the temporality of energy transitions: A response to critics. *Energy Research & Social Science, 22*, 232-237. doi: https://doi.org/10.1016/j.erss.2016.08.013.
Stirling, A. (2014). Transforming power: Social science and the politics of energy choices. *Energy Research & Social Science, 1*, 83-95. doi: https://doi.org/10.1016/j.erss.2014.02.001.
Strachan, N., Fais, B., & Daly, H. (2016). Reinventing the energy modelling–policy interface. [Comment]. *Nature Energy, 1*, 16012. doi: 10.1038/nenergy.2016.12.
Subramanian, A. S. R., Gundersen, T., & Adams, T. A. (2018). Modeling and Simulation of Energy Systems: A Review. *Processes, 6*(12), 238.

Suganthi, L., & Samuel, A. A. (2012). Energy models for demand forecasting—A review. *Renewable and Sustainable Energy Reviews, 16*(2), 1223-1240. doi: https://doi.org/10.1016/j.rser.2011.08.014.
Tainter, J. A. (1988). *The Collapse of Complex Societies*. Cambridge: Cambridge University Press.
Tainter, J. A. (2011). Energy, complexity, and sustainability: A historical perspective. *Environmental Innovation and Societal Transitions, 1*(1), 89-95. doi: http://dx.doi.org/10.1016/j.eist.2010.12.001.
Tainter, J. A., & Patzek, T. W. (2012). *Drilling Down: The Gulf Oil Debacle and Our Energy Dilemma*. New York: Copernicus.
Tapio, P., & Hietanen, O. (2002). Epistemology and public policy: using a new typology to analyse the paradigm shift in Finnish transport futures studies. *Futures, 34*(7), 597-620. doi: https://doi.org/10.1016/S0016-3287(02)00003-4.
Tidwell, J. H., & Tidwell, A. S. D. (2018). Energy ideals, visions, narratives, and rhetoric: Examining sociotechnical imaginaries theory and methodology in energy research. *Energy Research & Social Science, 39*, 103-107. doi: https://doi.org/10.1016/j.erss.2017.11.005.
Timma, L., Blumberga, A., Bazbauers, G., & Blumberga, D. (2017). Novel tools to study socio-technical transitions in energy systems. *Energy Procedia, 128*, 418-422. doi: https://doi.org/10.1016/j.egypro.2017.09.048.
Trutnevyte, E. (2016). Does cost optimization approximate the real-world energy transition? *Energy, 106*, 182-193. doi: https://doi.org/10.1016/j.energy.2016.03.038.
Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., & Robertson, E. (2014). Linking a storyline with multiple models: A cross-scale study of the UK power system transition. *Technological Forecasting and Social Change, 89*, 26-42. doi: https://doi.org/10.1016/j.techfore.2014.08.018.
Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., & van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change, 35*, 239-253. doi: https://doi.org/10.1016/j.gloenvcha.2015.08.010.
Urban, F., Benders, R. M. J., & Moll, H. C. (2007). Modelling energy systems for developing countries. *Energy Policy, 35*(6), 3473-3482. doi: https://doi.org/10.1016/j.enpol.2006.12.025.
Urueña, S. (2019). Understanding “plausibility”: A relational approach to the anticipatory heuristics of future scenarios. *Futures, 111*, 15-25. doi: https://doi.org/10.1016/j.futures.2019.05.002.
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 Beeck, N. (1999). Classification of energy models: Tilburg University & Eindhoven University of Technology.
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.
Van Poeck, K., Östman, L., & Block, T. (2018). Opening up the black box of learning-by-doing in sustainability transitions. *Environmental Innovation and Societal Transitions*. doi: https://doi.org/10.1016/j.eist.2018.12.006.
van Sluisveld, M. A. E., Hof, A. F., Carrara, S., Geels, F. W., Nilsson, M., Rogge, K., . . . van Vuuren, D. P. (2018). Aligning integrated assessment modelling with socio-technical transition insights:

An application to low-carbon energy scenario analysis in Europe. *Technological Forecasting and Social Change*. doi: https://doi.org/10.1016/j.techfore.2017.10.024.

Vance, A. (2015). *Elon Musk: Tesla, SpaceX, and the Quest for a Fantastic Future*. New York: Ecco.

Vandeventer, J. S., Cattaneo, C., & Zografos, C. (2019). A Degrowth Transition: Pathways for the Degrowth Niche to Replace the Capitalist-Growth Regime. *Ecological Economics, 156*, 272-286. doi: https://doi.org/10.1016/j.ecolecon.2018.10.002.

Vaughan, N. E., & Gough, C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters, 11*(9), 095003. doi: 10.1088/1748-9326/11/9/095003.

Voros, J. (2003). A generic foresight process framework. *Foresight, 5*(3), 10-21.

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.

Voros, J. (2009). Morphological prospection: profiling the shapes of things to come. *Foresight, 11*(6), 4-20. doi: doi:10.1108/14636680911004939.

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.

Wynne, B. (1984). The institutional context of science, models, and policy: The IIASA energy study. [journal article]. *Policy Sciences, 17*(3), 277-320. doi: 10.1007/bf00138709.

Yue, X., Pye, S., DeCarolis, J., Li, F. G. N., Rogan, F., & Gallachóir, B. Ó. (2018). A review of approaches to uncertainty assessment in energy system optimization models. *Energy Strategy Reviews, 21*, 204-217. doi: https://doi.org/10.1016/j.esr.2018.06.003.