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A review of socio-technical energy transition (STET) models

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ABSTRACT

Many existing technical feasibility and modelling studies in the energy field are criticised for their limited treatment of societal actors and socio-political dynamics, poor representation of the co-evolving nature of society and technology, and hence an inability to analyse socio-technical change. At the same time, prominent conceptual frameworks of socio-technical transitions that address these elements are often found to be difficult to operationalize in quantitative energy analyses that meet policy development requirements. However a new energy modelling paradigm has started to emerge for integrating both quantitative modelling and conceptual socio-technical transitions. This paper provides a taxonomy for this new model category: 'socio-technical energy transition' (STET) models. A review of existing STET models and their applications to the energy supply, buildings and transport sectors is provided. Following this review, the paper reflects on the extent to which these existing quantitative models captured the variety of factors covered in socio-technical transitions theory, highlights the challenges associated with their theoretical and behavioural validation, and proposes future development priorities for STET models.

1. The next frontier in energy modelling: operationalising socio-technical transitions

At a global scale, the core theme in early 21st century geopolitics is anthropogenic climate change. Greenhouse gas emission mitigation efforts are primarily directed towards the energy sector (Guivarch and Hallegatte, 2013; IEA, 2013; IPCC, 2014; World Bank, 2012), because major sources of emissions include the energy supply system, energy consumed in buildings, and energy consumed in transport (UNEP, 2012). However, many studies have shown that any transition of today's energy system to a state with dramatically lower greenhouse gas emissions is not only a technical matter (Skea and Nishioka, 2008). The behaviour, values and strategies of individual actors as well as policies, regulations and markets also shape energy system transitions (Edwards, 2011; Foxon et al., 2010). Understanding how such socio-technical energy transitions might be brought about is a major interdisciplinary research challenge.

The layout of this paper is as follows. The reminder of Section 1 lays out the separate approaches of socio-technical transitions and of quantitative energy modelling, and then supports the emergence of socio-technical energy transition (STET) models that links these two research domains. Section 2 gives a novel categorisation of the key elements of STET models – techno-economic detail, societal co-evolution and agent representation – and how these can be linked. Section 3 reviews the emerging STET modelling literature within this categorisation. Section 4 discusses key issues in disciplinary and interdisciplinary approaches across these three domains, including research development priorities, and Section 5 gives overall conclusions from this review of STET models.

1.1. Conceptual frameworks of socio-technical transitions

Conceptualising sectors of the economy as socio-technical systems means adoption of the 'wider system' view to encompass not only the natural and built components, such as energy resources or infrastructures, but the societal and institutional elements as well i.e., individuals and organisations (Foxon et al., 2010; Geels, 2005; Ottens et al., 2006; Verbong and Geels, 2010). Economic historians have long studied transitions in socio-technical systems. In the late 1980s and early 1990s, researchers at the International Institute for Applied Systems Analysis (IIASA) applied Kondratiev's concept of long macroeconomic cycles (Barnett, 2009) and Schumpeter's theories on business cycles (Schumpeter, 1939) to the study of innovation and the diffusion of new technologies (Ayres, 1989; Grübler, 1990; Marchetti, 1988). Detailed historical reviews of how past socio-technical transitions have occurred in energy systems have also complemented the wider study of technological innovation (Fouquet and Pearson, 1998, 2006; Fouquet, 2010; Grübler et al., 1999; Wilson and Grubler, 2011). The relatively young field of 'transitions studies' increasingly focuses on normative transitions towards more ecologically sustainable systems (Markard et al., 2012). Recent examples include the work of Araújo (2014), who discusses the relevance of transitions research for addressing future

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"energy mega-trends", and that of Chappin and van der Lei (2014), who use a socio-technical transitions approach to explore the literature on the adaptation of energy and transport systems to climate change.

Many theoretical frameworks for the analysis of socio-technical transitions have emerged over time, such as technological paradigms and trajectories (Dosi, 1982), evolutionary economics (Nelson and Winter, 1982), human–environment systems (HES) (Scholz, 2011), complex adaptive systems (Miller and Page, 2007), resilience and panarchy[1] (Dangerman and Schellnhuber, 2013; Gunderson and Holling, 2001), socio-ecological systems (Berkes and Folke, 2000), socio-metabolic shifts (Fischer-Kowalski, 2011), technological innovation systems (TIS) (Carlsson and Stankiewicz, 1991; Gallagher et al., 2012; Hekkert et al., 2007; Markard and Truffer, 2008), transition management (TM) (Rotmans et al., 2001), strategic niche management (SNM) (Kemp et al., 1998), and the multi-level perspective (MLP) (Geels and Schot, 2007; Geels, 2002, 2010, 2011).

Today's most influential body of innovation-focused transition research originates in the Netherlands, and is often called the "Dutch approach" (Chappin and Ligtvoet, 2014; Fischer-Kowalski and Rotmans, 2009; Grubler, 2012; Kemp, 2010; Lachman, 2013). Approaches that descended from the Dutch school are transition management (TM), strategic niche management (SNM), technological innovation systems (TIS), and the multi-level perspective (MLP). These are the approaches that feature most strongly in the study of sustainability related transitions (Markard et al., 2012).

Dutch school approaches are particularly suited for investigating socio-technical transitions in the energy supply, buildings, and transport sectors, as they focus on means of supplanting the incumbent system with radical alternatives, disruption of the status quo and the initiation of rapid change. Such a change is required in today's energy system if global climate change mitigation efforts are to be achieved. Such radical transitions are often conceptualised as society breaking out from "lock-in" to environmentally damaging systems (Arthur, 1989; Dolfsma and Leydesdorff, 2009; Unruh, 2000). The multi-level perspective (MLP) on socio-technical transitions (Geels and Schot, 2007; Geels, 2005) assumes that transitions emerge as the interplay of developments at multiple levels: niche innovations (micro-level), socio-technical regimes (meso-level) and the broader socio-technical landscape (macro-level). In the energy field, the MLP has been applied to transitions in energy (especially electricity) supply (Rosenbloom and Meadowcroft, 2014; Verbong and Geels, 2007, 2010; Yuan et al., 2012), transport (Marletto, 2014; McDowall, 2014), and the residential buildings sector (Horne et al., 2014; ONeill and Gibbs, 2013; Yücel, 2013).

There is no doubt that MLP and other conceptual approaches of socio-technical transitions provide valuable insights into the complex nature of energy transitions. However, operationalization of such approaches in quantitative terms and in formal modelling to inform future decisions, as opposed to understanding structural changes that occurred in the past, has been acknowledged to be difficult (Bergek et al., 2008; Berkhout et al., 2004; Genus and Coles, 2008; Markard and Truffer, 2008). In practice, much of the evidence base for policy action in the energy supply, buildings and transport sectors has to date been undertaken using quantitative energy models, as described below in Section 1.2. Thus, Squazzoni (2008), Timmermans et al. (2008), Holtz (2011), Papachristos (2014) and Halbe et al. (2014) all call for the integration of quantitative modelling into transitions theory in order to increase the policy relevance of the insights generated.

1.2. Quantitative energy modelling

Quantitative models of the energy system and its transition are widely used to quantify, understand and determine appropriate responses to climate change in the energy sector (Eom et al., 2015; Kriegler et al., 2015; SDSN and IDDRI, 2014), and are included in the work of the Intergovernmental Panel on Climate Change (IPCC) (Bruckner et al., 2014). Models are not only applied for global energy system modelling, but also at the scale of individual nations to form an evidence base for energy policy analysis, such as in Amorim et al. (2014), or Ekins et al. (2011). For readers seeking a broad understanding of this field, detailed systemic reviews of such models, their recent history and their applications have been synthesized by Jebaraj and Iniyan (2006), Bhattacharyya and Timilsina (2010), and Pfenninger et al. (2014).

The dominant theoretical paradigm in the analysis of formal energy economic models is to follow the normative neoclassical assumptions of rational choice, utility and profit maximisation, and perfect information (Samuelson and Nordhaus, 1985). Hourcade et al. (2006) define energy system analysis models into bottom-up, top-down, and hybrid classifications. Bottom-up models such as MARKAL (Loulou et al., 2004), MESSAGE (Messner and Strubegger, 1995), TIMES (Loulou et al., 2005) and OSeMOSYS (Howells et al., 2011) tend to include explicit sectoral and technology disaggregations, and favour technological detail at the expense of micro-economic realism and macro-economic completeness. Top-down models, such as GEM-E3 (Capros et al., 2013) or MERGE (Manne et al., 1995), are robust in their representation of macro-economic interactions and implicitly capture micro-economic behavioural factors, but conversely tend to lack the level of technological detail seen in bottom-up models. Hybrid approaches, such as CGE-MARKAL (Schafer and Jacoby, 2006), REMIND-R (Leimbach et al., 2010), or E3MG (Köhler et al., 2006), seek to combine insights from top-down and bottom-up models in order to compensate for their individual shortcomings.

To date, quantitative energy models of the type described above have tended to limit their scope to the description of techno-economic factors only, with the political, social and behavioural aspects of possible futures left for the end-user to frame exogenously. There have been less than a handful of attempts to bring socio-technical perspectives into such energy models, e.g., by linking models with normative stakeholder visions (Trutnevyte, 2014a), modelling governance storylines (Trutnevyte et al., 2014), or including behavioural heterogeneity (Strachan and Warren, 2011). Multiple authors, such as Foxon (2013), Hughes and Strachan (2010), Nielsen and Karlsson (2007), Pfenninger et al. (2014), and Trutnevyte et al. (2012), argue that energy modelling should go beyond a technology and economics focus and incorporate broader behavioural and social insights, i.e., to examine socio-technical transitions.

1.3. Socio-technical energy transition (STET) models for bridging socio-technical transitions and energy modelling

Conceptual socio-technical transition frameworks and energy models can provide complementary insights for understanding and shaping future energy transitions in the face of the challenges posed by anthropogenic climate change. This paper thus proposes a new concept of 'socio-technical energy transition' (STET) models, where formal quantitative energy models are developed that also capture the elements of socio-technical transitions, including societal actors and the co-evolutionary nature of policy, technology and behaviour. Past reviews have summarised a range of general transition modelling approaches (Halbe et al., 2014; Holtz, 2011; Timmermans et al., 2008), but these transition reviews include very few energy modelling studies. There are in fact a small but growing number of existing energy models that are already in line with the STET model concept. However, as these models do not explicitly link to named theoretical transition theories, they appear to have gone unnoticed in earlier reviews. For the first time, this paper takes a look at the wider energy modelling literature with the aim to gather and classify such STET models.

[1] In this context, the referenced authors use the term to refer to a linked hierarchy of adaptive cycles in the human–environment system.