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

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A B S T R A C T

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.

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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.

2. Requirements for socio-technical energy transition (STET) models

The requirements for models capable of capturing and exploring the dynamics of socio-technical energy transitions are first defined in order to classify STET models. The paper suggests three key requirements for STET models that stem from the paradigms of both energy modelling and socio-technical transitions theory:

A. Techno-economic detail: the evidence base for designing energy policy interventions is significantly strengthened when the socio-technical transitions are represented in adequate detail. STET models need to be able to represent how a socio-technical system might evolve from its incumbent state, and they should be equipped with the ability to explore the economic trade-offs between different options as cost is one of the key drivers of such transitions. STET models should also capture technically feasible energy transitions, e.g., that meet demand–supply or resource constraints. Although acknowledged, the latter is often neglected in the application of socio-technical transitions theories (Hansen and Coenen, 2014; Trutnevyte et al., 2012). While all models are ultimately stylized representations of reality, and no model can simultaneously capture all aspects of a real world system (Godfrey-Smith, 2006; Morgan, 2002; Sterman, 2002), STET models should at least include:
   - A disaggregated portfolio of technology options with different price and performance characteristics;
   - Bounded systems with operational or resource constraints.

B. Explicit actor heterogeneity: applying transitions theory requires conceptualising the behaviour of individual actors and constellations of actors who have the power to make decisions that shape the transition. STET models therefore need to acknowledge the existence and heterogeneity of multiple relevant actors. These actors might not be limited to different suppliers and consumers in the energy system, but could also include policymakers, regulators, and civil society organisations, all with different motives and rationales for action. Actors may not be purely led by economic considerations, but might act with bounded rationality (Simon, 1955, 1956). Actors may also possess a broader definition of rationality that, for example, includes strategic behaviour, such as when incumbent regime actors suppress niche players. STET models should trace the causes and impacts of transitions on heterogeneous actors. STET models should thus at least include:
   - Multiple explicit actors with differentiated selection criteria or behavioural parameters;
   - Actors that possess agency to shape transitions.

C. Transition pathway dynamics: first, to be of interest to goal-oriented policymaking, e.g., the transition to a low carbon energy system, STET models should evaluate normative goals so that model users can understand whether a transition is feasible and to compare different possible pathways (Chappin and Dijkema, 2008a). Second, socio-technical transitions typically unfold over long time periods as new technologies diffuse into the market and compete with alternatives. Long time periods are conceptualised in economic theory as being sufficient for all factors of production to become fully flexible i.e., where capital assets can be completely replaced, or where new labour can be trained. While it is difficult to generalise what time horizon is sufficient to capture socio-technical transitions in the energy sector, models should explore changes over several decades (as opposed to hours or years). In this way, the time delays and path dependencies associated with new technology adoption and behavioural change can be accounted for. Finally, the models must be able to capture the adoption of new technologies or behaviours that are capable of breaking the incumbent socio-technical regime out of a "locked-in" state. In summary, STET models should include:
   - Assessment of normative goals;
   - Time horizons sufficient for exploring long-term socio-technical change, path dependencies;
   - Radical alternatives to incumbent status quo technology or behaviour options.

This paper defines STET models as models that lie at the confluence of these three domains (A–C, as displayed in Fig. 1). Fig. 1 hence represents a novel categorisation of the key elements of STET models.

There are many examples of models in the literature which incorporate some, but not all of the STET model requirements. For both conceptual clarity and in order to orient STET models within the wider landscape of existing work, it is useful to reflect on examples of these "near-STET" models:

i. Economy energy and environment models, of the types defined by Hourcade et al. (2006), which are already discussed in Section 1.2, and;
ii. Sector-specific techno-economic models, such as those for the buildings (Cheng and Steemers, 2011; Firth et al., 2010; Johnston et al., 2005; Kesicki, 2012; Natarajan and Levermore, 2007), transport (Leighty et al., 2012), or electricity sectors (Barnacle et al., 2013; Barton et al., 2013; Pudjianto et al., 2013). Models in groups (i) and (ii) often include both comprehensive techno-economic detail (A) and the necessary ingredients to analyse transition pathway dynamics (C). However, while they can be used to explore how the costs and performance of energy systems could change over time, they do not capture the behaviour of actors (B). Typically this is carried out as under a "Story and Simulation" approach (Alcamo, 2008) where actor behaviours are described in the narrative storyline that accompanies the quantitative analysis. Actor contingent transition elements are sometimes separated from non-actor contingent ones in the scenario narratives e.g., in Hughes et al. (2013). Some models do account for parametric uncertainty in a way that could be said to account for heterogeneity in the decision making of actors (Trutnevyte and Strachan, 2013; Trutnevyte, 2014b), but cannot explore the effects of different transition dynamics on individual stakeholder groups, because the actors are not described explicitly. Models in groups (i) and (ii) can be used to identify various desirable future states of the energy system under analysis, for example, the least-cost system. They are however, not STET models because they cannot explore causal links between individual actor behaviour and transition dynamics.
iii. Agent-based or game theoretic simulations of energy systems include both a detailed techno-economic representation of the target system (A) and a focus on the interactions of multiple actors (B). However, they frequently do not capture key transition pathway dynamics (C), such as allowing for actors to change technologies or system constraints, or use sufficient time horizons to capture the system evolution through time. Examples from the power sector include studies of dynamic pricing in wholesale electricity markets (Weidlich and Veit, 2008), electricity trading in smart grids (Kahrobaee et al., 2014), or demand response (Zheng et al., 2014). These models can describe the short-term effects of changes to the electricity system conditions or its operation, but not socio-technical co-evolution over long time periods where the energy system infrastructure might be completely replaced. An example from the transport sector would be Mueller and de Haan's agent based micro-simulation of car fleet choices (de Haan et al., 2009; Mueller and de Haan, 2009), which captures the effects of transport policy interventions on consumer

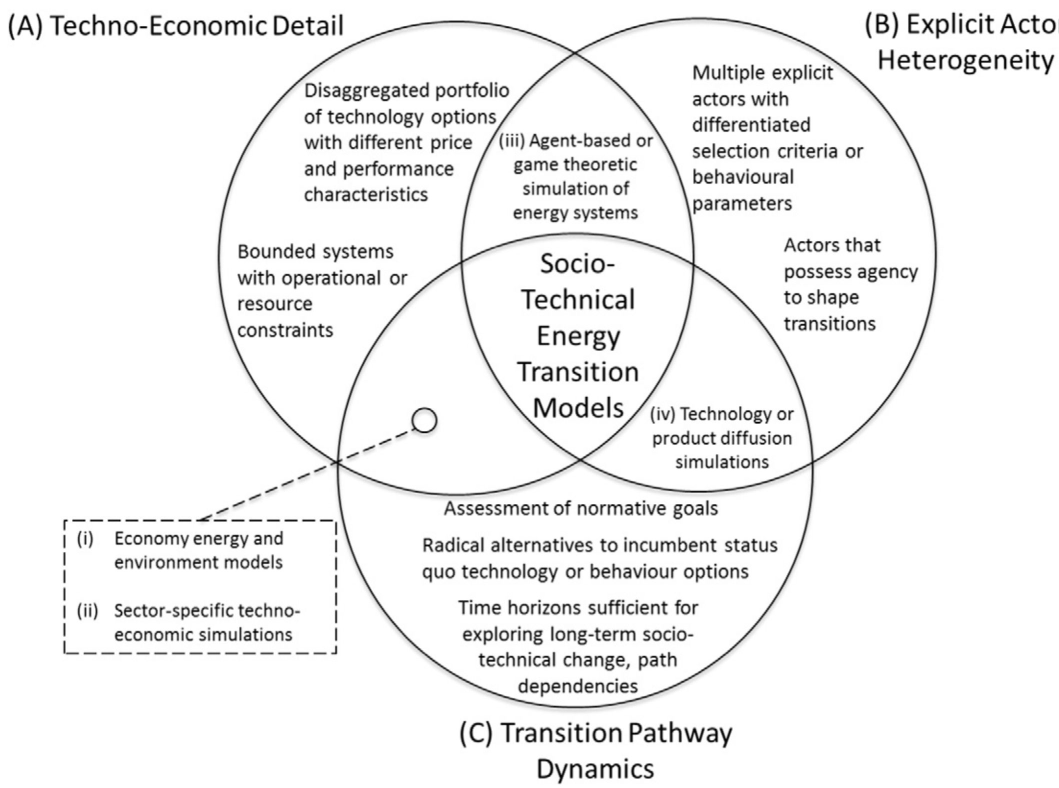

Fig. 1. Methodological requirements for socio-technical energy transition (STET) models.

preferences for vehicles, but cannot explore different socio-technical transitions because radical car technologies (alternative fuels, hybrid drive trains etc.) are not included explicitly in the model formulation.

iv. Technology or product diffusion simulations describe the uptake of radical technologies over long time frames (C) by heterogeneous actors (B). However, they often do so within descriptive frameworks that are incomplete in their description of technological alternatives beyond the product or technology of interest. Such models simulate uptake or growth of a technology within the target market, often using diffusion theory (Bass, 1969; Rogers, 1962), but are often limited in scope to binary choices between the niche technology of interest and the established conventional technology of the regime (i.e., there is no portfolio of technology options). As a result, the models only consider socio-technical evolution along a single predetermined technological pathway. Due to this narrow scope, the dynamics of marginal choice between competing options, STET domain (A), is often inadequately represented, which prevents different pathways from being explored. Energy sector examples include studies on the diffusion of biogas generation (Madlener and Schmid, 2009), bioenergy power plants (Beck et al., 2008; Kempener et al., 2009) and hydrogen vehicles (Huétink et al., 2010; Keles et al., 2008; Köhler et al., 2010; Meyer and Winebrake, 2009). Generic technology substitution models that aim to formalise socio-technical transitions theory can also be placed in this category due to their lack of techno-economic detail (Papachristos, 2011).

The possible routes to the development of STET models from these near-STET models are elaborated in Section 4.

3. Overview of existing STET models

This section provides an overview of STET models in the energy field, including energy supply, buildings and transport. As a starting point, two systematic keyword searches[2] were carried out using Elsevier Scopus, which is one of the World Wide Web's major academic literature databases (Falagas et al., 2008), covering a range of journal and conference repositories, as well as book chapters. This process identified a number of initial publications for detailed analysis. Further publications by authors whose work was identified as involving the development of STET models were subsequently investigated, yielding additional publications to analyse. Bibliographies from identified key publications were also followed to expand the list of documents for review.

3.1. Fields of application

Fourteen STET models were identified from the literature search, as shown in Table 1. A fifteenth model, Lagom RegiO (Wolf et al., 2013), was identified as having strong potential to fulfil the STET criteria but was excluded from further review. This is because the current published documentation is for the generic model and does not yet include an

[2] Searches were carried out on 13/11/2014.
The first search string applied was ALL ("socio-technical transition" OR "socio-technical transformation") AND TITLE-ABS-KEY ("model" OR "simulation"), which yielded 130 articles. The titles and abstracts were then manually reviewed for content by the authors to determine their relevance.
The second search string applied was ALL ("transition pathway") AND TITLE-ABS-KEY ("electricity" OR "supply" OR "energy" OR "generation" OR "transport" OR "buildings"). When limited to the Environmental Science, Energy, Social Sciences, Engineering, Earth and Planetary Sciences, Economics, Econometrics and Finance, Decision Sciences, Multidisciplinary, and Undefined categories, this yielded 301 articles. The titles and abstracts were then manually reviewed for content.

Table 1
Existing socio-technical energy transition (STET) models.

Model name	Demonstrated fields of application	References
BLUE-MLP	Power sector (UK)	Incorporating Behavioural Complexity in Energy-Economic Models (Strachan and Warren, 2011) Linking a storyline with multiple models: A cross-scale study of the UK power system transition (Trutnevyte et al., 2014)
CASCADE Model Framework	Power sector (UK)	CASCADE: An Agent Based Framework for Modeling The Dynamics of Smart Electricity Systems (Rylatt et al., 2013) Exploring Possible Energy Futures For The UK: Evolving Power Generation (Allen et al., 2013) Modelling sustainable energy futures for the UK (Allen and Varga, 2014)
Chappin's Power Sector Agent-Based Model (ABM)	Power sector (Netherlands)	Agent-based modelling of energy infrastructure transitions (Chappin and Dijkema, 2008b) Modelling Strategic and Operational Decision-Making—An Agent-Based Model of Electricity Producers (Chappin et al., 2007) On the impact of CO2 emission-trading on power generation emissions (Chappin and Dijkema, 2009) Simulating Energy Transitions (Chappin, 2011)
ElecTrans	Power sector (Netherlands)	An Exploratory Analysis of the Dutch Electricity System in Transition (Kwakkel and Yücel, 2012) A simulation-based analysis of transition pathways for the Dutch electricity system (Yücel and van Daalen, 2012)
ENGAGE DFR Module	National energy demand and supply	Agent-based modelling of climate policy: An introduction to the ENGAGE multi-level model framework (Gerst et al., 2013b) Discovering plausible energy and economic futures under global change using multidimensional scenario discovery (Gerst et al., 2013a)
RAND Computer Assisted Reasoning (CAR) Framework	Global energy demand and supply	Carrots and sticks for new technology: Abating greenhouse gas emissions in a heterogeneous and uncertain world (Robalino and Lempert, 2000) A new decision sciences for complex systems (Lempert, 2002)
Tran's Alternative Fuel Vehicle (AFV) Model	Passenger car market (UK)	Technology-behavioural modelling of energy innovation diffusion in the UK (Tran, 2012) Simulating early adoption of alternative fuel vehicles for sustainability (Tran et al., 2013)
Struben's Alternative Fuel Vehicle (AFV) Model	Passenger car market (California)	Essays on transition challenges for alternative propulsion vehicles and transportation systems (Struben, 2006a) Identifying challenges for sustained adoption of alternative fuel vehicles and infrastructure (Struben, 2006b) Transition challenges for alternative fuel vehicle and transportation systems (Struben and Sterman, 2008)
Transition Lab Framework	Ground vehicle transport (UK, US)	Modelling Socio-technical Transition Patterns and Pathways (Bergman et al., 2008a) A transitions model for sustainable mobility (Köhler et al., 2009)
Transition Lab Framework	Residential buildings (UK)	Transition to sustainable development in the UK housing sector: from case study to model implementation (Bergman et al., 2008b)
REMG and IMAGE/TIMER	Residential buildings (Multiple Countries)	Model projections for household energy use in India (van Ruijven et al., 2011) Model projections for household energy use in developing countries (Daioglou et al., 2012)
Charlier's Residential Sector Model	Residential buildings (France)	Evaluation of the impact of environmental public policy measures on energy consumption and greenhouse gas emissions in the French residential sector (Charlier and Risch, 2012)
Res-IRF and IMACLIM-R	Residential buildings (France)	Comparing and Combining Energy Saving Policies: Will Proposed Residential Sector Policies Meet French Official Targets? (Giraudet et al., 2011) Exploring the potential for energy conservation in French households through hybrid modelling (Giraudet et al., 2012)
Yücel's Housing Stock Model	Residential buildings (Netherlands)	Extent of inertia caused by the existing building stock against an energy transition in the Netherlands (Yücel, 2013)
Chappin's Consumer Lighting Agent-Based Model (ABM)	Residential buildings (lighting) (Netherlands)	An agent-based model of transitions in consumer lighting: Policy impacts from the E.U. phase-out of incandescents (Chappin and Afman, 2013)

example of its application to an energy transition. Of the remaining models, six have been applied to energy supply, three have been applied to transport, and six have been applied to buildings. One STET model, Transition Lab,[3] has been applied both to investigate transitions in transport and in buildings. Another STET model, BLUE-MLP, represents the energy supply, residential buildings and transport sectors simultaneously, but has yet to be applied to the study of transitions beyond the electricity sector.

Of the STET models used to investigate energy supply, four have been applied to study transitions in the electricity sector in individual countries (BLUE-MLP, CASCADE, ElecTrans, and Chappin's Power Sector ABM), with the remaining two focusing on global energy demand and supply (the RAND CAR Framework, and ENGAGE's DFR module). No models were found that have been applied to study transitions in other types of energy supply infrastructure, such as gas networks. STET models applied to the transport sector (Transition Lab, Tran's AFV Model, Struben's AFV model) were found to have focused on ground vehicle transport, although Transition Lab has also been used to replicate historical transitions in ocean vessel technology during model structure tests. No studies were found that applied STET models to socio-technical transitions in aircraft transport. Out of the six STET models used to investigate the buildings sector, five focused on transitions in residential dwellings (Transition Lab, REMG, Res-IRF, Charlier's Residential Sector Model and Yücel's Housing Stock Model), and one explored the Dutch residential lighting market (Chappin's Consumer Lighting ABM). No STET model studies were found that explored socio-technical transitions in non-residential buildings.

The remainder of this section assesses how the reviewed models meet the STET model requirements described in Section 2.

3.2. Techno-economic detail

The levels of techno-economic detail employed in each model are detailed in Table 2. All models have a base level of techno-economic detail sufficient to characterise the sectors under study, but different models vary significantly in the level of technological disaggregation and the types of innovations included. This can be illustrated with the STET models used to study energy supply. At one extreme, the RAND CAR framework and the ENGAGE DFR module are highly stylised, with both using only three competing technologies meeting annual demand–supply constraints. At the other extreme, the ElecTrans model is extremely detailed, employing almost 30 generation technologies and incorporating a merit-order dispatch algorithm. The other reviewed energy supply models can be located on a spectrum between these two extremes. The CASCADE framework was the only energy supply model that attempted to represent the spatial disaggregation of the future system. CASCADE was also the STET model with the most granular time slicing (48 per day). It is however, more limited than other energy

[3] The name referred to here is only used on one occasion by the authors, and is taken from the program user interface window shown in Fig. 2 of Bergman et al. (2008a).

Table 2
Techno-economic detail in reviewed STET models.

Model name	Disaggregated portfolio of technology options with different price/performance characteristics	Bounded systems with operational or resource constraints
BLUE-MLP	Multiple electricity generation technologies (coal, coal CCS, CCGT, nuclear, offshore wind) Detailed representation of end-use demand sectors, including options not to use energy	Energy supply–demand matching constraint Steady state end user demand growth linked to exogenous GDP assumption
CASCADE Model Framework	Multiple electricity generation technologies (coal, gas, nuclear, onshore wind, offshore wind, marine, biomass, solar) Spatial distribution of demand and resources (100 zones)	Energy supply–demand matching constraint Resource constraints (wind, solar availability, suitability for nuclear power plants) Weather Conditions Demand growth for electric heating and electric transport
Chappin's Power Sector Agent-Based Model (ABM)	Multiple electricity generation technologies (coal, natural gas, wind, biomass, nuclear)	Energy supply–demand matching constraint CO2 emission permits constrain fossil fuel use
ElecTrans	Multiple electricity generation technologies. End user demand groups can deploy micro-CHP, photovoltaics, 3 CHP options, 2 biomass options, 2 onshore wind options, and 3 offshore wind options. Supply actors can build 5 coal options, 7 gas options (including CHP), biomass, nuclear, onshore and offshore wind	Energy supply–demand matching constraint Explicit cap on new nuclear deployment CCS only available post-2020
ENGAGE DFR Module	Multiple energy generation technologies: carbon heavy, carbon light, and carbon-free systems	Energy demand–supply matching constraint
RAND Computer Assisted Reasoning (CAR) Framework	Three types of energy generation technologies: high, medium and low GHG-intensity	Energy supply–demand matching constraint Technology diffusion rates are constrained based on historical rates Steady state economy with output per capita exogenously specified
Tran's Alternative Fuel Vehicle (AFV) Model	Multiple vehicle technologies, 7 in total (petrol, diesel, hybrid electric vehicles, battery electric vehicles, plug-in hybrid electric vehicles, hydrogen fuel cell vehicles)	Total end-use transport demand constraint Exogenous transport demand growth
Struben's Alternative Fuel Vehicle (AFV) Model	Multiple vehicle technology platforms (demonstrated with up to 4 types in references, but model is designed to be scalable)	Total vehicle fleet size is described as a model constraint, with examples in the references holding the fleet growth parameter constant
Transition Lab Framework (Applied to Transport)	Multiple transition niches (conventional petrol/diesel internal combustion engine vehicles, biofuel vehicles, hybrid electrical vehicles, hydrogen fuel cell vehicles, public transport, walking/cycling, car sharing, reducing mobility demand using ICT)	Zero-sum game with a limited population of consumer agents that different niche innovations must compete for
Transition Lab Framework (Applied to Residential Sector)	Multiple transition niches (continue as usual, options to increase energy efficiency through changes to the building stock, thorough spatial planning, or through lifestyle and behaviour change, and a niche that focuses on increasing quality of life e.g., targeting fuel poverty)	Zero-sum game with a limited population of consumer agents that different niche innovations must compete for Housing stock grows over time due to exogenous demolition/build rates
REMG and IMAGE/TIMER	Multiple energy carriers (coal, traditional biomass, kerosene, LPG, natural gas, modern bio-energy, electricity) for multiple end-use energy demands (cooking, electrical appliances, space heating/cooling, water heating, lighting)	End-use energy demands are constrained and driven by population, household expenditure, population density, household size, and temperature The REMG model is linked to a computational general equilibrium model, IMAGE/TIMER, which provides feedback between demand and prices, as well as context on fuel prices and emissions intensity of fuels
Charlier's Residential Sector Model	Multiple building renovation options (double glazing, wall insulation, roof insulation, changing the heating system, renewable energy)	Energy demand of the housing stock is driven by population growth projections (exogenous) Housing stock changes over time due to build/demolition rates Energy prices follow International Energy Agency (IEA) projections
Res-IRF and IMACLIM-R	Multiple building renovation options, allowing switching between 3 types of energy carriers (electricity, natural gas, fuel oil) and 21 possible building fabric retrofit choices which involve taking different buildings from a lower energy performance certification to a higher certification (e.g., transitioning from class G to either class E, D, C, B, A) 3 performance categories for new build buildings (2005 building regulations, Low Energy Buildings, Zero Energy Buildings) Householders can also use less energy in response to increases in energy prices (price elasticity of demand is captured)	Space heating demand is a function of the housing stock size, which is subject to demolition and new build rates The Res-IRF model is linked to a computational general equilibrium model, IMACLIM-R, which passes on information about energy prices and the disposable income of householders
Yücel's Housing Stock Model	Multiple building renovation options, with 8 building energy efficiency levels depending on build year Households can also lower demand in response to energy price increases	Total number of households are depend on demolition and new build rates
Chappin's Consumer Lighting Agent-Based Model (ABM)	Multiple lamp types (70 in total, including incandescent, halogen, CFL and LED technologies)	A limited population of consumers each possess a fixed number of light fittings into which they can fit different lamp types

supply models in terms of the level of agency given to the modelled actors, which is described in Section 3.3.

The three transport models all include a number of competing innovations. Tran's AFV model demonstrated the greatest number of vehicle technologies (7 in total). The Transition Lab model is notable for including non-technological options for meeting mobility requirements such as mode shifts to public transport, walking and cycling, or reducing transport demand through increased use of ICT. Struben's AFV model can be distinguished by its spatially explicit framework and its actor disaggregation into consumers and fuel suppliers (described further in Section 3.3), features which allow it to explore in detail the coevolution of radical vehicle technologies and their supporting refuelling infrastructure in real world geographies.

The six energy models used to study the residential buildings sector differed substantially in their respective areas of focus, which affected the levels of techno-economic detail used. Chappin's Consumer Lighting ABM has a distinct focus on a sub-sector of building energy demand rather than exploring the residential sector as a whole. REMG focuses on energy transitions in emerging economies and uses a more detailed description of the drivers of demand growth than other models. A major expected transition trend in emerging economies is a radical switch from traditional biomass to modern energy carriers, so REMG studies

Table 3
Explicit actor heterogeneity in reviewed STET models.

Model name	Multiple explicit actors with differentiated selection criteria or behavioural parameters	Actors that possess agency to affect transitions
BLUE-MLP	Dynamic simulation with 3 heterogeneous end-use demand sector actors 1 supply sector actor	Actors affect technology deployment in the power sector and in the modelled end-use sectors. As existing capital stock reaches the end of its life, actors invest to replace energy technologies based on myopic expectations of levelised costs. Actors are differentiated by a heterogeneity parameter that describes their propensity to be more or less cost-optimising in their behaviour, as well as hurdle rates, price elasticities, intangible costs.
CASCADE Model Framework	Dynamic simulation of long-term power sector investments and agent-based modelling of operational strategy. The agent-based model includes “prosumers” (combined producer / consumer agents) in the domestic, commercial and industrial sectors, as well as market aggregators.	Actors affect the operation of the electricity market. The dynamic simulation sets the contextual scenario technologies deployed, level of intermittency on the system, costs etc. for the agent-based model. Within the agent-based model, the “prosumer” actors bid on the wholesale electricity market through aggregator agents who act as intermediaries, with different operational patterns emerging under different weather conditions and contextual framing scenarios.
Chappin's Power Sector Agent-Based Model (ABM)	Agent-based model with energy producers (6 main Dutch market players), government (1), the environment (1), consumers (1), the world market (1), the electricity market (1), and a CO2 market (1) as agents	Actors affect power sector technology portfolio. Energy producers supply electricity to the consumer, acquire resources and make changes to the physical system by either: • Dismantling power plants that are at the end of their life or earing low revenues; or • Investing, based either on multi-criteria score of costs, emissions, dislike of nuclear power or conservativeness or based on net present value (NPV). • Energy producers also decide to sell electricity based on marginal cost bids, and compete to acquire CO2 emission permits. The government agent allocates emission permits to market participants based on a pro-rata grandfathered emissions formula. The emissions market agent makes additional permits available based on a supply/demand formula that reflects pollution permit availability beyond the electricity sector.
ElecTrans	Agent-based model. Four types of end-user demand side agents: households, industrial, commercial and horticultural/agricultural consumers. Numerous explicit supply agents (one for each 15MWe > generation plant in the Netherlands), each allocated to 1 of 6 producer groups (based on the 6 main Dutch market players). One system operator/regulator agent is responsible for dispatch and pricing.	Actors affect power sector technology portfolio and system operation. End-user agents on the demand side can opt to purchase electricity from the grid or build their own supply capacity, based on costs and levels of environmental concern. Supply side producers bid on the electricity market and make investment decisions on generation plant capacity based on their own heterogeneous projections of return on investment (ROI). The system operator/regulator balances supply/demand and subsidises renewables by paying any differential.
ENGAGE DFR Module	Agent based model. Seven types of agent per country: international climate negotiators, capital goods producing firms (50 used in example), consumer goods producing firms (20 used in example), consumers (250,000 used in example), three types of energy technology firm, one type of energy production firm/utility.	Actors affect market shares of energy production technologies in their respective economies All actors operate with incomplete information, seeking to lower their total lifecycle costs Consumers sell their labour to firms and replace their stock of consumer goods as they reach their end of life Consumer goods producing firms produce the goods required and decide to build inventory or invest in production capacity Capital goods firms can invest in R&D to improve productivity and win market share Energy technology firms also invest in R&D to lower costs and compete to sell technologies to the utility agent
RAND Computer Assisted Reasoning (CAR) Framework	Agent-based model with an unspecified number (presumably flexible) of heterogeneous producers of composite goods who invest in energy supply and decide on their own consumption	Actors affect global GHG emission trajectories by investing in different energy production technologies, based on imperfect information about expected utility, including cost and performance of technologies, while exhibiting differentiated sensitivities to risk and heterogeneous attitudes towards cost/performance trade-offs
Tran's Alternative Fuel Vehicle (AFV) Model	Discrete choice modelling framework. Two types of heterogeneous consumer are modelled, early adopters (with preferences for alternative fuel vehicles based on hybrid vehicles) and mass-market consumers.	Actors affect vehicle stock portfolio through multinomial logit choice decision making based on vehicle prices, acceleration, range, CO2 emissions, and availability of refuelling infrastructure
Struben's Alternative Fuel Vehicle (AFV) Model	System dynamics model with heterogeneous consumers (scalable to number of competing vehicle technologies), automotive industry, and refuelling station providers as actors	Consumer actors affect vehicle fleet portfolio through selection of different vehicle technologies based on a multinomial logit framework. As more consumers adopt a particular technology platform, social exposure can affect choices made by actors looking to purchase new vehicles. The automotive industry and refuelling infrastructure providers act with bounded rationality and invest in R&D and refuelling stations based on what they perceive consumers want and adjust their decisions based on feedback over time.
Transition Lab Framework (Applied to Transport)	Agent-based modelling with each technology/mobility niche represented by an agent (7 in total), with a population of consumer agents (unspecified size, presumably scalable), with each consumer belonging to 1 of 3 groups with heterogeneous preferences (mainstream and green car drivers, non-drivers)	Each sustainable mobility niche agent (which represent individual technology or behavioural innovations) tries to gain support for their approach from a limited population of consumer agents. Niche agents grow stronger and more entrenched the more support they garner.

Table 3 (*continued*)

Model name	Multiple explicit actors with differentiated selection criteria or behavioural parameters	Actors that possess agency to affect transitions
Transition Lab Framework (Applied to Buildings)	Agent-based modelling with each niche innovation represented by an agent (5 in total), with a population of 10,000 consumer agents belonging to 1 of 3 groups with heterogeneous preferences (mainstream society, 'concerned' actors who have higher sustainability preferences, and 'active' actors who have the highest sustainability preferences)	Sustainable development niche agents compete with each other for support from the consumer agent population, with niches growing stronger and more dominant the more support they get. Housing stock changes over time in response to actor preferences and can be refurbished, demolished, and replaced with new-build buildings.
REMG and IMAGE/TIMER	Dynamic simulation, with 10 heterogeneous household groups, differentiated by urban/rural location and income quintile (i.e., 5 groups), who differ in their microeconomic assessment of costs/benefits of different technologies (applied discount rates, perceived costs etc.)	As capital stock turns over, actors affect the total demand for end-use energy demands and market shares of different energy carrier choices based on perceived costs (expressed as a multinomial logit choice function)
Charlier's Residential Sector Model	Dynamic simulation, with heterogeneous households differentiated by income quintile (i.e., 5 groups) who are found in 12 different types of dwelling (differentiated by 4 types of heating fuel, collective/individual heating systems, multi-occupancy buildings/private residences), and can be either tenants or homeowners in 5 family categories (single, couple without children, couple with children, single-parent family and other)	Actors affect the number and type of renovations that occur in the housing stock based on a discounted cost benefit analysis taking into account their tenure, duration of residence, income, availability of subsidies, etc. This consequently affects the overall levels of residential sector energy demand and GHG emissions
Res-IRF and IMACLIM-R	Dynamic simulation, with 4 heterogeneous actor classes, based on tenure (homeowners vs. tenants) and built form (detached dwellings vs. units in multi-occupancy buildings)	Actors affect the building stock portfolio and consequently the energy performance by making choices on whether to retrofit their buildings and how much to improve performance, based on myopic expectations of costs, with actor-specific discount rates, and intangible costs, and with a heterogeneity parameter also used to reflect an actor group's individual tendency towards or away from cost-optimising behaviour
Yücel's Housing Stock Model	Dynamic simulation, with 9 heterogeneous household groups, comprised of a matrix of 3 categories of building architecture/social income band (detached dwellings/high income, terraced dwellings/medium income, flats/low income), 3 dwelling lifecycle stages (early medium, late)	Actors can change the composition of the housing stock by making decisions about retrofit Actors invest in renovations when two conditions are met: when energy prices reach a threshold percentage of their household income, and when economic savings from the retrofit are expected to result in profit
Chappin's Consumer Lighting Agent-Based Model (ABM)	Agent-based modelling of heterogeneous households (250) and a manufacturer (1) acting as a retailer	Actors affect technology deployment. Households replace lighting when old lamps fail, deciding based on multi-criteria scores, based on price, efficiency, colour, temperature, light output, memory (lifetime before failure of different lamp technologies), social network impact (whether technologies are adopted by friends affects which perception of lamp types, brands and models). Manufacturer responds to government policy measures (user-defined), which change price and availability.

these explicitly without representing the building stock itself or potential building fabric improvements. The four models used to explore changes to buildings in high-income countries (France, UK, Netherlands) took divergent approaches. Charlier's Residential Sector model used an explicit description of retrofit intervention such as insulation and glazing, while the other models employed a simplified representation using energy performance bands (Res-IRF, Yücel's Housing Stock Model) or abstract efficiency improvements (Transition Lab). Transition Lab was the only model to employ options beyond improvements to the buildings themselves, such as the energy efficient spatial planning of settlements.

3.3. Explicit actor heterogeneity

The treatment of actor heterogeneity employed in each of the reviewed models is detailed in Table 3. Almost half of the studies reviewed were agent-based models, while the remainder used dynamic simulation, often with actors making selections through multi-criteria decision analysis or similar structures. From this overview it must be acknowledged that the dynamic simulation approaches seem to have been at least as successful as agent-based models in capturing the key characteristics of socio-technical transitions. Regardless of the approach taken, the type and number of actors represented, their level of agency to affect the system, and the representation of inter-actor dynamics varied significantly between models.

BLUE-MLP is a dynamic simulation model with four actors, each representing a social planner responsible for an economic sector. The actors make decisions myopically without advance knowledge of what will happen in other sectors and affect how the system transition unfolds by having demand-supply interactions with one another. ENGAGE, CASCADE, ElecTrans, the RAND CAR Framework and Chappin's Power Sector ABM employed agent-based modelling techniques, but differed in the level of agency possessed by actors and how actor interactions were structured. The CASCADE electricity sector framework employs two distinct models, a long-term dynamic simulation of strategic investment in the UK power system, and a short-term agent-based framework of electricity market interactions. CASCADE agents have limited agency, and while the transition framework can investigate changes in how different actors influence dynamic pricing in the electricity market, it cannot explore how different market players change their levels of investment in different electricity generation technologies over time. On the other hand, STET models like ElecTrans and Chappin's Power Sector ABM involve agents representing a diversity of market participants, all of whom can influence the technological pathway followed in the power sector, but do not address the dynamics of within-day electricity pricing.

The three transport models demonstrate different approaches to investigating transitions. Tran and Struben's respective AFV models represent different vehicle technologies as portfolios of options to be selected under dynamic simulation to assess how different groups of consumers with different attitudes might uptake different vehicle types over time. Transition Lab, on the other hand conceptualises the technologies themselves as agents who try and dominate the transport sector by capturing support from diverse consumer actors. Despite their different underlying model philosophies (agent-based vs. system dynamics), Transition Lab and Struben's AFV model both account for the bounded rationality of actors, who make decisions with imperfect information and adjust their behaviour based on feedback, and social exposure effects, where actors' decisions are influenced by the behaviour of other actors. Struben's AFV model is notable for taking a wider system perspective of the transport sector, representing not just consumers but also the automotive industry and refuelling station providers.

In the residential buildings sector, Transition Lab and Chappin's Consumer Lighting ABM employed agent-based modelling to represent trends amongst different actors. Although they have different foci, both models can be distinguished from the dynamic simulation studies by their incorporation of social preference dynamics. Both models aim to capture how increasing adoption of an innovation can affect consumer choice, possibly entrenching it as a dominant option over time.

3.4. Transition pathway dynamics

The way in which different reviewed STET models address energy transition dynamics is highlighted in Table 4. All models track key parameters such as the market share of different technologies, the overall levels of energy demand or the amount of carbon emissions produced. These parameters allow the model user to assess whether a normative transition has taken place or not. All models employ time horizons on the scale of decades, enabling longitudinal assessment of how trends change over time as opposed to snapshots of normative conditions at defined future time periods. All models include radical innovations in technology or behaviour as options that can be chosen by system actors, allowing for the possibility of break out from locked-in system conditions.

3.5. Model calibration, validation and treatment of uncertainty

The calibration, validation and treatment of uncertainty is an integral part of any type of modelling (Bennett et al., 2013). Table 5 explores how different models are calibrated, validated, and how they treat uncertainty. All of the models reviewed were calibrated using empirical data such as energy demands, technology performance and costs, while a smaller sub-set also included factors linked to broader macroeconomic developments such as economic growth and fuel prices. The parameters of most models were calibrated to the empirical data of the initial year of the model runs.

Several authors mentioned their attempts to validate their model structure and behaviour by using test runs, expert elicitation and comparisons with the literature. However, most of these validation attempts were vague in their published descriptions. From a validation perspective, Transition Lab and REMG are notable for their ability to closely replicate a number of historical socio-technical transitions. Despite the analysis of uncertainty being key to the provision of insights about long-term changes to energy systems, half of the models reviewed relied on deterministic sensitivity analyses rather than attempting more complex probabilistic approaches such as exploratory modelling.

4. Discussion

4.1. Detail and complexity

All reviewed models faced the classic modelling trade-off between depth and breadth. For example, across all reviewed models, approaches that are more stylised in terms of their techno-economic detail (Section 3.2) tend to be more complex in other areas, such as their representation of actor heterogeneity (Section 3.3) or transition pathway dynamics (Section 3.4). Socio-technical transitions in the energy supply, buildings and transport fields are highly context-specific (Trutnevyte et al., 2012). The level of detail that is appropriate in each domain will depend on the purpose of the model, such as whether it is designed to deliver case-specific insights for policy analysis or used for more general understanding of transition dynamics in a particular sector (Yücel and van Daalen, 2009).

It is possible that as a result of computational constraints, analytical tractability, or data availability, STET type models might never be as detailed in any single domain as their counterparts which do not try to integrate the three STET domains A–C outlined in Section 2. Realistically, STET models will look like the stylised illustration in Fig. 2, with the darker areas representing increased complexity in each of the three domains, and the lighter areas representing increased abstraction. In reality there is likely to be a spectrum of model detail in the three relevant dimensions and how they overlap, although the middle ground may always be an area where compromises need to be made.

From a future development perspective, it may be useful to reflect on the use of multiple models to achieve detailed insights in the 3 STET model domains. The "landscape of models" approach (Trutnevyte et al., 2014) proposes linking models together in order to extend the overall analysis boundaries and to compensate for the stylized scope of some models. A number of the STET models reviewed were linked frameworks that already comprised more than one model, such as the CASCADE framework, Res-IRF linked to IMACLIM-R, or REMG linked to IMAGE/TIMER. For such hybrid models the level of complexity may be deep in their core areas (e.g., techno-economics) but with far less detail in the other 2 spheres, potentially resulting in an imbalanced STET model (Ghersi and Hourcade, 2006).

4.2. Representation of co-evolution of technology and society

While some elements of socio-technical transitions may always lie outside of the capability of any formal analysis (McDowall, 2014), the authors believe that there are a number of areas for future development of STET models. One of these is improving the representation of co-evolutionary factors, such as social interaction. Struben's AFV model (a system dynamics type model), Transition Lab, and Chappin's Consumer Lighting Model (agent-based type models) included social mechanisms where actors were able to influence each other's choices. Many of the reviewed models appeared to omit this endogenous co-evolution of consumer preferences and this is an area for STET models to develop further. The review of social influence frameworks by Axsen and Kurani (2012) could be a useful starting point.

Many reviewed models concentrated on representing one type of actor, typically generic consumers, rather than a broader spectrum of actors. An improved diversity of actor types and heterogeneity within these types is desirable in order to allow representation of two-way interactions between actors; for example, how the automotive industry responds to consumer purchases of different vehicle platforms in Struben's AFV model or how consumers respond to and influence wider economic conditions through price elasticities in REMG, Res-IRF or ENGAGE.

4.3. Representation of socio-technical transition dynamics

All STET models captured elements of the dynamic, non-linear nature of socio-technical transitions, with feedback loops causing endogenous change to the system as a result of actor choices. Most of the models reviewed were designed to investigate transition dynamics in a single sector, and often calibrated to a specific national case. Most models limited their representation of innovations to radical technologies rather than also considering behavioural and lifestyle shifts.

The Transition Lab model is notable for being designed as a more generally applicable model, and is a computational implementation of a transitions framework by Haxeltine et al. (2008). BLUE-MLP has also been designed for investigating transitions in different economic sectors, although it has only been applied to the power sector to date. Both these models make explicit reference to the transitions theory lexicon, using terms such as "niche", "regime" and "landscape" in their structure. Transition Lab for example, represents the niche and the regime explicitly, with niches gaining strength and inertia as they grow in popularity, and globalised model parameters changing as a result of landscape level shifts such as policy interventions or social attitudes. Eventually, it is possible for a strong niche to replace the incumbent regime. While this approach is not a prerequisite for a STET model, it is useful to reflect that exploring the dynamics of transitions in future STET models could perhaps be facilitated through conceptual alignment with formal transition frameworks like the MLP. One example is the work of Papachristos (2011), which represents different MLP pathways

Table 4
Transition pathway dynamics in reviewed STET models.

Model name	Assessment of normative goals	Time horizons sufficient for exploring long-term socio-technical change, path dependencies	Radical alternatives to incumbent status quo technology or behaviour options
BLUE-MLP	Assesses CO_2 emissions, technology diffusion in supply and end-user sectors, end-use energy service demand, in response to behaviour and lifestyle inputs, carbon pricing	2010–2050, annual time steps	Electric heating technologies such as heat pumps, electric transport vehicles Low and zero carbon electricity generation technologies Non-energy using options include voluntary reductions in space heating and increased walking/cycling for transport
CASCADE Model Framework	Assesses CO_2 emissions, installed capacity of generation assets in different spatial zones, daily profiles of demand/pricing	Strategic long term model uses 2010–2050 with annual time steps Operational model uses a single representative day with 48 half hourly time steps	Electric heating, electric transport, low carbon electricity generation, 'smart' grid control signals
Chappin's Power Sector Agent-Based Model (ABM)	Assesses CO_2 emissions, technology portfolio of power producers	Demonstrated with time horizon spanning 0–75 years, annual time steps	Low and zero carbon electricity generation technologies
ElecTrans	Assess CO_2 emissions, installed capacity of different technologies deployed at a utility and micro-generation scale by different actors, wholesale electricity prices	2006–2040, 4 time steps/year	Low carbon and zero carbon electricity generators, embedded micro-generation within end-user groups
ENGAGE DFR Module	Assesses market share for different energy technologies, energy prices, GDP, energy intensity as a function of GDP, levelised carbon emissions per capita	2000–2100, annual time steps	Low carbon and renewable energy supply technologies
RAND Computer Assisted Reasoning (CAR) Framework	Assesses global GHG emissions, installed capacity of different energy supply technologies	1990–2100, annual time steps	Low carbon intensity energy supply technologies
Tran's Alternative Fuel Vehicle (AFV) Model	Assesses cumulative adoption of different vehicle technologies	2000–2035, annual time steps	Radical alternative vehicle drive trains including electrical and hydrogen cars
Struben's Alternative Fuel Vehicle (AFV) Model	Assesses adoption of different vehicle technologies, spatial deployment of refuelling infrastructure	Demonstrated with time horizon spanning 0–60 years, annual time steps	Radical alternative fuel vehicles
Transition Lab Framework (Applied to Transport)	Assesses cumulative adoption of different sustainable mobility niche developments, with niches acquiring strength the more they are adopted—the strongest niche becomes the regime.	2000–2050, annual time steps	Radical alternative vehicle technologies, mode shift to public transport/car pooling, reduced transport demand options
Transition Lab Framework (Applied to Residential Sector)	Assesses household energy use and CO_2 emissions, built environment density, penetration of mixed-use zoning so essential services are available locally to homes, public transport and walking/cycling uptake, waste to landfill, social cohesion	2000–2050 12 time steps/year	Includes radical changes to energy efficiency through direct intervention in building technologies, but also through revolutions in spatial planning, behavioural and lifestyle change
REMG and IMAGE/TIMER	Assesses total residential energy use, market shares of different energy carriers, CO_2 emissions	2007–2030, annual time steps	Radical transition from traditional biomass to modern energy carriers
Charlier's Residential Sector Model	Assesses total residential sector energy demand and GHG emissions	2006–2050, annual time steps	Energy efficient building stock retrofit, fuel switching to renewable energy
Res-IRF and IMACLIM-R	Assesses total energy demand from the building stock, energy performance of buildings, energy carriers used for space heating provision	2008–2050, annual time steps	Energy efficient retrofit of existing building stock, low energy new buildings
Yücel's Housing Stock Model	Assesses total residential energy consumption, energy performance of dwelling stock	2010–2050, annual time steps	Energy efficient retrofit of existing buildings stock
Chappin's Consumer Lighting Agent-Based Model (ABM)	Assesses uptake of different technologies in response to policy interventions	Demonstrated with time horizon spanning 0–40 years, annual time steps	Efficient low energy lighting technologies including CFL and LED lamps

and could be developed into a STET model through the addition of energy sector detail.

4.4. Adapting existing models

On the subject of adapting existing tools, Section 2 discussed a variety of model types that integrate 2 of the 3 STET domains A–C. It could be possible to adapt many of these models in future to add the missing domain, qualifying them as STET models and extending their range of insights.

For example, existing energy economy models and sector-specific techno-economic models could develop methods of incorporating explicit actor heterogeneity. A model framework of note is FTT-Power-E3MG (Mercure et al., 2014), which already addresses innovation-choice-diffusion dynamics of investors using distributions. Including an explicit characterisation of heterogeneous actors, such that the impact of different transition dynamics could be explored on different identifiable actor groups, would transform this framework into a STET model as defined in the taxonomy presented here.

Agent-based simulations of energy systems could be extended in order to capture transition dynamics such as the uptake of radical technologies that change the operation of the system and representing system evolution over long time periods. For example, electricity market models, such as those described in Weidlich and Veit (2008), could have their time horizons lengthened.

Technology or product diffusion models could be adapted to elaborate greater techno-economic detail and represent the target market as more of a bounded system so that the economics of marginal choice

Table 5
Calibration, validation, and uncertainty in reviewed STET models.

Model name	Model calibration	Model validation (structure and or behaviour)	Treatment of uncertainty
BLUE-MLP	Published examples include having the model calibrated to UK government 2010 energy balance statistics for the whole country and also to represent the UK's capital city of London individually	–	Stochastic modelling
CASCADE Model Framework	Not explicitly identified in references but assumed to be calibrated to UK data for the base year	–	–
Chappin's Power Sector Agent-Based Model (ABM)	Model is demonstrated with a starting portfolio of technologies, a number of power producers, level of electricity demand, and level of import capacity based on the Netherlands, although the model is scalable	Structure tests: validation of empirical structure and parameters, direct extreme conditions, boundary adequacy of structure, dimension analysis and face validation Behaviour tests: tests for extreme conditions, qualitative future analysis, comparison with accepted theory and sensitivity	Stochastic modelling, demonstrated with up to 3600 runs
ElecTrans	Calibrated to represent the Dutch electricity system in 2006 for validation, and calibrated to 2010 conditions for the main study	Model subjected to parametric testing to explore extreme values Model projections for wholesale prices compared with actual data for 2006–2011	Deterministic sensitivity analysis demonstrated with 8 scenarios used to test variation in carbon price trajectory, technological development rates, end-user attitudes
ENGAGE DFR Module	Calibrated to United States macroeconomic conditions and energy use data for year 2000, with historical rates of GDP growth and energy use growth per household	–	Stochastic model, demonstrated with 200 simulations
RAND Computer Assisted Reasoning (CAR) Framework	Calibrated to 1995 global market shares of technologies, their emissions and energy intensities, and total global emissions	–	Exploratory modelling: combinatorial solutions found using uniform distributions over known input ranges are filtered to find those that meet system constraints (example finds 1611 solutions)
Tran's Alternative Fuel Vehicle (AFV) Model	Vehicle stock portfolio calibrated to UK passenger vehicle market using historical data on licensed cars from 1999–2008 End-use transport service demand calibrated to UK historical passenger-km from 1990–2006	–	Deterministic sensitivity analysis demonstrated with 4 scenarios involving different consumer preference inputs
Struben's Alternative Fuel Vehicle (AFV) Model	Vehicle fleet and refuelling infrastructure in base year calibrated to represent California in 2002	Model behaviour tested, authors acknowledge requirement for more validation	Deterministic sensitivity analysis using different scenarios where input parameters are varied
Transition Lab Framework (Applied to Transport)	Calibrated to UK data circa 2000–2003 on total transport demand, model split, vehicle sales, consumer attitudes etc.	Model behaviour tested through simulation of historical transitions, such as transition from horse-drawn to motorised transport in the United States from 1850–1930 or transition from sail to steamships from 1850–1914. Authors acknowledge that successfully replicating a historical transition is data dependent.	Stochastic modelling, with consumers randomly seeded across niches in the initial base year
Transition Lab Framework (Applied to Residential Sector)	Household energy use, housing stock composition, built density, mixed use zoning, public transport and walking/cycling, waste to landfill and social cohesion calibrated to UK data circa 2000	As above	Stochastic, example demonstrates scenarios with different policy measures being run at least 20 times before results are viewed to inform conclusions
REMG and IMAGE/TIMER	Calibrated for India, China, South East Asia in general, South Africa, and Brazil Most extensive discussion of calibration is for India	Compared with IEA historical data for regions assessed. Also validated against historical fuel use transitions in India between 1971–2003, with a normalised root mean square error of 2.7% for fuels and 14% for electricity	Deterministic sensitivity analysis of variation to household expenditures and oil prices
Charlier's Residential Sector Model	Calibrated to represent France in 2006	Authors note that results are consistent with statistics after one time step i.e., in 2007	Deterministic sensitivity analysis of variation to energy prices and discount rates
Res-IRF and IMACLIM-R	Calibrated to represent France in 2007	Compared space heating expenditure, retrofit costs, rebound effect for space heating, price elasticities of demand, trends in energy intensity/m2	Deterministic sensitivity analysis using heterogeneity of decision makers and discount rates
Yücel's Housing Stock Model	Calibrated to represent the Netherlands in 2000	Model is subjected to parameter and structure tests	Deterministic sensitivity analysis varying demolition rate, construction rates
Chappin's Consumer Lighting Agent-Based Model (ABM)	Lamp/socket distribution in target population (Netherlands) calibrated to 1980 base year conditions and 2005 intermediate year conditions based on historical and survey data.	Model structure is parametrically tested to show that there are conditions under which many of the lamps could be the preferred option	Exploratory modelling: For each policy test, simulations are repeated 100 times with different consumer preference weighting factors to obtain a spread of results

between competing options can be captured. Papachristos (2011) has already been discussed as an example. Another approach is for models that are already used for evaluating specific innovations such as hydrogen fuel cell vehicles (e.g., Huétink et al., 2010), to be generalised more broadly to capture alternative competing technologies in the same sector.

Developing an 'ideal' STET model that has a rich representation in all domains A–C from existing work may prove to be too ambitious in all

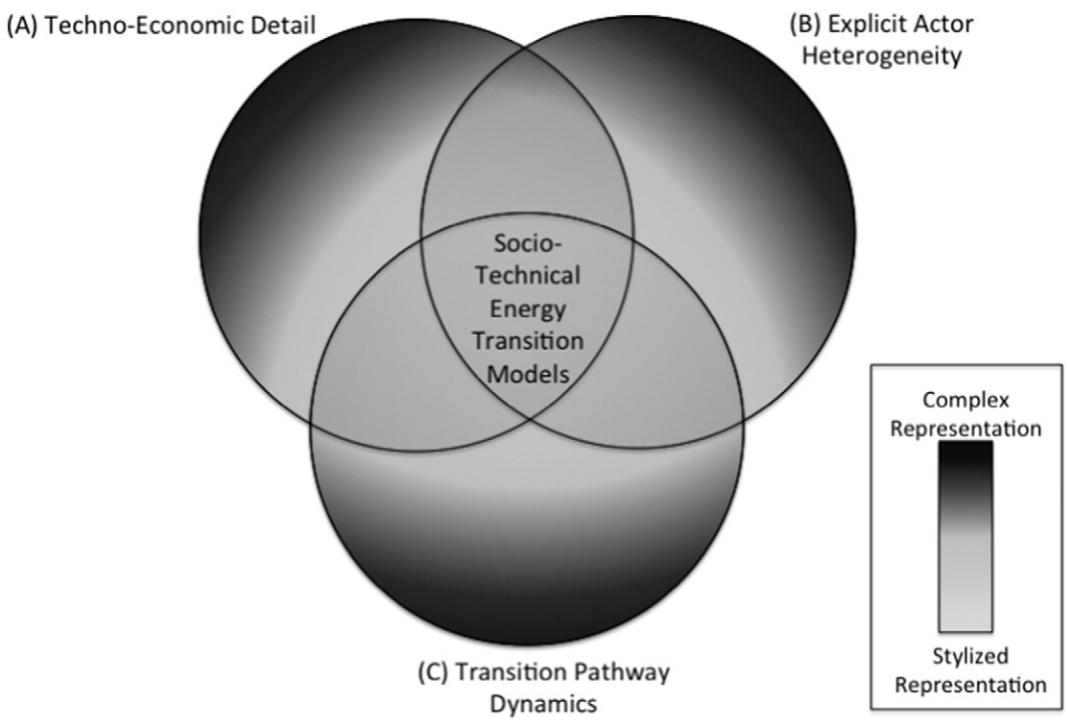

Fig. 2. Stylized representation of detail trade-offs in STET models.

applications and stylized representations could be required (Fig. 2). One approach to compensate for limitations in model capabilities could be to iteratively link a number of models or to apply multiple models in an ensemble fashion, as demonstrated in Trutnevyte et al. (2014).

4.5. Validation

It is comparatively easier to assess a model's structure and theoretical underpinning if it comes from a clearly recognised modelling paradigm and is mono-disciplinary in nature. Researchers working on STET models which integrate techno-economic detail, actor heterogeneity, and transition pathway dynamics have a greater challenge to overcome. In complex models that combine multiple domains, separating parameter uncertainty from model structure uncertainty can often be difficult, there is often a lack of historical data in an appropriate format for comparison, and it is possible to change multiple parameters or combinations of parameters to tune model outputs to mimic past trends (Beugin and Jaccard, 2011).

Many of the reviewed models employed some form of parameter or structure testing, but few had their outputs compared against empirical data (often termed behavioural testing). The extent to which the latter is necessary is sometimes the subject of intense debate in model-based science. Models are sometimes argued to be “valid” if their structure can be tested and they exhibit the “right behaviour for the right reasons” (Barlas, 1989), even in the absence of behaviour tests (Qudrat-Ullah and Seong, 2010). Others caution strongly against advocating structural validation at the expense of behavioural testing, denouncing it as “sloppy and lazy” (Sterman, 2002). A complex middle ground sometimes emerges, depending on the intended application of the model (Yücel and van Daalen, 2009).

A lengthy discussion on this subject is outside of the scope of this paper, but it is clearly impossible to empirically validate model projections in the sense of eliminating Knightian uncertainty, because there is no real information available about the future. That is to say, due to limited knowledge and computational capacity, all possible outcomes cannot be demonstrated and all impossible outcomes cannot be eliminated (Betz, 2010). While computational models are not crystal balls into the future, the act of constructing and using them is certainly useful for exploring the emergent phenomena found in complex systems. All of the reviewed STET models can be viewed as valuable because all of the revealed new findings that emerge only at the interplay of the A, B and C domains.

For example, publications using the ElecTrans model (Kwakkel and Yücel, 2012; Yücel and van Daalen, 2012) found several unique, counterintuitive, and policy-relevant results that could only arise from a STET model analysis including radical technological change, long time horizons, and a multi-actor system. Model results illustrated that sustainable energy subsides in the Netherlands were not guaranteed to drive a rapid shift to clean electricity generation in the near-term. Counterintuitively, this was found to be the case even under conditions with high carbon prices, or scenarios where costs for renewable generation followed optimistic trajectories. Additionally, the studies found that if the near-future window of opportunity posed by the retirement of a large fraction of the Netherlands' conventional generation plant was missed, this risked locking the Dutch electricity system into a fossil-dominated path until at least the next market investment cycle i.e., for decades. The authors were able to use model results to suggest a portfolio of policy interventions that might overcome systemic lock-in and enable a rapid energy transition to occur, even within a liberalised electricity market comprised of multiple profit-maximising agents. This example demonstrates the ability of STET models to encompass the socio-technical aspects of transitions rather than just the techno-economic. Their ability to explore complex, path dependent, multi-actor systems characterised by deep uncertainty shows the promise that this emerging model category holds for informing policy development.

5. Conclusions

The quantitative modelling of socio-technical energy transitions (STET), which merges the conceptual frameworks of socio-technical transitions with energy modelling, is a new frontier for research that is demanded by today's energy and climate change challenges. Many existing technical feasibility and modelling studies are criticised for their limited treatment of socio-political dynamics, the co-evolving nature of society and technology, and a lack of depiction of specific actors that bring about systemic change. At the same time, conceptual socio-technical transition frameworks that address these elements are often found to be difficult to operationalize in quantitative energy analyses in order to meet policy development requirements. The emergence of STET models has the potential to address these concerns, improving the understanding of how policies can be designed and implemented to bring about desirable normative futures for the energy system.

This paper defines STET models as quantitative models for understanding the socio-technical nature of energy transitions. These models are grouped under a novel taxonomy that covers three key characteristics. First, the models include comprehensive techno-economic detail on the sector under study, providing a portfolio of differentiated options within a bounded system description (e.g., supply–demand balance or resource constraints). Second, the models include explicit heterogeneous actors, who possess the ability to affect the character of transitions. Third, the models incorporate key transition dynamics, building-in options for radical innovations that can disrupt the incumbent socio-technical regime, representing changes over long (decadal) timeframes and monitoring transition metrics that can be used to assess normative goals (such as compliance with carbon emissions reduction targets).

This review analysed the small but emerging field of existing STET models in the energy supply, transport and residential buildings sectors. Additionally, several further families of models are described that address some but not all of the requirements for STET models. This paper's proposed STET model taxonomy could serve as a guide for researchers seeking to add the missing elements required for an improved depiction of socio-technical energy transitions. Such interdisciplinary model development is not straightforward and raises issues of the level of complexity possible across all three STET domains, and the theoretical and behavioural validation of new STET models. However, development of such STET models offer a unique possibility for interdisciplinary collaboration between transition scholars and energy modellers to combine insights from both fields. Developing the evidence base to underpin policies dealing with the socio-technical energy and climate challenge requires such innovative interdisciplinary research.

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