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Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling

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ABSTRACT

Hydrogen remains an important option for long-term decarbonisation of energy and transport systems. However, studying the possible transition paths and development prospects for a hydrogen energy system is challenging. The long-term nature of technological transitions inevitably means profound uncertainties, diverging perspectives and contested priorities. Both modelling approaches and narrative storyline scenarios are widely used to explore the possible future of hydrogen energy, but each approach has shortcomings.

This paper presents a hybrid approach to assessing hydrogen transitions in the UK, by confronting qualitative socio-technical scenarios with quantitative energy systems modelling, through a process of 'dialogue' between scenario and model. Three possible transition pathways are explored, each exploring different uncertainties and possible decision points. Conclusions are drawn for both the future of hydrogen, and on the value of an approach that brings quantitative formal models and narrative scenario techniques into dialogue.

1. Introduction

Hydrogen remains an important option for long-term decarbonisation of energy and transport systems, and modelling studies often suggest that hydrogen could be an important part of an affordable and achievable transition to a low carbon economy. Despite a recent period of disappointment following several years of hydrogen 'hype' (Bakker, 2010), technological progress in hydrogen technologies has been promising. Automotive firms have focused on vehicles running on pure hydrogen with fuel cells, and on-board compressed hydrogen, moving away from earlier work with liquid hydrogen or on-board conversion of other fuels. Costs have fallen, and there is increasing confidence from automakers that fuel cell vehicles are approaching commercial competitiveness.

However, studying the possible transition paths and development prospects for a hydrogen energy system is challenging. The long-term nature of technological transitions inevitably means profound uncertainties, diverging perspectives and

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contested priorities. Both modelling approaches and narrative storyline scenarios are widely used to explore the possible future of hydrogen energy, but each approach has shortcomings.

This paper presents a hybrid approach to examining hydrogen transitions in the UK, by linking qualitative transition scenarios with quantitative energy systems modelling. The approach acknowledges the contested nature of ways of understanding future possibilities by placing two different methods (participatory storylines and energy systems modelling) in explicit 'dialogue'. Three possible transition pathways are explored, each exploring different uncertainties and possible decision points, with modelling used to inform and test key elements of each scenario. The scenarios draw on literature review and participatory input, and the scenario structure is based on patterns identified in historical energy system transitions, reflecting insights relating to innovation system development and resistance to change.

2. Background and approach: scenarios and models for technology transitions

2.1. Modelling energy transitions

Formal models are powerful ways of exploring the dynamics of systems and hence play a crucial role in thinking about how those systems might develop in the future. A wide variety of models have been developed to inform the transition to a low carbon economy, and these have generated robust[1] insights into the likely importance and roles of various technologies, trends and policy instruments. In the context of hydrogen energy, three types of models[2] have been prominent:

- So-called "Bottom-up" energy system models (e.g. MARKAL and MESSAGE) evaluate the desirability of hydrogen within the context of overall decarbonisation. They model trade-offs with the wider energy system, and so provide greater techno-economic consistency than sectoral approaches, but they have weak spatial representation, and many have simplistic representations of technology dynamics and the economy-wide costs of energy transitions (Barreto & Kemp, 2008; Hourcade, Jaccard, Bataille, & Ghersi, 2006). Examples of studies addressing hydrogen transitions using such models include (Barreto, Makihira, & Riahi, 2003; Endo, 2007; Gül, Kypreos, Turton, & Barreto, 2009; Krzyzanowski, Kypreos, & Barreto, 2008; Mau, Eyzaguirre, Jaccard, Collins-Dodd, & Tiedemann, 2008; Strachan, Balta-Ozkan, Joffe, McGeevor, & Hughes, 2009; Yeh, Farrell, Plevin, Sanstad, & Weyant, 2008).
- System dynamics and agent-based simulation models examine interactions between agents (governments, consumers, car manufacturers). These models are valuable in showing how simple relationships can result in complex dynamics similar to previous attempts to foster alternative fuel transitions; and they can provide insights into the conditions under which heterogeneous actors might foster a transition through consumption, investment, policy and cooperation decisions. However, they lack the broader system view, without feedbacks and synergies between sectors in the wider economy. Examples in the field of hydrogen transitions include (Contestabile, 2010; Huétink, der Vooren, & Alkemade, 2010; Keles, Wietschel, Möst, & Rentz, 2008; Köhler, Wietschel, Whitmarsh, Keles, & Schade, 2010; Schwoon, 2008; Struben & Sterman, 2008).
- Infrastructure optimisation transition models. These optimise spatial and temporal aspects of infrastructure and vehicle deployment, but exogenise hydrogen demand. For a review, see (Agnolucci & McDowall, 2013).

Quantitative models used in the analysis of possible transitions have grown increasingly sophisticated, endogenising the effects of scale economies and learning (Schwoon, 2008), social network effects (Huétink et al., 2010; Mau et al., 2008), and strategic games between actors (Schlecht, 2003). Energy systems models have been adapted to incorporate better representation of behaviour (Daly et al., 2012; Mau et al., 2008), macro-economic developments (Strachan & Kannan, 2008); and technological change (Anandarajah, McDowall & Ekins, 2013).

However, on their own, none of these model types is able to provide a compelling account of transition dynamics, since in the real world the structure of the system itself evolves. In other words, the rules guiding development co-evolve with technologies, user behaviours and business strategies (Foxon, 2011). Moreover, there is scant agreement on the extent to which dominant rule structures used in models provide a good approximation of socio-technical developments over long time periods (Trutnevyte, 2014). As a result, existing models may be unable to represent the key issues that are widely recognised by stakeholders to be important. These issues then lie outside the scope of any formal analysis, potentially remaining unexamined tacit assumptions that guide decisions. Attempts to develop models of transitions dynamics that are informed by evolutionary and co-evolutionary thinking are developing, but are still in their infancy (Safarzyńska, Frenken, & van den Bergh, 2012).

[1] At least, robust in the face of the uncertainties that are considered to be most well characterised, following Lempert and Groves definition of 'robustness' of model outcomes (Groves and Lempert, 2007). D.G. Groves, R.J. Lempert, A new analytic method for finding policy-relevant scenarios, Global Environmental Change, 17 (2007) 73–85.

[2] Others have also been applied, such as Computable General Equilibrium models, but these have been less frequently used.

2.2. Socio-technical scenarios

Scenarios[3] are widely used to help inform decision-making in the face of significant uncertainty, particularly in fields with long-term planning horizons such as energy policy. A major reason for adopting an exploratory scenario approach as an analytic tool for considering possible energy decarbonisation transition paths is a belief that formal quantitative models are unable to adequately represent the dynamics of socio-technical change, for the reasons discussed above (Söderholm, Hildingsson, Johansson, Khan, & Wilhelmsson, 2011; Swart, Raskin, & Robinson, 2004). Rather than ignore the issues that are already informing stakeholder decisions because they are not tractable in a formal model, scenario approaches draw these out, make them explicit, and conduct thought experiments to test judgements about their importance.

Scenario storylines informed by participatory processes, though not always as analytically coherent or internally consistent in techno-economic terms, are thus able to capture, distill and explore ideas about the future that are currently shaping stakeholder perceptions, but that cannot be adequately represented in formal modelling frameworks. The resulting scenarios do not incorporate the technical rigour of models, but they can be valuable in making explicit widely held views about possible technology dynamics. This does not necessarily mean that these are more 'accurate' in terms of predicting what kinds of dynamics are likely. Indeed, that is not the core aim. Scenarios are 'learning machines' (Berkhout, Hertin, & Jordan, 2002) that can enable reflection on the realism or implications of widely held views, and on how stakeholders understand and relate to different possibilities. Rather than provide evidence to inform concrete decisions, such scenarios foster 'conceptual learning', i.e. providing new insights, perspectives and ideas on policy issues, a function seen as very important within the literature on the use of evidence in policymaking (Hertin, Turnpenny, Nilsson, Russel, & Nykvist, 2009).

Recent years have seen the development of scenario approaches designed specifically to inform understanding of possible technological transitions—shifts from one dominant socio-technical system to another (archetypal examples being the shift from sailing ships to steam ships, or from gas lighting to electric lighting). Informed by the burgeoning literature on technological transitions (Markard, Raven, & Truffer, 2012), such scenario approaches attempt to reflect understanding of the dynamics of technological change, focusing in particular on the relative durability of different institutional and socio-technical configurations, and the co-evolutionary dynamics of technologies, users and institutions (Elzen, Geels, & Hofman, 2002; Elzen, Geels, Hofman, & Green, 2004; chap. 11; Foxon, Hammond, & Pearson, 2010). In the arena of hydrogen energy, there have been several attempts to develop qualitative socio-technical scenarios inspired by transitions research to examine potential hydrogen transitions (Eames & McDowall, 2010; Van Bree, Verbong, & Kramer, 2010).

2.2.1. The UKSHEC II scenarios approach

This project goes beyond those previous socio-technical hydrogen scenarios by developing qualitative scenarios in parallel with modelling work. Quantitative modelling has been used in combination with scenario planning since the origins of the field (Wack, 1985). One common approach is the use of scenario storylines as tools for identifying and differentiating the values of key parameters for modelling exercises, with the resulting dynamics of change still determined by the model (e.g. Barreto et al., 2003). A second common alternative is the detailed quantification of narrative scenarios, to ensure that they are technically feasible and consistent (for example, Dutton et al., 2004).

Others have highlighted the way in which the complementary strengths of qualitative storyline scenarios and quantitative modelling tools can be put to good use by comparing and contrasting the insights and dynamics produced in each method (Alcamo, 2008, chap. 6; Ault, Frame, Hughes, & Strachan, 2008; Fontela, 2000), often using multiple iterations between modelling and scenario writing. Alcamo describes this as the 'SAS' (storyline and simulation) approach (Alcamo, 2008), and describes its use by the IPCC and others. In the energy field, examples of work of this kind include (Ault et al., 2008) and (Fortes, Alvarenga, Seixas, & Rodrigues, 2014), both of whom use energy system models to explore qualitative scenarios developed through participatory stakeholder processes. Recent work within the UK's Realising Transition Pathways project has also linked models to qualitative socio-technical transition scenarios, through quantification of storylines and iteration with various modelling tools (Foxon, 2013).

The UKSHEC II project follows in that tradition, though with a looser coupling of model runs and scenario storylines than is typically undertaken. In this project, socio-technical scenarios and energy system modelling have been used in parallel. The model is not forced to reproduce the dynamics of each storyline, and model runs are not to be understood as quantified versions of the storylines. Instead, modelling exercises are used to examine and inform elements of the scenarios, while the scenarios are used to challenge and confront the results suggested by the model. This can be described as a 'dialogue' between the two approaches, rather than a process of using one to provide input into the other, and with no attempt to arrive at fully quantified model-based equivalents to the qualitative storylines. The approach has similarities with approaches based on 'constructive conflict' in stakeholder dialogue (Cuppen, 2010), which attempt to confront different stakeholder positions, and thereby promote "an open exploration and evaluation of competing ideas

[3] There is frequently confusion about the purpose and utility of scenario approaches, in part due to the great diversity of applications, which arise from the fact that the future is profoundly uncertain and that not thinking about or making assumptions about the future is impossible. Confusion also arises because most models are run different with sets of input parameters, for which the term scenario is typically used. That model-specific use of the term scenario is distinct from what are here termed 'exploratory scenarios', which develop qualitative, narrative storylines of alternative possible futures.

and knowledge claims in order to achieve new ideas [and] new insights..." (Cuppen, 2010, p. 26). Here, the approach confronts two contrasting "worldviews", one derived from stakeholder opinion, the other a model that operates as a planner optimising the energy system.

3. Developing socio-technical storylines: methods and approach

The methodological approach used in this study followed a simple sequences of stages, similar to many other socio-technical scenario development exercises. The method draws on that suggested by Hughes (2013). Note that many of these stages are overlapping and iterative.

1. Development of theoretical framework for describing transitions.
2. Participatory involvement of expert stakeholders to scope key issues, uncertainties and possible dynamics.
3. 'Mapping' the system in terms of actors, regime structure, niches, and landscape developments, and identification of key strategic uncertainties and the branching points that they imply.
4. Writing of storylines, with a structure drawn from insights from transitions research, attempting to highlight key branching points and their possible implications.
5. "Dialogue" with modelling: use scenarios to identify issues that may not be addressed with models, and use models to highlight potential weaknesses in the scenarios.

3.1. Step 1: developing a theoretical framework for describing possible transitions

Two complementary and related theoretical frameworks, drawn from the technological transitions literature, are used to structure the analysis of the key uncertainties and the way in which they may unfold. This framework is briefly described here.

First, the analysis is situated within the multi-level perspective (MLP) on technological transitions (Geels, 2002), and draws on the typology of Geels and Schot in order to inform some basic transition 'types' (Geels & Schot, 2007). Their typology is based on two dimensions:

i. The timing of interactions (how mature is the niche when the regime comes under pressure).
ii. Nature of interaction (relationship of the niche innovation to the broader regime, i.e. is the niche innovation disruptive or re-enforcing to existing regime).

Beliefs about the status of hydrogen with regard to these dimensions differ. Geels and Schot offer four criteria for determining whether the niche innovation is mature: (a) the presence of a dominant design, (b) presence of powerful actors in the innovation system supporting the technology, (c) price/performance have improved and there are expectations of further improvement, and (d) the innovation is used in markets that cumulatively account for more than 5% market share. Hydrogen technologies meet the first three of these criteria, but fall short of the fourth, suggesting that they are not quite at the level of maturity that might enable a rapid transition. However, there is considerable uncertainty about how fast this level of maturity might arise. With regard to the nature of hydrogen as disruptive or re-enforcing the existing regimes, stakeholder opinions differ. Stakeholder interviews and participant observation make clear that while some see hydrogen as highly disruptive to existing regimes, others promote hydrogen precisely because they see it as fitting well into established industrial, commercial and consumer patterns of behaviour.

The typology provides a useful way of exploring the types of dynamics that may occur in the course of a transition, and in particular provides a way of structuring the types of interaction between events and processes occurring at different levels within the MLP. Each transition is therefore described in terms of its position within this broad typology.

The scenario-development approach used here complements the MLP by focusing attention on developments within co-evolving 'subsystems', drawing on Foxon's work on co-evolutionary processes in transitions (Foxon, 2011). While Geels and Schot's framework sheds light on archetypal dynamics between levels, Foxon's work provides a useful structure for thinking through the dynamics within the heterogeneous configurations of actors, networks and institutions that comprise regimes and niches. Based on observations of the hydrogen energy innovation system, Foxon's framework is adapted here, focusing as he does on user practices, technologies and business strategies, but also explicitly considering governments, and considering institutional changes as part of the dynamics of each subsystem, rather than existing as a distinct unit of analysis (similar to Freeman and Louca's (Freeman & Louca, 2001) treatment of institutional arrangements in each of their co-evolving subsystems[4]). This analysis of co-evolving sub-systems is used to shed light on the way in which niche-regime interactions may occur. These categories correspond well with the key areas of uncertainty highlighted by stakeholders and in the literature, and described in (McDowall, 2012a).

[4] See F&L p. 125. The framework adopted here also follows Freeman and Louca in excluding the natural environment (Foxon's 'ecosystems') from analysis.

3.2. Steps 2: participatory scoping and issue identification

Socio-technical scenarios are a way of examining, extending and confronting themes prevalent in actor perceptions and discourse about the future of the technology in question. An important step for this project was thus to identify uncertainties and issues prominent in stakeholder expectations and discourse around possible hydrogen transitions. This was undertaken through an initial participatory expert workshop, and a series of stakeholder interviews. Insights into stakeholder views were also gathered through participant observation at a series of UK and international hydrogen stakeholder events between 2010 and 2012. The storylines are thus rooted in ideas and views common among stakeholders engaged in debate and dialogue around hydrogen energy in the UK.

3.3. Step 3: mapping the system

A key step in the construction of socio-technical scenarios is an analysis of the incumbent socio-technical regime, an assessment of the various niches and emerging innovation systems that may threaten it, and an overview of the pressures at the landscape level. For the sake of brevity, this paper does not elaborate these issues in detail, and in any case socio-technical accounts of these are given by a number of authors (see summary in Table 1).

3.4. Step 4: identification of strategic uncertainties and possible branching points

The fourth stage identified key uncertainties and possible branching points. This step identified the uncertainties and transition dynamics prominent in stakeholder discussions, in the literature, and which have been important in historically analogous transitions. These were structured according to the theoretically-informed framework developed in stage 1. Uncertainties and potential branching points are highlighted for each of the subsystems identified as relevant in niche-regime interactions, and at the landscape level.

This section reports briefly on insights from literature review, a stakeholder workshop and stakeholder interviews. Based on the adaptation of Foxon's co-evolutionary approach and the Geels and Schot multi-level framework, critical uncertainties for three dimensions of niche-regime dynamics are identified: (i) technologies, (ii) user practices, (iii) business strategies and government policies (i.e. strategic actions of major actors). In addition to these three, a fourth set of critical uncertainties that occur within the broader energy system landscape is also examined.

3.4.1. Technologies

Despite significant technical progress in recent years (James & Spisak, 2012), including related to reductions in platinum catalyst requirements and associated costs, doubts remain about the ability of hydrogen technologies to reach benchmark performance targets at an acceptable cost. Significant analysis has gone into examining the implications of these technological uncertainties, and as a result the uncertainties can be regarded as relatively well characterised. That is to say, there is a high degree of alignment about which unknowns are known and how important they might be.

Possible branching points:

- Automotive hydrogen fuel cell and storage systems reach performance and costs that are close to incumbent vehicles, such that foreseeable carbon prices or air quality regulations are expected to render them a truly competitive option in the near term, with mass production.
- Battery electric vehicle technologies undergo sufficient range enhancements, cost reductions, and recharging speeds to render them an attractive option for a sizeable portion of consumers. This branch would greatly diminish the prospects for hydrogen.

Table 1
Key features of the niches, regimes and emerging innovation systems of relevance to hydrogen and fuel cells.

	Key features	References
Hydrogen niches	Market niches (forklift trucks, back-up power, telecoms remote power); Also 'technological niches': the California Air Resources Board's Zero Emission Vehicle mandate; demonstration programmes; the R&D units in automotive firms	Agnolucci and McDowall (2007), McDowall and Eames (2006)
Car-based transportation regime	Dominance of car as a mode of personal mobility; close relationship of car industry and state; ubiquity of road, refuelling and maintenance infrastructure; well-articulated rules and user needs, etc.	Marletto (2011) and Van Bree et al. (2010)
The broader UK energy system regime	Dominance of natural gas (for space and water heating) and electricity (for lighting and consumer appliances). Mature and well established infrastructures, increasing pressure to decarbonise energy use by deploying renewable power technologies and fuel switching to electricity.	Foxon et al. (2010) and Shackley and Green (2007)
The emerging hydrogen and fuel cell innovation system	Strong R&D capabilities, entrepreneurial firms, clear articulation of search and alignment of actors; failure so far to build significant markets.	Bakker, Van Lente, and Meeus (2011), McDowall and Ekins (2011), Ruef and Markard (2010) and Schaeffer (1998)

3.4.2. *User practices*

User practices have generally been less well addressed in the literature examining hydrogen energy transitions than have other aspects (McDowall, 2012a; McDowall, 2012b). Many studies simply ignore this as a source of uncertainty, choosing to believe that users will continue to relate to vehicles in the same way as they currently do. Four issues with respect to user behaviour appear particularly important: (i) Consumer willingness to adopt limited-range electric vehicles; (ii) Plugging-in behaviour, and the resulting implications for electric charging infrastructure; (iii) Consumer willingness to adopt vehicles when only a portion of fuelling stations provide hydrogen; (iv) Emergence of new models of ownership, and potential for new technologies to lead to changing user practices, resulting in a co-evolution of user practices and technologies.

These are issues seen as having critical importance within the leadership of automotive companies (KPMG, 2012), but they have received relatively little attention in the research literature. The issue that has received least attention is that concerned with the potential of new ownership models, such as car sharing, which has been shown to reduce overall ownership and change the profile of the fleet (Firnkorn & Müller, 2012; Martin, Shaheen, & Lidicker, 2010). With different ownership options, it is possible that existing market segments for vehicles will become more pronounced, as consumers would no longer need a vehicle that met all conceivable needs. Alternative ownership options for infrastructure have also been suggested, such as through user co-operatives (Thomas, 2012).

Possible branching points:

- Rejection/acceptance of significant numbers of BEVs and other plug-in vehicles.
- Rejection/acceptance of fuel cell vehicles following market introduction.
- Differentiation of vehicle demands as a result of market changes and social innovation in ownership models.

3.4.3. *Business strategies and government policies*

In addition to consumers, whose practices were addressed above, four groups of actors will be critical in determining how and whether a transition to a hydrogen energy system takes place:

1. **Governments**. Both national and local governments play a key role as regulators, and in shaping the market environment for hydrogen technologies through supportive policies for low carbon transport.
2. **Incumbent automotive firms**. These firms are the technology leaders, but all of them maintain a portfolio of low-carbon vehicle options and none are likely to commit wholly to any one technology choice.
3. **Incumbent fuel providers** (owners and operators of existing petrol stations). Even more than automotive firms, fuel companies investing in infrastructure take on very significant first mover risks.
4. **Emerging hydrogen and fuel cell firms**. These are the actors at the core of the advocacy coalition lobbying for hydrogen.

Possible branching points include:

- Widespread local government adoption of zero emission zone policies
- The success of failure of initiatives to commercialise hydrogen vehicles, potentially backed by national governments concerned to protect and promote their automakers' technology. In particular, the emerging 'H2Mobility' programmes in Germany and the UK and equivalent exercises elsewhere.

3.4.4. *Uncertainties in related regimes and at the landscape level: what is happening within the wider energy system?*

How might the wider energy system evolve, and how would this affect the prospects for hydrogen? Most studies examining possible transition pathways for hydrogen focus on the transport sector and the potential adoption of hydrogen in vehicle fleets. However, there has been increasing interest in the ways in which hydrogen energy systems may play broader roles in sustainable energy systems, facilitating the deployment of low carbon primary energy sources by enabling long-term, inter-seasonal storage of energy, and by mediating between power, heat and transport markets. In particular, there is growing interest in the potential of "power-to-gas" projects, in which hydrogen is produced when surplus renewable electricity would otherwise be curtailed, and is then injected into gas networks, decarbonising gas while providing a flexible demand service to the power system. In the UK, where distributed gas dominates domestic heating, there is a question as to whether the gas network will need to be decarbonised or decommissioned in order to meet carbon targets.

Key uncertainties include the possible evolution of markets for the provision of heating in a low-carbon future; the availability and cost of key resources; and the ability of energy systems to cope with increasing levels of intermittent generation.

Possible branching points of relevance to hydrogen include:

- Decision (or not) to begin decommissioning the natural gas distribution system in the 2020s, with heating increasingly provided by electricity instead of gas.
- Failure to achieve sufficient electricity grid management through 'smart' systems and efficiency measures.

3.5. Write scenario storylines

This step involves combining scenario elements and uncertainties as described in Sections 3.3 and 3.4 into narratives that illustrate the implications of key uncertainties and capture the major issues discussed by stakeholders.

3.6. Step 5: the dialogue between scenarios and modelling

The final stage is to test elements of the scenario storylines with a quantitative modelling framework, and use the scenario storylines to interrogate the model, by bringing them into a dialogue of 'creative conflict' (Cuppen, 2010). This project used a single model, the UK MARKAL model (Kannan, Strachan, Balta-Ozkan, & Pye, 2007). MARKAL is a technologically detailed optimisation model that uses linear programming to find the least cost energy system from a database of energy technologies to meet an exogenously specified set of energy service demands (Fishbone & Abilock, 1981; Loulou, Goldstein, & Noble, 2004). MARKAL models have been widely used to examine possible hydrogen transitions in the UK and elsewhere (Endo, 2007; Gül et al., 2009; Krzyzanowski et al., 2008; Strachan et al., 2009; Tseng, Lee, & Friley, 2005; Yeh et al., 2008).

Much of the modelling work discussed here is published in fuller form elsewhere (Dodds & McDowall, 2013; Dodds & McDowall, 2014). Further description of the basic model details are therefore not provided here, and this paper focuses instead on the way in which the modelling and scenario work was used in complementary ways. The dialogue between the scenario and modelling involved two elements.

First, the scenario storylines were used to 'ask questions of the model', by examining where the storyline differed from the explicit or implicit assumptions embedded in the model structure and data. This process revealed ways in which the model was unable to reflect either options or dynamics thought likely to be important in stakeholder discourse. This process revealed assumptions that would otherwise have remained implicit and opaque within the model. Where possible, the model was adapted to enable exploration of potential transition options that had previously been missing (such as differentiation of vehicle markets). Resulting model runs were conducted to examine the implications of introducing these different possibilities, and testing their techno-economic characteristics.

Second, the model was used to question and confront the scenarios, by showing where certain scenario elements may involve unrealistic energy market dynamics, such as the penetration of technologies that appear to be far from cost-effective, or where scenarios appear to overstate the importance of elements whose techno-economic significance appears less when examined in a formal quantitative framework. Where scenario storylines were found to involve elements that appeared unrealistic when analysed with the model, these were re-examined and if necessary revised (see Fig. 1).

4. Hydrogen transition scenarios and modelling for the UK

4.1. Background common to all scenarios

There are common features of all scenarios, which define the broader 'state of the world' in which these futures unfold. In this state of the world, there is (a) continued global emphasis on achieving decarbonisation; (b) continued global geopolitical

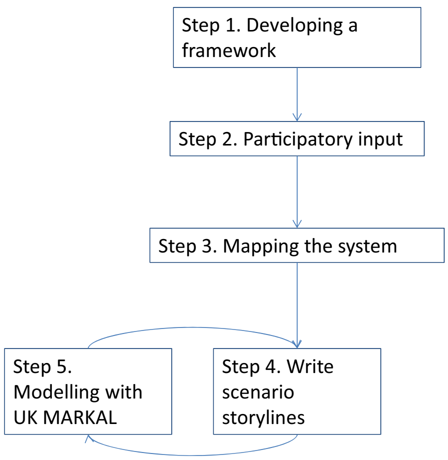

Fig. 1. Diagram showing development of scenarios and interaction with modelling.

stability; (c) continued long-run economic growth, periodic recessions notwithstanding. These background conditions provide part of the landscape conditions common to each scenario.

4.2. Scenario summaries

Summaries of all scenarios are presented in Table 2.

Scenario 1. "Car of the future" – 2010–2050

Headline summary

This scenario is a relatively straightforward **transformation** of the existing transport vehicle regime, in response to continued and increasing pressure from governments to reduce transport sector GHG and air pollution emissions. In this scenario, the behavioural and structural dynamics of the transport sector remain intact, with hydrogen FCVs replacing the ICE as the dominant form of personal transport. This scenario is similar to many found within the broader hydrogen futures literature, which tends to envisage relatively unproblematic shifts towards use of hydrogen as a direct replacement for petroleum in fuelling road vehicles.

Key branching points: Failure of battery electric vehicles to attract significant customers; tepid performance of PHEVS because of challenges in charging and consumer behaviour shifts. Alignment among automotive firms and governments around hydrogen as the technology for decarbonisation of the transport sector, along with good progress in technology performance and cost reduction.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Research and development activities in hydrogen and fuel cell vehicles continue to yield strong progress in driving down costs and improving performance.
- **Behavioural uncertainties**. Consumers prove resistant to battery electric vehicles, which only penetrate in niches and in response to generous but expensive government incentives. PHEVs are more popular, with increasing uptake in the medium term, but limited plug-in opportunities and high battery costs continue to act as a barrier to dominance.

Table 2
Summaries of the scenarios.

	Car of the future	Horses for courses	Hybrid fuels
Transition type	Transformation	Reconfiguration	De-alignment/re-alignment
Key branching points	Weak uptake of BEVs and PHEVS Alignment among automotive firms and governments around H_2. Good progress in technology	Rapid growth of car-clubs; ownership of BEVs as second-cars; new business and ownership models enable FCVs to enter market in some market segments.	Decarbonisation of gas becomes increasingly prominent, with rise of 'power-to-gas'.
Technology	R&D activities in H_2 and FCVs continue to yield strong progress in driving down costs and improving performance.	H_2 technologies show steady development, as do other low carbon vehicle technologies	H_2 technologies show steady development, as do other low carbon vehicle technologies.
Behaviour	Private car remains dominant. Consumers are resistant to BEVs, which only penetrate in niches. PHEVs are more popular, but limited plug-in opportunities and high battery costs prevent dominance.	Consumer behaviour evolves with the introduction of new technologies, and the emergence of social innovations in car ownership, particularly car clubs.	Consumers maintain similar characteristics as today. There is a reluctance to embrace new vehicle technologies unless they provide significant personal benefits.
Business strategies and government policy in the transport regime	Automotive firms turn to FCVs as the long-term goal for their vehicle portfolios. Governments of countries with large automotive sectors attempt to initiate a transition. Major launches of vehicles are accompanied by a big infrastructure investment programme.	Uptake of BEVs as second cars; growth of car clubs using FCVs, which act as a key niche for the establishment of hydrogen infrastructure. Urban emissions standards become important in converting taxis to hydrogen.	There is a system failure: despite evidence that FCVs would work well, there is a failure to overcome the barriers to it. Some efforts are made, but these are not strong enough in the near term. H_2 is developed elsewhere in the energy system, and introduced by infrastructure and utility companies to support power and heat system, ultimately facilitating adoption in the transport sector.
Energy system	Early power sector decarbonisation; electrification of much of heat demand; integration of renewables is facilitated through smart grid and demand-side management. Concerns over bioenergy sustainability limit the contribution of biofuels.	Similar to car of the future scenario.	Significant deployments of renewables create a looming 'balancing crisis', with significant costs associated. In response, the gas industry actively promotes decarbonisation of gas, exploring biogas and hydrogen injection.
Implications for hydrogen	Rather rapid adoption of hydrogen FCVs, beginning in the mid-2020s.	Slower transition to H_2 in transport, beginning in earnest from the mid-2030s.	H_2 becomes important niche in heat and power. Longer term sees H_2 widespread in transport (in 2040s) and throughout energy system.

- **Business strategies and government policy in the transport regime**. Automotive firms increasingly see fuel cell vehicles as the long-term goal for their vehicle portfolios. Governments of countries with large automotive and fuel cell sectors provide support for attempts to initiate a transition, seeing potential first-mover advantages – or the slightly different first mover defence – in which governments use stringent air quality legislation to 'lock-out' cheaper but less technologically advanced imports from emerging economies. The infrastructure strategy is a 'build it and they will come' approach, in which major launches of vehicles are accompanied by a big infrastructure investment programme.
- **Energy system dynamics**. This scenario envisages an energy system decarbonisation trajectory similar to that illustrated in the UK Carbon Plan: early power sector decarbonisation is followed by electrification of much of heat demand, and is facilitated through smart grid-enabled demand-side management and conservation measures. However, political uncertainty continues to surround bioenergy, inhibiting both policy and investments in capacity for biofuels production.

Scenario narrative

This scenario sees the major automotive firms increasingly backing hydrogen and fuel cells from 2015 onwards, in the face of tepid consumer responses to battery electric vehicles, political battles over the sustainability of biofuels, and intensifying decarbonisation and low-emission vehicles policy in key market regions (Japan, Germany, and California). Leadership in hydrogen FCVs is increasingly seen as a key route to long-term dominance of automotive markets. Plug-in hybrids are an important transition technology, with range extending engines being replaced with fuel cells. Battery electric vehicles remain a niche, popular as a second car in wealthier regions, but never replacing more than a portion of vehicle kilometres. As markets for hydrogen vehicles become established during the early 2020s in Germany, Japan and the US, prices for such vehicles fall. In the face of competition from automotive producers in emerging economies, the Japanese, European and American automotive giants increasingly lobby for tighter emissions standards to ensure that only firms with advanced powertrain technology can compete.

Following success of initial markets elsewhere, the UK government facilitates the development of initial infrastructure, introducing strong tax incentives for FCV purchases, infrastructure investments, and hydrogen fuel. Regional governments concerned to protect their automotive sectors (e.g. Midlands) provide support for some early infrastructure, as do regions (e.g. London) with air quality problems.

Buses provide an important early market in the UK, with hydrogen buses increasingly on the roads in the largest UK cities by 2020–2025 on a commercial basis rather than as demonstrations. Hydrogen FCV market entry into car markets begins in earnest from about 2025, following introduction among early adopters in 2016. Hydrogen is produced largely from fossil fuels, with carbon capture and storage.

4.2.1. Insights from modelling in UK MARKAL

As a perfect-foresight[5] optimisation model, UK MARKAL represents a world with low barriers to transition, perhaps implicitly assuming high alignment among stakeholder deploying infrastructure and vehicles together. The model decision-structure is thus relatively close to the dynamics of the storyline, in which alignment is high and barriers to technology adoption are minimised through strategic cooperation of dominant actors.

Cost assumptions for hydrogen vehicles used in the modelling are based on cost forecasts that assume global hydrogen technology success (as indeed is common in energy system model representation of new technologies including hydrogen, except those applying endogenous technology learning; Anandarajah et al., 2013). Even so, the model prefers to deploy hydrogen only from 2035 onwards, rather later than the 2025 described in the narrative. The optimisation procedure means that the least-cost carbon abatement opportunities are pursued, and options are not selected until they form part of that least-cost low-carbon solution. Even if hydrogen vehicles are relatively attractive, they will only enter the market where there are no cheaper uses for limited supplies of low-carbon energy. The model suggests that in earlier periods low-carbon primary energy is better used to displace coal-fired power generation, and the unabated use of gas in heating, while the adoption of more-efficient hybrid electric vehicles reduce the competitive edge of hydrogen vehicles. The model does not take into account, however, the market preparation work and niche markets required to enable rapid uptake in 2040 and beyond. In the real world, the market entry date in the narrative of 2025 might be necessary to achieve sufficient initial sales and infrastructure build-up to enable mass deployment in the 2030s as depicted in the modelling results.

Scenario 2. "Horses for courses" 2010–2050

Headline summary

This scenario is a **reconfiguration**. The new regime grows out of the old regime, picking up lots of innovations, with substantial changes to the regime's basic architecture. This scenario argues that structural changes and social innovation, alongside technological substitution, are a likely response to the pressures of decarbonisation and the emergence of new technologies.

[5] "Perfect foresight" in this context, means that the model optimises across all time periods simultaneously. That is, the optimisation algorithm 'knows' all the input data (future costs, future demands, etc.), and optimises the entire time period (2010–2050) with that knowledge.

Key branching point: Breakdown of current paradigm of vehicle ownership and operation, rapid growth of car-clubs and ownership of BEVs as second-cars, with disruptive companies entering the automotive sector.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Hydrogen technologies do not progress more rapidly than competing low-carbon vehicle technologies, but continue to show strong development in terms of performance, durability and cost.
- **Behavioural Uncertainties**. Consumer behaviour evolves with the introduction of new technologies, and the emergence of social innovations in car ownership, particularly car clubs.
- **Business strategies and government policy in the transport regime**. Uptake of battery electric vehicles as second cars; growth of car clubs using FCVs, although they remain a small overall portion of the market in early years, these clubs act as a key niche for the establishment of hydrogen infrastructure. Urban emissions standards are important in converting taxis to hydrogen.
- **Energy system**. Similar to car of the future scenario.

In this scenario, globally heterogeneous approaches emerge to low carbon vehicle policies, with some countries placing more emphasis on electric vehicles, biofuels or hydrogen, in response to national industrial strengths, differing policy approaches to fostering innovation, and different policy priorities. Automotive firms continue to back diverse portfolios and continue to develop EV, PHEV and FCV technologies. Car markets become increasingly complex, with different fuels and drivetrains common, unlike the current dominance of internal combustion engines with either petrol or diesel. Technological advancements are forthcoming in all powertrain technologies, with no powertrain achieving a breakthrough that enables it to dominate all parts of the car market.

Social innovation is a key feature of this scenario: car clubs and new ownership models enable more efficient use of cars as capital goods. That is, changes in normative and cognitive rules around 'ownership'. This facilitates a growing differentiation of vehicle markets, with consumers either owning or accessing different vehicle types for different purposes. Uptake of electric vehicles is strong in this scenario, with hydrogen FCVs and diesel PHEVs competing in the market for larger vehicles. Policy emphasis is on emissions reduction rather than supporting the development of a particular industrial choice, implying a shift away from technology-specific support mechanisms such as the RTFO and grants for plug-in vehicles. Hydrogen emerges more strongly only in the longer term (i.e. from 2035).

This scenario highlights an emerging debate in the recent literature around the idea of a portfolio of complementary options across the transportation fleet. The concept has attracted both advocates (McKinsey, 2010) and critics (Bakker & Van der Vooren, 2011).

4.2.2. Insights from modelling in UK MARKAL

Many aspects of this scenario are not suitable for analysis within the MARKAL modelling paradigm. Indeed, this exercise highlighted the limits of an energy system model framework for understanding transport technology choice in scenarios in which social innovation and flexible consumer preferences play a prominent role. The process reveals the implicit and conservative assumptions in such models concerning market structure and user behaviour. Though increasingly prominent in stakeholder opinion (see, e.g. KPMG, 2012), scenarios in which new business models, social innovation and new powertrain types disrupt established patterns of vehicle ownership have been poorly integrated into the energy system modelling frameworks most prominent in major strategic energy policy decisions.

Models examining hydrogen energy transitions have tended to build-in the assumption that a single technology will dominate road transport vehicle demand. Bottom-up energy system optimisation models, including the UK MARKAL model used in this analysis, follow this approach, with vehicle technologies competing to fulfil consumer demand for car-based transport. This scenario prompted a revision of the model to examine whether a differentiation of vehicle demands, such that large and small vehicle technologies compete to fulfil distinct demands, makes a different to technology choice in the model. The assumptions behind the modelling, as well as results, are reported in detail in (Ekins, Anandarajah, McDowall, & Usher, 2011) and (Dodds & McDowall, 2014). Contrary to the scenario storyline, the modelling suggests that technology choice is similar across vehicle classes in most model runs. The modelling suggests relatively minor differences in adoption timing and rates within different market segments, but in general model outcomes did not vary substantially between the model version in which vehicles markets are assumed to be homogenous vs. that in which technologies compete in semi-distinct market segments (such as smaller cars vs. larger cars). Here, model and storyline disagree. While the linear optimisation formulation of the model does not envisage differentiated vehicle markets resulting in greater heterogeneity of vehicle technology, the weaknesses of the model representation of consumer behaviour suggest that the storyline remains a valid possibility.

Scenario 3. "Hybrid fuels"

Headline summary

The storyline explores a future in which hydrogen plays a limited role in transportation to 2050, but is involved in a **de-alignment/re-alignment** within the heat and power regime, leading to a shift in the energy system context for decarbonising transport fuels. This de-alignment/re-alignment is caused by a rapid loss of confidence in the early 2020s in the direction of development in power and heat regimes, as a result of disappointing uptake of efficiency measures, slower than anticipated power grid upgrades, and resulting cost escalation associated with the penetration of high levels of intermittent renewables.

Key branching point: This scenario explores the possibility that commitment to existing gas infrastructure results in a redirection of decarbonisation efforts away from the focus on electrification in the reference case, to include decarbonisation of gas. This has a wider effect on the availability of hydrogen, and ultimately its use in transport. A second key branching point is technology choice in CCS, with pre-combustion gasification emerging as the key CCS technology. This enables the flexible production of hydrogen and electricity.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Hydrogen technologies do not progress more rapidly than competing low-carbon vehicle technologies. Hydrogen remains confined to niches, some of which gradually grow, but which do not represent an important role within the energy system.
- **Behavioural uncertainties**. Consumers maintain similar characteristics as today. There is a general reluctance to embrace new vehicle technologies unless they represent significant personal benefits. Electric vehicles make progress as second cars, and hybrids and eventually PHEVs are the incremental route to transport decarbonisation.
- **Business strategies and government policy in the transport regime**. There is a system failure: despite evidence that a hydrogen system would probably work well, there is a failure to overcome the barriers to it. Some efforts are made, but these are insufficiently strong in the near term.
- **Energy system dynamics**. Two major developments distinguish energy system developments in this scenario. First, significant deployments of renewables and nuclear during the 2010s and early 2020s create a looming 'balancing crisis', with significant costs associated with natural gas balancing plant, and particularly associated with the very significant seasonal variations in energy demand, resulting in very low capacity factors for some dispatchable plant. Second, the gas industry is increasingly active in promoting decarbonisation of the gas grid, exploring biogas and hydrogen injection.

Scenario narrative

In many countries, gas companies begin strategic activities to resist the 'all-electric' low carbon future presented in many long-term decarbonisation scenarios: lobbying emphasises the inter-seasonal and strategic storage benefits of gas, investments in biogas, hydrogen and CHP. Globally, there is growing interest in hydrogen in gas grids, with increasing R&D dedicated to end use applications and infrastructure issues. This was led by Germany and the Netherlands. Hydrogen plays a role in transport only in the long-term. In the 2020–2030 timeframe, progress with hydrogen fuel cell vehicles is still too slow to justify major infrastructure investments. Some vehicle niches do exist: buses, various military applications, and niches in which zero emissions and fast refuelling are required.

Strong development of renewables takes place in the UK, in particular the offshore wind energy grid. However, uptake of domestic efficiency measures is disappointing, and the seasonal variation in heating demand exceeds the capacity of the low-carbon power network. There is some interest in storage projects, various models of demand-side management and smart grid technology are attempted, and there is investment in biogas. The UK government closely watches attempts to introduce hydrogen vehicles elsewhere, but decides not to intervene in markets to promote FCVs above other ultra-low emission vehicles. Instead, biofuels, PHEVs and EVs are seen as sufficient, alongside renewed investments in commuter rail and other alternatives to cars. In the long-term, roles for hydrogen throughout the energy system enable further decarbonisation of transport, but hydrogen vehicles do not enter the transport market until 2035, and are not widespread until the 2040s.

4.2.3. Insights from modelling in UK MARKAL

Previous work with UK MARKAL had assumed that the natural gas grid would start being retired from 2020 onwards. In line with the 'hybrid fuels' scenario, Dodds and McDowall (2013) revisited the representation of gas grids in UK MARKAL, and tested the importance of current investment programmes and decarbonisation options for the future of the grid. This work provides at least some support for the notion in this scenario that the gas grid may provide a route for hydrogen to become established as a part of the energy system, through injection of hydrogen into gas distribution networks, or wholesale conversion of some (or ultimately all) of the network.

In this case, the modelling informed a change in the scenario storyline. A previous version of the storyline emphasised the UK Government decision to require the replacement of all iron gas distribution pipes with safer polyethylene pipes by 2030 (the Iron Mains Replacement Programme). However, the modelling suggested that, despite the significant sunk investments this programme represents, it was not itself a decisive development that represents a branching point. This is because despite the large scale of the investments, they are dwarfed by both the value of the existing assets, and by the value of energy flowing through the network (and the costs associated with carbon emissions under a strict decarbonisation target). Thus the significance of the iron mains replacement programme, which an intuitive approach had suggested might be important, appears less decisive when examined in a formal quantitative framework.

5. Discussion and conclusions

5.1. Key insights for hydrogen transitions:

The analysis makes clear that there are many possible routes by which hydrogen may play a role in a low-carbon UK energy system. In particular, the scenarios highlight three key important key uncertainties and knowledge gaps for hydrogen transitions:

- The ‘car of the future’ scenario posits a case in which a high degree of alignment and collaboration between various industry sectors and government takes place. This is effectively the implicit assumption within many system models, since the co-ordination failures that would prevent this from occurring are not represented in most model frameworks. Yet the plausibility of this scenario must be confronted by the limited and partial nature of historical precedents for this kind of transition (with none a perfect analogy). The uncertainties associated with the transition governance capacity of key actors are enormous.
- Conventional analytic techniques and scenarios may have underestimated the potential importance of innovation in car ownership models, and more broadly in social innovation with respect to transport needs. It seems plausible that these could influence adoption and patterns of use of both conventional and alternative vehicle types, though understanding (and particularly modelling) how this might work in practice is highly uncertain.
- Roles for hydrogen outside transport may be valuable in themselves as renewables gain market share, and this could facilitate infrastructure transitions: assumptions about the dynamics of the rest of the energy system are highly relevant for the future of hydrogen in transport, yet are often excluded from hydrogen transition analysis in order to focus on more analytically tractable issues. In particular, the potential for hydrogen to play a role in decarbonising gas networks appears promising in both the storyline and the modelling.

5.2. Reflections on method

The work reported in this paper has illustrated the value of using both narrative storylines informed by participatory scenario approaches and formal quantitative models in exploring possible long-term transitions. The qualitative storyline scenarios resulted in both tests of model structure that showed sensitivity to tacit assumptions, and also revisions to model structure that demonstrated the importance of issues that have been of interest to stakeholders but neglected in the literature modelling possible transitions. At the same time, the quantitative modelling revealed areas in which scenarios placed too much emphasis on issues that appear to be techno-economically less important.

Previous work with socio-technical scenario approaches (with notable exceptions, such as the UK’s Transition Pathways project) has arguably tended to neglect the quantitative dimensions, such as the rates of transition that are plausible, or the relative techno-economic significance of different investments and scenario elements. At the same time, analysis of hydrogen with energy system models has tended to focus on a relatively narrow range of uncertainties and possibilities, and model structures have tended to obscure issues around implications of behavioural change or systemic energy system change.

The point is that thinking about radically alternative futures is necessarily an exercise that can only be informed in a limited way by changing the parameters of a given model. While it has been useful to use scenarios as structures for developing a set of input parameters to modelling exercises, it is perhaps unfortunate that fewer studies use qualitative scenarios informed by stakeholder participation to highlight different possible structural issues in the models that are applied to a given problem.

In conclusion, bringing narrative socio-technical storylines into ‘dialogue’ with quantitative energy systems modelling can yield insights that could be missed if these tools are used independently. This analysis has focused attention on key branching points and uncertainties analysed within the UKSHEC II project. However, it does not represent a comprehensive analysis of conceivable transition pathways, and should not be seen as attempting to do so.

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