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Energy Model, Boundary Object and Societal Lens: 35 years of the MARKAL model in the UK

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Abstract

Technical energy models operate within social systems and those that perform particular social as well as technical functions are more likely to be used. We illustrate this with the example of the MARKAL energy system model in the UK, a model that is also widely used internationally. In the UK, MARKAL modelling has a long history helping underpin government energy and climate policy. We trace the use of the model from its initial development in the mid-1970s to the present day, highlighting attributes that contribute to its role as a successful 'boundary object' for different but interconnecting energy policy communities. We suggest that changing images of the energy policy problem have enabled MARKAL to shift from an initial role in identifying technologies to reduce oil dependency to playing a key role in target-oriented climate policy. Furthermore, we argue that the ability of MARKAL to perform different roles for different groups has served to embed and institutionalise the model in the energy policy community. Moreover, the capacity of the model to represent detailed technology options has accorded with a technological focus that has suited prevailing, shared conceptions of the energy-climate policy problem.

Highlights

The MARKAL energy model has had significant influence on UK energy policy in recent years

MARKAL's influence derives from three inter-related factors:

(a) Adaptation to changing images of the energy-climate problem

(b) Connection of different communities with shared interests (i.e. a boundary object)

(c) A technological focus, suiting prevailing conceptions of climate mitigation policy

Keywords

Energy modelling

Policy images

Boundary objects

1. Introduction

The MARKAL energy system model was originally developed under the auspices of the International Energy Agency (IEA) in the late 1970s and is arguably one of the most successful energy models of recent decades. In 2001, Seebregts *et al* took the view that: "*The MARKAL family of models is unique, benefiting from application in wide variety of settings and global technical support from the international research community. Implementation in more than 40 countries and by more than 80 institutions, including developed, transitional, and developing economies indicates wide acceptability*" [1, p. 75-76]. Since then, application of the model has continued to increase and today it is used in nearly 70 countries [2] and has provided underpinning analysis for more than 90 peer-reviewed journal articles in the period 2004 to 2014. The United Kingdom (UK) Government and its agencies have been longstanding users of the MARKAL model and, in recent years, MARKAL modelling has been used extensively to inform UK energy and climate policy. Results from MARKAL have provided inputs to documents including the *2003 Energy White Paper* [3], the *2007 Energy White Paper* [4], the *2011 Carbon Plan* [5] and the Committee on Climate Change reports *Building a Low-carbon Economy* [6] and *The Fourth Carbon Budget* [7].

In this paper, we describe the use of MARKAL in the UK and provide an account of its enduring appeal to academic and policy communities by reference to the concept of a boundary object [8, 9]. Drawing on the authors' collective experience of MARKAL, we interrogate its role in shaping UK energy and climate policy, with a particular focus on the period from 2001 to 2011. Our interest is not so much in MARKAL's technical characteristics or policy application *per se*, but rather in how MARKAL has successfully served the differing but intersecting needs of academic and policy communities over a sustained period of time, helping to rationalise major and innovative climate and energy policy commitments. We suggest that MARKAL has brought together mutually supportive epistemic communities across academic and policy worlds, helping to develop and maintain a networked and influential community with shared assumptions and goals in which economic and technical models are privileged.

Our motivation is to add to the body of work that understands energy system analysis as in need of social as well as technical contextualisation, but our findings also have relevance to other topical areas of energy social science, including communication and persuasion, social psychology and politics and political economy [10]. In short, we suggest that the particular characteristics of the MARKAL model – highly specialist, cost-based, technology-rich – have allowed it to span the differing but related logics of government and academia and sustained its use by these communities over several decades.

We further reflect on how the model has both been advantaged by changing understandings (images) of the energy policy problem, as climate objectives have increased in importance, while also playing a role in policy path creation, supporting significant climate policy commitments. Seeking to explain the above, we connect literatures on (a) scientific models as active boundary objects in policy development and (b) the way in which changing images of a policy problem can allow new analytic and policy options to enter the political and policy space. We observe how MARKAL has played a transformative role in this context, while itself also being transformed, as the MARKAL modelling process has become target-oriented. Finally, we note how the use of MARKAL to support the policy process has not gone unchallenged.

2. Theory

2.1 The MARKAL energy systems model

The MARKAL energy model was originally developed as part of a programme of energy technology systems analysis and strategy development initiated in 1976 by IEA countries, in the aftermath of the 1973/74 oil embargo by the Organization of Petroleum Exporting Countries (OPEC). In 1980, this programme became an Implementing Agreement of the IEA known as the Energy Technology Systems Analysis Programme and continues to support and promote the use of MARKAL to this day.

MARKAL belongs to a class of bottom-up energy systems models. These models aim at a solution that satisfies the demand for energy services through a disaggregated and technology-oriented approach to modelling energy supply and demand. In the case of MARKAL, the solution is usually represented as a set of technologies that represents the least cost configuration for an energy system that meets both the exogenously specified demands and any additional constraints, such as those on emissions. Using this approach it is possible to identify the potential contributions of different energy supply and demand technologies under a wide range of future possible scenarios, as well as the costs involved.

The original objective of the model was "*to assess the long-term role of new technologies in the energy systems of the participating countries and thereby provide focus for current research-and-development (R&D) support*" [11, p. 353]. Specifically MARKAL was designed to help in understanding [ibid, p. 353-54]:

"*(a) the relative attractiveness of existing and new energy technologies and energy resources in satisfying plausible future demands for useful energy;*

(b) the time evolution of the introduction of and investment costs for new technologies and resources and the time evolution of the decline in use of existing resources, especially imported petroleum;

(c) the sensitivity of future energy systems to different goal choices and ordering, with system cost, the amount of imported petroleum, and the relative contributions of nuclear, renewable, and fossil resources being the criteria of interest; and

(d) the long-range effect of conservation and efficiency improvements on the energy system."

In recent years, MARKAL has been used by a wide-range of organisations in many different countries to model energy systems at a variety of spatial scales from global applications, through regional and national models, to the local-level, such as a single city [12 – 18]. These studies have also ranged in focus from analysing changes to the entire energy system to examining the prospects for particular sectors or technologies. New variants of the model have also been developed that have arguably increased its usefulness and relevance in both policy and academic circles, as we show in Section 4.

2.2 Models, policy images and boundary objects

In this section, we connect the idea of scientific models and their output as boundary objects to the theory of changing policy images (beliefs and values) as a facilitator of policy change. In this regard, external pressures can raise the political and policy salience of particular issues, enabling and driving change [19]. We also see the theory of policy change as punctuated equilibrium as particularly relevant. This perspective views policy change as taking the form of relatively long periods of stasis being 'punctuated' by shorter periods of change [20, 21] (c.f. Kingdon's concept of a time-limited 'policy window' [22]). Policy stasis is explained by the dominance of closed groups of policy experts, which can be interrupted by a changing image or understanding of the nature of the policy problem [19]. Driving these changes are competitive processes, both between government departments and in wider society, in which actors seek to achieve policy change that is consistent with their agendas [21].

Our argument is, firstly, that MARKAL's changing use through the period circa 1990 to 2011 reflects a change in the prevalent image of the energy policy problem. This has been from one in which the UK government saw its primary role as setting a framework within which the market could deliver the energy needs of the country, to a policy image of a climate–constrained world in which radical changes to the UK energy system would be required, with the attendant need for more active government involvement to identify how this low carbon transition could be achieved and which technologies might require support. MARKAL has been well positioned to allow consideration of new goals and configurations for the energy system; moreover, the changing use and nature of MARKAL offer an insight into the changing perceptions of energy policy, as this became integrated with climate policy

Secondly, that this changing use has been strongly supported by the way in which MARKAL and its output have successfully functioned as a boundary object, simultaneously connecting and meeting needs in different communities, providing and supporting shared understandings of the changing image of the policy problem. As van Egmond and Zeiss [21] observe, the idea of the boundary object has proved useful in explaining the hybrid nature of scientific models used in policy - that is, the way in which such models are not only based on mathematical representations of the world, but are also shaped by, and play a role in shaping, the social world in which they are embedded [21, 23]. Science and policy scholars have previously studied the relationship between modelling practices and policy practices [24 – 27], in general observing that models play a role in co-ordinating policy practice. This is not just in the rhythm of modelling runs and policy use of modelling output, but more specifically in terms of the way in which models provide 'discursive spaces' in which shared understandings are created between modellers and policymakers [25]. Previous understandings (shared perspectives) are made tangible in the form of numbers and their implications. In this way, models make policy in a sense that is stronger than simply informing: depending on their mode of use, they can define the terms in which questions are posed and answers given. Through the process of their use, the different parties involved retain their own norms and natures but they are connected by the model, which satisfies the needs of all [8].

Bringing these ideas together, we can see that scientific models may, through their role as boundary objects that facilitate intersecting agendas in different communities, support the entry of new ideas and perspectives into policy discourse. In turn, this can facilitate and reinforce new policy images and hence policy change. We draw on the different types of boundary object identified by Star's [9] and Carlile's [28] specification of the characteristics of successful boundary objects, arguing that MARKAL's longevity owes much to both its successful functioning as a boundary object and the supportive contingency (circumstances) of a changing image of the energy policy problem that has favoured technological innovation and intervention.

The idea of the boundary object developed from the application and development of the ideas of translation and *interessement* in the actor network (ANT) literature [8, 29]. Essentially this concerns the recruitment of human and non-human entities into networks for a given purpose. Those recruiting need to persuade potential recruits that engagement in the proposed activity will be to their benefit. In an historical case study of Berkeley's Museum of Vertebrate Zoology, Star and Griesemer [8] show how objects such as preserved animal and plant specimens functioned as boundary objects in their connection of different social and professional interests, including the museum scientists, conservationists and trappers. These people pursued their own agendas but also co-operated to mutual benefit, with the objects constituting their point of interconnection.

Two decades later Star revisited the boundary object, in part to emphasise how the concept goes beyond the interpretative flexibility that is inherent in all objects and indeed on which, as Star observes, constructivism relies [30]. She observed that those using the boundary object concept have rarely referred to aspects other than its interpretative flexibility: other attributes of the concept include the material and organizational structure of different types of boundary objects and the issue of scale or granularity. Here we make use of the former in connection with Carlile's work [28]. Similarly, our case also emphasises the importance of information and professional spheres [30], as do other cases making use of the boundary object idea [28, 31, 32]. Star also refers to the way in which a boundary object may become standardized and eventually exclude others and we discuss this too. The most fundamental, defining feature of a boundary object, however, remains its active connection of different social worlds with different agendas. It is this that we argue MARKAL has achieved over a sustained period of time.

Helping to define a successful boundary object, both Carlile [28] and Fong *et al* [33] consider the applied problem of knowledge management across functional boundaries in the context of manufacturing and engineering project management. Carlile refers to two pre-identified aspects of spanning knowledge boundaries and proposes a third, complementary aspect. The first aspect of a successful boundary object is termed *syntactic* and implies the need to establish an agreed, shared and stable syntax or means of communication across contexts (e.g. the hexadecimal zero or one in binary computer code and associated rules) [28]. The second, *semantic* aspect concerns the ability to convey meaning and relates to the interpretation of information transmitted, based on the premise that the same information can often be interpreted differently [ibid]. The third aspect Carlile terms *pragmatic* in recognition of the way in which particular knowledge often has indirect consequences that are significant and which may have a bearing on the willingness of groups or individuals to share that knowledge, but which are not intrinsic to the knowledge itself. These indirect consequences will often relate to social, commercial or financial interests and agendas [28].

Carlile [28] further argues that a successful boundary object is one that enables the above aspects to be clarified, negotiated and dealt with by different social groups who have over-lapping interests. We suggest not only that MARKAL has performed these functions well across groups with a close interest in energy policy, but that it also does so by spanning Star's (exemplar) categories of boundary objects [9]. As summarised by Carlile these are: *repositories* (e.g. databases) that supply a common reference point; *standardized forms and methods* that provide a shared format for solving problems; *objects or models*, representations that can be used across contexts; *maps of boundaries*, which may overlap with the objects or models category, and which represent the dependencies and boundaries that exist between different groups or functions at a more systemic level (e.g. process maps and computer simulations).

Much of the boundary object and organisation literature concerns collaboration under conditions of dissensus or disagreement [31]. In the context that we study here, while energy and climate policy have long been subject to different periods of political contestation, there has been at least a discursive-level consensus in the UK regarding the need to mitigate greenhouse gases (GHGs), with disagreement being focussed primarily on the nature of appropriate policy responses. MARKAL's role in this has been to act as a means of exploring some of those policy options, arguably relying on the epistemically privileged position of science [34, 35] to play the role of a 'value-neutral' tool. Rather than connecting positions of fundamental policy dissensus, therefore, what MARKAL has done is to connect communities of practice [36] that have different institutional and professional logics and rationales. Whereas academics tend to have an interest in opening up debate, policy practitioners more often have an interest in closing it down (cf [37]). Yet MARKAL has satisfied both. Often this connecting role falls to boundary organisations acting as intermediaries between different social and professional worlds, including those dealing with climate science and other environmental policy [38, 39], rather than to objects such as models. Here, though, it is the decision-aid itself that we focus on.

In this regard it is also worth observing that MARKAL plays a role as a scientific, value-neutral tool, despite embodying a variety of value-laden assumptions and what are essentially educated guesses as to future technology costs. As Haefele and Rogner [40, p. 344] said of IIASA modelling in the 1980s, "*we consider such modeling a craft and not a science or an art*": arguably this applies equally to MARKAL and to any models where input assumptions regarding the future strongly condition model output, but where the reliability of those assumptions is at the same time unavoidably uncertain and unknown.

3. Materials and methods

To provide data for the above argument, we have thematically organised the literature relating to UK government use of MARKAL over an extended period from the late 1970s. Some 70 policy and other documents have been examined, with close analysis of 21 items. Selection of organising themes was guided by the objective of providing a relatively neutral overview of the history of MARKAL usage in the UK, knowledge of which is grounded in personal experience of MARKAL by members of the author team, some of this being close and sustained for many years[1]. Specifically, the organising themes are: (i) the stated goals and policy ambition of the document supported by MARKAL; (ii) the specific role of MARKAL in providing that support; (iii) related policy positions and modelling context; (iv) explicit and implicit criticisms, acknowledgement of limitations and defence of MARKAL. A list of the main data sources is provided as supplementary material to this paper.

The literature examined includes government policy documents, parliamentary committee documents, statements from non-governmental organisations and some related expert critique of MARKAL. A database of literature was assembled as above and organised and searched with Nvivo, in addition to manual coding, with the search focusing on references to models and MARKAL.

[1] The authors collectively have many decades of experience in developing and running different versions of the MARKAL model in the UK and internationally, as well as working with others to frame model inputs and analysing and interpreting model outputs for both academic and policy purposes.

Changing use over time was evidenced and tracked, with this use being observable in the application of the model, i.e. the purposes to which it was put. Evidence for the changing policy image of the energy problem is inferred from the change in policy objectives, which are treated as external to (though supported by) the model. Inference of the functioning of MARKAL as a boundary object is primarily based on observation of its simultaneous use: (a) in support of key UK Government energy-climate policy documents; (b) in support of recommendations by the UK Committee on Climate Change regarding greenhouse gas emissions budgets and (c) by the small UK academic-consultancy modelling community. We relate the historical overview to boundary object characteristics and categories in the Discussion.

4. Results

4.1 Use of MARKAL by the UK Government

Changing images of the energy policy problem have enabled MARKAL to shift from an initial role in technology assessment, driven by concerns about oil import dependency; to a context of liberalised energy markets in the 1990s in which its main use was to identify priorities for R&D; to a key role in target-oriented climate policy, as reducing greenhouse gas emissions increased in policy salience through the 2000s. This shift involved a change from using the model to focus on the relative prospects of specific technologies in order to inform R&D priorities, towards a focus on the costs and possible evolution of the entire energy system to meet carbon targets. Even more particularly, it came to involve the use of MARKAL to envisage radical changes in that system: MARKAL as a quantitative visioning, scenario generation tool. Throughout these changes, the model continued to play a valuable role for the key parties involved.

4.1.1 Use of MARKAL before the year 2000

The UK was involved in the initial development of the MARKAL model through the participation of scientists from the UK Atomic Energy Authority (UKAEA). Early results from the development and application of a UK MARKAL model were presented to an IEA Steering Group in 1979 and then formally published in 1980 [41]. Much of the early modelling used scenarios that considered the trade-off between price (measured as the total cost of the energy system) and security of supply (represented by the quantity of imported oil) under different assumptions about the availability and rate of deployment of a range of new energy technologies [42, 43]. During the early 1980s scientists from UKAEA continued to use MARKAL in a number of projects that both further developed the software and applied the model to examine various aspects of the UK energy system [44]. Nevertheless, probably because of the Government's hands-off approach to energy policy at this time [45], use of the model declined over the decade, with the UK reporting in 1989 that the Department of Energy had not made "*comprehensive use of the MARKAL facility in recent years*" [46, p. 11-2].

However, in the early 1990s the UK MARKAL model was completely reconfigured and updated, and used by the Energy Technology Support Unit (ETSU), then part of UKAEA, to underpin a major appraisal for government of the prospects for a wide range of energy technologies and the implications for associated RD&D programmes [47], and a related assessment of renewable energy [48]. Summaries of the results, describing the use of MARKAL, were published in 1994 by the Department of Trade and Industry as Energy Papers 61 and 62 respectively [49, 50]. Over the following four years, the UK MARKAL model was modified and enhanced by ETSU (which was privatised as part of AEA Technology plc. in 1996) in a variety of studies for the Department of Trade and Industry. This included further assessments of the future prospects for renewable energy in support of the UK New and Renewable Energy Programme [51] and analysing the implications of abating air pollutant emissions from the UK energy system for the Energy and Environment Programme [52].

Despite this increased use, MARKAL remained at the periphery of mainstream energy policy-making in the UK for most of the 1990s, with the Government preferring to rely on quantitative analysis from econometric models operated by the Department of Energy and later the Department of Trade and Industry. These models principally relied on the historical analysis of drivers and trends in energy markets to provide insights about how they may evolve in the future and the implications for CO_2 emissions [53 – 55]. Policy-makers were mostly interested in understanding how future energy supply and demand would evolve, rather than asking questions about how it could or should develop. So for example, one of the main aims of the projections published in 1995 in Energy Paper 65 was "*to monitor the general development and direction of energy markets….*" [54, p. 6]. Econometric models are well suited to analysing relatively stable energy markets, such as those seen in the late 1980-90s when past trends and relationships could reasonably be expected to continue. They are not, however, suitable for envisaging large, long-term transitions in the technological make-up of an energy system, such as the kind that would be needed to tackle the problem of climate change.

4.1.2 Use of MARKAL after 2000

Since 2000, the environmental goals of energy policy, particularly in relation to climate change, have come to dominate in the UK. The 22nd report of the Royal Commission on Environmental Pollution (RCEP): *'Energy – The Changing Climate'*, published in 2000, played a highly influential role in this process, urging the government to '*adopt a strategy which puts the UK on a path to reducing carbon dioxide emissions by some 60% from [2000] levels by about 2050*' [56, p. 28].

These changing priorities meant that policy-makers needed energy models that could answer different questions; among the most important being the expected costs of meeting a given emissions reduction target and the portfolio of technologies needed to make those emissions reductions. A MARKAL-type model is well suited to providing answers to both of these questions in terms acceptable to the bureaucratic norms regarding the appraisal of proposals by the public sector, as embodied in the Treasury Green Book [57]. Moreover, it provides a way to imagine, comprehend and explore the dynamics of the complexity of the energy system and to identify potential technological pathways to meeting targets. Both themes are evident in the sections below, where we show how MARKAL has served the needs of intersecting UK constituencies.

4.1.2.1 The 2003 Energy White Paper

In 2001, AEA Technology plc was commissioned by the Department of Trade and Industry (DTI) to use MARKAL in a project "*to develop a range of 'bottom-up' estimates of carbon dioxide emissions from the UK energy sector up to 2050, and to identify the technical possibilities and costs for the abatement of these emissions*" [58, p. 6]. The results of this project were reported in the 2003 Energy White Paper (2003 EWP) *Our Energy Future* [3].

Responding to the challenge of climate change, the EWP2003 set out to give "*a new direction in energy policy*" [3, p. 3] and acknowledged that "*until now the UK's energy policy has not paid enough attention to environmental problems"* [3, p. 8]. Here the changing image of policy problem provided an opportunity to use MARKAL to explore whether there were plausible future configurations of the energy system that could deliver the 60 % CO_2 reduction recommended by the RCEP. The EWP gives significant prominence to MARKAL results relating to the economic costs of the transition, including its impact on future levels of GDP and the costs of carbon abatement per tonne[2]. This led to the 2003 EWP concluding that "*[our analysis] suggests that the cost impact of effectively tackling climate change would be very small"* [3, p. 9] and the estimates from MARKAL were noted as being consistent with values in a review by the Intergovernmental Panel on Climate Change.

In an evaluation of the RCEP report, the Institute for European Environmental Policy [60, p. 51] notes the importance of the MARKAL analysis: "*DTI carried out a parallel modelling exercise using the MARKAL model, and concluded from this that the technology required could be installed at a relatively modest cost…… It is understood that this exercise overcame a key barrier to acceptance of the 60 per cent target, and appears greatly to have helped develop a positive attitude to carbon reductions in government*."

However, the findings of the White Paper, and the role played by MARKAL, were not without their critics. During a hearing of the House of Lords Select Committee on Economic Affairs, Dr. Dieter Helm of the University of Oxford noted: "*The MARKAL model …. was used to produce the answer in the White Paper, which suggests that the cost to the GDP of this 60 per cent reduction in* CO_2 *by 2050 would be so low as to be equivalent to the error term in forecasting forward…..What you see going in determines what comes out the other end. That is where my criticisms of the assumptions going into the model, in particular in respect of the costs of wind and the cost of energy efficiency, have been published. That is why in the detail I do not happen to subscribe to the notion that the GDP costs of all this are low*" [61, Qu. 271].

The Government defended their use of MARKAL, explaining that "*a very high amount of sensitivity analysis was carried out in the process*" [61, Qu. 304]. However, Helm's evidence and that of other critics led to the House of Lords concluding that "*We are concerned that UK energy and climate policy appears to rest on a very debatable model of the energy-economic system and on dubious assumptions about the costs of meeting the long run 60% target*" [62, para. 94]. Despite this, and we suggest drawing strength from the heightening policy salience of climate change, MARKAL continued to play an important analytical role as the Government further developed its more pro-active energy policy.

[2] The figures for GDP loss were not a direct output from the model (the version of MARKAL used could not calculate these). Rather, they were calculated off-model using MARKAL output and additional simple assumptions. A DTI memo describing the 2003 EWP modelling notes that "*there is great uncertainty about the forecasts which [MARKAL] provides*" [48, p. 5] and that "*this type of approach is better suited to consideration of long-run impacts than transitional costs*" [ibid, p. 6].

4.1.2.2 The 2007 Energy White Paper

In 2007 the Government released another Energy White Paper '*Meeting the Energy Challenge*' [4]. This made use of a newer version of MARKAL, known as MARKAL-MACRO, which links MARKAL to a simple macro-economic model. Unlike the standard version of MARKAL, MARKAL-MACRO can directly estimate the impacts on GDP of emissions reduction. Use of this new model broadly confirmed the earlier off-model estimates of GDP impacts, but many of the limitations associated with the 2003 MARKAL version, such as the omission of transition and behavioural costs, were still relevant.

Perhaps as a result of the earlier criticism, the EWP 2007 discusses in some detail the costs estimates and their limitations, making clear how and why MARKAL results can "*be expected to produce lower-bound estimates of the costs of carbon abatement*" [4, p. 292]. Additionally, the 2007 EWP compensates for some of the weaknesses of MARKAL by also drawing on the results of other models, notably the Oxford Energy Industry Model, which was used to capture the short term dynamics of reducing carbon emissions and thus to investigate the significance of transition costs [63].

Yet the use of MARKAL to support the 2007 EWP went far beyond calculating GDP impacts. The 2007 EWP explains its use of MARKAL-MACRO in the following terms: "*for the period to 2050, we have used a model of the entire UK energy system (UK MARKAL-MACRO model) to explore the changes to the amount and use of energy required if we are to deliver our goal of reducing carbon emissions by 60% by 2050 at least cost*" [4, p. 194]. The EWP itself contains fourteen direct references to various insights from the modelling work and these instances are further complemented by numerous graphical figures in the supplementary material supporting the White Paper [64]. These include projections of sectoral abatement levels and changes in the primary energy mix through to 2050.

4.1.2.3 The 2008 Climate Change Act and 2011 UK Carbon Plan

Following the 2007 EWP, the Government published a draft Climate Change Bill, which became an Act of Parliament in 2008. This put in place a new legislative framework of five-year carbon budgets and established an independent Committee on Climate Change (CCC) to advise government on the level of these budgets. A long-term emissions target was written into the Act, but strengthened from the original 60% recommended by the RCEP to become an 80% emissions reduction target by 2050 [65].

The most recent use of MARKAL within UK energy policy has been in *The Carbon Plan* (CP), published by the government in 2011 [5], which sets out proposals and policies for meeting the first four carbon budgets (covering the period to 2027). This report made use of the Elastic Demand version of MARKAL (see Section 4.2) to envisage how best to achieve emission reduction targets [66]. The CP states that "*in line with our principle of seeking the most cost effective technology mix, our starting point for this has been to take the outputs of the 'core' run of the cost-optimising model, MARKAL*" and that this core run "*illustrat[es] the technologies likely to contribute to reducing emissions, and the most cost effective timing for their deployment*" [5, p. 16].

4.2 Use of MARKAL by the Committee on Climate Change

While the CCC shares the need of central government to analyse costs and technology pathways, it is not in the position of having to justify specific legislative proposals. Government departments have a strong need for tools that provide closure around specific options, whereas the CCC is able to take a more reflective and advisory approach – including more explicit acknowledgement of the many uncertainties.

The CCC report '*Building a Low-carbon Economy'* [6] uses the MARKAL Elastic Demand (MED) model to examine the economic and technological implications of reducing carbon emissions by both 80% and 90% by 2050 [67, 68]. MED is another variant on the standard version of the MARKAL model, in which the level of demand for energy services varies according to the costs of meeting them, based on a set of user-specified price elasticities. The report describes at some length the main attributes of MARKAL and how the MED version differs from the standard model. It also discusses the various model runs that were undertaken and the implications of the results for policy.

A number of the major conclusions from the report were supported by results from MARKAL. These included that "*the costs of meeting the 80% target are affordable*" [6, p. xvii], "*decarbonisation of the power sector is key to achieving emission reduction targets*" [6, p. xv] and that "*[low carbon electricity] would also support decarbonisation of other sectors, namely heat and transport*" [6, p. xvi].

A frequently referenced limitation of the MARKAL model is the assumption of perfect foresight, meaning that the model is unable to capture the impact of uncertainty associated with factors such as technological innovation rates or fuel prices. While this limitation of modelling results is acknowledged and discussed in publications from government departments, modelling in support of the CCC's fourth carbon budget report [7] goes much further to overcome these limitations. This was achieved by using the stochastic formulation of MARKAL to deepen the focus on a whole range of uncertainties [69]. The result of this approach is that one is able to study optimal 'hedging' strategies in the face of key mid-term uncertainties. This goes some way to studying the importance of the implicit assumption of certainty that the normal MARKAL procedure embodies. As the CCC note "*while, in reality, uncertainty is not typically resolved at a single point in time known in advance, using this functionality helps to provide insights into appropriate planning responses under uncertainty*" [7, p. 120].

4.3 Use of MARKAL by the academic modelling community

Until 2005, the use of MARKAL in the UK had been confined to government agencies or consultancies working under contract for government, rather than academia. This changed with the advent of the UK Energy Research Centre (UKERC), funded by the UK Research Councils' Energy Programme. A key priority, identified early on by UKERC, was the need to enhance the UK's ability to conduct analysis of the energy system as whole, through an energy system modelling capacity [70]. UKERC negotiated access to the UK MARKAL model with the DTI and funded the capacity to conduct a significant revision to the model database.

For the UK academic community, MARKAL has provided a tool for examining a series of issues in energy system evolution and, in the case of some model variants, for exploring a (limited) set of interactions between these energy system developments and wider economy. The researchers using it have, over time, endeavoured to test the importance of different structural model features in providing enhanced understanding of energy system dynamics. This has been achieved through a series of projects that have both applied different variants of the model developed by the ETSAP community, and linked the UK MARKAL model to a number of other analytical frameworks. The development of a UK version of the MARKAL-MACRO model in 2007 was a major experimental test of the importance of macro-economic feedbacks on energy system development [71]. Subsequent model experiments have examined the importance of spatially-constrained infrastructures by linking MARKAL to a geographical information system [72], enabling representation of demand-responses to price rises through the use of MARKAL-ED [73], examining regional representation [74], and testing the importance of uncertainty and assumptions about foresight with Stochastic-MARKAL [69].

These examples illustrate the value of the model as perceived by its academic users – it provides a system for examining the potential importance or otherwise of system elements (technologies, policies, costs) as well as perspectives and decision heuristics (macro-economic equilibrium, stochastic optimisation, the importance of spatial resolution). These experimental developments have been understood principally as intellectual exercises seeking to unpick the relative importance of different structural relationships within the energy system, not as simple answers to policy questions. However, the policy-relevance of the work has always been evident (as witnessed by the use of the models by policy-makers), and the potential of the model to inform policy is a clear part of the value that researchers see in the work [70].

This dual research and policy role creates some tensions. Modellers are keen to deliver to policymakers the insights that they believe can be most usefully drawn, while being at pains to communicate the limitations of the approach. Nonetheless, this has proved to be consistently challenging. A tool that provides a highly detailed picture of 50 years of future energy system development naturally lends itself to over-interpretation—it is easy to see it as a forecast or 'truth machine'. The following quote, from a working paper reporting MARKAL results published by UKERC, exemplifies the way that modellers are keen to provide caveats about what the model is seeking to do. *"An important point to re-stress is that MARKAL is* not *a forecasting model and* does not *predict the future UK energy system over the next 50 years. Instead it offers a systematic tool to explore the trade-offs and tipping points between alternative energy system pathways, and the cost, energy supply and emissions implications of these alternative pathways"* [75, p. iv]. The extent to which policy users choose to take heed of such caveats is likely in part to be influenced by particular policy preferences and objectives at the time.

MARKAL provides a synthesising framework through which consistent representations of possible futures can be explored. This is valuable not only for the academics directly involved in using the model – it also provides a set of scenarios that can be used by other academics as background conditions against which to conduct their own work. This is a useful function – if one wants to use a scenario of future carbon intensity of the power sector, for example, a MARKAL output provides this as part of a broader, internally consistent energy scenario. As a result, the model outputs condition the intellectual and future-oriented thinking of the energy research community more broadly – a role that has earned it critics as well as support for its conditioning and legitimating of particular ways of thinking about energy policy.

5. Discussion

Our argument is that an evolving image of the challenges facing UK energy policy has supported changing but sustained, if differentiated, use of MARKAL by several different but intersecting policy communities. MARKAL and its output have successfully connected social groups, or communities of practice [36], with different but related understandings. From information flow and systems perspectives, Fong *et al* [33, p. 16-17], similarly to Carlile [28] observe that the value of a boundary object depends primarily on how well it can "*decontextualize knowledge on one side of a boundary and recontextualize it on the other side*." MARKAL is far from readily comprehensible to all, but we suggest that its technological focus has given it an enduring appeal to those with private or public interests in advancing the new technologies required for energy system transformation. We illustrate some of these features of MARKAL in Table 1, organised by Carlile's [28] categorisation.

Table 1 Boundary object characteristics in MARKAL (after [28])

Model features	Syntactic	Semantic	Pragmatic
Metrics	Monetary, energetic and emissions units of measurement	The key metrics have intellectual and political comprehensibility across contexts	The key metrics matter across contexts: they have policy legitimacy, significance and implications for regulatory regimes, fiscal regimes and R&D funding programmes
Ability to model future, technologically-focussed scenarios	Relatively consensual definitions of the environmental performance of particular technologies	Shared understanding of the nature of specific technologies	Technological innovation widely perceived as desirable and supported by various constituencies
Optimisation	Single, clear definition of 'best' outcome for the energy system	Shared understanding of criteria against which to evaluate system performance	Alignment with bureaucratic norms of policy appraisal

The model has a number of other, interrelated attributes that lend themselves to playing a boundary object role. First, its primary decision criterion is cost, which is given primacy in much UK policy decision-making because of the importance of the Treasury Green Book guidance. Second, MARKAL makes it possible to imagine, comprehend and explore the dynamics of long-term energy systems change in an internally consistent way, and it thus provides one form of understanding of how long-term targets might be achieved. This meets a need of both academic researchers trying to systematically understand the evolution of energy systems and of the policy community who are interested in the implications of alternative energy system configurations. Finally, MARKAL results lend themselves to flexible discursive representation: that is, the model's mode of analysis, being scenario based, and its relatively complex nature and output, lend themselves to alternative and selective interpretation, representation and also generation through iterative runs under changed starting conditions.

As a technology-centred, optimisation model, MARKAL sets in the foreground the more knowable and more analytically tractable elements of developments in the energy landscape, while leaving in the background the associated changes to the political, cultural and behavioural dimensions that also will be needed, as well as (largely) the implications for the macro-economy. In giving the image of a clear, technology-based pathway, the model also provides some sense of control over the structure and evolution of the energy system. As such, it facilitates the (perhaps tacit) belief that it is possible to 'plan' an explicitly 'optimal' (in cost terms) transition to a low-carbon energy system. Indeed, one of MARKAL's appeals is that, in contrast to econometric modelling approaches, it is not confined by historical relationships and hence allows users to envisage radically different energy systems.

This capacity for facilitating new visions and new scenarios seems to help in gaining consensus across influential communities. One could even say that there is an *affective* role to scenario tools such as MARKAL, in that they give *hope* that different energy futures are possible. In a sense such tools are socially progressive, capable of supporting the imagining of radically different futures, freed from modelling the constraints imposed by some of the more difficult realities noted earlier. Others, too, have commented on the role of technological imaginaries in aspects of UK energy policy [76]. To date little has been said of the role of models in this regard, which we suggest in the case of MARKAL has been highly influential.

Yet, as noted above, the aspects of the future that MARKAL envisages are limited and largely technical. MARKAL is able to examine radical change within the energy system but the model is not designed to capture directly those dimensions of change that are more emergent, uncertain, ungovernable and harder to quantify. These include aspects of political, social, corporate and other understandings of, and responses to, attempts to manage a transition. In turn these relate to, for example, perceptions of the distribution of costs and benefits to different parts of society; issues of market structure; the institutional and policy arrangements required to enact change as depicted in MARKAL scenario results; and the culturally and socially embedded nature and determinants of consumer energy demand. In short, MARKAL can envisage new technical configurations for the energy system but questions about the political feasibility of achieving such changes, and the institutional arrangements and political strategies necessary for this, are unaddressed. Arguably, the absence of such considerations in the model or their reduction to indirect representation (e.g. through user-defined constraints), helps to connect elite communities by the act of elision: controversy is avoided or reduced by the reductionist shift to technical parameters. Thus, the nature of MARKAL itself determines what can and cannot be modelled and further shapes policy through its own authority and the legitimacy given to its output, particularly through the privileging of techno-economic and numerical information.

In section 2.2, we refer to Star's observation that over time a boundary object can become standardized and hence *exclusive* [30]. This may have mixed consequences: on the one hand it strengthens and to some extent institutionalises the object, while on the other it hinders debate and resists challenge – even if that challenge may be seen by some as justified (e.g. the critique of technocratic and scientistic models by Stirling [77]). Table 2 illustrates some examples of the challenges that MARKAL has resisted and the justifications put forth in its defence (also see section 4.1.2.1 above). While resistance to challenge is not a necessary or sufficient condition for an entity to function as a boundary object, it is an attribute that follows from the ability to secure consensus among influential parties.

Table 2 Critique, justification and defence of the use of MARKAL for the 2003 Energy White Paper

Document text	Source
The results depend on the assumptions - on technology availability and costs - that are made in the model. However, the assumptions used reflected expert opinion, informed by workshops with industry experts.	[3, p. 28]
The basic structure of the model, therefore, is that it might be expected to produce fairly low estimates of costs to GDP. i. because it is looking to the long-term it is not concerned with adjustment costs associated with markets being out of balance; ii. because it contains no information about hidden costs or other barriers that may constrain the take-up of otherwise cost-effective options.	[59, p. 7]
…….. we must be careful in the way we use MARKAL and in the conclusions we draw from it. In our work we have been trying to test out various visions of the future – not to predict a single picture for 2050, or the path towards it. We have explored different assumptions ………. On the basis of that wide range of analyses we are then looking for general conclusions that seem to be robust across the model runs, or for what the sensitivities can tell us about what matters most in leading to either relatively low or high costs of moving to a low carbon economy. Used in this way the approach can give useful insights.	[59, p. 5]
The MARKAL results look to be very much in the range of the results from that wider review.	[59, p. 7]
It is very important in this context to bear in mind that one of the advantages of MARKAL is to show you that if you pick certain assumptions you get particular answers. It turns out the government was deeply interested in a solution to the climate change problem which was largely based on wind and energy efficiency and not much else, particularly not nuclear power. It matters which precise assumptions are used as to which policies ministers and their officials think are the most efficient policies to pursue. What I am suggesting is this is extremely thin ice. The policies chosen depend upon the assumptions that went into that model and I am not at all clear in the policy process that the people making decisions fully understood how dependent they were on the nature of the assumptions that were going into the answer.	[61, Qu. 271]
On MARKAL, it is one of the great strengths of MARKAL that it is a garbage in, garbage out model. All good models are garbage in, garbage out. The way you assess a model is: are the inputs garbage? Any model where you put in garbage and produce useful knowledge would be a very curious model indeed. It is not at all a criticism of MARKAL.	[61, Qu. 407]
MARKAL is a widely used and tried modelling framework which has around 150 licensed users world-wide and has been applied in different variants in several countries including the US, the Netherlands, China and Japan.	[78, p. 17].

At the same time, though, MARKAL has experienced a number of developmental stages and different versions of the models can be and have been used, tailored for different purposes. This gives the model a somewhat different identity in different contexts, as different versions of the tool are – in Star's words [30] 'tacked' between. For example, the elastic demand version of MARKAL was developed by academics as part of a UK Energy Research Centre project [75] to examine a broad range of decarbonisation pathways for the UK and later modified by AEA Technology on behalf of the CCC (for instance the global discount rate was lowered from 10 % to 3.5 % to align with policy appraisal norms) to investigate a smaller range of carbon reduction targets and policies to help inform its advice to the UK Government on future carbon budgets [67].

In our view, MARKAL and newer, similar models (such as the recent IEA-ETSAP model called TIMES [79] and the ESME model developed by the Energy Technologies Institute [80]) are unlikely to be replaced in their particular role until the policy image of the climate-energy problem changes once again, or until alternative models are perceived to perform the same role in a better or preferable way. In this respect, UK energy modelling has been described as in need of a broader range of analytical tools [70] and perhaps a likely scenario (and one that is showing some signs of being realised) is that MARKAL becomes supplemented by a number of tools suited for related but different purposes: as and when the energy-policy problem becomes perceived as more differentiated and multi-faceted, so opportunities for policy entry by additional and/or alternative tools will arise. If these tools are to succeed, it is important that they, too, are able to deliver output capable of being rendered (translated) by and for multiple influential constituencies and, moreover, of supporting the interests of those communities.

Sustaining a role as a boundary spanning object in this context requires an ability to respond to changes in the wider priorities and concerns of the day; at least, the concerns of the modellers and the various government agencies commissioning modelling work. Scenarios and model-based projections tend to reflect the concerns of their time [81] and MARKAL appears to have been no exception. Thus the sequence of MARKAL work in the UK reveals a shift away from a limited set of questions in the 1990s ('how should we spend R&D money?' [47, 48, 49, 50]), reflecting a more laissez-faire approach to energy policy, towards questions relating to a more technology-focused, interventionist and centralised approach to energy strategy. The early 2000s saw questions about the 'feasibility' of significant GHG reductions [3, 56, 58], followed by questions about the 'affordability' of deep cuts [4, 64, 82]. At a time when climate change concern was at its height, MARKAL scenarios were generated to reflect very deep decarbonisation targets, up to 95%, reflecting ambitious 'how low can we go' rhetoric about climate change [67].

Once social and political consensus around the need for decarbonisation became entrenched in legislation, use of MARKAL also shifted towards questions about technology choices and pathways [66, 75]. Moreover, 'uncertainty' regarding the choice of pathways became a more central concern (as exemplified in the development of stochastic MARKAL for the UK Climate Change Committee [69] and the increasing use of the related model ESME [83] which highlights uncertainty around input parameters). In this respect study of models, policy analysis tools and their use can provide as much insight into key actors' understandings of the world as insight into the nature of the tools themselves.

6. Conclusions

We have described the way in which the MARKAL energy system model and its variants have achieved significant influence in UK energy and climate policy over a considerable period of time. We have accounted for this influence in terms of MARKAL and its output being transferable across contexts and both timely and flexible in its ability to fulfil a policy need for an energy model that supports alternative, technological, long term visions that are freed from some of the constraints of econometric alternatives. MARKAL's target-oriented capabilities and technological focus arguably reduce the opportunity for controversy and political friction, while serving the needs of private as well as public sector constituencies with an interest in the major research, innovation and deployment needs of energy system transformation. Despite the relative opacity of the model for outside observers, and the limitations of numerical models in terms of capturing important qualitative aspects of energy system change, for the time being MARKAL continues to function as a successful boundary object, capable of being deployed in response to changing images of the climate-energy policy problem.

In this regard, MARKAL's policy use meets Star and Griesemier's [8] basic attribute of a boundary object, namely the connection of social worlds in a form that can differ from more localised (academic) versions. We have also shown how MARKAL has the more specific, subsidiary attributes of a boundary object as identified by Carlile and others [28, 33]. Moreover we have referred to the scale of use of MARKAL internationally, this being another of Star's conditions for a boundary object [30]. Although we haven't been able to trace and compare this use internationally, this would make for another interesting project. It also remains to be seen how the model fares as alternatives begin to come to prominence. In terms of other, further work, it would be instructive to consider a broader range of energy-climate policy tools and knowledge-commissioning processes as part of science-policy interfaces, specifically in energy policy contexts, not only in the UK, but internationally (cf [32]). Certainly in our experience of UK and other national energy policy, modelling-related epistemic communities have proved and continue to prove relatively understudied but influential networks.

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Supplementary Material

Table A1 Key data sources

Year	Organisation	Title of document and web address	Supporting model (MARKAL) resources / Further details
2003	Department of Trade and Industry	White Paper: Our energy future - creating a low carbon economy http://webarchive.nationalarchives.gov.uk/20091002214428/http://www.berr.gov.uk/files/file10719.pdf	Supporting evidence: DTI, 2003. Options for a low carbon future. http://webarchive.nationalarchives.gov.uk/20070603164510/http://www.dti.gov.uk/files/file14769.pdf
2003	Royal Society	Royal Society response to the House of Lords Science and Technology Committee Inquiry into 'How will the UK meet its greener energy targets' http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/publications/2003/9770.pdf	
2005	House of Lords	Economic Affairs Committee Hearing. 22 February 2005. Questions 264-279 http://www.publications.parliament.uk/pa/ld200506/ldselect/ldeconaf/12/5022206.htm	Comments from Dieter Helm
2005	House of Lords	Economic Affairs Committee Hearing. 22 March 2005. Questions 400-419 http://www.publications.parliament.uk/pa/ld200506/ldselect/ldeconaf/12/5032201.htm	Comments from Paul Ekins
2007	Department of Trade and Industry	Energy White Paper: Meeting the Energy Challenge http://webarchive.nationalarchives.gov.uk/20121205174605/http:/www.decc.gov.uk/assets/decc/publications/white_paper_07/file39387.pdf	Supporting evidence: DTI, 2007. The UK MARKAL Energy Model in the 2007 Energy White Paper http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file38979.pdf
2007	Commission for Integrated Transport	Transport and Climate Change http://www.cambridgeenergy.com/archive/2007-02-08/commission-integ-trans.pdf	
2007	Department of Trade and Industry	The Future of Nuclear Power. The Role of Nuclear Power in a Low Carbon UK Economy. http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file39197.pdf	
2007	WWF	Consultation on the draft Climate Change Bill: Response by WWF-UK	

Year	Organisation	Title of document and web address	Supporting model (MARKAL) resources / Further details
		http://assets.wwf.org.uk/downloads/climate_bill_response.pdf	
2008	Committee on Climate Change	Building a low carbon economy - the UK's contribution to tackling climate change http://archive.theccc.org.uk/aws3/TSO-ClimateChange.pdf	Supporting evidence: AEA, 2008. MARKAL-MED model runs of long term carbon reduction targets in the UK (Phase 1). http://archive.theccc.org.uk/aws3/MARKAL-MED%20model%20runs%20of%20long%20term%20carbon%20reduction%20targets%20in%20the%20UK%20-%20AEA%20-%20Phase%201%20report.pdf AEA, 2008. MED model runs of long term reduction targets in the UK (Phase 2). http://archive.theccc.org.uk/aws3/MARKAL-MED%20model%20runs%20of%20long%20term%20carbon%20reduction%20targets%20in%20the%20UK%20-%20AEA%20-%20Phase%202%20report.pdf
2008	House of Commons	Commons debates. 21 January 2008 : Column 1638W http://www.publications.parliament.uk/pa/cm200708/cmhansrd/cm080121/text/80121w0032.htm#0801225000045	Question on the cost of solar electricity generation in the UK MARKAL-macro model
2008	House of Commons	Public Bill Committee. 26 February 2008. C249 http://www.publications.parliament.uk/pa/cm200708/cmpublic/energy/080226/pm/80226s01.htm#08022679000034	Comments from The Minister for Energy (Malcolm Wicks)
2008	House of Lords	Economic Affairs Committee. 6 May 2008. Q1-17 http://www.publications.parliament.uk/pa/ld200708/ldselect/ldeconaf/195/8050602.htm	Comments from Paul Ekins and Neil Strachan
2008	ARUP	LENS consultation response http://www.ofgem.gov.uk/Networks/Trans/Archive/ElecTrans/LENS/Documents1/080611_ARUP_Response_to_LENS_consultation.pdf	

Year	Organisation	Title of document and web address	Supporting model (MARKAL) resources / Further details
2008	World Development Movement	Adding capacity at Heathrow airport: Department of Transport Consultation http://www.wdm.org.uk/sites/default/files/heathrowconsultationresponse25022008.pdf	
2009	House of Commons	Commons debates. 12 Jan 2009 : Column 118W http://www.publications.parliament.uk/pa/cm200809/cmhansrd/cm090112/text/90112w0026.htm	Question on the robustness of MARKAL and its use by different organisations
2010	UK Energy Research Centre	UKERC response to DECC 2050 Pathways Analysis: call for evidence http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=1145	
2011	Committee on Climate Change	The Fourth Carbon Budget. Reducing emissions thought the 2020s. http://archive.theccc.org.uk/aws2/4th%20Budget/CCC-4th-Budget-Book_plain_singles.pdf	Supporting evidence: University College London, 2010. UK MARKAL Modelling – Examining Decarbonisation Pathways in the 2020s on the Way to Meeting the 2050 Emissions Target http://archive.theccc.org.uk/aws2/4th%20Budget/CCC%20MARKAL%20Final%20Report%20-%20UCL%20Nov10.pdf
2011	Nuclear Free Local Authorities Secretariat	Government consultation on overarching energy national policy statement (en-1) and for nuclear power generation (en-6) http://nfznsc.gn.apc.org/docs/consultations/NFLA_NPS_Response_2011.pdf	
2011	Department of Energy and Climate Change	Planning our electric future: a white paper for secure affordable and low-carbon electricity https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48129/2176-emr-white-paper.pdf	
2011	Her Majesty's Government	The Carbon Plan: Delivering our low carbon future https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf	Supporting evidence: AEA, 2011.Pathways to 2050 - Detailed analysis. MARKAL Model Review and Scenarios for DECC's 4th Carbon Budget Evidence Base. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48073/2270-pathways-

Year	Organisation	Title of document and web address	Supporting model (MARKAL) resources / Further details
			to-2050-detailed-analyses.pdf
2012	Friends of the Earth	Written evidence from Friends of the Earth to the Energy and Climate Change - First Report. Draft Energy Bill: Pre-legislative Scrutiny http://www.publications.parliament.uk/pa/cm201213/cmselect/cmenergy/275/275we19.htm	

Table A2 Examples of the underpinning evidence base: energy policy goals, specific problems and use of MARKAL

Theme	Document	Page	Illustrative Quotations
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	6	Our country needs a new energy policy. Despite the improvements we have made over the last five years, today's policy will not meet tomorrow's challenges. We need to address the threat of climate change. We must deal with the implications of reduced UK oil, gas and coal production, which will make us a net energy importer instead of an energy exporter. And over the next twenty years or so we will need to replace or update much of our energy infrastructure.
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	6	The opportunity to shift the UK decisively towards becoming a low carbon economy where higher resource productivity - producing more with fewer natural resources and less pollution - will contribute to higher living standards and a better quality of life.
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	6	[The new energy policy] reflects, and will reinforce, our wider commitment to sustainable development
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	11	… to put ourselves on a path to cut the UK's carbon dioxide emissions - the main contributor to global warming - by some 60% by about 2050, as recommended by the RCEP, with real progress by 2020
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	11	… to maintain the reliability of energy supplies
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	11	… to promote competitive markets in the UK and beyond, helping to raise the rate of sustainable economic growth and to improve our productivity; and
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon	11	… to ensure that every home is adequately and affordably heated.

Theme	Document	Page	Illustrative Quotations
	Economy, London: DTI; 2003.		
Policy goals and ambitions	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	11	We do not propose to set targets for the share of total energy or electricity supply to be met from different fuels. We do not believe Government is equipped to decide the composition of the fuel mix.
Policy goals and ambitions	Great Britain, House of Lords. Select Committee on Economic Affairs. The Economics of Renewable Energy. Volume II: Evidence. HL (2007-08, 195-II); 2008.	Qu. 3	Professor Ekins: The key considerations for UK energy policy I think were outlined in both the White Papers which the Government has produced over the last five or so years: the reduction in carbon emissions, energy security, competitive markets and/or competitiveness (depending on how you want to interpret that particular third objective), and something to do with affordability which might or might not be expressed in terms of fuel poverty. The balance to be accorded to those four objectives is of course a political matter. My reading of the situation at the moment is that the Government is giving most attention to the reduction of carbon emissions, but energy security is coming up fast on the inside track and may indeed overtake it at some point. I think that the concern about competitive markets and competitiveness is always with us, so to speak, and some commentators think that the objective of fuel poverty—specifically its effective abolition by 2016—has lost ground somewhat against the other objectives. That is how I would characterise the objectives.
Policy goals and ambitions	Great Britain, House of Lords. Select Committee on Economic Affairs. The Economics of Renewable Energy. Volume II: Evidence. HL (2007-08, 195-II); 2008.	Qu. 4	Lord Lawson: I would like to follow up that question of cost and system integration. I was very interested, Professor Ekins, in your saying that you think that energy security is coming to the forefront; I think you are probably right.
Image of the policy problem	Department of Trade and Industry. Meeting the energy challenge, London: DTI; 2007	6	We face two long-term energy challenges: tackling climate change by reducing carbon dioxide emissions both within the UK and abroad; and ensuring secure, clean and affordable energy as we become increasingly dependent on imported fuel.

Theme	Document	Page	Illustrative Quotations
Image of the policy problem	Department of Trade and Industry. Meeting the energy challenge, London: DTI; 2007	7	At home it is likely that the UK will need around 30-35GW of new electricity generation capacity over the next two decades and around two thirds of this capacity by 2020. This is because many of our coal and most of our existing nuclear power stations are set to close. And energy demand will grow over time, despite increased energy efficiency, as the economy expands.
Image of the policy problem	Department of Trade and Industry. Meeting the energy challenge, London: DTI; 2007	9	The starting point for our energy policy is to save energy.
Image of the policy problem	Department of Trade and Industry. Meeting the energy challenge, London: DTI; 2007	4	We need to tackle climate change and energy security together.
Image of the policy problem	Department of Trade and Industry. Meeting the energy challenge, London: DTI; 2007	5	Our aim will be to ensure that companies have a wide range of low carbon options available so we can retain a diverse energy mix, which is good for our security of supply, and will help us to become a low carbon economy
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	17	A broad vision of the energy system of 2020 is described below. This is a scenario. It draws on several sources, including modelling work for the white paper, the DTI's Foresight programme and other scenarios.
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	20	This white paper is based on a large amount of analysis and modelling. We are publishing separately documents which form part of that work, on estimates of the cost and potential for various long-term low carbon options; on the background outlook for energy demand and emissions between 2000 and 2050; an initial assessment of the impact of the policies as set out in this white paper; and background calculations to achieving carbon cuts of between 15-25 million tonnes of carbon in 2020.11
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	28	A wide range of analytical work has supported the white paper. This included work by the Government's interdepartmental analysts group on long-term reductions in greenhouse gas emissions, following which the DTI commissioned Future Energy Solutions to use the MARKAL modelling approach to look at the costs and

Theme	Document	Page	Illustrative Quotations
			options for a substantial CO2 reduction by 2050. 21
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	28	The analysis suggests that for many of the assumptions tested the cost of reducing CO2 emissions by 60% by 2050 was in the range £200-300 per tonne of carbon. GDP in 2050 was reduced by 0.5-2.0%, equivalent to an average annual reduction of between 0.01 and 0.02 percentage points from a business as usual GDP growth rate of 2.25% per annum.
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	28	Higher costs were indicated if innovation in low-carbon technologies was limited, if energy efficiency improved only in line with past trends, or if both new nuclear build and carbon capture and storage were completely excluded in the longer term.
Use of MARKAL	Department of Trade and Industry. Our Energy Future - Creating a Low Carbon Economy, London: DTI; 2003.	28	To be on track for the 15-25 MtC reduction beyond current baselines that we are aiming at, MARKAL indicates costs of reducing carbon in 2020 in the range £10-80 per tonne of carbon.
Use of MARKAL	Department of Trade and Industry. Options for a low carbon future. DTI Economics Paper No. 4, United Kingdom; 2003.	155	Comparison of the overall costs with and without the constraint gives us information on the costs of meeting the constraint.