Applied Energy 169 (2016) 607–628

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of energy systems models in the UK: Prevalent usage and categorisation

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HIGHLIGHTS

- We review UK academic and policy literature since 2008 on energy systems modelling.
- We find that nearly 100 models are referenced within academic literature.
- We propose a classification schema and define its suggested usage.
- The UK model landscape is considered and 22 models are classified within the schema.

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form 15 November 2015
Accepted 7 February 2016
Available online 23 February 2016

Keywords:
Energy tools
Energy models
Energy systems
Energy systems modelling
Energy policy

ABSTRACT

In this paper, a systematic review of academic literature and policy papers since 2008 is undertaken with an aim of identifying the prevalent energy systems models and tools in the UK. A list of all referenced models is presented and the literature is analysed with regards sectoral coverage and technological inclusion, as well as mathematical structure of models.

The paper compares available models using an appropriate classification schema, the introduction of which is aimed at making the model landscape more accessible and perspicuous, thereby enhancing the diversity of models within use. The distinct classification presented in this paper comprises three sections, which specify the model purpose and structure, technological detail and mathematical approach. The schema is not designed to be comprehensive, but rather to be a broad classification with pertinent level of information required to differentiate between models.

As an example, the UK model landscape is considered and 22 models are classified in three tables, as per the proposed schema.

1. Introduction

The problem of sustainable energy is naturally unique to each decision maker depending on their circumstances, which include geographical location, the sectoral coverage and available resources. Whilst the World Energy Council coined the phrase *energy trilemma* to describe the core challenges of sustainable energy, an on-going debate focusses around the United Nation's set 17 Sustainable Development Goals (SDGs), which replace the previous Millennium Development Goals and cover a broad range of sustainable development issues. Specifically, Goal 7 states "Ensure access to affordable, reliable, sustainable, and modern energy for all". This issue concerns the world as a global unit, though it tends to define the political debate of energy supply in individual countries or continents. With the growing concern of Climate Change [1], energy supply and demand has become an increasingly important issue.

Due to the increasing global demand for energy, as well as the strict emissions targets, actors within the energy system have to make complex decisions based on risk-based assessments about the future. Since the specific objectives vary amongst actors, there is a direct need for support tools which aid the decision making process around energy systems.

Owing to the complexity of the problem, scenario exercises have been developed in recent years, which can inform about possible future pathways, as well as defining and testing energy policy [2]. To aid quantification of scenario detail, especially in relation to trends and technological influence, energy systems models are often utilised. Such models simulate or explore the evolutionary response to disparate policies, which may be technological, economical or social. Accordingly, energy systems modelling is

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http://dx.doi.org/10.1016/j.apenergy.2016.02.044

inherently inter-disciplined, involving social and geographical research as well as scientific and engineering disciplines.

The existing landscape of energy models is varied [3–5] and each model has its own unique blend of paradigms, techniques and solutions. There are several prominent models, which have been developed over many decades and which span wide topical areas. These include MARKAL (the MARKet ALlocation model) [6] and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental impact model) [7], both of which have several variants aimed at increasing their functionality and applicability.

However, the total range of choices and variables in systems modelling is so vast (and sometimes disparate) that it is unlikely that one single model could (or perhaps should) incorporate them all at once. Taylor et al. acknowledge that "UK energy modelling has been described as in need of a broader range of analytical tools" and state that the predominant tool, MARKAL, might be replaced only "by a number of tools suited for related by different purposes" [8]. Indeed, a recent approach is to develop a "storyline" and incorporate several models with varying focii to achieve different objectives within one framework [9]. With such approaches emerging in the decision making process in energy systems, the choice of models or tools becomes pivotal.

This paper focusses on the prevalence of energy systems models within literature in the UK. In addition, models are compared side-by-side using a classification schema developed here. This schema is designed to be used as a decision support tool, for example to aid researchers identify gaps within the modelling field or to assist the wider range of actors in selecting models to investigate specific issues or questions. The overall objective of this work is to highlight the wide diversity of models already available and support decisions.

In Section 2, we perform a literature review and identify the predominant models utilised and topics of interest within the field. In Section 3, the introduction of a classification schema is proposed, which aims to categorise existing models and a broad, but detailed, classification schema is suggested in Section 4. A subset of models used within the UK are categorised in Section 5 with information valid as of May 2015.

2. The model landscape

Energy systems models were first designed after the 1970s oil crisis, with an objective of maintaining energy stability. At that time, there was a negligible variable generation component and limited option for storage technologies (which existed in the form of fuel supply). Instantaneous stability of the grid came through grid inertia of synchronous plants and spinning reserve capacity.

However, with the realisation of global climate change, the emphasis of models has moved towards environmental issues, including CO_{2e} emissions. From a modelling perspective, this has notable consequences: the addition of variable generation (solar PV and wind sources) has cost implications (new infrastructure, demand balancing, etc.) and there are longer-term issues related to technological change within the system. These modifications to the energy system are not necessarily easily reflected in existing algorithms, which may not have been designed to cope with variable generation sources.

The rapid changes in the energy market (with emerging technologies) have not always been mirrored in somewhat bulky energy models and the models which have been adapted can seem disjointed. Added to the fact that many comprehensive models have a tendency to be opaque (sometimes referred to as in-transparent) and inaccessible, the choice of models to use for specific scenarios is complex.

The full landscape of energy models accounts for the full range of actors (producers, generators, suppliers and end users), which in turn implies the inclusion of all energy sectors (electricity generation, heating, industrial usage, residential demand, transportation), economical aspects (costs, tariffs) and social aspects (policy, planning, risk, social practices/behaviours).

In addition to the broad purpose of models, there is a large set of mathematical approaches in the landscape. Models using optimisation and simulation techniques are plentiful, but are being joined by those utilising neural networks, agent-based modelling, complexity science and fuzzy theory [3,10,11].

2.1. Academic literature review

In order to identify the full and complex landscape of existing models and their uses within literature, the ScienceDirect search facility was utilised to select all papers since 2008 mentioning "energy systems model UK" (as four distinct words, not a phrase). The result of this search was over 1600 papers, though papers neither concerning the UK nor originating from the UK were removed. The product was 423 publications though the majority of these focus on energy efficiency measures (typically related to energy saving strategies within industrial buildings). The results shown in this section only relate to a subset of 110 papers, specifically related to energy systems modelling in the UK. It can be noted, however, that the main conclusions are broadly valid between both sets of publications.

The subset of 110 papers are disparate in their content and range from implementation of a single technology within the wider system context to the impact of policy decisions. Compelling reviews of the subject can be found in Allan et al. [12], Connolly et al. [13], Pfenninger et al. [4], Pilvachi et al. [14], and Strachan [15]. A review of the MARKAL model over the past 35 years is given by Taylor et al. [8] and a classification of techno-economic energy models is given in [16].

Reviews of the application or use of particular models or tools include: UK MARKAL with reference to bioenergy [17], hybrid modelling approaches (MARKAL-MACRO) [18], Marginal Abatement Cost (MAC) curves [19] and multi-criteria analysis for renewable energy technologies [20].

A whole energy systems approach has been taken by [21–23], whilst infrastructure networks are discussed in [24]. There is a plethora of literature around necessary infrastructure for hydrogen energy: a review of hydrogen studies is found in [25], the SHIPMod model is introduced in [26], spatial development studies are detailed in [27,28], hydrogen transitions are discussed in [29–31], the Scottish market is modelled in [32], potential benefits are promoted in [33] and an investment-led approach is developed in [34].

In contrast, some authors choose to focus on one or two single sectors, rather than a whole systems approach. Papers can be found which cover the oil and gas sectors [35–38], data centres [39], the transport sector [40–45] and domestic sector [46–52].

Smaller scale systems analysis is undertaken for micro-grids [53,54] and for urban or district scales [55–59]. The models used within these latter papers include VantagePoint, TURN and land-use transport models.

A range of long-term UK energy scenarios are presented in [60]. A review of UK and international scenarios is given in [2], whilst [61] discusses the predictive ability of existing scenarios against actual data. The impact of scenarios on policy have been discussed in [62]. Specific pathway development is discussed in [63–67]. An approach for linking storylines with multiple models is proposed in [9]. Direct uncertainties are discussed in [68,69] in relation to energy decarbonisation targets.

Naturally, within this field there are a multitude of papers which discuss the design, assessment and impact of energy policy [70–78]. There are also publications which discuss the complexity of energy systems and possible modelling approaches [11,79], the importance of modelling to policy [80] and baseline "Business as Un-Usual" calculation [81].

The precise construction of economic formulae form the basis of one area of research in energy systems [82–87]. For example, rebound effects are discussed in several papers [88–90], where AMOSENVI, SELMA, ELESA and CDEM (Community Domestic Energy Model) are used.

Due to the social implications of climate change, energy demand and technological change, there are a number of papers that investigate these effects: Bale et al. look at how social networks enhance adoption of technologies [91], Butler et al. discuss the effects of public values on policy [92], whilst Bazilian et al. even promote open source software and crowd-sourcing [93].

Many different energy technologies are discussed within the complete subset of 110 papers, but specific solutions are discussed in reference to heat pumps [94], gas-fired power plants [95], storage solutions [96], CCS in the North-sea [97], wind power [98,99], bioenergy [100–102] and marine energy [103].

MARKAL and MESSAGE models are heavily referenced and utilised within the subset of papers considered. However, there are also many other models being introduced including: the UK Transport Carbon Model (UKTCM) [104], a chemical transport model CMAQ [105], E3MG [106], OSeMOSYS [107], a temporal MARKAL model [108], a mixed-integer linear programming (MILP) tool for the design of a distributed energy system [109], the Biomass Value Chain Model (BVCM) [110], a dynamic model of the natural gas industry [111], modelling micro-CHP systems for domestic energy supply [112], usage of renewable energy technologies for electricity generation [113] and a Monte Carlo model of the combined gas and electricity network [114].

In order to identify the full list of models utilised by energy systems modellers in the UK (and their prevalence), we have surveyed the 110 papers listed above. Nearly one hundred models were cited within the papers, all with disparate aims and objectives within the modelling environment. An ordered list of the models according to prevalence in the literature is shown in Table 1. The mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers) is also shown on the graph. This indicator provides a qualitative assessment of penetration within the literature; a low mean citation indicates low impact on the field, whereas a high mean citation count indicates a high level of penetration within the literature. For example, the BHCP model only appears once in the literature, but its high citation count indicates that the model has been promoted widely to a large audience.

It is clear that the MARKAL model (and its variants e.g. UK MARKAL, MARKAL-MACRO, MARKAL Elastic Demand, TIMES, SAGE) is highly used within academic literature and underpin much research of the UK energy market. A breakdown of the appearances of MARKAL and MESSAGE variants within literature is shown in Fig. 1.

Considering the annual referencing of models since 2008, use of the MARKAL and MESSAGE models has remained relatively constant, as can be seen in Fig. 2. It can also be seen that papers referencing MARKAL/or MESSAGE models do not form the majority of the published work. (It should be noted that literature is only included until May 2015, such that 2015 only contains 5 months.)

The sectoral coverage of literature is shown in Fig. 3. The titles "economic sector" and "commercial sector" have been purposefully left exactly as they appear in the publications (despite natural overlap), in order to fully represent the literature. With interest in energy efficiency and CO_2 reduction being so high, it is perhaps

Table 1
The list of models as they appear in academic literature since 2008. A mention in a paper results in one "appearance". Also shown is the mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers). The MARKAL model (and its variants) is clearly dominant in the existing literature.

Model	Appearances	Mean citations
MARKAL total	59	16.4
Other MARKAL	27	19.4
MESSAGE total	15	33.3
POLES	9	13.0
PRIMES	9	43.6
BREHOMES	8	14.0
ESME	8	3.5
BREDEM	6	20.3
LEAP	6	58.8
WASP	6	64.5
E3MG	5	16.4
MDM-E3	5	21.0
NEMS	5	74.0
DECC energy model	4	8.0
HOMER	4	98.3
MATLAB	4	28.5
OSeMOSYS	4	8.3
TDM	4	21.3
UKTCM	4	17.5
DECarb	3	25.3
DECC 2050 calculator	3	11.3
DER-CAM	3	133.0
EnergyPLAN	3	107.0
RETScreen	3	101.7
SAP	3	6.0
TEMOA	3	10.3
UKDCM2	3	23.3
WITCH	3	19.3
AMOSENVI	2	25.5
CDEM	2	10.5
DNE21	2	4.5
DTI energy model	2	12.0
DynEMo	2	1.0
EMCAS	2	152.5
GEM-E3	2	5.5
IPAT	2	15.5
MEDEE	2	11.5
MODEST	2	20.5
REDGEM	2	3.0
SHIPMod	2	5.0
State-task network	2	10.5
TIMER	2	5.0
TRNSYS	2	149.0
TURN	2	2.5
WADE	2	16.5
4see	1	3.0
ADEPT	1	5.0
AEOLIUS	1	298.0
BALMOREL	1	298.0
BCHP	1	298.0
BRM	1	4.0
BVCM	1	1.0
CMAQ	1	2.0
COMPOSE	1	298.0
DENO	1	8.0
E4cast	1	298.0
ELESA	1	16.0
ELMOD	1	7.0
EMINENT	1	298.0
EMPS	1	298.0
EnerGIS	1	8.0
energyPRO	1	298.0
ENPEP	1	298.0
ENUSIM	1	5.0
GAINS	1	2.0
GCAM	1	8.0
GET	1	5.0
GRAPE	1	5.0
GTMax	1	298.0
H2RES	1	298.0

(continued on next page)

Table 1 (*continued*)

Model	Appearances	Mean citations
HYDROGEMS	1	298.0
IKARUS	1	298.0
IMACLIM	1	8.0
IMAGE	1	8.0
INFORSE	1	298.0
Invert	1	298.0
MCA	1	4.0
MERGE-ETL	1	8.0
Mesap PlaNet	1	298.0
MiniCAM	1	298.0
ORCED	1	298.0
PERSEUS	1	298.0
PLEXOS	1	7.0
ProdRisk	1	298.0
RAMSES	1	298.0
REMIND	1	8.0
RESOM	1	2.0
SELMA	1	16.0
SimREN	1	298.0
SIVAEL	1	298.0
STREAM	1	298.0
UKENVI	1	38.0
UniSyD3	1	298.0
VantagePoint	1	0.0
WEPS	1	3.0
WILMAR	1	298.0

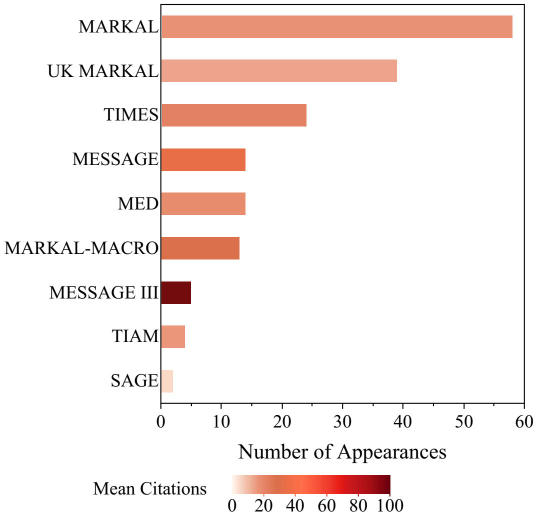

Fig. 1. The breakdown of MARKAL and MESSAGE model variants from the categories "MARKAL Total", "Other MARKAL" and "MESSAGE Total" in Table 1. The colour of each bar relates to the mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers) as detailed in the colourbar.

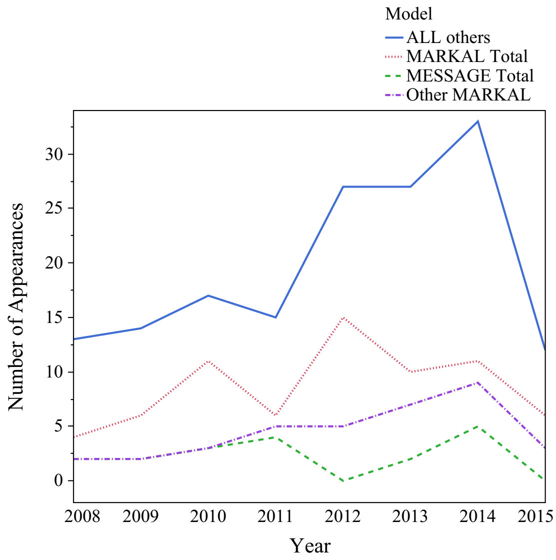

Fig. 2. The number of appearances in academic literature by year for the predominant models against all other models. (N. B. Papers are only counted until May 2015 inclusive, such that 2015 counts are for only 5 months.)

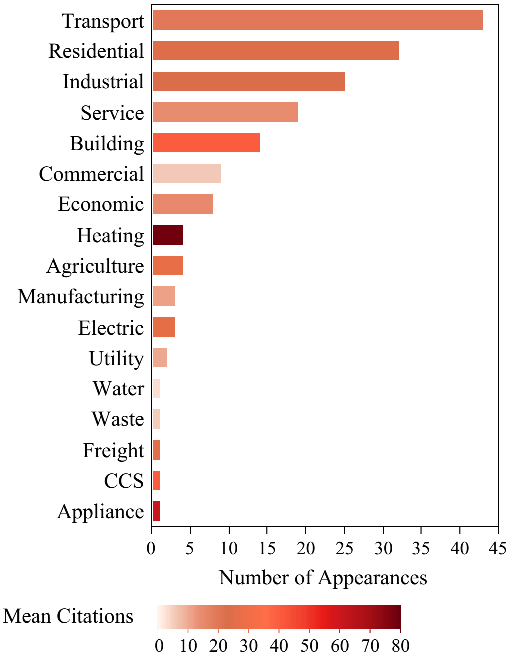

Fig. 3. The number of appearances of various sectors within academic literature since 2008. The colour of each bar relates to the mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers) as detailed in the colourbar.

unsurprising that reference to the transport and residential sectors is so prevalent. The coverage of renewable energy technologies is shown in Fig. 4 and a list of common mathematical phrases is shown in Fig. 5.

2.2. Policy paper review

In order to understand the prevalence of energy systems modelling within UK policy papers since 2008, the following papers have been reviewed: the 2008 White Paper on Nuclear Power [115], the 2009 Renewable Energy Strategy [116], Electricity Market Reform (EMR) Impact Assessment [117], the Fourth Carbon Budget [118], the 2011 Renewable Energy Review [119], the 2011 Energy White paper [120], the 2012 Bioenergy Strategy paper [121], the 2012 Gas Generation Strategy [122] and the 2013 Heating Strategy [123].

The prevalence of energy systems models within these nine policy papers was considered independently from academic literature and the results are shown in Fig. 6. It can immediately be noticed that the range of models is different from and considerably smaller than that in academic literature and, whilst only nine papers are considered, the predominant model is still MARKAL and its variants. Only one policy document refers directly to the Redpoint Energy System Optimisation Model (RESOM) by name [123], all

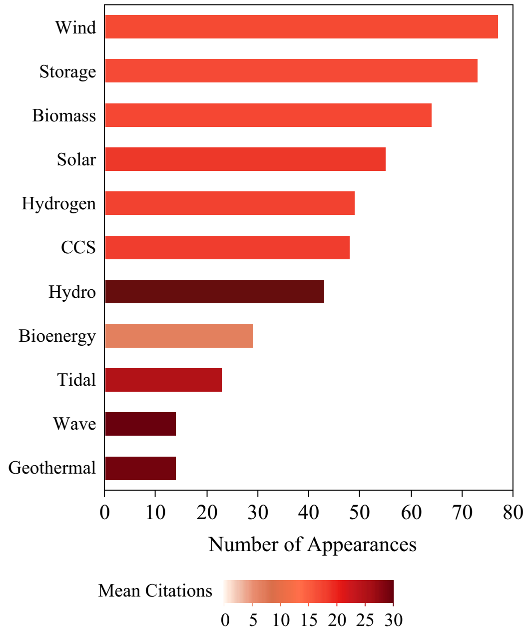

Fig. 4. The number of appearances for renewable energy technologies. The colour of each bar relates to the mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers) as detailed in the colourbar.

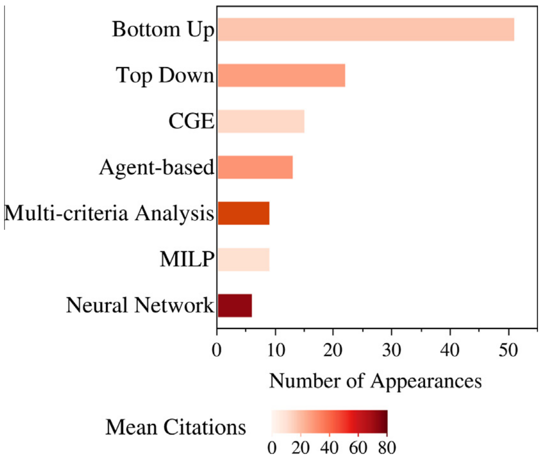

Fig. 5. The most common mathematical phrases as they appear in academic literature. The colour of each bar relates to the mean number of citations per model (the total number of citations for papers citing the model divided by the total number of papers) as detailed in the colourbar.

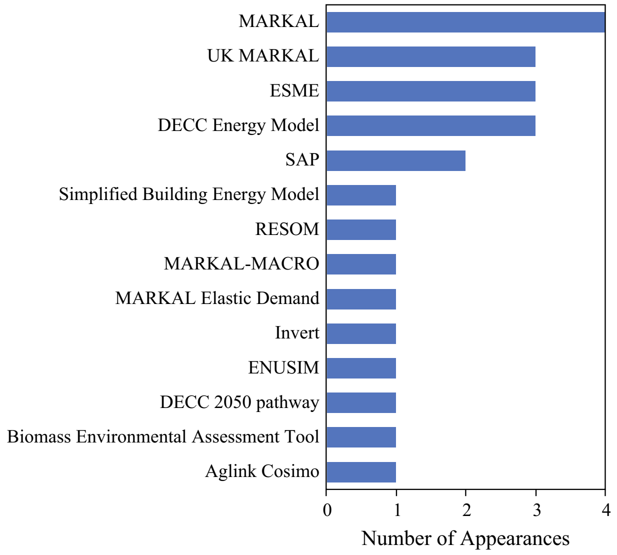

Fig. 6. The ordered list of models as they appear within nine government policy papers reviewed.

of the policy papers refer to externally commissioned modelling performed by Redpoint energy. We can therefore infer that RESOM is a highly utilised model within UK governmental research. Two papers (2011 Energy White paper and EMR Impact Assessment) do not mention any specific modelling tool used, but refer to Redpoint modelling.

3. The need for a uniform classification schema

In the previous section, we have shown that only a select few models are routinely used for energy systems modelling in the UK. Whilst some excellent reviews already exist, it is still very difficult to differentiate between models (especially across separate review papers) and for all energy actors to understand the basis for each model. In order to encourage wider usage of a broad range of models, it is necessary to describe each model in clear detail and to classify the objectives and structure. It could also be prudent in future to have this information in one location (for a dynamic source of information, this could take the form of a website). This approach allows for subsequent users to identify the potential application of each model and to choose accordingly.

In order to make the landscape of models more transparent, we propose the design and implementation of a single classification schema, which would encompass a wide range of factors relevant to energy modelling. This schema could then be utilised by a broad audience in deciding whether the right tools exist and then which combination of tools to use. Over the past two decades, many categorisation theories have been suggested [124–129], though none has been adopted as good practise. Due to the vast numbers of models, any single categorisation is somewhat arbitrary, though categorisation can be invaluable for selecting the appropriate tool for a given problem. Indeed, incorrect application of a tool or opaque modelling (where the detail of the model is not fully available) can lead to misinterpretation of outputs, which can have lasting (and possibly expensive) consequences (for example, see [130]).

In the next section, we propose a single, consistent schema, which attempts to draw together the most pertinent information in an accessible manner. The intention is threefold:

1. When presenting new models, developers should define these fields in early literature and in documentation (ideally in clear tables), such that a clear and accurate representation is made.
2. When writing up research which employs an energy model, these fields should be defined, such that a fuller understanding of the results and outputs can be gained (especially when the model used has been modified for the research project).
3. New literature reviews referring to energy models should follow this guidance when comparing models (ideally in tabular format), such that consistency in the literature is maintained.

There are a few common approaches to categorisation of models into general themes. The prevalent strategy taken in much existing literature for model classification is to define the analytical approach of a model (e.g. “top-down” or “bottom-up”), the methodology (e.g. simulation or optimisation) and the mathematical approach (type of programming techniques utilised). For example, the phrase (or paraphrase) "MARKAL is a widely-applied bottom-up, dynamic, linear programming optimisation model" is widely used (e.g. [131–133]) (for examples of other common mathematical jargon used in the literature see Fig. 5). However, it has been accepted in the UK that such phraseology, whilst neither inappropriate nor problematic, was not likely to be understood by the non-academic actors interacting with this research [134]. Therefore, the field can appear opaque to non-specialists. The description and information given about models is crucial to a wide audience (i.e. all actors within energy systems). Indeed, it is often the model's purpose, structure and implicit assumptions that are the pertinent information. Without clear (and understandable) descriptions of model objectives and detail, it remains complicated for policy makers to decide on relevant tools to use for certain exercises. This might be concluded from Table 1, in which use of the majority of models appear to be limited. Of course, it can also be argued that these same models have narrow focii and are therefore inapplicable to more general modelling requirements.

4. A proposed classification schema

In this paper, classification schemes are merged from various sources [3,135–138], with an intention of finding a broad set of categories that attempts to differentiate between models. The schema suggested here comprises 14 categories, which account for the purpose, structure, approach, mathematical and technological detail. This schema is purposefully not comprehensive to the point of completeness; some categories have not been included, as will be discussed in Section 4.4. Some developers/authors will wish to add further detail to the schema. However, it is strongly recommended that the fields proposed in this paper are included, in order to achieve consistent comparison across the model landscape. In this way, future literature on energy systems modelling will become more readily transparent and the use of a wider range of models should increase, where relevant.

The proposed classification scheme is shown in three separate tables detailing (a) the model purpose and structure in Table 2, (b) the technological detail in Table 3 and (c) the mathematical detail in Table 4. Where they are not readily apparent, some details of the classification structure will be highlighted in the following subsections.

4.1. Classification: purpose

4.1.1. The model purpose

The justification of developing energy systems models is to answer specific questions which will lead to practical decision making. The final aim can be to investigate any aspect of multi-disciplinary energy systems. For example, models can be used to examine:

- interactions across the energy system,
- possible pathways to decarbonisation,
- the impacts of (sometimes competing) policy goals and objectives,
- costs associated with certain energy scenarios.

Within the set of existing models, it is necessary to separate *general* purposes from *specific* ones.

The general purpose may be one of (a) forecasting, (b) exploring and (c) backcasting.

Table 2
Classification of energy systems models and their options – purpose and structure.

Model	Name of model and developer	
1. Purpose of the model	**General**	Forecasting Exploring Backcasting
	Specific	Energy demand Energy supply Impacts Environmental Appraisal Integrated approach Modular build-up
2. Structure of the model: internal assumptions & external assumptions	Degree of endogenization Description of non-energy sectors Description of end-uses Description of supply technologies **Supply** or **Demand** analysis tool	
3. Geographical coverage	Global Regional National Local/community Single-project	
4. Sectoral coverage	Energy sectors Other specific sectors Overall economy	
5. The time horizon	Short Medium Long Term	
6. The time step	Minutely Hourly Monthly Yearly Five-yearly User-defined	

The specific purpose field is aimed to be descriptive and considers the aspects on which the model itself focusses. This is the main field which can aid general differentiation between model objectives.

4.1.2. The model structure

Energy systems models can be described by their underlying structure and their implicit assumptions. This field aims to clarify the fundamental basis of the model, clearly accounting for the assumptions and model design. Each developer decides on the assumptions that will be implicitly coded into the model (internal assumptions) and those that will be left to the user to input (external assumptions). Hourcade et al. [128] defined four characterisations of this classification (as shown in Table 2), though each of these dimensions allows for a somewhat arbitrary ranking (i.e. "more" or "less"). Hourcade et al. lists some external assumptions that may be made, which include population growth, economic growth, energy demand, energy supply, price and income elasticities of energy demand, existing tax system and tax recycling.

Some economic variables within models are determined by the model itself (*endogenous*) or are assumed to be determined by factors outside of the model (*exogenous*). The assumptions made at this point can be crucial when deciding on which tool to use. As an example, over a given time period, the costs associated with one specific technology can either be input as time-series data or alternatively the learning curve can be implicitly modelled within

Table 3
Classification of energy systems models – technological detail. Fields listed on the right-hand side are given for indicative purposes only and are not comprehensive. Not all sectors are included, but rather the fields should represent the level of granularity in specific industries with high interdependency between supply and demand.

Model		Name of model
7. Renewable Technology Inclusion		Hydro Solar (PV and thermal) Geothermal Wind Wave Biomass Tidal
8. Storage Technology Inclusion		Pumped-hydro energy storage Battery energy storage Compressed-air energy storage Hydrogen production/storage/consumption
9. Demand Characteristic Inclusion	**Transport Demand**	Internal-combustion vehicles Battery-electric vehicles Vehicle-to-grid electric vehicles Hydrogen vehicles Hybrid vehicles Rail Aviation
	Residential Demand	Heating Lighting Cooking Appliance usage Smart Appliances & Smart metres
	Commercial Demand	Offices Warehousing Retail
	Agricultural Demand	
10. Cost Inclusion		Fuel prices Fuel handling Investment Fixed Operation & Maintenance (O&M) Variable Operation & Maintenance (O&M) CO_2 costs

the code. The outputs may depend on the implicit model assumptions, as well as user data entry.

When developing models, decisions must be made as to the mathematical constraints being placed on the system. For example, such constraints might include:

- Energy demand must be satisfied at all times.
- User defined CO_{2e} emissions targets are met.
- Production and consumption of energy must balance, allowing for transmission, storage and losses.
- Energy system must satisfy certain other constraints (e.g. sufficient capacity to meet peak demand for electricity and heat, capacity to sustain generation during sustained periods of low variational generation).
- Technological links can be specified by users and respected by the model (e.g. enough suitable rooftops for roof-mounted solar PV installations).

Additionally, models typically calculate either supply *or* demand outputs and it is appropriate to clarify exogenous inputs. Such detail should be included in this field of the classification.

4.1.3. Sectoral coverage

The inclusion of sectoral coverage is crucial for users to appreciate the main ingredients of the model. This field discerns between whole energy systems models and single sector (or multi-sector) models, for example.

Table 4
Classification of energy systems models – mathematical description.

Model	Name of model
11. The Analytical Approach	Top-Down Bottom-Up Hybrid Other
12. The Underlying Methodology	Econometric Macro-Economic Micro-Economic Economic Equilibrium Optimization Simulation Stochastic/Monte-Carlo Spatial (GIS) Spreadsheet/Toolbox Backcasting Multi-Criteria Accounting
13. The Mathematical Approach	Linear programming Mixed-integer programming Dynamic programming Fuzzy logic Agent based programming
14. Data Requirements	Qualitative Quantitative Monetary Aggregated Disaggregated

4.1.4. The time horizon and time step

Due to the different modelling techniques, no explicit definition of the time horizon exists within existing classification. It is possible to arbitrarily define a time frame to be:

Short term 5 years or less.
Medium term Between 5 and 15 years.
Long term Over 15 years.

The time horizon field should ideally detail the exact timeframe in consideration (for example, 2015–2050), if relevant. The time horizon may be user-defined, but typically a time frame is still associated with the model's focus (i.e. a long term model of about 100 years for which the user can choose the exact period).

The time step is sometimes hard-coded within models, but at other times it can be defined as a variable input by the user. This field should give detail accordingly.

4.2. Classification: Technological detail

The second part of the classification schema focusses on the technological detail contained within the model (Table 3). The detail shown in the table is meant only for indicative purposes and is purposefully not comprehensive. Some energy models use internal databases to model specific technologies (with given parameters and limited user interaction), whilst others are flexible to new inputs (users may even define modules to define new technologies). Therefore, this section of the schema is useful to define the type of technologies allowed by the models.

The technological detail is split into 5 sections: renewable technologies, storage technologies, demand characteristics, costs and supply/demand detail. The choice of these sections was made on the basis of prevalent usage in the literature (i.e. the top-cited sectors are transport and residential), as well as expected future research priorities (papers regularly cite renewable technologies

Table 5
Energy systems models categorised in this paper. This list forms the a random set of 22 energy systems models utilised in the UK at present.

Model	Full name	Citation(s)
DECC 2050 calculator	Policy tool from UK Government	[142]
DECC DDM	Dynamic Dispatch Model developed by UK Government	[143]
DSIM	Dynamic System Investment Model	[144]
DynEMo	Dynamic Energy Model	[145]
E3MG	Environment-Energy-Economy Model	[146]
EnergyPLAN	Advanced energy systems analysis computer model	[147]
ESME	Energy System Modelling Environment	[148]
LEAP	Long-range Energy Alternatives Planning System	[149]
MARKAL	MARKet Allocation model	[6,150,151]
MARKAL-MACRO	A hybrid version of the MARKAL program	[152]
MDM-E3	Multi-sectoral Dynamic Model	[153]
MESSAGE-III	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	[7,154]
NEMS	National Energy Modelling System	[155]
OSeMOSYS	Open Source Energy Modelling System	[107]
POLES	Prospective Outlook on Long-term Energy Systems	[156]
PRIMES	An EU-focused energy systems simulation model	[157]
RETscreen	Software suite for Renewable-energy and Energy-efficient Technologies	[158]
SAGE	System for the Analysis of Global Energy Markets	[151]
TIAM	TIMES Integrated Assessment Model	[159]
TIMES	The Integrated MARKAL-EFOM System	[160]
UKENVI	Energy-economy CGE model of the UK economy	[161,162]
WASP	Wien Automatic System Planner	[163]

and storage). The level of cost inclusion is important to define the econometric nature of the model.

It should also be noted that the level of granularity within this table reflects the high-interdependency between supply and demand within these sectors (particularly residential). It should be noted however that, whilst commercial and industrial sectors (including agriculture) are highly energy intensive, energy efficiency strategies are usually implemented as cost savings measures and therefore exhibit less interdependency. Further breakdown of the demand characteristic may be included as required.

For simple models, these sections could be combined in one detailed field. Adding more distinct fields is not recommended, since this could diminish the clarity of the schema.

4.3. Classification: mathematical approach

The third section of the classification schema defines the mathematical approach of the energy model. For some users, this information may be irrelevant (e.g. some policy makers, who do not need to understand the inner mathematical basis), however it could be crucial for other users wanting to understand the working mechanism of the model, since it depicts the complexity of the approach. It also differentiates between a focus on economics and/or technologies (via the *analytical approach*).

4.3.1. The analytical approach

In energy systems modelling, the analytical approach can be generalised into three main groups:

Top-down models Generally focus on behavioural realism with focus on macro-economic metrics. They use historically derived variables to analyse aggregate behaviours and are useful for studying economy-wide responses to policies and other drivers. Sometimes referred to the *pessimistic economic paradigm* [139].

Bottom-up models Focus on the system level and may incorporate a wider range of policy options. They are technologically explicit and are useful for studying specific technical opportunities and can include cost and emissions implications. Bottom-up models typically rely on significant historic data. Sometimes referred to the *optimistic engineering paradigm* [139].

Hybrid models Introduce moderate technological detail within a macro-economic approach. These can be either of two forms: (1) a coupling of existing bottom-up and top-down models (“soft-linked”) or (2) a single integrated model which blends features of both top-down and bottom-up models (“hard-linked”).

Notably, top-down models tend to be more pessimistic than bottom-up models about the costs of energy policies, but it can also be argued that bottom-up models are overly optimistic [139]. The gap between the baseline results of the two approaches is often attributed to the difference in input (exogenous) assumptions: bottom-up models focus on energy and technology issues, ignoring consumer preferences and potential hidden costs, whilst top-down models often over estimate the future cost of low-carbon technologies. Some models can be considered to belong in either (both) top-down or bottom-up categories, depending on their specific usage, whilst hybrid models aim to bridge the differences between the approaches. Comparisons between the difference in top-down and bottom-up approaches (with specific reference to climate change policies) are detailed by van Vuuren et al. [140]. Some of the major strengths and weaknesses of top-down and bottom-up approaches are highlighted in Scrieciu et al. [141].

As with some other of the classification categories, a model may not fit into any of these three groups, leading to a categorisation of “other”.

4.3.2. The underlying methodology

This section will focus on the common methodologies found in the literature. This list is by no means definitive; due to expanding computational ability, novel approaches are always being designed, which may impact on the state-of-the-art energy systems models.

Econometric Models Econometrics is defined as “applying statistical techniques in dealing with problems of an econometric nature” [127]. Therefore, econometric models use derived, statistical relationships from past behaviour in order to model future behaviour. Econometric models can either be derived from deterministic or stochastic economics models.

Table 6
List of prevalent UK energy systems models, their purposes, structure and coverage (as defined in categories 1–6 in Table 6).

Model (Developer)	Purposes	Model structure (assumptions)	Geographical coverage	Sectoral coverage	Time horizon	Time step
DECC 2050 Calculator (DECC)	**General:** Forecasting	Costs are treated as exogenous to the model, but some level of technological learning is used. Underlying data is input based on MARKAL outputs from various scenarios. Outputs are user driven, not market based.	UK single region	Energy Sector.	Medium, long term. 2010–2050	5-year
	Specific: Energy supply, based on meeting environmental emissions targets	**Supply**: Modelled **Demand**: N/A				
DECC DDM (DECC, developed by LCP)	**General:** Exploring	Investment decisions are based on projected revenue and cashflows. Economic, climate, policy, generation and demand assumptions are external inputs to the model. No stochastic modelling of uncertainty.	GB single region	Electricity sector	Medium, long term. 2010–2050	Yearly (Half-hourly basis for sample days)
	Specific: Energy demand, supply, matching demand and supply, environmental impacts.	**Supply**: Exogenous **Demand**: Modelled				
DSIM (Imperial College London)	**General:** Exploring	Considers the tradeoffs between long-term and short-term decisions.	Multi-regional	Electric power system	Short-term (hourly or one year)	Minutely
	Specific: Energy demand and supply, power systems model, specifically designed to model storage and variable generation	Generation operating cost is determined by fuel prices and carbon prices **Supply**: Modelled **Demand**: Exogenous				
DynEMo (UCL)	**General:** Exploring	Simplification of individual elements (such as technologies). Some system dynamic aspects are not captured due to temporal resolutions.	Single energy system – applied to the UK and France	Whole energy sector	Short, medium, long term. 4 seasons, peak days, weekend and weekday day	User-defined (from hourly to yearly)
	Specific: Energy demand, supply, with renewable energy integration. Integration with domestic sector, including household behaviours.	**Supply**: Exogenous **Demand**: Exogenous				
E3MG (Cambridge Econometrics)	**General:** Exploring	Each technology is represented by 21 characteristics.	Global (20 world regions)	E3 (energy-environment-economy) system	Up to 2100	Annually until 2030 and then every 10 years until 2100
	Specific: An econometric simulation model of the global energy-environment-economy system	Fuel prices are exogenous The transport sector is not detailed **Supply**: Adjusts to meet demand **Demand**: Calculated from econometrics				
EnergyPLAN (Aalborg University)	**General:** Exploring, forecasting	Explicit technological detail specifically related to new technologies	National, State, Regional	Electricity, heat, and transport sectors.	1 year, but combined can make a medium-term scenario	Hourly

(*continued on next page*)

Table 6 (*continued*)

Model (Developer)	Purposes	Model structure (assumptions)	Geographical coverage	Sectoral coverage	Time horizon	Time step
	Specific: Energy supply and demand, with focus on future options	**Supply**: Calculated **Demand**: Exogenous				
ESME (ETI)	**General:** Exploring	Models all the major flows of energy.	UK, split into 12 regions (Scotland, Wales, Northern Ireland, 9 English Regions)	Whole energy sector (incl. buildings, transport, industry)	Two scenarios: short-scale (yearly fluctuations) and long-term (50 years).	Time-slices according to subdivisions of a year: 2 seasons (summer, winter), 5 intraday (overnight, morning, mid-day, early evening, late evening)
	Specific: Demand, supply, environmental impacts	Exogenous assumptions on end use services. No implicit technological learning. **Supply**: Modelled **Demand**: Exogenous				
LEAP (Stockholm Environmental Institute Boston, USA)	**General:** Exploring, forecasting	**Supply**: simple description of end-uses and supply technologies, including some renewable.	Local, national, regional, global.	All sectors (incl. industry, transport, household, service and agriculture).	Medium, long term	Annual
	Specific: Demand, supply, environmental impacts. Integrated approach. the objective includes energy policy analysis, environmental policy analysis, biomass- and land-use assessment, pre-investment project analysis, integrated energy planning, full fuel cycle analysis. Applicable to industrialised as well as developing countries.	**Demand**: rather high degree of endogenisation and description of all sectors in economy				
MARKAL (International Energy Agency, IEA/ ETSAP)	**General:** Exploring	Low degree of endogenisation, focuses only on the energy sector, detailed description of end-uses and (renewable) energy technologies possible. Options are available to model the internalisation of certain external costs, endogenous technological learning and the representation of uncertainty.	Local, national.	Energy sector only	Medium, long term.	User-defined
	Specific: Energy supply with constraints. The objective includes target-oriented integrated energy analysis and planning through a least cost approach.	**Supply**: Modelled **Demand**: Exogenous				
MARKAL-MACRO (Brookhaven National Laboratory, USA)	**General:** Exploring	Neo-classical growth model with nested substitution (CES) between capital/ labour aggregate and energy. Energy is represented as the weighted sum of useful energy demands in the MARKAL sub-model. Maximisation relevant to national budget constraints.	Local, National	All sectors.	Medium, long term.	User-defined

	Specific: Demand, supply, environmental impacts. Integrated approach for economy-energy-environmental analysis and planning. The objective is to maximise utility (discounted sum of consumption) from a neo-classical macro-economic perspective.	**Supply**: Modelled **Demand**: Exogenous				
MDM-E3 (Cambridge Econometrics)	**General:** Forecasting **Specific:** A framework for generating forecasts and alternative scenarios, analysing changes in economic structure and assessing energy-environment-economy (E3) issues and other policies	The model disaggregates industries, commodities, and household and government expenditures, as well as foreign trade and investment. Assumption of global fossil fuel prices. Technologies are modelled (bottom-up) via the Energy Technology Model (ETM) **Supply**: Exogenous (via Electricity Technology Model) **Demand**: Modelled	9 former Government Office Regions, Wales, Scotland and Northern Ireland	E3 (energy-environment-economy) system	Up to 2030	Not known
MESSAGE-III (International Institute for Applied System Analysis, IIASA, Austria)	**General:** Exploring **Specific:** Energy demand and supply, environmental impacts. Modular package. the objective includes generation expansion planning, end-use analysis, environmental policy analysis, investment policy. **Supply**: Modelled **Demand**: Exogenous	Detailed description of energy end-uses and (renewable) energy technologies	Local, national.	Energy sector.	Short, medium, long term.	User-defined, but a multiple number of years
NEMS (US Energy Information Administration, EIA)	**General:** Exploring **Specific:** Model of the US energy-economy interaction Balances generation and consumption along with prices.	Demand-side is disaggregated into four sectors (industry, transport, residential and commercial) Most technologies included (except hydrogen technologies, wave and tidal) Two assumptions are economic growth and oil prices. **Supply**: 4 supply modules **Demand**: 4 end-use demand modules	National State Regional (22 regions of the US)	Energy system	Medium term (25 years)	Yearly
OSeMOSYS (Open source research community incl. UCL)	**General:** Exploring **Specific:** Modular package. Energy supply and demand with constraints. Technologically implicit and very easy to use.	Limited learning curve and time commitment to build and operate **Supply**: Modelled	Flexible	Energy sector	Medium, long term. 2010–2050. 3 seasons (summer, intermediate, winter), 2 intraday (day, night)	5-year

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Table 6 (*continued*)

Model (Developer)	Purposes	Model structure (assumptions)	Geographical coverage	Sectoral coverage	Time horizon	Time step
		Demand: Exogenous				
POLES (European Commission)	**General:** Forecasting	All energy prices are determined endogenously and the endogenous price forming mechanism cannot model the price volatility induced by short term market expectations and/or geopolitical instabilities.	Global (split into 47 regions)	15 energy demand sectors	Up to 2050	Yearly
	Specific: Detailed econometric, long-term global energy outlooks with demand, supply and price projections by main region, CO_2 emission MAC curves, and emission trading systems analyses, technology improvement scenarios, with exogenous or endogenous technological change	**Supply**: Simulated				
		Demand: Simulated				
PRIMES (National Technical University of Athens, NTUA)	**General:** Exploring	Tariffs and prices are endogenous, reflecting costs and market conditions	EU28 member-states and Western Balkans countries (Albania, Bosnia-Herzegovina, FYR of Macedonia and Serbia including UNMIK and Montenegro), Switzerland, Norway and Turkey.	All energy sectors	Medium to long-term	Yearly
	Specific: Provides detailed projections of energy demand, supply, prices and investment to the future	Closed-loop between demand and supply System-wide constraints influence all sectorial sub- models Self-supply of energy services is also priced Perceived costs and uncertainty factors are included and are related to policies				
		Supply: Simulated				
		Demand: Simulated				
RETscreen (CEDRL/ Natural Resources Canada)	**General:** Exploring	Detailed description of supply technologies for generation expansion.	Local, national.	Energy Sector.	Long-term (up to 50 years)	Monthly or Yearly
	Specific: Energy supply. Specially designed for renewable energy technologies.	**Supply**: N/A				
		Demand: N/A				
SAGE (ETSAP)	**General:** Exploring	Extensive technological detail. Difficult to add new technologies. The regional demand forecasts are made based on the demand trends, economic and demographic drivers, energy equipment stock and technological changes.	Global (15 regions) but regional or country specific study possible	Whole energy sector	Medium, Long term.	User-defined
	Specific: Energy system and energy trading	**Supply**: Modelled				
		Demand: Exogenous				

TIAM (ETSAP)	**General:** Exploring	Energy supply with constraints (unique to run). Planning through a least cost approach.	Global multi-region (15 regions)	E3 (energy-environment-economy) system	Medium to long-term	Flexible time-slices are segregated into: 3 seasons (summer, intermediate, winter), 2 intraday (day, night)
	Specific: Decarbonisation pathways, technology assessment, global policy TIAM is the global multi-regional incarnation of TIMES	**Supply**: Modelled				
		Demand: Exogenous				
TIMES (ETSAP)	**General:** Exploring	Energy supply with constraints (unique to run). Planning through a least cost approach.	Global, national, regional, local	Whole energy sector	Medium, Long term.	Commodities may have their own, user-chosen time-slices. These flexible time-slices are segregated into three groups: seasonal (or monthly), weekly (weekday vs weekend), and daily (day/night).
	Specific: Decarbonisation pathways, technology assessment, least-cost assessment	**Supply**: Modelled				
		Demand: Exogenous				
UKENVI (University of Glasgow, University of Strathclyde)	**General:** Forecasting	Key parameter values of UKENVI are not econometrically estimated. Real government expenditure is taken to be exogenous.	Regional, National	Energy (coal, oil, gas) and renewable and non-renewable electricity and Economy	Medium to long term	Annual
	Specific: Environmental assessment of macro-economic policy	**Supply**: Modelled				
		Demand: Exogenous				
WASP (International Atomic Energy Agency, IAEA)	**General:** Forecasting	Power system analysis with constraints. Finds the economically optimal generation expansion policy for an electric utility system, utilising probabilistic estimates. Constraints can be places on carbon emissions.	National	Power Sector	Medium to long-term (up to 30 years)	12 load duration curves for a year
	Specific: Pathways analysis, comprehensive planning tool for electric power system expansion analysis	**Supply**: Modelled	State			
		Demand: Exogenous	Regional			

Table 7
Technological detail of energy models (categories 7–11 from Table 3).

Model (Developer)	Renewable technology inclusion	Storage technology inclusion	Transport inclusion	Residential inclusion	Cost inclusion
DECC 2050	**Calculator**	Wind (Onshore & Offshore)	Storage, demand shifting & interconnection	Domestic transport behaviour	Average temperature of homes
Cost data	generated from MARKAL (as implicit scenario input)				
		Wave		Shift to zero emission transport	Home insulation
		Tidal Stream		Choice of fuel cells or batteries	Home heating electrification
		Tidal Range		Domestic freight	Home heating (non-electric)
		Biomass	International aviation	Home lighting & appliances	
	SolarPV		International shipping	Electrification of home cooking	
	Solar thermal Geothermal Hydroelectric				
DECC DDM	Solar PV	Pumped storage	Not included	Residential demand data (from Electricity Demand Model, EDM)	Capital and operational costs
	Wind (Onshore & Offshore) (3 levels of wind load factor data)				Commodity prices
	Biomass				Requires input assumptions of the costs of all generation types Plant costs (Does not consider network costs)
DSIM	Wind Solar Hydro Geothermal	Electricity storage Heat storage Pumped hydro	Not included	Not included	System operating cost Generation operating costs
DynEMo	Wind Solar Tidal flow Wave	Storage and fuel switching: Electric vehicles Synthetic liquids Distric heat Pumped storage	Cars Rail Aviation	Occupancy Temperature Hot water Appliances Dwelling Solar hot water Heater Gas boiler Heat pump Heat store Heat fuel mix	Final costs analysed – not details known
E3MG	Solar PV Marine Bio-waste Wind Hydro	Storage and CCS included (no details known)	No detailed representation, but accounts for petrol, diesel or electricity options	Not included	Fuel prices Carbon pricing
EnergyPLAN	Wind (Onshore & Offshore) Solar PV Wave Power River Hydro	Electricity storage unit (hydro or battery). Electrolysers	Fuel inputs for cars and other transport units Hydrogen vehicles Battery Electric Vehicles	Heat supply and distributed generation from individual buildings (e.g. boiler)	Fuel costs (purchasing, handling, taxes, CO2 costs) Investment costs (capital, the lifetime of each unit, interest rates) Operation costs (variable and fixed O&M costs)

ESME	Solar Tidal Hydro Wave Wind Recoverable heat Geothermal Biomass	CCS Pumped hydro (Storage can be either diurnal or seasonal)	Not included	Not included	Cost is defined as the annualised investment, operations and maintenance costs for the technologies deployed, plus aggregate fuel costs and energy import costs. It includes capital cost, fixed costs & variable costs (Taxes, subsidies and other policies which affect the price of technologies or fuels are absent)
LEAP	All technologies	All technologies	Road Rail Air Water	Lighting Cooking Heating Appliances Building shell (split into rural and urban)	All energy related costs
MARKAL	Hydro Solar Wind Biomass Geothermal	Only night-day storage. Storage Plants Pumped storage Some individual demand devices can be operated as night storage devices	Cars Buses Light trucks Commercial trucks Medium trucks Heavy trucks Two wheelers Three wheelers International aviation Domestic aviation Freight rail transportation Passengers rail transportation Internal navigation International navigation (bunkers) Non-energy uses in transport	Space Heating Space cooling Hot water heating Lighting Cooking Refrigerators and freezers Cloth washers Cloth dryers Dish washers Miscellaneous electric energy Other energy uses	Each year, the total cost includes the following elements: (1) Annualized investments in technologies; (2) Fixed and variable annual Operation and Maintenance (O&M) costs of technologies; (3) Cost of exogenous energy and material imports and domestic resource production (e.g., mining); (4) Revenue from exogenous energy and material exports; (5) Fuel and material delivery costs; (6) Welfare loss resulting from reduced end-use demands. (7) Taxes and subsidies associated with energy sources, technologies, and emissions.
MARKAL-MACRO	As MARKAL	As MARKAL	As MARKAL	As MARKAL	As MARKAL
MDM-E3	Nuclear electricity Hydro electricity Biomass Wind Solar PV Solar thermal Marine Geothermal	Storage integrated (no details known)	Not included	Not included	Macroeconomic modelling of: GDP, household expenditures, fixed investment, exports, imports Fuel prices The wholesale prices of fossil fuels such as coal, oil and gas are assumptions
MESSAGE-III	User-defined. Technologies are defined by their inputs and outputs, their efficiency and their variability if more than one input or output exists	Storage and conversin technologies can be simulated in MESSAGE as well as carbon sequestration	Not included	Not included	Economic characteristics include investment costs, fixed and variable operation and maintenance costs, imported and domestic fuel costs and estimates of levelised costs and shadow prices. User defined constraints on new investment rates

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Table 7 (*continued*)

Model (Developer)	Renewable technology inclusion	Storage technology inclusion	Transport inclusion	Residential inclusion	Cost inclusion
NEMS	Wind (Onshore & Offshore) Geothermal Solar thermal Solar PV Biomass Hydro	Not known	6 car sizes 6 light truck sizes 63 conventional fuel-saving technologies for light-duly vehicles Gasoline, diesel and 14 alternative-fuel vehicle technologies for light-duty vehicles 20 vintages for light-duty vehicles Regional, narrow and wide-body aircraft 6 advanced aircraft technologies Light, medium and heavy freight trucks 37 advanced freight truck technologies	24 end-use services 3 housing types 50 end-use technologies	Electricity sales Fuel prices Cogeneration supply and fuel consumption Renewable technology costs GDP Interest rates
OSeMOSYS	Flexible due to modular design (Any combination of input fuels to produce any combination of output fuels)	Flexible due to modular design (Any combination of input fuels to produce any combination of output fuels)	Flexible due to modular design (Any combination of input fuels to produce any combination of output fuels)	Flexible due to modular design (Any combination of input fuels to produce any combination of output fuels)	Costs incurred by each technology, incorporates daily operation of power plants
POLES	Combined Heat and Power Biomass Solar PV Solar Thermal Small Hydro Wind (Onshore & Offshore) Biofuels for transport Fuel Cell Vehicle (PEM) Stationary Fuel Cell (Gas, Hydrogen)	CCS	Road (passenger and goods) Rail (passenger and goods) Air transport	Fuel and electricity costs Renewable technology vehicles	Detailed assessment of the costs associated with the development of low- or zero-carbon technologies
PRIMES	Thermal solar Geothermal Biomass and waste (5 bio-energy types and several feedstock types) Solar PV Solar thermal Wind (Onshore & Offshore) Hydro (lakes, run of river) Tidal Wave energy	Several electricity storage technologies including hydro with reservoir, hydro pumping, compressed air storage and hydrogen-based storage	Passenger and goods transport (including subdivisions)	5 categories of dwelling 5 typical energy uses Electric appliances are considered as a special sub-sector	Explicit cost analysis,. Including capital costs, variable costs, O&M, etc. Inclusion of taxes, subsidies, certificate prices, congestion fees, tariffs for use of infrastructure
RETScreen	Comprehensive technology (and product) database	Only battery energy storage (not hydrogen)	Not included	Not included	User enters the initial, annual, and periodic costs for the proposed case system. Alternatively, user enters incremental costs.
SAGE	As MARKAL	Only night-day storage. Storage Plants Pumped storage Some individual demand devices can be operated as night storage devices	As MARKAL	As MARKAL	As MARKAL

TIAM	As MARKAL	CO2 capture and underground storage, biological carbon sequestration	As MARKAL	As MARKAL	As MARKAL
TIMES	As MARKAL	Flexible. Storage processes “consume” commodities at one time-slice and release them at another	As MARKAL	As MARKAL	As MARKAL
UKENVI	Hydro	Not included	Included – no information known	Not included (but includes household income)	Costs of production included
	Wind				Capital and investment calculation
WASP	Wind Wave Tidal Hydro Biomass	Pumped hydro	Not included	Not included	Capital investment costs Fuel costs O&M Fuel inventory costs Salvage value of investments Cost of energy demand not served

Macro-economic models Macro-economic models focus on the entire economy, taking energy into account only as a sub-part. Specific technical information is not included and the models often require a high level of expertise to use them.

Economic Equilibrium Models Economic Equilibrium methodologies focus on very long-term growth paths and are used to study the complete economic system. The energy sector is included within this wider system. Focus is placed on the interrelation between economic sectors. These models are sometimes called **resource allocation models**. Models can be classified into either *general equilibrium* (simultaneous equilibrium in all sectors) or *partial equilibrium* (equilibrium only in parts of the market).

Optimisation Models Mathematical optimisation can be used to find a preferred mix of technologies, given certain constraints and can be used in both top-down and bottom-up approaches. An objective function to be minimised is defined and this function can involve cost, fuel usage, emissions or even return on investment (to be maximised). As a powerful technique to identify a (theoretically) least-cost solution, it assumes that real-world decisions are made only on the basis of low cost, which is sometimes not favourable. This method is typically data intense and complex.

Simulation Models These models simulate the behaviour of energy producers and consumers in response to prices, income, and other signals. The models describe a logical representation of a system and attempt to reproduce its operation. They can simulate the uptake of technologies better than optimisation models, but simulations often be complex and opaque, due to the requirement of assumptions about behavioural factors. Due to the lack of a full equilibrium solution, models can lead to apparent “negative” costs.

Backcasting Models This methodology identifies desirable future outcomes and uses expert knowledge to define the path (and policies) that will lead to this aspiration.

Multi-criteria Models The practice of multi-criteria decision analysis (MCDA) is concerned with the evaluation of a set of possible courses of action or alternatives. Multi-criteria models include a wide set of measures, only some of which are economic. This approach is not widely used in energy systems modelling.

Accounting Models These models include descriptions of key performance characteristics of an energy system, which allows users to explore the implications of resource, environment and social cost decisions. Accounting models are often simple and transparent, with no prior assumptions about market behaviour or optimal choices.

4.3.3. Mathematical approach

The mathematical approach defines the underlying programming approach taken in the model. The most common approaches are linear, mixed-integer and dynamic programming. However, newer models are being developed with state-of-the-art development approaches, including fuzzy logic and agent based programming, to name just two of many. It is possible that a single model will incorporate several approaches, in order to achieve the best output.

4.3.4. Data requirements

All energy systems models require some input of data. This field attempts to specify the level of data that is necessary to each model and the aggregation (or lack of) of such data. In specific cases, this field could be used to define the exact data required (specific data sets) and whether the data is internal (already implicit in the code) or external (to be provided by the user). However, for the usage in

Table 8
Mathematical detail of energy models (categories 12–15 from Table 4).

Model (Developer)	Analytical approach	Underlying methodology	Mathematical approach	Data Reqs
DECC 2050 Calculator	Bottom-up	Accounting model, Spreadsheet	Output from MARKAL (linear programming)	Quantitative, monetary, disaggregated.
DECC Dynamic Dispatch Model	Bottom-up	Optimisation	Not available.	Quantitative, monetary, disaggregated.
DSIM	Bottom-up	Cost Optimisation	Linear Programming	Quantitative, disaggregated
DynEMo	Bottom-up	Simulation, Spreadsheet	Dynamic programming	Quantitative, monetary, disaggregated
E3MG	Hybrid	Non-equilibrium	Not known	Quantitative, monetary, disaggregated
EnergyPLAN	Bottom-up	Simulation, Operation optimisation, investment optimisation	Analytical programming	Quantitative, monetary, aggregated
ESME	Bottom-up	Cost Optimisation, Monte-Carlo	Linear Programming	Quantitative, monetary, disaggregated
LEAP	Hybrid	Accounting model	Not available	Quantitative, monetary, aggregated, disaggregated. (Low data requirements due to lack of optimisation)
	(Demand: top-down, supply: bottom-up)	Demand: econometric or macro-economic. Supply: simulation		
MARKAL-MACRO	Hybrid (MACRO part is top-down, MARKAL part is bottom-up)	Macro-economic for MACRO and partial equilibrium through optimisation for matching demand and supply in MARKAL.	Dynamic programming (non-linear)	Qualitative, monetary, aggregated, disaggregated.
MARKAL	Bottom-up.	Toolbox/Optimisation	Linear programming, dynamic programming.	Quantitative, monetary, disaggregated.
MDM-E3	Hybrid (macroeconomic top-down and industrial bottom-up)	Simulation	Not known	Quantitative, monetary, disaggregated
MESSAGE-III	Bottom-up	Optimisation.	Dynamic programming	Quantitative, monetary, disaggregated.
NEMS	Hybrid	Agent based Accounting Optimisation for the electricity sector Simulation for each demand sector	Coupled partial equilibrium and linear programming	Quantitative, monetary, disaggregated
OSeMOSYS	Bottom-up	Optimisation (uses LEAP interface)	Linear Programming, Can be mixed-integer programming	Quantitative, monetary, disaggregated
PRIMES	Hybrid	Agent based	Equilibrium model	Quantitative, monetary, disaggregated
POLES	Hybrid	Cost minimisation, Simulation	Recursive dynamic, Partial Equilibrium framework	Quantitative, monetary, disaggregated.
RETscreen	Bottom-up	Spreadsheet/Toolbox, Statistical.	N/A	Quantitative, monetary, disaggregated.
SAGE	Bottom-up	Optimisation	Linear Programming, Dynamic programming	Quantitative, monetary, disaggregated
TIAM	Bottom-up	Cost Optimisation	Linear Programming, Dynamic programming	Quantitative, monetary, disaggregated
TIMES	Bottom-up	Cost Optimisation, Toolbox	Linear Programming, Dynamic programming	Quantitative, monetary, disaggregated
UKENVI	Top-down	Computable General Equilibrium model, Macro-economic	Not available	Quantitative, monetary, aggregated and disaggregated
WASP	Bottom-up	Optimisation Simulation	Linear programming, Dynamic programming	Quantitative, monetary, disaggregated

this paper, this field is not intended to be very implicit regarding data requirements (see Section 4.4 below).

4.4. Other classification fields

In order to define a concise classification schema, it is not possible to include all relevant detail about energy models. Decisions have to be made as to whether to include information or not, based on the level of "added value". In the previous section, we have chosen fields that account for the majority of essential information. In doing so, we have knowingly omitted other pertinent information, that may be just as relevant for other stakeholders. We provide two reasons in way of justification for this decision: (a) additional fields may not be relevant for newly developed models, which have not gained significant entry into the field and (b) the overall schema must be concise if it is to prove useful. The latter justification is necessarily vague: a truncation of fields is always arbitrary, but a protracted schema with too many fields can be confusing and unusable.

Examples of inclusion of additional information incldue Connolly et al. who comment on the availability of models and their downloads [138] and Bhattacharyya et al. who quote the user skill level requirement and level of documentation [137]. The following fields were considered in designing this schema, but have purposefully not been included, though they may be of benefit to policy makers:

- Availability of the model (e.g. open-source, free or by license).
- Number of users (indicating the usage of the model).
- Price of the model.
- Learning time (may indicate complexity and level of skills required).
- Other technological detail, including other relevant energy sectors.
- Requirement of an internal/external database of information.
- Treatment of uncertainty/risks.
- Level of available documentation.

5. Example: the UK landscape of energy systems models

In order to illustrate use of the classification schema proposed above, we have reviewed a subset of energy systems models, chosen randomly from the wide range of models listed in Table 1. The aim of this section is to provide a working comparison of models within the defined schema of this paper; the aim is not to include all models utilised in the UK (by academics, industry or policy makers).

For this paper, 22 different models have been chosen from across the model landscape. Detail on these models is given in Table 5. Each model is classified according to the schema presented in Section 4. The information is split into three separate tables, corresponding to the three classification sections: (a) model purpose, (b) technological detail and (c) mathematical detail. These are shown in Tables 6–8.

6. Conclusions

We have reviewed both academic literature and policy papers in the UK since 2008 covering the topic of energy systems modelling. A review of modelling is undertaken and the predominant features of existing models are evaluated. The main findings are:

- Nearly 100 models are referenced within academic literature.
- Within policy documents, only 14 models were directly mentioned.
- The most predominant model is MARKAL and its variants.
- The full range of available models is not readily utilised in academic research nor policy papers.
- Side-by-side comparison of models is impeded by lack of clarity in model characteristics.

Since we show that only a select few models are routinely used for energy systems modelling, we recommend the introduction of a classification schema for use within both academia and policy, which would provide a decision support tool for energy systems modelling. The proposed schema contains pertinent information regarding all types of models and is purposefully designed to be inclusive, whilst also remaining concise. The aim of the schema is to promote the full availability of models and their specific applicability.

We propose a classification schema and test it on a subsection of the existing UK energy model landscape, leading to a comparison of 22 models.

In conclusion, we strongly recommend the future use of a classification schema as a decision support tool, in order to extend the current modelling capability in the UK and potentially globally.

Acknowledgements

The authors wish to thank Sheer Khan, Mohamed Pourkashanian, Grant Wilson, Matt Billson, Jose Mawyin and Huw Birch for useful and interesting conversations during the progress of this research. This work has been financially supported by EPSRC – United Kingdom Grant EP/I032541/1 ("Photovoltaics for Future Societies").

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