UK TIMES Model Overview

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1 INTRODUCTION

UKTM (the UK TIMES Model) portrays the UK energy system, from fuel extraction and trading, to fuel processing and transport, electricity generation and all final energy demands. The model generates scenarios for the evolution of the energy system based on different assumptions around the evolution of demands, future technology costs, measuring energy system costs and all greenhouse gases (GHGs) associated with the scenario. UKTM is built using the TIMES model generator: As a partial equilibrium energy system and technologically detailed model, is well suited to investigate the economic, social, and technological trade-offs between long-term divergent energy scenarios.

Following the full open-source launch in January 2015, UKTM will be the central long-term energy system pathway model used for policy analysis at the Department of Energy and Climate Change (DECC) and the Committee on Climate Change (CCC), including the 5th Carbon Budget Report. In research, UKTM will be used for a variety of cutting-edge research topics including behavioural modelling, the representation of technology learning and diffusion, increasing the spatial and temporal detail in energy systems modelling, linking UKTM with macroeconomic modelling frameworks as well as exploring the land-energy-water nexus.

This document gives an overview on UKTM and is structured as follows. The next chapter describe the process of UKTM's development, including the evolution from UK MARKAL. The methodology of the underlying TIMES model generator and the software used for UKTM are outlined in Chapter 3. This is followed by an overview of the model structure as well as key assumptions and data. Finally, Chapter 5 presents the use of UKTM for policy and the various research areas at the UCL Energy Institute.

2 UKTM HERITAGE AND DEVELOPMENT

2.1 THE PURPOSE OF UKTM

UKTM is used to identify the energy system that meets energy service demands with the lowest discounted capital, operating and resource cost, subject to constraints such as greenhouse gas emission targets and government policies. It allows us to draw insights about the relative importance of different technologies, costs and policies in divergent long-term energy system scenarios, including the use of different fuels to satisfy energy demands across the economy. It is built using the widely-used TIMES model generator developed by IEA-ETSAP (Loulou et al., 2005) and can be characterised as a partial equilibrium, bottom-up, dynamic, linear programming optimisation model.

As the successor to UK MARKAL, UKTM has a very strong lineage. UK MARKAL and its variants have underpinned a wide range of UK policy analyses (Strachan et al., 2009) including the Energy White Papers (EWP) in 2003 and 2007, the Climate Change Bill 2008, and the CCC and DECC fourth carbon budget reports (Figure 1). UKTM offers the same types of output for policy analyses as UK MARKAL but with many improvements and new features.

Studies using UK MARKAL have also underpinned many research collaborations and academic publications since 2006.

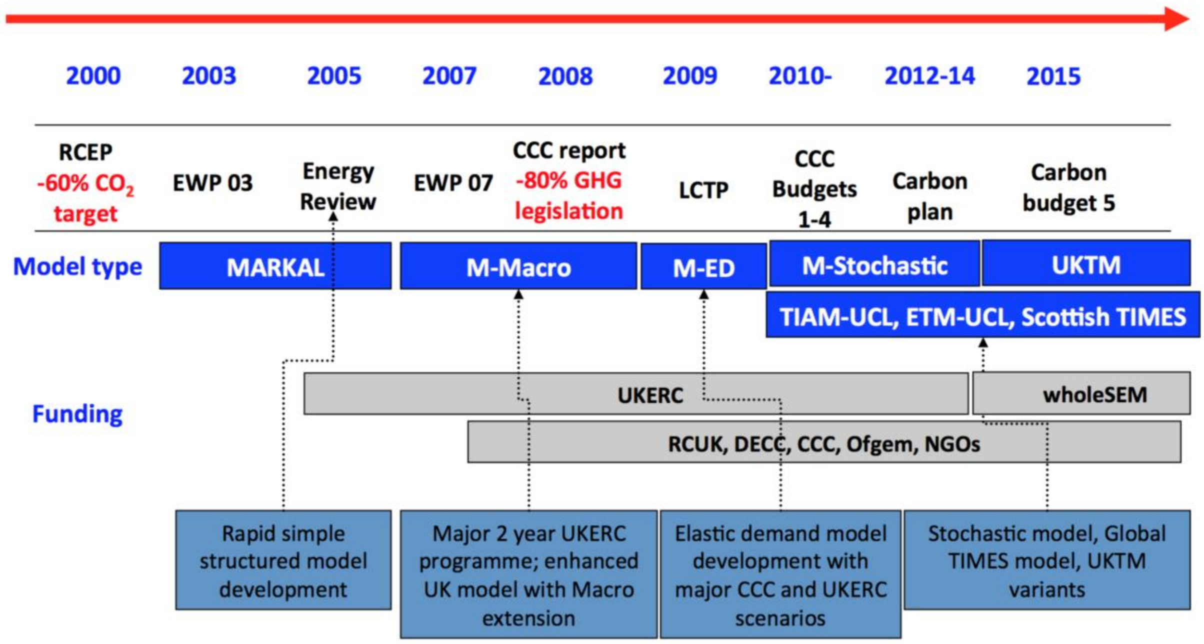


Figure 1. Influence of UK MARKAL on UK government policy. EWP = energy white paper; CAT Strategy = Carbon Abatement Technologies Strategy; CC Bill = Climate Change Bill; CCC = Committee on Climate Change; LCTP = Low Carbon Transition Plan.

2.2 The development of UKTM

UK MARKAL was originally developed to provide insights for the Energy White Paper 2003. It was adopted and completely revised by the UCL Energy Systems team[1] in 2005 and has been developed continuously since then. The development of the model was originally funded by the UK government but the UK Energy Research Centre[2] has more recently been the principal source of support. A detailed account of the development of UK MARKAL is available in

Reasons for developing a new model to replace UK MARKAL broadly fall into two categories: Firstly, TIMES is now a preferred as a model generator, being more flexible and internationally developed. A second motivation was to take the opportunity of moving model platforms to undergo a comprehensive review and revision of UK MARKAL's design, underlying data and assumptions.

3 The TIMES energy systems model generator

3.1 TIMES methodology

TIMES (The Integrated MARKAL-EFOM System) is a model generator for local, national or multi-regional energy systems (Loulou et al., 2004). It was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the

[1] http://www.bartlett.ucl.ac.uk/energy/research/themes/energy-systems
[2] http://www.ukerc.ac.uk/support/Energy+Systems

International Energy Agency (IEA)[3]. The TIMES/MARKAL family of modelling tools are being used by approximately 177 institutions in 69 countries.

TIMES itself is not a model, but a modelling tool that generates an energy system model for a given scale or number of regions depending on the inputs of the user. UKTM is one of three TIMES generated models developed by the UCL Energy Institute Energy Systems team: TIAM-UCL (TIMES Integrated Assessment Model UCL) is a global model with a climate damage function (Anandarajah et al., 2011), and ETM-UCL (European TIMES Model UCL) is a multi-regional model of Europe's energy system[4].

TIMES is generally used to generate vertically integrated models of whole energy systems, regional, national or global, but can also be used to study elements of an energy system in isolation. For the region being modelled, the user provides projections of baseline energy service demands (lighting, heating, car travel etc.) as well as a description of the existing stock of energy technologies (efficiencies, retirement profiles, inputs and output fuels, operational costs), the characteristics of future technologies available, and a projection of future energy supply and trade. TIMES uses a linear optimisation objective function to chose the level of investment and operation of energy system technologies and fuel supply/trade in order to minimise total system cost (or maximise the total discounted producer and consumer surplus) subject to technical, environmental and economic constraints.

The participants of this system are assumed to have perfect foresight, in that decisions are made with the full inter-temporal knowledge of future policy, technological and economic developments. Hence, under a range of input assumptions, which are key to the model outputs, TIMES delivers an economy-wide solution of cost-optimal energy market development.

Beyond the basic TIMES model there are extensions available to the user. These include the following:

- Lumpy investments
- Stochastic programming and tradeoff analysis
- Endogenous technological learning (MIP formulation)
- Linkage with a one-sectoral macroeconomic model (TIMES-Macro)
- Climate module
- Damage functions
- Price elastic supply curves

3.2 MODEL BUILDING: DATA INPUT, MODEL GENERATION & SOLVING, OUTPUT HANDELING

ETSAP developers have developed a package of tools along with TIMES to deal with model generation, from data input, model generation and solving, to handling model outputs. Figure 2 describes this package of tools. UKTM uses the TIMES model generator and the VEDA system for these purposes. VEDA-FE (front end) and VEDA-BE (back end) are data handling systems, which

[4] http://www.ucl.ac.uk/energy-models/models/etm-ucl

are typically the only software programmes that a user needs to interact with to build and run a TIMES model (Gargiulo, 2009).

VEDA-FE takes all inputs to the model in the form of a variety of Excel files with flexible structures. The user can specify all inputs and assumptions of the model, and generate scenarios within VEDA-FE. It then generates a model and uses the GAMS environment to produce a model solution, which is passed to VEDA-BE in the form of text output. VEDA-BE produces user-defined tables and graphs for the interpretation of results for the user. The VEDA system is described by KANORS (http://support.kanors-emr.org/).

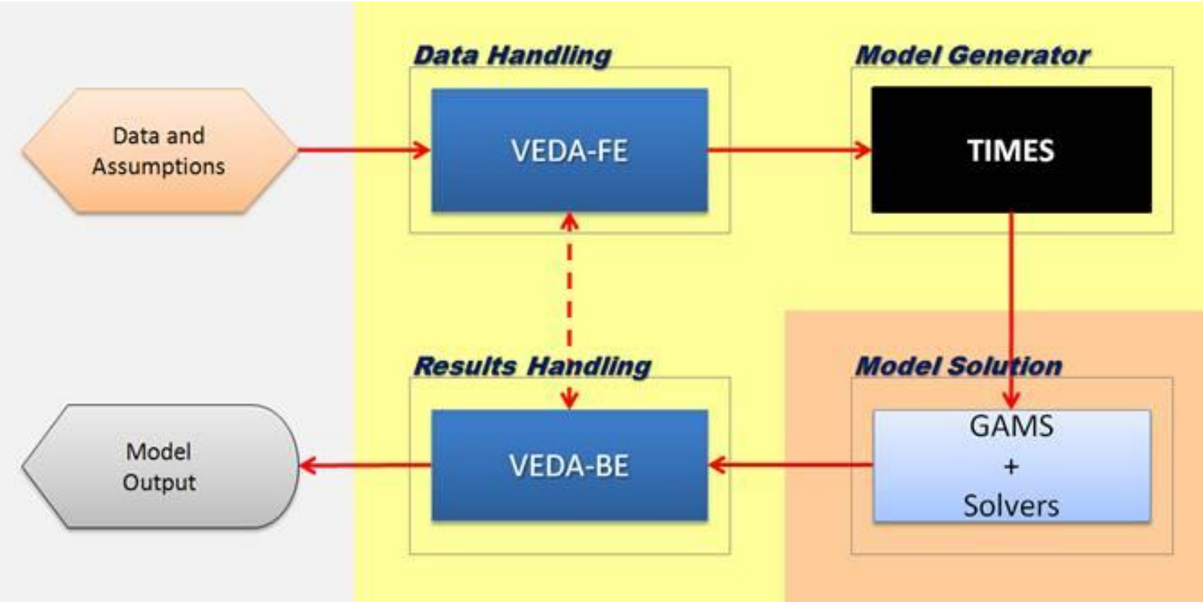


Figure 2: Overview of the system for building, running and interpreting results of TIMES models using VEDA-FE and VEDA-BE.

4 UKTM Overview

4.1 Model structure

The UKTM Reference Energy System (RES) is a network description of energy flows with a description of all technologies that are involved (or potentially involved) in the production, transformation and use of various energy forms. To satisfy energy demand services required by economic activities, demand devices/technologies that transform energy carriers into useful demands are used. Storable energy carriers, like gasoline, diesel fuels are produced by processes technologies while non-storable energy forms like electricity and heat are generated by conversion technologies. The process and conversion technologies use primary energy forms obtained from energy resources technologies. Figure 2 shows a highly simplified RES of the UK energy system for illustration.

UKTM has eight sectors, divided into three supply side and five demand sectors:

- Supply sectors:
    - *Resources and trade (RSR):* Contains domestic resources, extraction infrastructure, fuel trading and system-wide emissions accounting.

- Processing and infrastructure (PRC): Refineries, hydrogen production, biofuel production, energy infrastructure.
- Electricity (ELC): Electricity generation and transmissions and distribution grids.

- Demand sectors, which include distributed generation:
  - Residential (RES)
  - Services (SER)
  - Industry (IND)
  - Transport (TRA)
  - Agriculture (AGR)

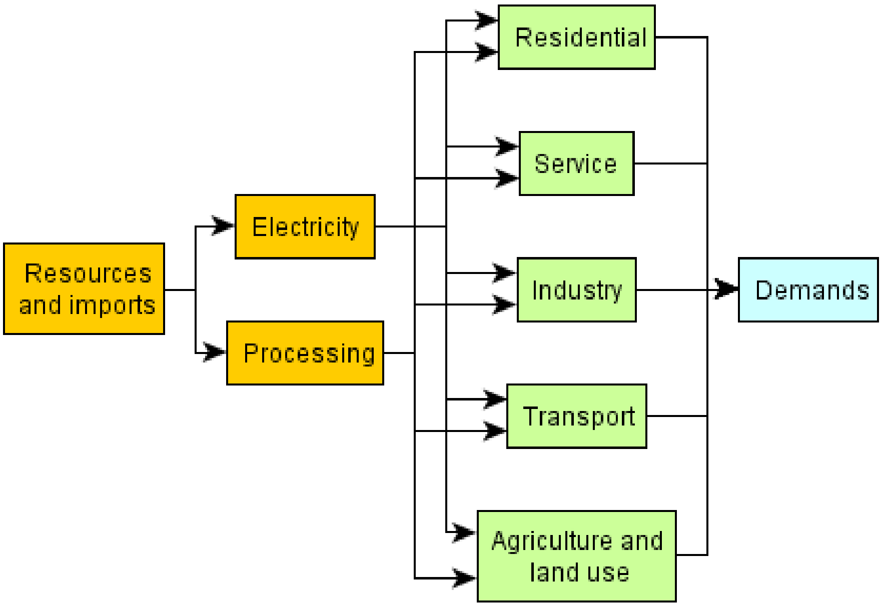


Figure 3: Simplified RES of the UK energy system

While the vast majority of the energy flows through the system from left to right across the RES in Figure 3, there are two-way links between each of the three supply side sectors. For example, LFO and electricity is used in oil extraction.

The five end-use demand sectors are based on the division in the Digest of UK Energy Statistics (DUKES) (2010). Each of the end-use sectors is modelled separately but consistently: Energy carriers from the supply sectors enter each end-use sector through *sectoral distribution technologies*, which are responsible for accounting sectoral fuel consumption, calibrating the 2010 fuel flow and sector-specific emissions accounting. These technologies can also be used for applying a transport cost for delivering fuels to sectors. Thereafter, fuels enter sector-specific infrastructure, for example transport refuelling infrastructure and electricity distribution and metering for the residential sector. Fuels are then consumed by end-use technologies, which deliver energy service demands (ESD). Figure 4 describes this process in a simplified way.

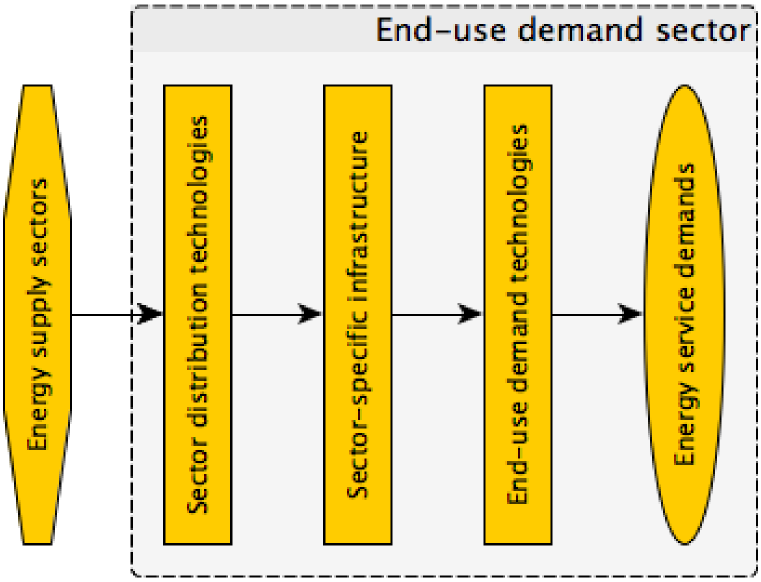


Figure 4: Generic, simplified RES for end-use demand sectors.

Each sector is described in the model in two input files to VEDA: A base-year (BY) template file, which describes the Reference Energy system (RES), all technologies (including retirement profiles), fuel flows and emissions in 2010, and a SubRES file, which describes all future possible technologies available to the model. Data in these Excel files are organised into flexible data tables which are inputted to VEDA and converted into a database for TIMES to generate a model.

The data in BY and SubRES files largely link to backing spreadsheets for each sector, which contain the source data or derivations of inputs. In this way, the source or assumptions behind most of the input data can be traced. Along with BY and SubRES files, the input files also consist of files describing user constraints, the global parameters used and energy service demands. Figure 5 describes the collection of model input and supporting files.

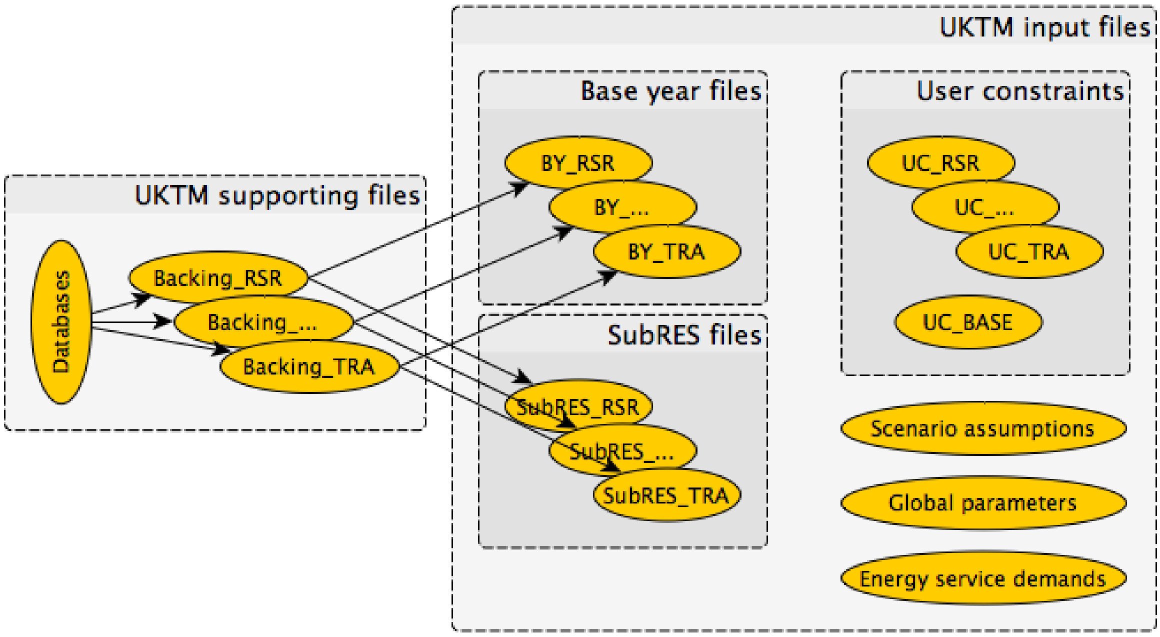


Figure 5: Outline of file structure of UKTM and backing spreadsheets.

4.2 KEY ASSUMPTIONS AND DATA

UKTM has flexible time periods, and can be run for any time horizon up to 2100. In the basic model run there are two single-year time periods representing 2011 and 2012, are used for calibration, and then a single three year period, and thereafter five year periods for 2015, 2020 etc.

UKTM contains four seasons and each season is represented using a typical day with four time-slices, meaning 16 time-slices are used in total. The seasons have equal length and were implemented to enable the representation of inter-seasonal storage processes. The intra-day time-slices broadly represent peaks and troughs of electricity *demand*. The 16 time-slices are summarised in Table 1. UKTM represents electricity and heat using day/night time-slices, natural gas and hydrogen using seasonal time-slices and everything else on an annual basis.

Season	Intra-day period	Time represented	Notes
Winter (W) Spring (P) Summer (S) Autumn (A)	Night (N)	00:00–07:00	Lowest demand
	Day (D)	07:00–17:00	Includes morning peak
	Evening peak (P)	17:00–20:00	Peak demand
	Late evening (E)	20:00–00:00	Intermediate

Table 1. Time-slices in UKTM.

Global parameters describe aspects of energy-economy wide input parameters such as system-wide discount rate, seasonal and diurnal fraction of time. A key financial global parameter is the model discount rate, which is set to 3.5% as recommended in the HM Treasury Green Book (HM Treasury, 2011).

Energy system models often suffer from user constraint creep over time with additional constraints added for particular studies or other reasons, which are reasonable at the time but eventually lead to an inconsistent set of constraints as a whole (Dodds et al., in review). For

UKTM, all of the user constraints are documented here with reasoning in order to avoid this situation in the future.

While constraints are sometimes defined on particular technologies to avoid unexpected model results, they should ideally restrict underlying behaviour and let the model freely choose compatible technologies. For example, in the residential sector, consumer preferences for water heating systems can be represented by setting a lower limit on the number of houses with such systems rather than by limiting the use of electric heating technologies directly. This is the approach used in UKTM where possible.

In UKTM, user constraints that are required for basic model operation, for example by making the fuel cell and boiler parts of micro-CHP technologies work properly together, are stored in UC_BASE. Other constraints that represent real-world phenomena which are not strictly physical limitations on the energy system are stored in separate UC_*** scenarios for each sector.

4.3 Calibration

UKTM energy flows in 2010 are calibrated to UK energy data from the Digest of UK Energy Statistics (DECC, 2011). DUKES presents fuel consumption in energy terms for broad groups of fuels (e.g. aggregated petroleum products) but most sectoral fuel consumption balances are presented in mass terms. It was therefore necessary to convert these masses to energy terms where necessary and it was not always possible to identify the original conversion factors. Moreover, some data appeared inconsistent between tables and the causes of these discrepancies could not be identified through consultation with the DUKES team at DECC.

It was necessary to revise the CHP statistics to be consistent with the bottom-up representation of technologies in UKTM. In DUKES, fuel use for CHP is split into fuel assumed to produce electricity, which is counted under electricity, and fuel assumed to produce heat, which is counted either as heat sold where appropriate or as part of the general final sector fuel consumption where that the CHP plant serves. Using the separate DUKES CHP statistics, the fuel use for CHP and district heating was estimated for each sector and removed from the electricity, heat sold and end-use sectors. All CHP plants are now modelled in the end-use sectors to which they provide heat rather than the electricity sector. However, they still produce grid electricity so that the electricity peaking equation[5] is calculated correctly.

4.4 Emissions accounting

UKTM tracks CO_2, CH_4, N_2O and HFCs both across the whole energy system and in each sector. This double counting acts as a check that the model is calibrated and running correctly. The global tracker for energy-related emissions accounts for the emissions embedded in all fuels entering and leaving the system boundary, during resource mining, fuel trading and CO_2 sequestration. Emission coefficients for fuels are embedded at resource level. To account for the exported resources and value added fuel (e.g. diesel, gasoline), relevant negative emission coefficients are included in this module. Global emissions from non-energy processes cannot be accounted for in the same way so are instead summed at each relevant process.

[5] The electricity peaking equation ensures there is sufficient generation capacity to meet peak demands so should include all electricity generation in the system.

Sectoral emissions accounting occurs when fuel is first combusted in a sector, for energy process emissions, and at the point of production for non-energy emissions. This approach is applied consistently for all four types of emissions.

5 POLICY ANALYSIS AND RESEARCH AREAS WITH UKTM

5.1 POLICY ENGAGEMENT

The representation of policies in UKTM is very flexible and is an integral part of the definition of each scenario. The detailed technological nature of UKTM allows the simulation of a wide variety of both micro measures, such as targeted subsidies to groups of technologies, and broader policy targets, such as limiting GHG emissions, across the energy system or in specific sectors, implementing a broad carbon tax or a permit trading system for emissions. TIMES models have been used to model the complex interactions of different sets of policy instruments, for example the case of feed in tariffs (Götz et al., 2011). Other examples could include requirements around import dependency based on energy security priorities or limiting coal-based electricity generation or limiting the amount of internal combustion vehicles in cities for pollution abatement.

As a baseline, UKTM is set up to run policy free, as a basis to compare alternative futures. In this way, policies can by defined and included or not in runs in a very flexible way. A class of parameters in the TIMES model are used for representing policy and economic conditions, which include a range of costs attached to the investment, dismantling, maintenance and operation of a technology. In addition, taxes and subsidies can be defined in a very flexible manner. Policy parameters also include cumulative or annual bounds on the overall or net production of any energy or emissions carriers.

UKTM will be strongly involved in policy analysis being DECC's central long-term energy system pathway model. By making UKTM fully open source and with a strong cooperation between DECC, CCC and the UCL Energy Institute, a more transparent, productive and consistent energy modelling-policy interface is created. Moreover, UKTM meets the QA and model verification standards of DECC. In addition, an expert user group of UKTM is established (via a memorandum of understanding) to test, improve and apply the model.

5.2 RESEARCH STRANDS

5.2.1 TECHNOLOGY LEARNING AND DIFFUSION

Technology change will play a pivotal role in reaching the long-term targets in the energy sector in terms of decarbonisation, energy security and economic competitiveness. At the same time, the process of technology innovation and diffusion is subject to substantial uncertainties and path dependencies. Moreover, it has to be taken into account that technological change in the energy sector can be supported by different policy instruments, comprising both *supply-push* and *demand-pull* mechanisms.

The basic target of this research focus is to advance our understanding of how to formally model the process of technological change in quantitative energy economic models. So far, conventional energy system models either treat technological change as purely dependent on time (i.e. by setting exogenous assumptions on the development of technology costs) or use reduced-form representations of technology learning, concentrating mainly on *learning-by-doing*.

Three main research areas have been identified. In general, a focus will be put both on technological learning and the process of diffusion of new technologies.

- Improve the conventional representation of endogenous technology learning in energy models by including multi-factor learning approaches and by looking at technological change under uncertainty and myopic expectations;
- Look at learning from a global-local perspective to better understand the importance of spill-overs across regions and time and of how national circumstances can influence the process of technology learning and the adaptation of new technologies;
- Analyse technology learning and diffusion of demand-side technologies taking into account the specific characteristics of these technologies and the variety of (non-economic) factors that influence technology uptake.

5.2.2 Behavioural modelling

Technology-oriented energy system models like UKTM are often criticised for ignoring critical aspects of the decision-making behaviour of different economic agents, as they rely mainly on financial costs as the key decision variable for technology choice assuming that technologies that provide the same energy service can be regarded as perfect substitutes.

The aim of this research strand is therefore to improve the behavioural realism in energy systems modelling. This helps to represent crucial market barriers and imperfections as well as consumer heterogeneity and also allows to analyse the mitigation opportunities in the energy system from behaviour change. Several research directions are planned: (1) developing discrete choice modules for the transport and residential sectors linking to UKTM; (2) integrating endogenous mode choice based on time budgets into UKTM to represent travel behaviour and (3) reviewing and improving the use of price elasticities and hurdle rates in energy system models.

5.2.3 Spatial and temporal modelling

Transitioning to a low carbon energy future needs long-term planning and technically feasible solutions. Energy systems models like UKTM are strong at analysing long-term decarbonisation pathways. However, they usually lack the necessary spatial and temporal detail to model a high integration of variable renewable energy sources (RES), flexible generation, storage and interconnection. Variable RES and electricity demand vary with time and space and the energy system is constrained by the location of the current infrastructure in place. Averaging over time and space can lead to erroneous conclusions (e.g. averaging wind availability and demand does not capture events such as low wind availability and high demand when the usage of backup plants or stored electricity is necessary). Investment decisions regarding renewable energy generation, transmission and storage are interconnected. Recently, there have been first approaches for more detailed temporal modelling in order to account for fluctuating RES but these disregard the modelling of spatial characteristics. With this research strand we aim at closing the gap in methodologies combining long-term planning with an adequate spatio-temporal resolution to model a high integration of variable RES and answering the following research questions: What is the system optimal location of variable RES? What are the cost effective, technically feasible long-term decarbonisation strategies leading to a low carbon power system? What is the role of flexible elements, storage and grid upgrades facilitating the market introduction of renewables??

We are linking UKTM with a dispatch model which allows us to combine the benefits of two models: An energy system model to analyse decarbonisation pathways and a power dispatch model which can evaluate the technical feasibility of those pathways and give additional market insights. The dispatch model we developed minimizes annual variable electricity production costs. The model includes equations describing balancing, storage types, plant specific maximum and minimum production, ramping rates and renewable in feed. In its current version the model runs hourly for one year and has 90 regions based on transmission grid segments. A future version will include the representation of the transmission grid.

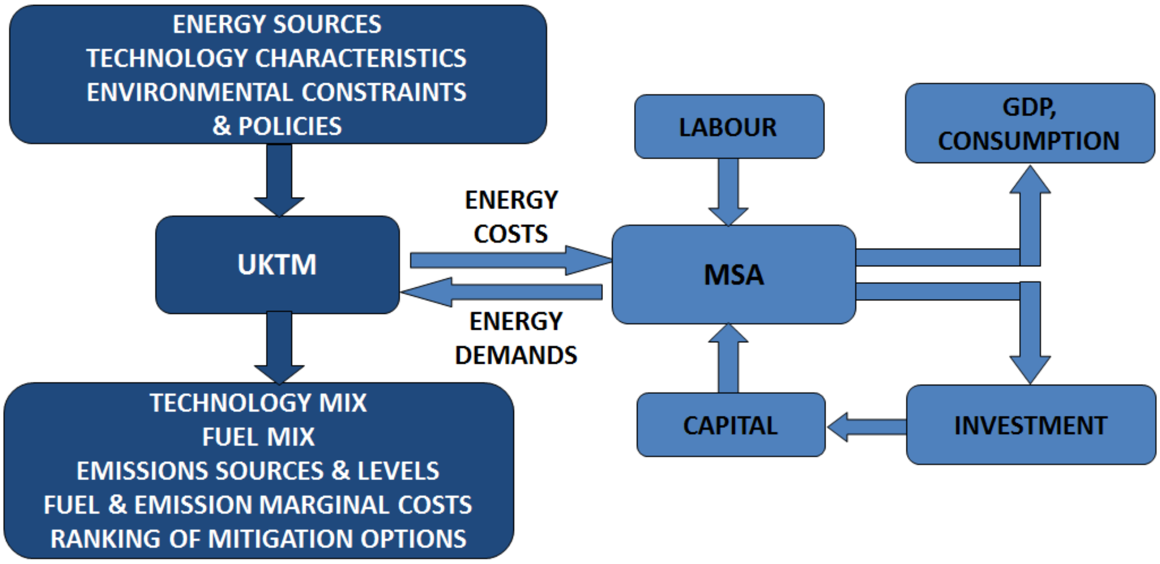
In a first case study we studied the spatial and temporal disaggregation of wind energy (Zeyringer et al., 2014). For this work we use highly spatially and temporally resolved wind time series for potential sites of onshore wind power installations. We introduced 90 wind energy regions into UKTM, which differ in their potential and availability factors. Results show that compared to a run with one average wind region the spatially disaggregated run leads to a higher share of wind energy. Using the built capacities from UKTM in the dispatch model until 2050 shows higher curtailment in the dispatch model compared to UKTM and in 5% of the hours supply did not fulfil demand. These results indicate that the energy system model installs a too high amount of baseload capacity and not enough flexible generation for the system to operate without disconnecting demand.

Further research will focus on linking the dispatch model back to UKTM by introducing minimum requirements of flexible generation, storage or transmission line upgrades for different variable RES penetration rates. As a result the long-term model will be able considering short- term dynamics and spatial differentiation of renewable energy production and produce more robust decarbonisation pathways.

5.2.4 MACROECONOMIC LINKAGES

UKTM-MSA

A hard-linked macro-economic module (Macro Stand-Alone) has been combined with the new UK TIMES model developed at UCL. MSA was developed by Kypreos and Lehtila (2013) and is a single-sector general equilibrium neoclassical optimal growth model where inter-temporal regional utility is maximised subject to constraints on production. The module takes into consideration the effect changes on the energy system will infer on the economy as a whole, essentially changing TIMES from a partial to a general equilibrium model. The national production function is a nested Constant Elasticity of Substitution between a capital/labour composite, representing the rest of the economy, on one hand and energy services on the other. Part of total production is used to cover energy demands while the remainder can either be consumed by households or used for investments in the capital stock. The linkage to MSA is the annual energy systems costs which are determined by TIMES, while the demands for energy are the feedback from MSA module into TIMES.



The original soft linking from TIMES with MACRO is described in Remme and Blesl (2006). This is based upon the earlier MARKAL-MARCO model from Manne and Wene (1992) and described in Kypreos (1996) and Loulou *et al* (2004).

GTAP-UCL

A longer-term project is the development of a top-down multi-sector computable general equilibrium model at the UCL Energy Institute which will eventually be soft-linked with TIMES to provide a state-of-the-art hybrid energy modelling tool. GTAP-UCL uses the GTAP8 database which contains trade data on 129 regions and 57 economic sectors for 2007. The model is a system of non-linear equations representing consumer utility maximisation and producer profit maximisation/cost minimisation where demand and supply of goods and factors achieve market equilibrium through relative price changes. Energy is included through physical IEA data and CO2 emissions are calculated explicitly within the model. We are currently undertaking a number of improvements to the GTAP-UCL to include more explicit representation of electricity generation technologies in the database, a more realistic inclusion of energy in the nested production function, the inclusion of water in agriculture and updating from a static to a dynamic process. The development of the CGE model will provide more economic sectoral information than with the aggregated UKTM-MSA described above by considering the explicit trade-offs and feedback between energy technology choices and different sectors within the economy.

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