Model Variants

Introduction

This chapter describes a number of model variants using the UK MARKAL database and framework, namely Macro (Strachan and Kannan, 2008), elastic demand (Anandarajah et al., 2009), spatial (Strachan et al., 2009), and temporal (Kannan, 2008). These were designed for specific projects to investigate specific research and policy questions of interest. Additionally, technology specific models include hydrogen technology (Balta-Ozkan et al., 2009) and biomass focused models. Future model variants will investigate staged optimization, stochastic decision making, life-cycle analysis (LCA), and international trade.

- Introduction
  - MARKAL-Macro (M-M)
    - M-M Overview
    - M-M governing equations
    - M-M linkage
  - MARKAL Elastic Demand (MED)
  - Stochastic MARKAL
  - Spatial Variant
    - Demand disaggregation
    - Supply disaggregation
    - Infrastructure disaggregation
      - Liquid hydrogen
      - Pipeline hydrogen
  - Temporal Variant
    - Disaggregation of ESDs
    - Disaggregation of energy resources
    - Electricity storage technology
  - References

MARKAL-Macro (M-M)

M-M Overview

MARKAL-Macro (M-M) hard-links a detailed energy systems model (MARKAL) with a simple neoclassical growth model. Hence M-M combines MARKAL's rich technological characterisation of energy system with a dynamic inter-temporal general equilibrium model. Using this approach, M-M allows both a aggregated demand-side response to supplement supply-side technology pathway optimisation, as well as allowing direct analysis of the impacts of various energy and environmental policies on the growth of the economy.

The model maximizes the discounted utility function subject to a national budget constraint. In M-M, there are three other economic agents in addition to suppliers and consumers of energy (the energy market), as in MARKAL. These additional economic agents are producers, which supply other goods and services, consumers and a generic capital market. All these markets are assumed to operate in a single sector with perfect foresight. Demand changes respond to a single price elasticity and are asymmetric with price. However sub-sectoral demands will react differently dependent on the overall economic implications of their reductions (expressed via demand marginals). Figure MV1 summarises the integration process, together with the key inputs and outputs from the MARKAL and Macro components respectively.

Figure MV1: MARKAL-Macro overview schematic
M-M was developed based on the pioneering work of Manne and Wene (1992). M-M maximizes, under a pre-determined economic growth path, the discounted sum of utility derived from consumption. The basic input factors of production are capital, labour and energy service demands. The economy's outputs are used for investment, consumption and inter-industry payments for the cost of energy. Investment is used to build up the stock of (depreciating) capital, while labour is exogenous.

The demand levels and cost of energy is the link between MARKAL and the Macro module. Useful energy services that are given by MARKAL are aggregated to form the energy input in the production function of the Macro module. On the other hand, output can be used towards consumption, capital accumulation or energy service purchases, and this information is passed from the Macro module to MARKAL. With this connection between MARKAL and Macro, MARKAL-Macro can establish a baseline and resultant changes for energy consumption, carbon emissions, technology choices, and GDP.

MARKAL-Macro integrates a simple macro model within a technology rich framework. Despite its simplicity, this is one of the very few hard-linked top-down bottom-up modelling few approaches. Other examples that undertake this linkage include MESSAGE and AIM. This single sector macro module has limits to its usefulness and hence insights it can give. There is no disaggregation of capital flows to different sectors nor international capital flows. This means that the model cannot look at competitiveness issues nor relative performance of industrial sectors. Similarly there is no government sector; this means that some policies with direct investments in energy, or conversely changes in government revenues, cannot be fully investigated. However, the model does allow a wide range of policies to be investigated including price instruments (trading, taxes, subsidies), technology and efficiency standards and technology/resource portfolios. Furthermore any macro-economic simplicity must be balanced against retaining MARKAL's technological richness and depiction of the energy system.

**M-M governing equations**

A compact structure ensures that only six principal equations govern the operation of the Macro model in M-M.

**Equation 1 - Utility Function:** The objective function of M-M is the maximization of the discounted log of consumer utility, summed over all periods, with an end of horizon term. The formulation is a non-linear (NLP) optimization, adding significantly to solution time.

$$UTILITY = \sum_{t=1}^{T-1} (udf_t)(\log C_t)$$

$$+ (udf_T)(\log C_T)/[1 - (1 - udr_T)^{\gamma_T}],$$

$$udf_t = \prod_{t=0}^{T-1} (1 - udr_t)^{\gamma_t},$$

$$udr_t = (kpVs)/(kGdp) - depr - grow_t,$$

Where:
- $C_t$: consumption in period $t$
- kpVs: the optimal value share of capital in the labour-capital aggregate.
- kGdp: the initial capital-to-GDP ratio
- depr: annual depreciation of the capital stock
growt: is the potential growth rate of the economy
udrt: utility discount rate for period t
udft : utility discount factor for period t

**Equation 2 - Usage of Production:** The output (production) of the economy via the Macro module is used for consumption, investment and energy costs (ECT represents the financial link between MARKAL and Macro)

\[ USE : \quad Y_t = C_t + I_t + EC_t, \]

Where:
- \( I_t \): investment in period t
- \( EC_t \): energy costs in period t

**Equation 3 - Production Function:** National production is from three substitutable inputs via a nested CES function. Under this formulation capital and labour substitute directly for one another, and then their aggregate is then substituted for a separable energy aggregate. (Ddm,t represent the physical links between MARKAL and Macro).

\[ PRD : \]
\[ Y_t = \left[ akl(K_t)^{\rho}L_t^{\rho(1-z)} + \sum b_{dm}(D_{dm,t})^{\rho} \right]^{1/\rho}, \]
\[ L_0 = 1, \quad L_t = (1 + grow_t)^n y L_{t-1}, \]
\[ \alpha = k p v s, \]
\[ \rho = 1 - 1/ESUB, \]

Where:
- \( ak l, b d m \): coefficients determined by a base year benchmarking procedure
- \( K_t \): the capital stock accumulated up to period t
- \( L_t \): the labour in period t
- \( D_{dm,t} \): the demand for energy services of type dm in period t
- \( grow_t \): is the potential growth rate of the economy
- \( n y \): number of years per period,
- \( ESUB \): the elasticity of substitution between the energy and the capital-labour aggregates

The benchmarking procedure for \( ak l, b d m \) allows different energy demands to vary according to their reference or shadow prices. Values for \( b d m \) for each demand are found from the reference prices from a conventional MARKAL run. Via a first order optimality condition (Equation 3a) for the partial derivative of production with respect to demand, the marginal change in output is equal to the cost of changing that demand:

\[ \left[ Y / D_{dm} \right]^{1/\rho} \cdot b_{dm} = \text{price(ref)}_{dm} \]

Once \( b_{dm} \) is found, \( ak l \) is the only remaining unknown variable in the production function which is then solved to find \( ak l \).

In practice this has two main results. First, different demands will be altered based on the cost of changing that demand. So if it is very expensive to reduce a particular demand, then this will be reduced relatively less. Secondly, great care is needed to have smooth (and certainly not zero) shadow prices which can occur due to over-constrained runs. This ensures that the marginal output (demand) responses are realistic.

**Equation 4 - Capital Accumulation:** Provides new capital through investment, accounting for depreciated capital

\[ K_{t+1} = tsrvK_t + (ny/2)(tsrvI_t + I_{t+1}), \]

**CAP :**
\[ tsrv = (1 - depr)^n y, \]
\[ I_0 = (grow_0 + depr)K_0, \]

Where:
- \( tsrv \): capital survival fraction
- \( depr \): annual depreciation rate
- \( growt \): potential growth rate of economy

**Equation 5 - Terminal Conditions:** A final equation ensures sufficient investment for replacement and constant growth of capital

\[ TC : \quad K_T(grow_T + depr) \leq I_T. \]

**Equation 6a and 6b - Linking Equations:** MARKAL supply activities are linked to MACRO demand variables through 2 equations:

\[ \sum_j supply_{j, dm, t} X_{j,t} = a e c i f a c_{dm, t} D_{dm, t}. \]
\[ \sum \text{cost}_{j,t}X_{j,t} + c \sum \text{cost}_{t}X \text{CAP}_{t}^2 \text{CAP}_{t+1} = EC_t, \]
\[ \text{CAP}_{t+1} = \expf \text{CAP}_{t} + X \text{CAP}_{t+1}, \]

Where:
- \( X_j \): an activity of MARKAL supplying energy service demand of the form \( dm \) proportional to supply\( j, dm \)
- \( \text{aeifacdm} \): autonomous energy efficiency improvements factor
- \( \text{cost}_{j,t} \): the cost for each activity and period
- \( \text{CAP}_{t} \): the capacity for technology \( t \) during period \( t \)
- \( X \text{CAP}_{t+1} \): the amount of capacity installed beyond the capacity expansion factor \( \expf \) for technology \( t \) in period \( t \)

Equation 6a allows an autonomous trend to be added to each demands for MARKAL Macro. This is especially key as demands are now an endogenous metric within the Macro module, and thus the autonomous component can calibrate demands to a previous MARKAL run or to forecast demands (converted into energy service demands). This process is also termed demand decoupling (as demands are decoupled from a linear relationship with economic growth).

Equation 6b is designed to smooth technology penetration and hence ensure the stability of the Macro run. The choice of its parameters is a matter of some consideration to define both the maximum technology expansion and also to have a realistic soft constraint to smooth that penetration. In addition this non-linear equation needs to be defined for each technology and is a non-trivial modeling issue.

**M-M linkage**

There are a number of key differences between MARKAL and M-M:

- The models have different objective functions - cost minimization vs. utility maximisation
- M-M demands are now an endogenous variable
- A differentiation costing mechanism is employed for end-use technologies. This correctly accounts for the energy sector's share of economic production, but gives a relatively differing input assumption set for demand technologies
- Lower bound changes to ensure non-zero and consistent demand marginals
- Some sectors have been simplified (notably residential with aggregated demand services for existing and new dwellings)
- M-M computational issues (non-linear optimization) means that the model matrix is collapsed into 10 year periods in order to solve in a reasonable time (<1 hour)

To successfully run M-M, a range of parameters need to be estimated and tested. In addition, the Macro run needs to be calibrated to both potential GDP growth rates and energy demands – this is achieved via a specific demand decoupling factor (DDF) utility. This process is in addition to the MARKAL base year (2000) calibration using national energy statistics.

First of all, the Macro variables need to be defined and in most cases are set from standard macroeconomic statistics. For other aggregated parameters, an estimated realistic value needs to be subjected to sensitivity testing. The labour index at time 0 is set to 1 and is the only variable to be specified completely exogenously. Table MV1 details major Macro parameters, with typical values from Taylor (1995).

**Table MV1: Key macro parameters in DTI-DEFRA analysis**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP0</td>
<td>£ 1035.5</td>
<td>Base year (2000) UK GDP</td>
</tr>
<tr>
<td>GROWV</td>
<td>2%</td>
<td>Projected annual GDP growth rates are defined per time step</td>
</tr>
<tr>
<td>KGDP</td>
<td>2.4</td>
<td>Initial capital-to-GDP ratio</td>
</tr>
<tr>
<td>KPVS</td>
<td>24%</td>
<td>Optimal value share of capital (vs. labour)</td>
</tr>
<tr>
<td>ESUB</td>
<td>0.3</td>
<td>The aggregated elasticity of substitution is not available from statistics; hence ESUB is varied and results analyzed. Lower end estimates are more appropriate for models with detailed technological substitution and conservation options in end-use sectors</td>
</tr>
<tr>
<td>EC0</td>
<td>From MARKAL run</td>
<td>Energy costs in the initial period (2000)</td>
</tr>
<tr>
<td>DEPR</td>
<td>5%</td>
<td>Annual depreciation of the capital stock</td>
</tr>
<tr>
<td>DMTOL</td>
<td>0.5</td>
<td>Demand level tolerance – fraction by which the Macro demands can be lowered and sets a lower bound</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>IVETOL</td>
<td>0.5</td>
<td>Investment level tolerance – fraction by which the Macro investment can be lowered and hence sets a lower bound</td>
</tr>
<tr>
<td>DIFFDMDS</td>
<td>0 or 1</td>
<td>Flag to employ differential costing</td>
</tr>
<tr>
<td>QFAC</td>
<td>0 or 1</td>
<td>Flag for quadratic cost penalty factor</td>
</tr>
<tr>
<td>EXPF</td>
<td>15%</td>
<td>Percentage annual increase for quadratic cost penalty factor</td>
</tr>
<tr>
<td>SCALE</td>
<td>1000</td>
<td>Scaling factor to ensure M£ and B£ units are comparable</td>
</tr>
</tbody>
</table>

Two final issues are encountered in setting up M-M runs. Firstly, only the energy-specific capital costs for a given technology need to be considered within ECt (to correctly account for only the energy related costs in the production function). This is generally done by subtracting the smallest INVCOST from all technologies fulfilling a given demand thus obtaining the differential costs of each technology, and not the full costs. Secondly MARKAL’s shadow prices of the demands (normally used as reference prices) need to be smooth and certainly non-zero. However, they often are heavily distorted in period 1, due to the heavy constraining usually employed to calibrate MARKAL to the energy statistics in the initial period, and hence initial bounds must be lowered to ensure less variation.

**MARKAL Elastic Demand (MED)**

An elastic demand version (MED) accounts for the response of energy service demands to prices at the individual demand level. Note as the UK model does not represent trade and competitiveness effects, and as a partial equilibrium energy-economic model does not include government revenue impacts, it hence does not provide an assessment of macro-economic implications (e.g. GDP).

A simplified representation of energy supply and elastic demands is given in Figure MV2. The standard MARKAL model optimization, when energy service demands are unchanging - i.e. are a straight vertical line on the horizontal axis - is on (discounted) energy systems cost, i.e. the minimum cost of meeting all energy services. In MED, these exogenously defined energy service demands have been replaced with demand curves (actually implemented in a series of small steps). Following calibration to a reference case that exactly matches the standard MARKAL reference case, MED now has the option of increasing or decreasing demands as final energy costs fall and rise respectively. Thus demand responses combine with supply responses in an alternate scenario (e.g. one with a CO₂ constraint).

Figure MV2: Representation of MED supply-demand equilibrium

In MED And also in the MARKAL Micro formulation which includes non-zero cross price elasticities, demand functions are defined which determine how each energy service demand varies as a function of the market price of that energy service. Hence, each demand has a constant own-price elasticity (E) in a given period. The demand function is assumed to have the following functional form:

\[
\frac{ES}{ES_0} = \left(\frac{p}{p_0}\right)^E
\]

Where: \( ES \) is a demand for some energy service; \( ES_0 \) is the demand in the reference case;
$p$ is the marginal price of each energy service demand; 
$p_0$ is the marginal price of each energy service demand in the reference case; 
$E$ is the (negative) own-price elasticity of the demand.

In this characterization, $ES_0$ and $p_0$ are obtained by running standard MARKAL. $ES_0$ is the energy service demand projection as defined by the user exogenously (as a function of social, economic and technological drivers). $p_0$ is the marginal price of that energy service demand determined endogenously by running the reference case. A simple calibration process ensures that the MED reference case is consistent with the reference case run in the standard model (based on use of the standard case total system cost (MED-BASEOBJ) and undiscounted annual system cost (MED-BASEANNC)).

Three additional MED parameters are required when undertaking an MED run:

**MED-ELAST:** Elasticity of demand. This indicates how much energy service demands rise/fall in response to a unit change in the marginal cost of meeting the demands (See Table MV2)

**MED-VAR:** Variation of demand. This limits the upward / downward movement of demand response. In the UK model, this is set to a limit of 50% reduction in demand / 25% increase in demand. i.e., demand increases are considered to be less sensitive to price changes.

**MED-STEP:** Defines the steps on the demand curve; for demand decreases, this has been set at 20 (2.5% reductions) and 10 for demand increases (for consistency with MED-VAR parameter).

### Table MV2: Price elasticities of energy service demands

<table>
<thead>
<tr>
<th>ESD code</th>
<th>Sector and Description</th>
<th>Price Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICH</td>
<td>Industry and agriculture</td>
<td>Chemicals</td>
</tr>
<tr>
<td>IIS</td>
<td>Iron &amp; steel</td>
<td>-0.44</td>
</tr>
<tr>
<td>INF</td>
<td>Non ferrous metals</td>
<td>-0.44</td>
</tr>
<tr>
<td>IOI</td>
<td>Other industry</td>
<td>-0.32</td>
</tr>
<tr>
<td>IPP</td>
<td>Pulp and paper</td>
<td>-0.37</td>
</tr>
<tr>
<td>AGRI</td>
<td>Combined agriculture</td>
<td>-0.32</td>
</tr>
<tr>
<td>R-ELEC</td>
<td>Residential Electrical appliances</td>
<td>-0.31</td>
</tr>
<tr>
<td>R-GAS</td>
<td>Gas appliances</td>
<td>-0.33</td>
</tr>
<tr>
<td>RH-S-E</td>
<td>Space heat (existing)</td>
<td>-0.34</td>
</tr>
<tr>
<td>RH-S-N</td>
<td>Space heat (new homes)</td>
<td>-0.34</td>
</tr>
<tr>
<td>RH-W-E</td>
<td>Water heat (existing)</td>
<td>-0.34</td>
</tr>
<tr>
<td>RH-W-N</td>
<td>Water heat (new homes)</td>
<td>-0.34</td>
</tr>
<tr>
<td>SCK</td>
<td>Services Cooking</td>
<td>-0.23</td>
</tr>
<tr>
<td>SCL</td>
<td>Cooling</td>
<td>-0.32</td>
</tr>
<tr>
<td>SETC</td>
<td>Electrical appliances</td>
<td>-0.32</td>
</tr>
<tr>
<td>SH-S</td>
<td>Space heating</td>
<td>-0.26</td>
</tr>
<tr>
<td>SH-W</td>
<td>Water heating</td>
<td>-0.26</td>
</tr>
<tr>
<td>SLIT</td>
<td>Lighting</td>
<td>-0.32</td>
</tr>
<tr>
<td>SREF</td>
<td>Refrigeration</td>
<td>-0.25</td>
</tr>
<tr>
<td>TA</td>
<td>Transport Air (domestic)</td>
<td>-0.38</td>
</tr>
<tr>
<td>TB</td>
<td>Bus</td>
<td>-0.38</td>
</tr>
<tr>
<td>TC</td>
<td>Car</td>
<td>-0.54</td>
</tr>
<tr>
<td>TF</td>
<td>Rail (freight)</td>
<td>-0.24</td>
</tr>
<tr>
<td>TH</td>
<td>HGV</td>
<td>-0.61</td>
</tr>
<tr>
<td>TI</td>
<td>Air (international)</td>
<td>-0.38</td>
</tr>
<tr>
<td>TL</td>
<td>LGV</td>
<td>-0.61</td>
</tr>
<tr>
<td>TR</td>
<td>Rail (passenger)</td>
<td>-0.24</td>
</tr>
<tr>
<td>TS</td>
<td>Shipping (domestic)</td>
<td>-0.18</td>
</tr>
<tr>
<td>TW</td>
<td>2 wheelers</td>
<td>-0.41</td>
</tr>
</tbody>
</table>

The elasticities used in this analysis (Table MV2) are long-run elasticities (due to the MED model's 5 year time periods and perfect foresight assumptions), and are derived from three key sources:

1) Other MARKAL modelling teams outside the UK (Loulou and van Regemorter, 2008);
2) MDM-E3 macro-econometric model (Dagoumas, 2008), and
3) the BERR energy model (BERR, 2006a).

A combination of the proportional change in prices ($p/p_0$) and the elasticity parameter ($E$) determines when the energy service demand changes by the step amount. Note that changes in energy service demand also depend on the availability and costs of technological conservation,
efficiency and fuel switching options. The variation parameter sets the ultimate limit to the demand change and the step parameter determines the size of the increment the model can select for that variation. This formulation means that each demand response is log-linear but the overall demand function is NOT log-linear as different demand steps are triggered by different price changes, depending on the elasticities.

It is important to note the aggregate nature and sparse empirical basis for the price elasticities of energy service demands. Elasticities for energy demand and fuel demands are somewhat more readily available, so that sensitivity analysis around the elasticities becomes important.

Now the MED objective function maximises both producer surplus (PS) and consumer surplus (CS) - this is the combined area between the demand function and the supply cost curve in Figure MV2. This is affected by annualized investment costs; resource import, export and domestic production costs; taxes, subsidies, emissions costs; and fuel and infrastructure costs as before in the standard model. However, in addition the MED model accounts for welfare losses from reduced demands - i.e. if consumers give up some energy services that they would otherwise have used if prices were lower, there is a loss in utility to them which needs to be accounted for. Note that the MED model actually calculates the change in area under the shifted demand curve.

In the MED policy scenarios, transfers between producer surplus (PS) and consumer surplus (CS) are possible. In general if the policy case has higher prices (e.g., from a CO\textsubscript{2} constraint) it is likely that the PS may take some of the CS; with the opposite occurring if the policy case prices fall – i.e., then CS takes some of the PS (this may be seen in Figure 1 by shifting the Equilibrium Price line up or down). The exact mechanisms of this will depend on the shape of the two curves, and of course on how prices are being passed through (or not). However, in a higher price policy case, the combined surplus (PS + CS) will \textit{always be lower}. In a lower price policy case, the combined surplus (PS + CS) will \textit{always be higher}.

The sum of consumer and producer surplus (economic surplus) is considered a valid metric of social welfare in microeconomic literature, giving a strong theoretical basis to the equilibrium computed by MED.

**Stochastic MARKAL**

The objective function of the stochastic MARKAL model is different to that in deterministic scenarios. It computes the expected cost of a scenario based upon a single average hedging strategy that minimises the cost of a probability weighted set of future scenarios. Thus, in addition to the solutions from MARKAL Elastic Demand, the model also computes equilibrium between 'here-and-now' decisions that must be made before uncertainty is resolved and 'wait-and-see' decisions that can be delayed until better information is available (Hu & Hobbs 2009). Stochastic MARKAL is a 2-stage stochastic model, with the second stage specified as that in which the uncertainty is resolved. Up to this point, Stochastic MARKAL computes a hedging strategy, a social welfare maximising optimum based upon the resolution of multiple probability-weighted future scenarios. This hedging strategy is considered optimal and is solves one of the issues with deterministic models: multiple possible future strategies can be accounted for in just one model run. Analysis of hedging strategies can result in insights additional to those available through the comparison of multiple deterministic scenarios (Loulou et al., 2004).

Figure 1 shows a stochastic hedging strategy to the year 2010, with four separate recourse strategies from 2015 onwards. Note that the hedging strategy is not an average of the deterministic scenarios, but responds to the exponentially increasing costs under higher CO\textsubscript{2} caps. In this case, the value of a CO\textsubscript{2} cap is unknown until the 3\textsuperscript{rd} model period. In contrast, under the assumption of perfect foresight, the dashed lines represent the optimum strategy when the emissions cap is known from 2000. The stochastic model allows a relaxation of the assumption of perfect foresight, quantification of future uncertainty through metrics such as the Expected Value of Perfect Information (EVPI) and insights into optimal near-term strategies that minimise the expected costs of future uncertainties.
Spatial Variant

For analysis of plausible gaseous and liquid hydrogen (H₂) infrastructures and delivery systems with the UK MARKAL model, a process was carried out to soft-link a Geographical Information Systems (GIS) based spatial model. This necessitated spatial disaggregation of hydrogen demand, supply and infrastructures.

Demand disaggregation

GIS data collection (Strachan et al., 2007) was focused on describing physical and socio economic characteristics of the UK's regions (or centres) in cost and feasibility terms. In defining these demand regions, Output Areas (OA) – based on 125 UK households sets - are used for the spatial unit of analysis (National Statistics, 2001).

The UK's nine urban H₂ demand centres were initially identified by population and fully assessed using GIS data (Figure MV3). These centres represent single urban entities (in the case of London) or key city groups (for example, Liverpool, Manchester and Salford in the urban centre of “Lancashire”). Having done this, it was assumed that any OA sharing a boundary with an OA that contained one of these major cities was also a part of the same urban conurbation. Using a step-wise process, and working outwards from the cities contained within them, urban centres were defined as either:
1.an OA containing one of the previously identified main cities;
2.an OA sharing an adjacent boundary with a main city OA (i.e. #1), or;
3.an OA sharing an adjacent boundary with #2.

Figure MV3: UK urban demand centres
A dataset containing all these nine identified urban centres was then intersected with further UK GIS datasets to identify all the remaining areas in the UK. These were divided in the GIS model into one of three settlement types: ‘other urban’, ‘rural-sparse’ and ‘rural-less sparse’. In broad terms, within this project other urban areas are all settlements with populations over 10,000, with rural-less-sparse having >50% and rural-sparse having >80% in small communities. These aggregated regions were then allocated an averaged UK location in the GIS model.

Then, as illustrated in Table MV3, transport energy service demands (in billion vehicle kilometres) for LGVs (TL), HGVs (TH), passenger rail (TR) and freight (TH) were disaggregated based on population share of each region. For buses (TB), and cars (TC), demand is weighted by London’s disparate share relative to population, with London hosting Europe’s largest bus network and correspondingly having a far lower car ownership level. Remaining demands are distributed among the other regions based on their population shares. Domestic (TA) and international aviation (TI) energy service demands including saturation effects in airport infrastructure to limit energy use, with resultant growth in passenger numbers doubling 2000 levels by 2050. are disaggregated based on airport passenger flows. In terms of final energy demand, two-wheelers (TW) are proportionally very small (<1% in 2000). Also, domestic shipping (TS) is a diverse sector and small overall contributor. If international shipping was apportioned to the UK energy balance this would be a more significant contributor to UK transport emissions, and hence both are treated in aggregate.

Table MV3: Disaggregation of transport energy service demands by regions
Supply disaggregation

The location of potential UK H\textsubscript{2} supply points was based upon the anticipated use of UK resources in a CO\textsubscript{2} constrained economy, as well as current industrial locations. This firstly included regional variation in the UK’s remote renewable (offshore wind, onshore wind, wave, tidal) resources (BERR, 2006b). From this GIS data source, remote Scottish renewables (for dedicated H\textsubscript{2} production) were split out in the model to avoid double counting with the overall UK renewable potential for electricity and heat provision. A second key consideration via the GIS interface was carbon sequestration sites, with the general location of offshore oil and gas fields used to map primary sites for CO\textsubscript{2} storage in the UK (Holloway, 2007). A third factor was the expected location of Liquid H\textsubscript{2} and LNG terminals (in order to facilitate liquid H\textsubscript{2} imports as well as utilizing combined LNG gasification / LH\textsubscript{2} liquefaction processes technologies). Existing and future terminals and storage facilities have been mapped using data on planned (as of November 2006) major new gas projects.

Based on this data, and to remain within modelling computational limits, six sites were chosen to summarize and represent key UK resource options and are detailed in Table MV4.

Table MV4: Potential UK hydrogen supply points

<table>
<thead>
<tr>
<th>Supply point</th>
<th>Area</th>
<th>H\textsubscript{2} production</th>
<th>Carbon constrained H\textsubscript{2} production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peterhead</td>
<td>Coal, natural gas, large scale electrolysis, CCS</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Teesside</td>
<td>Coal, natural gas, large scale electrolysis, LH\textsubscript{2}, LNG terminals</td>
<td>CCS, LH\textsubscript{2}, LNG terminals</td>
</tr>
<tr>
<td>3</td>
<td>Humberside</td>
<td>Coal, natural gas, large scale electrolysis</td>
<td>CCS</td>
</tr>
<tr>
<td>4</td>
<td>Isle of Grain, Thames</td>
<td>LH\textsubscript{2} L\textsubscript{2}, LNG terminals, natural gas, large scale electrolysis</td>
<td>LH\textsubscript{2}, LNG terminals</td>
</tr>
<tr>
<td>5</td>
<td>Milford Haven, Wales</td>
<td>LH\textsubscript{2} L\textsubscript{2}, LNG terminals, coal, large scale electrolysis</td>
<td>LH\textsubscript{2}, LNG terminals</td>
</tr>
<tr>
<td>6</td>
<td>North West Scotland</td>
<td>Renewables</td>
<td>Renewables</td>
</tr>
</tbody>
</table>

Infrastructure disaggregation

The topological focus of the model was in linking these disaggregated 12 major demand Intermediate demand centres along H\textsubscript{2} infrastructure routes route are not served by these major infrastructure routes. and 6 supply options. Three H\textsubscript{2} infrastructure options are considered: liquid delivery by tankers, large-scale gaseous pipeline networks, and small-scale on-site production.

Liquid hydrogen

A core assumption is that liquid hydrogen (LH\textsubscript{2}) delivery costs are only dependent on distance rather than scale, as the latter would affect the frequency rather than the volume of regular tanker delivery to a given transport fuelling facility (Yang and Ogden, 2007). Following mapping of demand city points (and averaged demand centres for regions J-K), the GIS model was used to identify the most likely routes for LH\textsubscript{2} transportati on using a cost-weighted shortest path function, weighted in favour of travel via motorways. This enabled the calculation of distances between each of the twelve future demand sites The 3 aggregated demand centres (J-L) are assigned averaged UK geographical sites based on weighting of these areas based on their distribution throughout the UK. and six supply points (Table MV5), which were then translated into costs and efficiencies in the UK MARKAL model.

Table MV5: LH\textsubscript{2} averaged transportation distances

<table>
<thead>
<tr>
<th>Supply Centre</th>
<th>Distance (km)</th>
</tr>
</thead>
</table>
Pipeline hydrogen

Based on the 6 supply points, the GIS approach was utilized to construct feasible H\textsubscript{2} pipeline infrastructures to the 9 urban demand regions. Due to low demand densities, other demand regions (J-K) do not have the option of gaseous H\textsubscript{2} pipelines. Pipeline H\textsubscript{2} flow rates (Joffe, 2008) are calculated as:

Equation (1):

\[ Q = 0.0498 \times D^{2.4191} \sqrt{\frac{P_1^2 - P_2^2}{L}} \]

where \( Q \) is the H\textsubscript{2} flow rate (Nm\textsuperscript{3}/s), \( L \) is the pipeline length (m), \( D \) is the pipe diameter (m), and \( P_1 \) and \( P_2 \) are the inlet and outlet pressures (Pa), respectively.

Using input cost data, together with H\textsubscript{2} vehicle conversion efficiency per mode, and expected pipeline losses, the distance and then costs of the pipeline infrastructure is built up in predetermined deployment networks to meet regional demands. The H\textsubscript{2} pipelines must adhere to least cost paths generated by the GIS model, along existing main road routes where possible and avoiding lakes and large rivers (with further consideration of topology, existing housing and infrastructures). In addition the pipeline networks must be built up sequentially from supply points to nearer demand regions, before being extended to more remote regions and other modes.

Each H\textsubscript{2} pipeline deployment option is thus implemented via a 'meta' infrastructure that ensures only valid combinations of fixed integer increments can be built. H\textsubscript{2} meta infrastructures are applicable to buses, cars and LGV vehicles modes, have a 20-year planning horizon to begin operation from 2030, and eventually meet all of a given region and transport mode capacity. For computational reasons the model has access to only 100 feasible pipeline meta-infrastructures (listed in Strachan et al., 2007). These are based on combinations of supply points, demand regions and modes, with an example centred on from Teesside supply point illustrated in Figure MV4.

Figure MV4: Gaseous hydrogen pipeline 'meta' infrastructure example
Temporal Variant

The standard time slices for the electricity and heat sectors are described in Chapter 2 of the documentation. The newly developed flexible time slicing features (Nobel, 2006) partially redresses the limitation on approximation of load curve by allowing the user to enumerate the elements of the diurnal and seasonal splits, but to do so without otherwise changing the basic depiction and operation of the power sector (electricity and heat) in the model. Since MARKAL has embedded knowledge with respect to the meaning of certain time-slices (e.g., ‘D’ = day or peak time, ‘N’ = night or off-peak time) the equivalent knowledge is passed to the model. More specifically, MARKAL needs to know the one daily division corresponding to the time during which electricity storage may occur (e.g., pumped hydro, night storage device) and the base load constraint is to be imposed (YNITE, default Y=’N’). As a result the user identifies the one daily division to be used for the base load variables (YBAS, default = ‘D’).

The UK temporal MARKAL has twenty annual time periods via five diurnal and four seasonal. The five diurnal periods were selected to capture key trends in the actual electric demand profile. On an average winter day, the UK electricity demand begins to increase in the morning (6:00 – 9:00) and then in the evening (16:00 – 20:00), the latter being the highest (see Error! Reference source not found.). Demand is more or less stable during daytime though with some fluctuations. In the late evening (20:00 – 23:00) demand begins to decline and stays at a lower level during the night period (23:00 – 6:00). To represent these key trends the five diurnal time-periods are used. In additional to the diurnal variation,
electric demand also varies seasonally. For the temporal MARKAL we choose four main seasons based on variability of key ESD and intermittent renewable resources. Table MV6 shows the five diurnal and four seasonal break ups.

**Table MV6: Annual split of diurnal and seasonal periods**

<table>
<thead>
<tr>
<th>Diurnal split (Y)</th>
<th>Seasonal split (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1: Morning: 6:00 – 9:00</td>
<td>S1: Winter: December – February</td>
</tr>
<tr>
<td>D2: Daytime: 9:00 – 16:00</td>
<td>S2: Spring: March – May</td>
</tr>
<tr>
<td>D3: Evening peak: 16:00 – 20:00</td>
<td>S3: Summer: June – August</td>
</tr>
<tr>
<td>D4: Late evening: 20:00 – 23:00</td>
<td>S4: Autumn: September – November</td>
</tr>
<tr>
<td>D5: Night storage: 23:00 – 6:00</td>
<td></td>
</tr>
</tbody>
</table>

Table MV7 shows the fraction of annual hours (QHR (X)(Y)) for the 20 time slices. ESDs and renewable energy resources are disaggregated within these 20 time slices based on a wide range of literature data (see next sections). For power plant operation D5 is set as night storage (YNITE) while D1 is set as Base (YBAS). Figure MV5 illustrates its load curve in temporal MARKAL in an average winter and summer day. It can be seen that now the load curve has a closer fit with the actual peak and intermediate demands. Moving to a higher number of time periods and seasons could improve the fit but this was limited by data availability.

**Table MV7: QHR(Y)(Z) fraction of 20 periods in temporal UK MARKAL**

<table>
<thead>
<tr>
<th></th>
<th>D1 Morning (3 hours)</th>
<th>D2 Day time (7 hours)</th>
<th>D3 Evening peak (4 hours)</th>
<th>D4 Late evening (3 hours)</th>
<th>D5 Night storage (7 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (Winter)</td>
<td>3.08%</td>
<td>7.19%</td>
<td>4.11%</td>
<td>3.08%</td>
<td>7.19%</td>
</tr>
<tr>
<td>S2 (Autumn)</td>
<td>3.15%</td>
<td>7.35%</td>
<td>4.20%</td>
<td>3.15%</td>
<td>7.35%</td>
</tr>
<tr>
<td>S3 (Summer)</td>
<td>3.15%</td>
<td>7.35%</td>
<td>4.20%</td>
<td>3.15%</td>
<td>7.35%</td>
</tr>
<tr>
<td>S4 (Spring)</td>
<td>3.11%</td>
<td>7.27%</td>
<td>4.16%</td>
<td>3.11%</td>
<td>7.27%</td>
</tr>
<tr>
<td>Total</td>
<td>100% (8760 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure MV5: Actual electricity demand versus its representation in temporal MARKAL**

Disaggregation of ESDs

Residential space heating and hot-water services are diurnally disaggregated based on electric demand profiles for heating and hot-water (Abu-Sharkh, 2007). The seasonal heating demands are estimated based on degree-days using the UK Domestic Carbon Model (ECI, 2007). Demand pattern of space cooling is assumed to be that of the heating demand but assumed to be occurred only in summer (S3). Diurnal and
seasonal variation of lighting service is estimated based on electric demand for lights (Stokes et al., 2004). Electricity demands for cold appliances (e.g. refrigerator/freezers) are assumed to be uniform. Electricity demands profile of miscellaneous appliances is taken from Stokes et al. (2004). Diurnal demand profile of cooking service is assumed based on expert judgement which follows the trend in-between the heating and lighting demand profile, while no seasonal variation is considered for cooking.

Unlike the residential sector, ESD in the service sector is very diverse and data availability is very limited. Thus the diurnal disaggregation for heating, lights and other appliances were estimated based on average electrical demand of non-domestic customers (Elexon, 2007). For refrigeration a uniform demand is assumed. The seasonal variation of heating demand is assumed as in the residential sector. All space cooling is assumed to be occurred in summer. Lighting and other electrical appliances demand was assumed to be the same in spring and autumn but the summer and winter demands are assumed at a ratios of up to 2:3.

The transport sector ESDs are in billion vehicle kilometres and they are not disaggregated because potential for use of electricity in transport sector is very small and its contribution to instantaneous peak is marginal. However, plug-in hybrid vehicle technologies are modelled via electricity storage which often optimize operation of base load plants.

It is assumed that the industrial demand pattern remains uniform both diurnally and seasonally. Thus its ESDs were not disaggregated. However the day time (D2) ESDs is adjusted by three percentage points to account for the higher electricity demand for administrative office equipment while its corresponding night demand is proportionally lowered. This 3% is derived from series of parametric analysis to reproduce overall electricity demand profile. The agriculture electricity demand is not disaggregated due to lack of data and its insignificant quantity compared to the other sectors.

**Disaggregation of energy resources**

Advantages of having greater detail of seasonal representations is to account for seasonal variations of intermittent renewable energy sources. The UK seasonal and diurnal wind resources availability is taken from Sinden (2007). This availability factor is referred to the annual capacity factor (Enviros, 2005) to generate seasonal capacity factors (CF(Z)(Y)). Wave energy is fairly closely correlated to wind strength and therefore seasonal cycles appear similar to those of wind (BERR, 2004). Thus off-shore seasonal availability pattern is assumed for the wave energy technologies. For other renewable energy resources, like tides, neither seasonal availability nor diurnal variation is included. For solar energy availability, daylight hours based on sunrise and sunset hours are used, with average monthly sunshine hours (Met Office, 2007) used for seasonal variation. An annual average capacity factor of solar PV system (IEA, 2005) is then distributed across the 20 time periods to generate seasonal capacity factors. Though availability of other energy resources like biomass is seasonal the model assume they can be physically stored and thus they are not disaggregated.

**Electricity storage technology**

A key advantage of having greater diurnal representation is to investigate electricity storage at both supply and demand sides. In MARKAL electricity storage technology use electricity in one time slice (YNITE) and they do not contributes to peak load. This YNITE period is the one and only diurnal time period electricity can be stored. The stored electricity is released as electricity or ESD during non-YNITE slices. In temporal MARKAL, user defines the storage period, which is D5 in our case. The UK MARKAL model has two sets of electricity storage options via supply and demand side storages. Since electricity storage is limited to one time period (YNITE) in MARKAL, the model is not strictly used for analysing intermittent resources or grid balancing mechanisms. Instead it is used to identify least cost energy pathways by taking into account key supply and demand side load variations.

One of the supply side storage is pumped hydro. A second supply side storage is hydrogen-based electricity storage wherein electricity is stored as hydrogen produced via electrolysis.

Two demand side storages are firstly night-stored electric heating system which is commonly used in the UK using off-peak electricity tariffs (or so called economy 7 utility tariff). In the temporal MARKAL, electric storage heaters are enabled both in the residential and service sectors with a max limit of 30% of the total electric heating can be met with storage heaters. The second demand side electricity storage is plug-in hybrid vehicles for cars and LGVs fleets. These technology use electricity to charge cars/LGVs. Appropriate electricity storage technologies (i.e. charging) are modelled so as to charge the plug-in hybrid vehicles either during night-time and/or any day-time. But only the night-time charging (i.e. D5 in our case) serve as the electricity storage technology while day time charge contributes to peak demand.

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