Overview of Energy-Economic Modelling

Parliamentary Office of Science and Technology (POST) Training Seminar

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Overview of Session

• **Part I**
  – The science vs. art of energy modelling

• **Part II**
  – UK TIMES: An well-known energy systems optimisation model

• **Part III**
  – Sample results on the UK’s long-term decarbonisation pathway
What this seminar is NOT...

• “Energy: Predicting the Future - Macro-economic & decarbonisation modelling”
  – I have never made a long term energy forecast in my life!

• Only sometimes is replicating historical trends a good idea
  – The past is not a good guide to the future
  – Models can replicate the past by tuning various combinations of their component variables
  – There can be a modelling trade-off between statistical validation and theoretical underpinnings

• Today I am going to talk about exploratory modelling of possible futures
  – Insights from comparing different futures is much more important than any one scenario
What this seminar is...

• Energy policy across the globe is grappling with a set of unprecedented challenges:
  – Including decarbonisation, security, competitiveness, equity

• Energy models provide essential quantitative insights into these 21st Century challenges
  – Energy models have very different methodologies, and are targeted at different research questions
  – Energy models are built, run, critiqued and applied by people

• Let’s open the black box of energy modelling
  – Energy modelling insights and policy making iteration
What are energy models?

• What models are *not*
  – A generator of research papers or consultancy funding
  – A name based on a zippy acronym
    • e.g., GREEN, BLUE; PRISM, CUBE; ALPHA, GAMMA, DELTA; ALBATROSS

• UCL-Energy’s approach to modelling
  – There will never be a universal model which will answer all questions
  – A range of models (& model linkages) are required for any given problem
  – Developing an expert/educated community of developers and users is critical
  – Models are only as good as the data you have to populate / challenge them
What is a mathematical energy model?

• A simplified imitation of the real thing
• A series of equations that together (try to) represent characteristics of a real-world system
• Based on observed and/or inferred data and insights
  – But may also rely heavily on scenario specific assumptions (especially for very long time horizons and complex systems)

Uses of a model:
• A framework for analysing the modelled system

A model is not:
• A crystal ball that predicts the future
...And an energy system model?

• Models used for system level analysis
  – Usually all main sectors included (in some form)
  – Spatial, temporal and economic interactions also considered

• Focus varies between models
  – Technology, (macro)economics, integrated assessment
  – Local, global and everything in between
  – Temporally usually from some decades to hundreds of years

• Decision environments differ
  – Social planner vs heterogeneous agents

• Common characteristic: Describe interactions and interdependencies of the components of a highly complex system
Model characterization based on...

- Economic coverage
  - Partial vs. General equilibrium
  - Top down vs. bottom up

- Environmental coverage
  - Emission coverage
  - Integrated assessment vs energy system

- Geographical coverage
  - World, country, region, city...

- Time horizon
  - Static, short, medium, long term to very long term (100-200 years)

- Purpose of the model
  - Forecasting, scenario analysis, stylized dynamics

- Foresight and uncertainty
  - Deterministic, myopic, stochastic
  - What is uncertain, how is uncertainty resolved, how does it affect results?

- Solution algorithm/approach

All of these have implications for interpreting the results.
Computable General Equilibrium models

- General equilibrium (static or dynamic)
  - e.g. EPPA, MERGE
- Focus on the economy, little detail on technology
- Consists of:
  - Tables of transaction values
  - Production function (labour, capital, materials, energy, other)
  - Elasticities for capturing behavioural responses (e.g., price, demand, trade, income elasticities etc)
- Solve model with a set of exogenous parameters (representing technology, wages, prices, and exchange rates) to bring all markets into equilibrium

Simulation models

- Partial Equilibrium (usually)
  - e.g. POLES, TIMER, GCAM
- Simulate a ‘system’ by representing the relationships between key parts of it
  - Tries to capture observed dynamics (optimisation vs. simulation)
- Based on, e.g. use of multinomial logit functions or econometric relationships
- Can include relatively much detail on technology

Optimisation models

- Optimise an objective subject to constraints
  - e.g., MARKAL, TIAM-UCL, MESSAGE
- Usually minimisation (over given time period) of costs for the energy system
- Partial equilibrium
- Prescriptive, usually “a social planner with perfect foresight” (additional constraints often used for descriptive purposes)
- Starting point the representation of a system. Then add:
  - an objective function – e.g. sum of simulated costs, to be minimised
  - specified constraints – e.g. power supply must equal or exceed demand
  - Some mathematical technique to seek the optimum (e.g. linear programming)
Model Usefulness: Quote #1

• “All models are wrong but some are useful”
  – George Box

• My alternate version
  – “Some models are right, (or at least in practice, right enough), and even the wrong ones can still be useful”
Model Complexity: Quote #2

• “entia non sunt multiplicanda praeter necessitatem"
  – "entities must not be multiplied beyond necessity"
  – William of Ockham: 1288 – 1348

• In modelling terms:
  – Simplicity-elegance-parsimony
  – Complexity as necessary
    • **BUT** energy-economic system is inherently complex
  – Problem drives modelling and analysis
Model Quantification: Quote #3

• “Model for insights, not numbers”
  – Hill Huntington, 1982

• But decision makers don’t really want insights!
  – They really want numbers
  – And they don’t deal with uncertainty very well
Building and using a model, what matters?

Some critical modelling issues

- Technology
  - Development drivers and trends, learning, surprises

- Behaviour
  - Heterogeneous agents (firms, individuals) vs. a social planner, emergence (agent based modelling?)

- Scale
  - Spatial: Local vs. national vs. global (policies, technologies, infrastructures)
  - Temporal: Months, years, decades, centuries. Surprises and responses to signals

Interpreting the model results

- What do the results mean?
  - Long term, global, perfect foresight, deterministic, social planner ≠ short term, local, stochastic, agent based
  - Interpretation highly model (and scenario) specific, requires careful consideration!

- What can they be used for?
  - Can be very useful for, for example, policy advice, but need to be communicated properly (what is covered, what is assumed)
  - Generally: Not forecasts, but insights on the system (dynamics)!

Uncertainty!
UKTM – The UK TIMES Model

- **Overview**
  - Integrated energy systems model
  - Least cost optimization
  - Partial equilibrium
  - Technology rich

- **Successor to UK MARKAL**

- Used by UCL and DECC
Components of an Energy System Model

* Energy system topology & organization

* Numerical data

* Mathematical structure
  – transformation equations
  – bounds, constraints
  – user defined relations

* Scenarios and strategies

** Energy system topology & organization

** Numerical data

** Mathematical structure
  – transformation equations
  – bounds, constraints
  – user defined relations

** Scenarios and strategies

RES

Time Series

GAMS Model

Cases

\[ P_{\text{BHKW}} = \eta_{\text{BHKW}} \cdot P_{\text{Coal}} \]
\[ O_{\text{BHKW}} = \epsilon \cdot P_{\text{Coal}} \]
\[ Q_{\text{BHKW}} = \eta_2 \cdot P_{\text{Coal}} \]
## Energy systems modelling for UK policy

<table>
<thead>
<tr>
<th>Year</th>
<th>Model Type</th>
<th>Funding</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>MARKAL</td>
<td>UKERC</td>
<td>Rapid simple structured model development</td>
</tr>
<tr>
<td>2003</td>
<td>EWP 03</td>
<td>RCEP</td>
<td>Energy Review</td>
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<tr>
<td>2005</td>
<td>EWP 07</td>
<td>CCC</td>
<td>Energy Review</td>
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<tr>
<td>2007</td>
<td>M-Macro</td>
<td>wholeSEM</td>
<td>Major 2 year UKERC programme; enhanced UK model with Macro extension</td>
</tr>
<tr>
<td>2008</td>
<td>M-ED</td>
<td>RCUK, DECC, CCC, Ofgem, NGOs, FP7</td>
<td>Elastic demand model development with major CCC and UKERC scenarios</td>
</tr>
<tr>
<td>2009</td>
<td>M-Stochastic</td>
<td>UKTM</td>
<td>Stochastic model, Global TIMES model, UKTM variants</td>
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<tr>
<td>2010-4</td>
<td>LCTP</td>
<td></td>
<td></td>
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<tr>
<td>2012-14</td>
<td>CCC Budgets 1-4</td>
<td></td>
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<tr>
<td>2015</td>
<td>Carbon plan</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Carbon budget 5</td>
<td></td>
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<tr>
<td>Year</td>
<td>Energy Policy Landmark</td>
<td>Modelling study</td>
<td></td>
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<td>------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------</td>
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<tr>
<td>1992</td>
<td>Dept. of Energy disbanded; OFGEM as independent regulator; Energy Efficiency Office created</td>
<td>Updated Emissions Projections (UEP)</td>
<td></td>
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<tr>
<td>1993</td>
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<tr>
<td>1994</td>
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<td></td>
<td></td>
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<tr>
<td>1995</td>
<td>UNFCCC negotiations; Nuclear review</td>
<td>UEP</td>
<td></td>
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<tr>
<td>1996</td>
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<td></td>
<td></td>
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<tr>
<td>1997</td>
<td>Kyoto Protocol</td>
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<tr>
<td>1998</td>
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<tr>
<td>1999</td>
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<td></td>
</tr>
<tr>
<td>2000</td>
<td>UNFCCC 3rd National Communication; Renewable electricity obligation (RO), Climate change levy (CCL)</td>
<td>UEP</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>Royal Commission on Environmental Pollution (-60% CO₂ target)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td></td>
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<tr>
<td>2003</td>
<td>Energy White Paper</td>
<td>MARKAL</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>UK emissions trading scheme; EUETS National allocation plan Phase I; Climate change agreements (CCA); Carbon Trust</td>
<td>UEP</td>
<td></td>
</tr>
</tbody>
</table>
## UK Energy Policy Timeline (2)

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy Policy Landmark</th>
<th>Modelling study</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>UKERC commissioned</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Energy White Paper</td>
<td>UEP; MARKAL-Macro</td>
</tr>
<tr>
<td>2008</td>
<td><strong>Climate Change Act (-80% GHG target)</strong>  &lt;br&gt; DECC founded. (CCC) formed and inaugural report</td>
<td>UEP; MARKAL-Macro, MDM-E3</td>
</tr>
<tr>
<td>2009</td>
<td>Scottish Climate Change Act  &lt;br&gt; Low Carbon Transition Plan for 1st, 2nd, 3rd carbon budget periods (2008-12, 2013-17 and 2018-22)</td>
<td>UEP; MARKAL spatial, AMOS</td>
</tr>
<tr>
<td>2010</td>
<td>4th carbon budget (2022-27)</td>
<td>UEP; MARKAL Stochastic, DECC Calculator, Zephr</td>
</tr>
<tr>
<td>2011</td>
<td><strong>Carbon Plan</strong>  &lt;br&gt; Green Deal; Green Investment Bank</td>
<td>UEP, Global TIAM-UCL MARKAL elastic demand</td>
</tr>
<tr>
<td>2012</td>
<td>Electricity Market Reform (CO₂ floor price, emissions standard, feed in tariff)  &lt;br&gt; Review of carbon budgets and competitiveness</td>
<td>UEP, DSIM, AMOS, MRIO</td>
</tr>
<tr>
<td>2013-</td>
<td>4th carbon budget review (2022-27)  &lt;br&gt; Review of carbon budgets and energy prices</td>
<td>UEP, TIAM-UCL, ESME</td>
</tr>
<tr>
<td>2015</td>
<td>5th carbon budget</td>
<td>UKTM, range of models</td>
</tr>
</tbody>
</table>
## UK GHG budgets

<table>
<thead>
<tr>
<th>5 year Carbon budget</th>
<th>Years</th>
<th>Budget (MtCO₂e)</th>
<th>% reduction vs 1990 levels</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2008-2012</td>
<td>3,018</td>
<td>23%</td>
<td>Achieved</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>2013-2017</td>
<td>2,782</td>
<td>29%</td>
<td>On target</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>2018-2022</td>
<td>2,544</td>
<td>35%</td>
<td>Legislated</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2023-2027</td>
<td>1,950</td>
<td>50%</td>
<td>Legislated</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>2028-2032</td>
<td>1,765</td>
<td>57%</td>
<td>Proposed by CCC in Dec 2015 (DECC response due)</td>
</tr>
</tbody>
</table>
The low-carbon transition in the UK

80% GHG emission reduction until 2050

- Reduction until 2030 mainly due to energy efficiency improvements in electricity generation & industry
- Rising consumption after 2030 can be attributed to rising electricity consumption & increasing use of biomass (partially with CCS)
- Consumption of petroleum products is more than halved
- Use of biomass and nuclear energy rises by about 5 times until 2050
Electricity generation...

2010

- Coal: 20%
- Nat. Gas: 18%
- Oil: 7%
- Biomass: 4%
- Chp: 2%
- Wind: 4%
- Other RE: 18%
- Nuclear: 18%
- Hydrogen: 34%
- Imports: 4%

Total: 339 TWh

2050

- Coal: 13%
- Nat. Gas: 14%
- Oil: 3%
- Biomass: 13%
- Chp: 6%
- Wind: 3%
- Other RE: 13%
- Nuclear: 3%
- Hydrogen: 65%
- Imports: 3%

Total: 455 TWh

...and final energy consumption

2010

- Coal: 42%
- Nat. Gas: 18%
- Oil: 4%
- Biomass: 4%
- Chp: 2%
- Wind: 4%
- Other RE: 18%
- Nuclear: 18%
- Hydrogen: 34%
- Electricity: 2%
- Imports: 4%

Total: 6487 PJ

2050

- Coal: 16%
- Nat. Gas: 16%
- Oil: 15%
- Biomass: 28%
- Chp: 24%
- Wind: 28%
- Other RE: 16%
- Nuclear: 16%
- Hydrogen: 1%
- Electricity: 24%
- Imports: 1%

Total: 5887 PJ
Emission reduction and carbon prices

GHG emissions by sector [Mt CO2eq]
- HFC
- N2O
- CH4
- CO2 - Processing
- CO2 - Transport
- CO2 - Residential
- CO2 - Industry
- CO2 - Services
- CO2 - Agriculture
- CO2 - Hydrogen
- CO2 - Electricity

Carbon price [£/t CO2eq]
- 190 £/t CO2eq

Emission reduction:
- HFC: -33%
- N2O: +20%
- CH4: -17%
- CO2 - Processing: -39%
- CO2 - Transport: -18%
- CO2 - Residential: -58%
- CO2 - Industry: -4%
- CO2 - Services: -59%
- CO2 - Agriculture: -296%
- CO2 - Hydrogen: -84%
- CO2 - Electricity: -17%

Carbon price:
- 2020: 25 £/t CO2eq
- 2025: 50 £/t CO2eq
- 2030: 75 £/t CO2eq
- 2035: 100 £/t CO2eq
- 2040: 125 £/t CO2eq
- 2045: 150 £/t CO2eq
- 2050: 175 £/t CO2eq
The impact of technology uncertainty

The reference case shows a consistent, least-cost pathway to achieve the UK’s low-carbon energy transition, but ...

**Feasibility of large-scale energy investment projects?**

- **Biomass availability?**
- **Barriers to investments in the end-use sectors?**

**Comparative scenario analysis on the reference case**

<table>
<thead>
<tr>
<th>Name</th>
<th>Alternative assumptions on technology availability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INVESTMENT</strong></td>
<td>No new investments in nuclear and CCS technologies</td>
</tr>
<tr>
<td><strong>BIOMASS</strong></td>
<td>Low biomass availability; based on CCC Bioenergy Review - Constrained Land Use Scenario</td>
</tr>
<tr>
<td><strong>BARRIERS</strong></td>
<td>Higher hurdle rate (20%) on highly efficient and innovative technologies</td>
</tr>
<tr>
<td><strong>PESSIMISTIC</strong></td>
<td>Pessimistic scenario, combination of the three cases above</td>
</tr>
</tbody>
</table>
Scenario comparison

Carbon price

REFERENCE
INVESTMENT
BIOMASS
BARRIERS
PESSIMISTIC
## Costs in perspective [All in 2010 £]

<table>
<thead>
<tr>
<th>Expenditure</th>
<th>2010 cost (B£/yr)</th>
<th>2050 cost (B£/yr)</th>
<th>per 2010 UK capita (£/yr)</th>
<th>per 2050 UK capita (£/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK GDP</td>
<td>1,400</td>
<td>3,100*</td>
<td>23,400</td>
<td>47,700</td>
</tr>
<tr>
<td>-80% GHG costs</td>
<td></td>
<td>63 – 187#</td>
<td></td>
<td>970 - 2900</td>
</tr>
<tr>
<td>Final energy consumption</td>
<td>75</td>
<td>166*</td>
<td>1,250</td>
<td>2,550</td>
</tr>
<tr>
<td>UK Bank bailout</td>
<td>500</td>
<td></td>
<td>8,300</td>
<td></td>
</tr>
<tr>
<td>Health budget</td>
<td>124</td>
<td>270*</td>
<td>2,060</td>
<td>4,200</td>
</tr>
<tr>
<td>Education budget (to 18 years)</td>
<td>58</td>
<td>130*</td>
<td>970</td>
<td>2,000</td>
</tr>
<tr>
<td>BP, Shell, Exxon profits</td>
<td>6 - 25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear decommissioning</td>
<td>46</td>
<td></td>
<td>760</td>
<td></td>
</tr>
<tr>
<td>New nuclear weapons</td>
<td>16</td>
<td></td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Public renewable energy R&amp;D</td>
<td>0.15</td>
<td></td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>
Thank you for your attention!

• Whole Systems Energy Modelling Consortium: www.wholeSEM.ac.uk

• UCL-Energy Models: www.ucl.ac.uk/energy-models