UK Energy-economic modelling

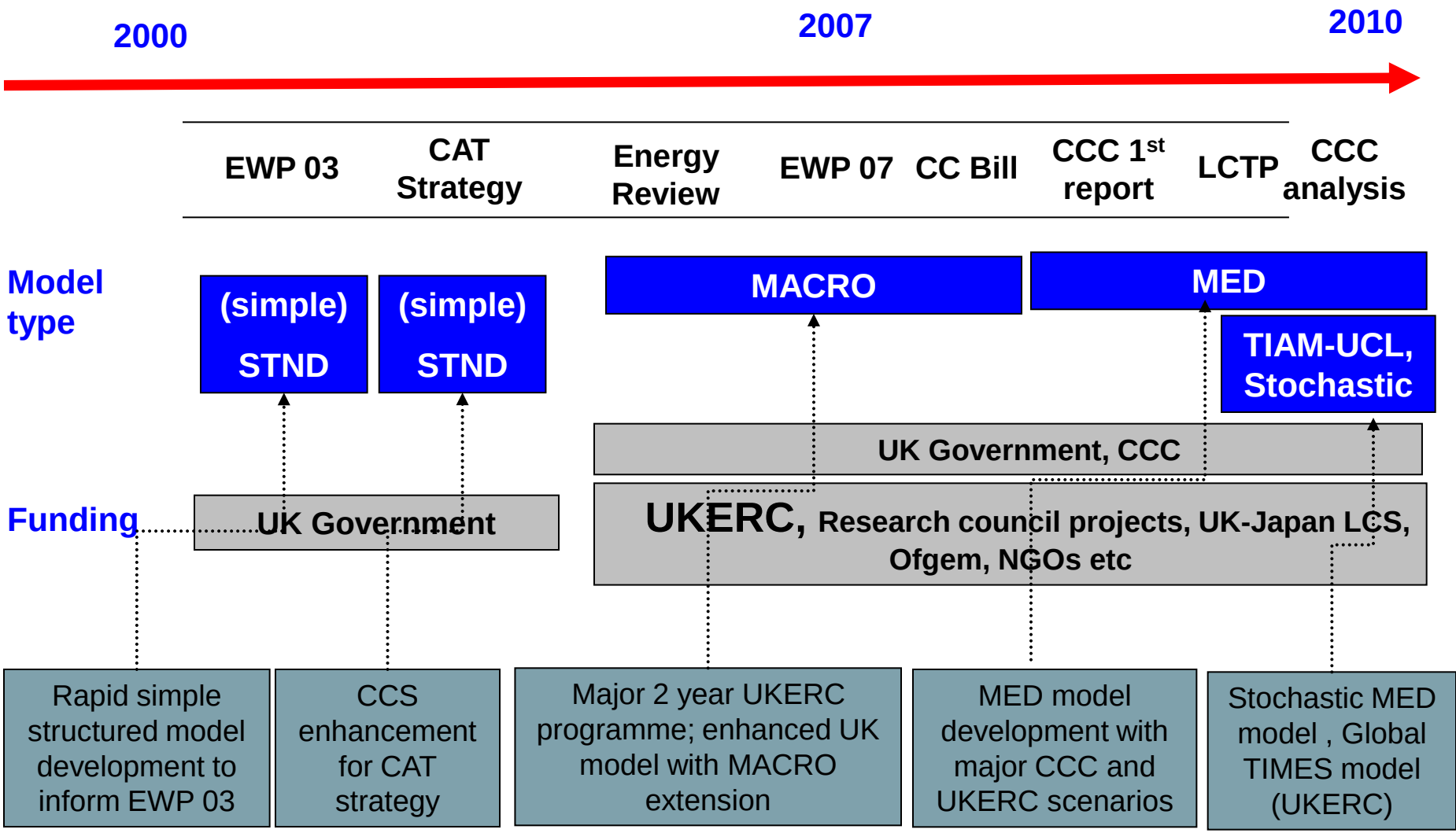
An overview of the UK MARKAL/TIMES family

Dr Neil Strachan, Dr Gabrial Anandarajah, Steve Pye, and Will Usher
n.strachan@ucl.ac.uk

UCL Energy Institute, University College London

July 2010

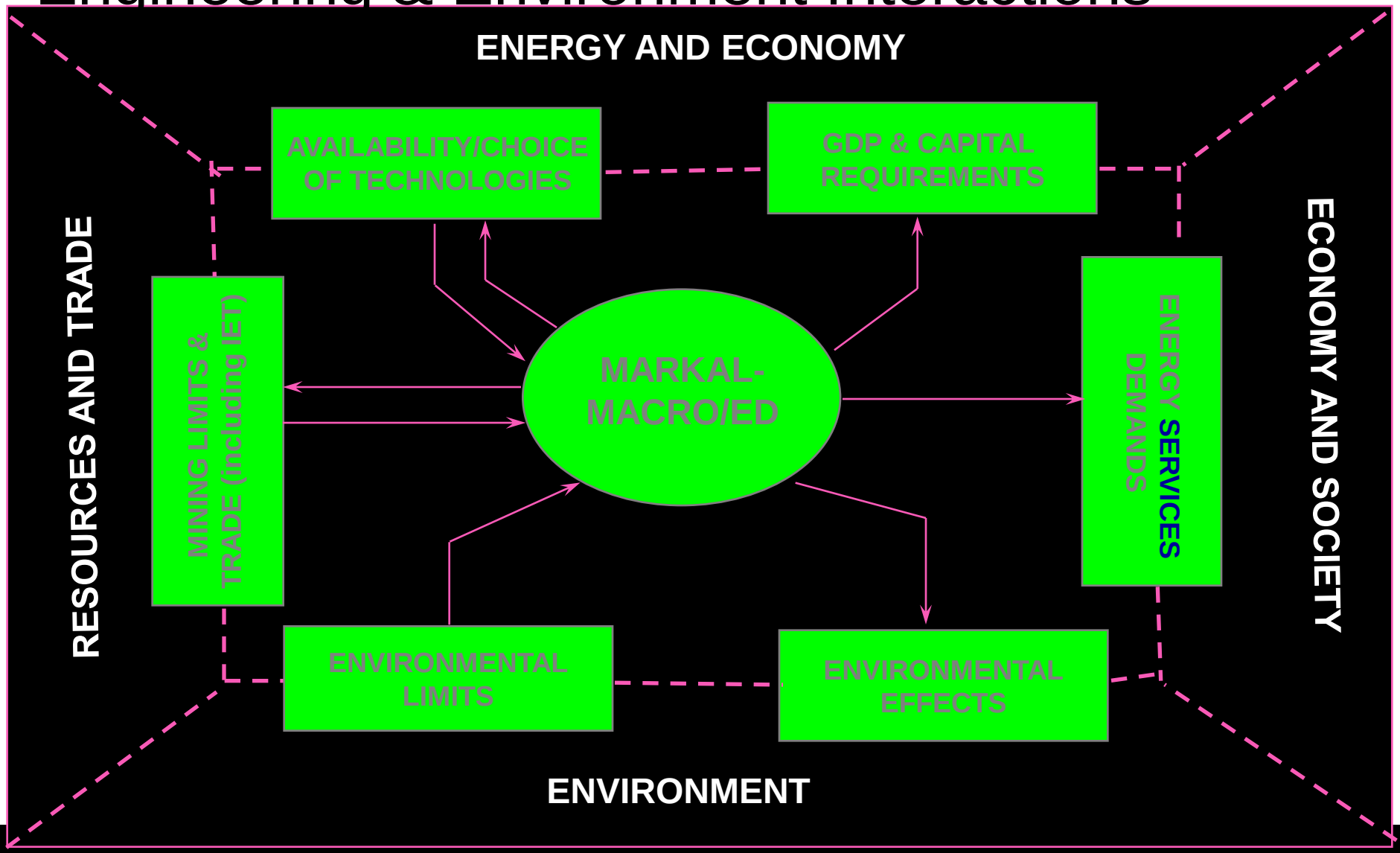
MARKAL/TIMES modelling for UK policy



Thinking on E4 modelling

- "*All else being equal, the simple answer is the correct one*" (*or all else being equal, the simplest model is the best one*). William of Ockam, 12th century
- "*All models are wrong but some are useful*". George Box, 1979
- "*Model to generate insights, not numbers*". Hill Huntington, 1982

Assessing Energy, Economy, Engineering & Environment Interactions



Model typology and examples

UCL-EI models in **bold**

- Macro-economic interactions (top-down)
  - General equilibrium (CGE) – SAM plus production functions (capital, labour, energy etc), dynamic assumptions etc (e.g., SGM, **GEM-E3** etc)
  - Macro-econometric models (e.g., E3MG)
- Technological detail (bottom-up)
  - Optimisation models, partial equilibrium (e.g., **MARKAL**, MESSAGE. **Osemosys** etc)
  - Simulation (including econometric) models (e.g., NEMS, POLES)
- Microeconomic behaviour
  - Sectoral; e.g. transport (time – NTM), electricity (regulation – WASP)
  - Non rational/perfect behaviour-markets-information (e.g., CIMS, **Anderson**)
- Hybrid models – “elephant and the mouse”
  - Top-down with technology (e.g., EPPA etc)
  - Bottom-up with price, macro responses - (e.g., **MARKAL**, MERGE, CIMS)
- Integrated assessment (**TIAM**, GCAM etc)

UK MARKAL-TIMES Family

- Standard MARKAL
  - Energy system optimisation
- MARKAL-MED
  - Full partial equilibrium with detailed demand response
- MARKAL-Macro
  - General equilibrium
- Stochastic MARKAL
  - Stochastic programming
- MARKAL-GIS
  - Infrastructure focus (e.g. H_2); mixed integer
- MARKAL 2-Region
  - England-Scotland
- TIAM-UCL
  - Global model (16 region); Integrated Assessment
- Other variants (e.g., local air pollutants, material flows, MGA, goal programming)

Overview of UK MARKAL model family

- A **least cost optimization** model based on life-cycle costs of competing technology pathways (to meet **energy demand services)**
  - **Alternate specifications of objective function**
- **Partial equilibrium** model assuming rational decision making, perfect information, competitive markets, perfect foresight
- **Technology** rich bottom-up model
  - end-use technologies, energy conversion technologies, refineries, resource supplies, infrastructures etc
- An **integrated energy systems** model
  - Energy carriers, resources, processes, electricity/CHP, industry, services, residential, transport, agriculture, emissions, taxes, demands
- Physical, economic and policy **constraints** to represent UK energy system and environment
- Model and data **validation**
- Emphasis on **sensitivity and uncertainty analysis**
- **Variant Extensions**

Running the UK MARKAL models

- Objective function
  - MARKAL minimises discounted energy system costs
  - M-M maximises overall discounted utility
  - MED maximises total societal welfare (producer & consumer surplus)
- Initial calibration to UK energy system in year 2000
  - Depiction of existing infrastructures, installed energy technologies, current policies, physical constraints
  - Calibration for final energy, CO_2 emissions & electricity generation
- Model then optimizes in 5-year time steps through to 2050
  - Changing energy resources supply curves
  - Exogenous trends in energy service demands
  - Changing technology costs (vintaging & exogenous learning curves)
  - Physical and policy constraints
  - Taxes and subsidies
  - (And in M-M, MED) varying energy service demands
- A full range of scenarios and sensitivity analysis is carried out in a systematic ‘what-if’ framework

Key input and output parameters

1. **System configuration** - potential energy pathways and interactions
2. **Resource supply curves** - imports and domestic production
3. **Energy service demands** - to a detailed sub-sectoral level
4. **Technology characterisation** - capital costs, O&M costs, efficiencies, availabilities etc
5. **Constraints** – physical and policy driven

- Total and annual energy system costs
- Primary energy, final energy - by sector and/or by fuel
- CO_2 - by fuel, sector; marginal emissions prices
- Imports, exports & domestic production of fossil & renewable fuels
- Electricity generation mix– by fuel and by technology
- Transport fuels, transport technology by mode
- Use of conservation, efficiency
- **MED -** Behaviour change in individual demand services, welfare
- **MARKAL-Macro (M-M) -** GDP, consumption, investment, energy costs
- **Stochastic** - hedging and recourse strategies
- **TIAM-UCL** - emissions trading, endogenous learning, fossil fuel resource pricing

Model documentation

- All online at www.ukerc.ac.uk
  - Full module-by-module documentation
  - Peer review (ECN Netherlands)
  - Stakeholder engagement
- Peer reviewed publications include:
  - Anandarajah G., and N. Strachan (2010) *Interactions and Implications of Renewable and Climate Change Policy on UK Energy Scenarios*, Energy Policy, in press
  - Jablonski S., N. Strachan, C. Brand and A. Bauen (2010), *The Role of Bioenergy in the UK's Energy Future: Formulation and Modelling of Long-Term UK Bioenergy Scenarios*, Energy Policy, in press
  - Strachan N., S. Pye and R. Kannan (2009) *The Iterative Contribution and Relevance of Modelling to UK Energy Policy*, Energy Policy, Vol. 37, No. 3, pp. 850-860
  - Strachan N., N. Balta-Ozkan, D. Joffe, K. McGeevor, and N. Hughes (2009) *Soft-Linking Energy Systems and GIS Models to Investigate Spatial Hydrogen Infrastructure Development in a Low Carbon UK Energy System*, International Journal of Hydrogen Energy, Vol. 34, No. 2, pp. 642-657
  - Kannan R. and Strachan N. (2009) *Modelling the UK Residential Energy Sector under Long-term Decarbonisation Scenarios: Comparison between Energy Systems and Sectoral Modelling Approaches*, Applied Energy, Vol. 86, No. 4, pp 416-428
  - Strachan N. and R. Kannan (2008) *Hybrid Modelling of Long-Term Carbon Reduction Scenarios for the UK*, Energy Economics, Vol. 30, No. 6 pp. 2947-2963
  - Strachan N., S. Pye and N. Hughes (2008) *International Drivers of a UK Evolution to a Low Carbon Society*, Climate Policy, Vol. 8, S125-S139
  - Anandarajah G., P. Ekins and N. Strachan (2010) Chapter 5: Pathways to a low carbon future, Energy 2050: the transition to a secure low carbon energy system for the UK, Eds P. Ekins, J. Skea, M. Winskel, Earthscan
  - Strachan N. and J. Skea (2010), Chapter 11: UK energy change in an uncertain world: fuels, resources and carbon, Energy 2050: the transition to a secure low carbon energy system for the UK, Eds P. Ekins, J. Skea, M. Winskel, Earthscan
  - Kannan R, Ekins P. and N. Strachan (2008) The Structure and Use of the UK MARKAL Model, chapter 12 in International Handbook on the Economics of Energy,(eds) L. Hunt and J. Evans, Edward Elgar Publishing, pp 285-310.

MARKAL v 3.21 (end 2008)
Key updates for UKERC Energy 2050

- Updated energy service demands
  - e.g., residential non-cost drivers from UKCDM model
- Energy service demand elasticities from modelling literature
- All existing policy measures as of 2007 are implemented
  - RO, RTO, CCL, EU-ETS, CERT etc
- Resource costs in line with IEA & BERR 2008 revisions
- 10% global discount rate and technology specific 'hurdle' rates
- Range of model improvements:
  - Expanded categorisation of UK CCS and wind resources;
  - New biomass and new hydrogen chains;
  - Improved treatment of electricity intermittency;
  - Buildings technology updates (micro-CHP and heat pumps);
  - Transport technology updates (plug-in hybrid electric vehicles);
- Calibrated base year (2000) to DUKES data

MARKAL v 3.24 (end 2009)

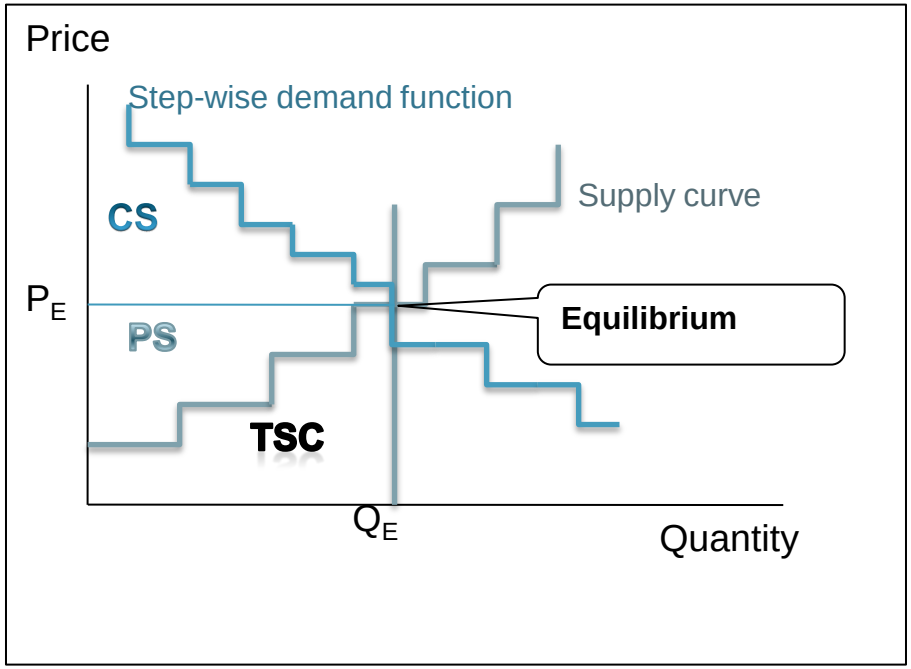
Key updates for CCC 4th budget assessment analysis

- UK MARKAL recalibrated to updated 2000 data
  - NAEI – for CO_2 emissions
  - DUKES – for energy balance
  - New non energy sector
- Build rate constraints
  - Pre- and post-2030: CCS, nuclear, distributed generation, large coal, natural gas CCGT, hydrogen production, wind, marine
- Discounting (to 5%), and reduced hurdle rates
- Resources
  - CCC 2009 fossil fuel prices
  - Biomass supply chains
- Transport
  - International & domestic aviation energy service demands updated
- Electricity and Heat
  - EU electricity imports
  - Biomass CCS
  - Improvements to characterisation of renewable heat and CHP & district heating technology
  - CCS updated storage potential and costs
  - CCS retrofits
  - Less optimistic on costs and efficiencies for coal plant and coal CCS plant
- Industry
  - Increased flexibility in subsectors fuel and process substitution
  - Reduced ESD floors
- Residential and services
  - Updated heat pump data and constraints

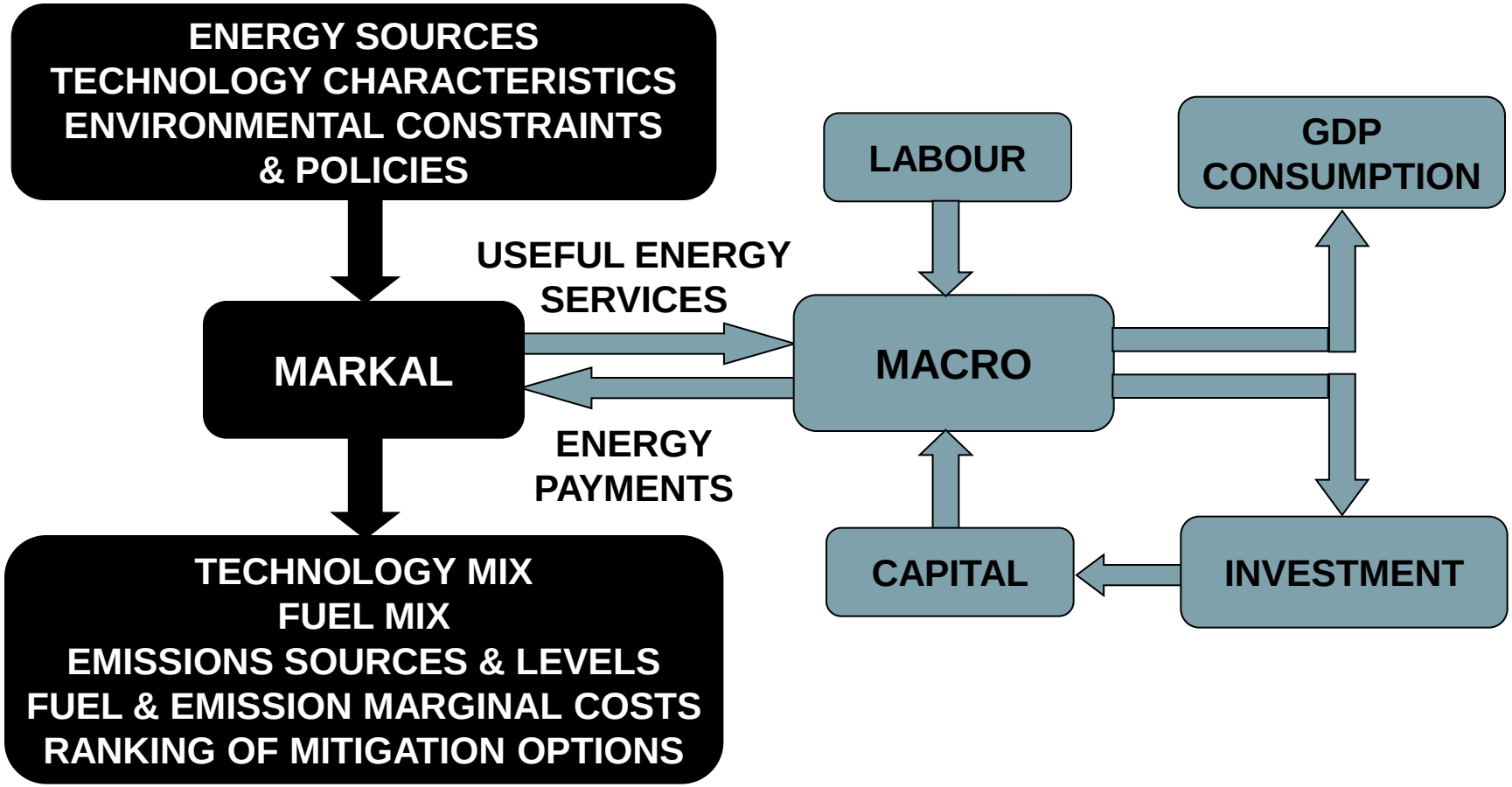
UK MARKAL and UK MED

- Standard MARKAL optimises (minimises) discounted energy system cost
  - Annualized capital costs (technologies & infrastructures), resource costs, variable costs, taxes, salvage values
  - Minimisation over: regions (r), time periods (t), seasons (s), demands (d), technologies (k), commodities (c), emissions (p), resource levels (l)
  - s.t.: meet energy service demands, capacity constraints, commodity balances, electricity and heat peaks, seasonal availability
  - s.t: wide range of user defined constraints
- Initial calibration to UK energy system in year 2000
  - Solves through 2050 based on technological change, demand changes, resource prices, taxes, policies etc

- MARKAL Elastic Demand
- Endogenous energy service demands
- Own price elasticity: $(D/D_0) = (P/P_0)^{-E}$
- Hence MED maximises total societal welfare (producer plus consumer surplus)



UK MARKAL Macro (M-M) model



M-M equations

$$
\begin{aligned}
UTILITY &= \sum_{t=1}^{T-1}(udf_t)(\log C_t) \\
&\quad + (udf_T)(\log C_T)/[1-(1-udr_T)^{ny}], \\
udf_t &= \prod_{\tau=0}^{t-1}(1-udr_\tau)^{ny}, \\
udr_t &= (kpvs)/(kgdp) - depr - grow_t,
\end{aligned}
$$

$$
PRD: \quad
\begin{aligned}
& Y_t = \left[akl(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum b_{dm}(D_{dm,t})^{\rho}\right]^{1/\rho}, \\
& L_0 = 1, \quad L_t = (1+grow_{t-1})^{ny}L_{t-1}, \\
& \alpha = kpvs, \\
& \rho = 1 - 1/ESUB,
\end{aligned}
$$

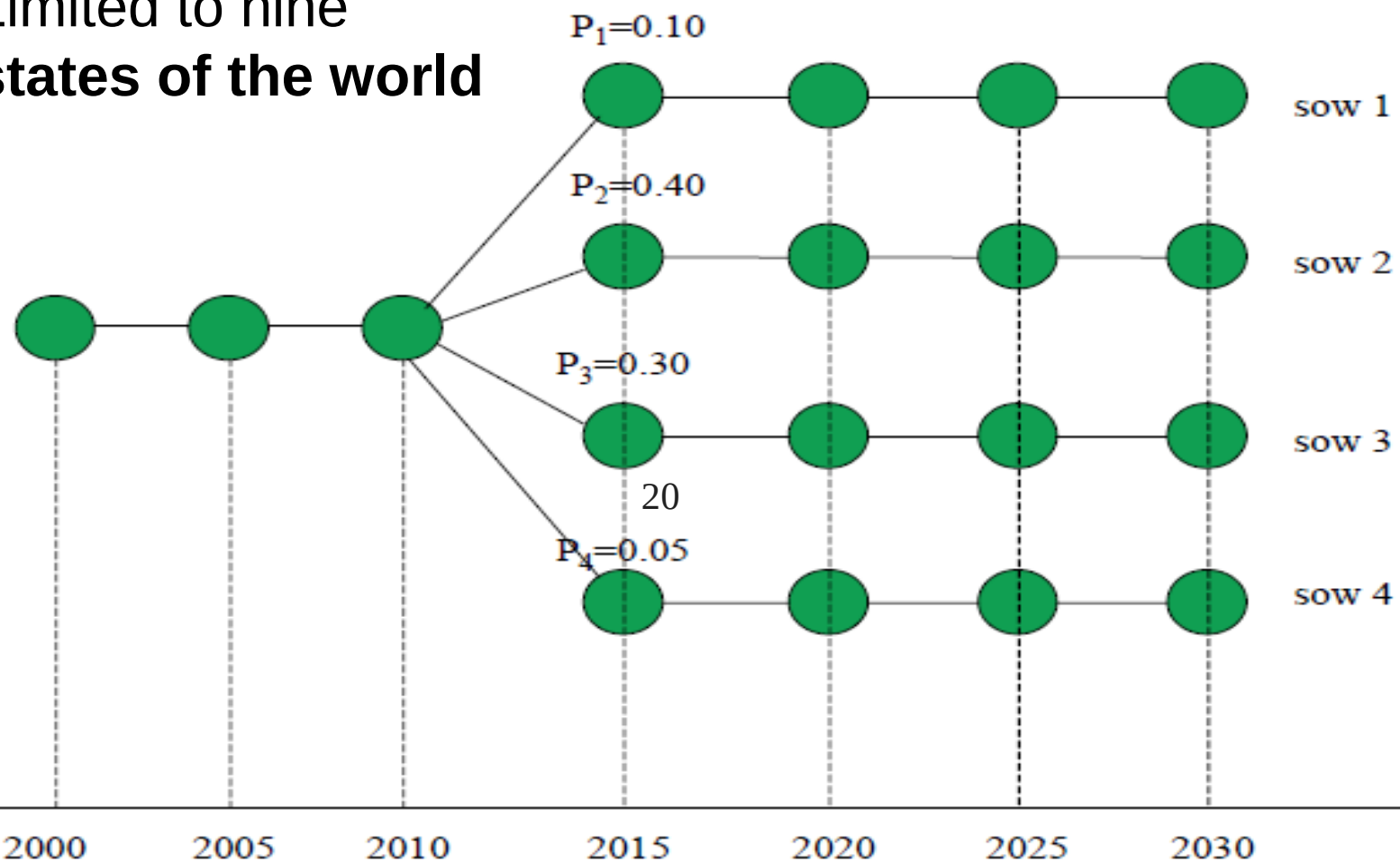
$$USE: \quad Y_t = C_t + I_t + EC_t,$$

$$
CAP: \quad
\begin{aligned}
& K_{t+1} = tsrvK_t + (ny/2)(tsrvI_t + I_{t+1}), \\
& tsrv = (1-depr)^{ny}, \\
& I_0 = (grow_0 + depr)K_0,
\end{aligned}
$$

$$TC: \quad K_T(grow_T + depr) \leqslant I_T.$$

Stochastic MARKAL decision tree

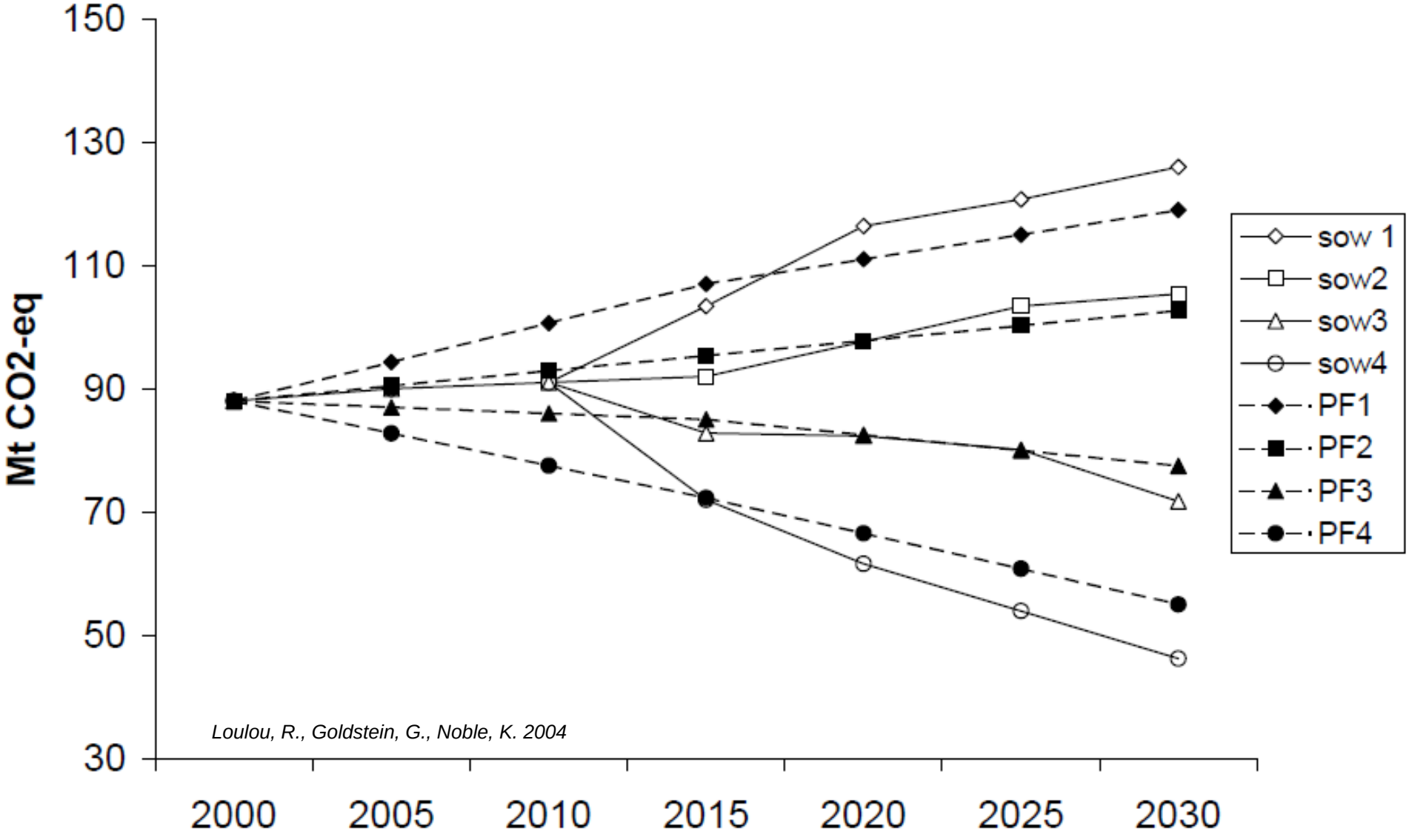
- Two stage programming
- Limited to nine **states of the world**



Stochastic MARKAL overview

- A different Objective Function
  - $Expected\ Cost_{Scen} = \sum(Cost_{SOW} * Prob_{SOW})$
- Stochastic programming as one method to account for uncertainty
  - What decision will perform well on average?
  - What are the robust technologies under uncertainty?
- Results include:
  - ONE Hedging strategy
  - MULTIPLE Recourse strategies (one for each SOW)
- Expected Cost of a scenario
  - Sum of all probability weighted costs of the hedging strategy and future states of the world
  - Alternative formulation via expected utility

Stochastic example: GHG emission trajectories



TIAM-UCL
IEA-ETSAP TIMES Integrated Assessment Model

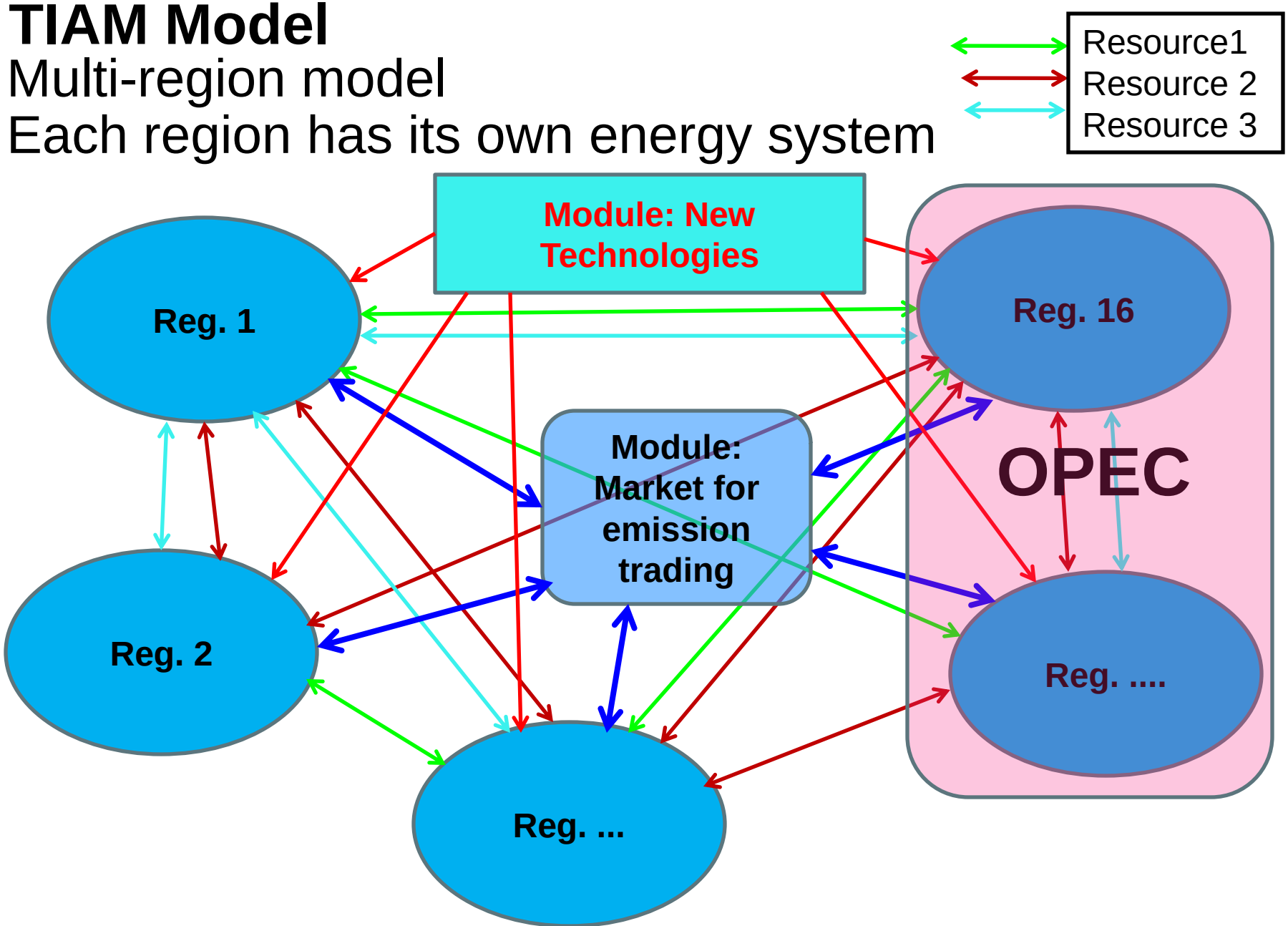
- Global partial-equilibrium LP optimisation model
- Objective function – minimise global welfare costs
  - Annualised capital costs, O&M costs, fuel costs, taxes/subsidies, salvage values, demand changes
- 16 regions, including explicit UK region
- Flexible time horizon through to 2100
- Whole energy system
  - Technological and sectoral completeness
- Multi-emissions, plus reduced-form climate module
- Initial UCL research priorities
  - Global climate architectures and emissions trading
  - Resource flows (oil and gas markets)
  - Endogenised technological change

16R TIAM-UCL Model Development

- ***Note this is a HUGE model – it pushes practical modelling limits***
- Fully calibrated 16R TIAM-UCL model
  - IEA data (base year is 2005)
  - Elastic demand version enabled
- Updated scenario files
  - Resources, technologies, demand drivers, demand elasticities
- Implementation of climate change mitigation policies
  - Emissions tax, cap-and-trade
- Data management and results reporting
  - VEDA FE, VEDA BE
- 16R TIAM-UCL global model under testing
  - Results at June 2010 UKERC Assembly
- Conference papers being written
  - Carbon tax vs. cap-and-trade: Implications on developing countries emissions
  - The UK energy system in an uncertain world: Insights from different modelling scales
  - Global climate change mitigation: What is the role of demand reduction?

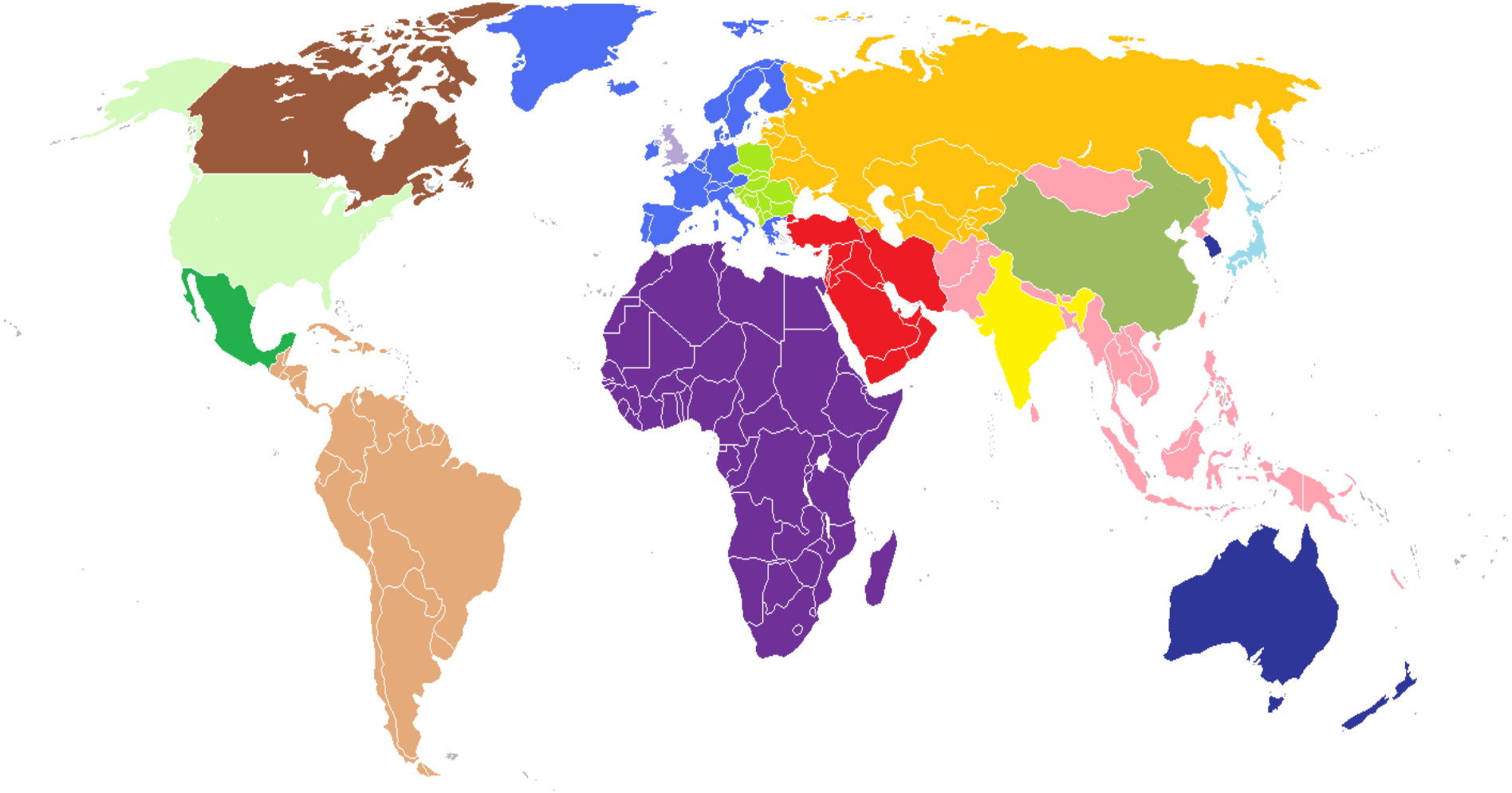
TIAM Model

- Multi-region model
- Each region has its own energy system



Regions in 16R TIAM model

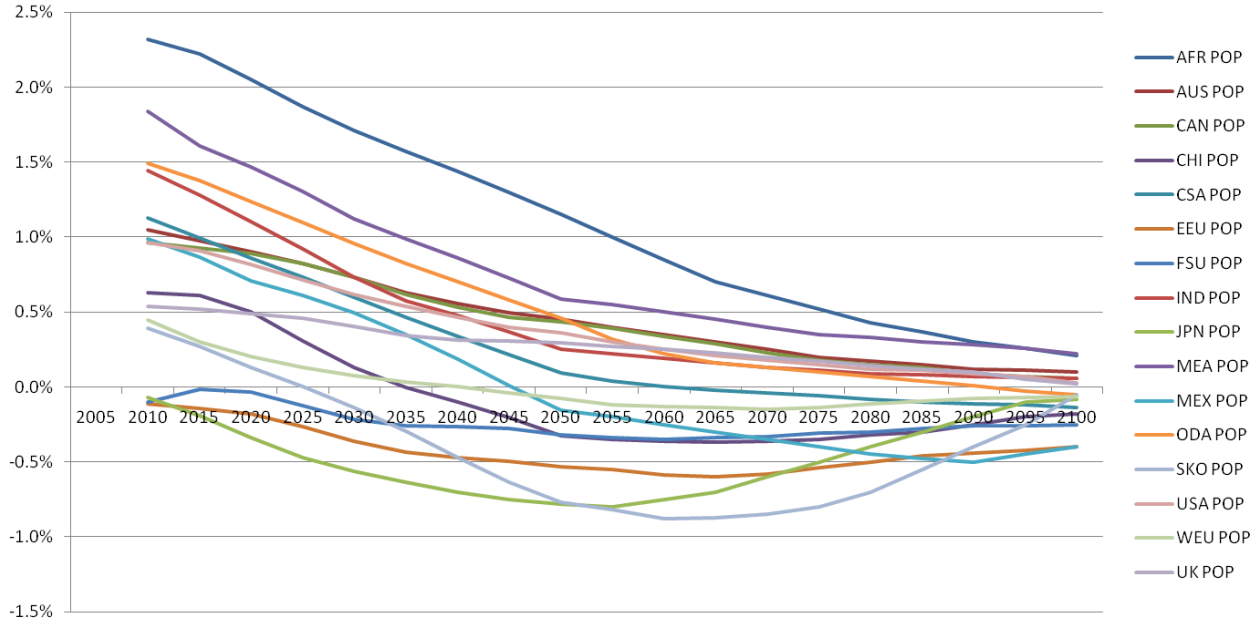
Regions: Africa, Australia, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United Kingdom, USA, Western Europe



Example of deep structural and parametric uncertainties:
Energy service demands in TIAM-UCL

- Exogenous base year energy service demands
  - Transport, residential, services, industry, agriculture, other sectors
- Energy services demand for future years is projected
- Drivers: GDP, population, Number of household, GDP/P, sectoral output, etc
  - $Demand_t = K*(Driver_t)^{elasticity}$

- Large uncertainties over long-term global drivers
  - e.g., projections of annual population growth rates



MARKAL
(Selected Advantages and Disadvantages)

- Advantages
  - Well understood least-cost modelling paradigm (efficient markets)
  - International support network through the IEA's ETSAP network
  - Interactions within entire energy system
  - Transparent framework and assumptions on data, constraints etc
- Disadvantages [and remedies]
  - MARKAL is data intensive (characterization of technologies and RES)
    - Data sharing and collaboration improving the situation
  - Results sometimes sensitive to small changes in data assumptions
    - Stepped supply curves and market share algorithms
  - Limited ability to model behavior
    - Growth constraints, "hurdle" rates, demand elasticities (MED)
  - Limited representation of economic impact of energy policy
    - MARKAL Macro and other linkages
  - Spatial and temporal aggregation
    - Linkages to GIS frameworks (DfT Horizons), multi-region models

Advantages of TIAM-UCL global model

- Energy and climate policies (carbon tax, cap-and-trade) for a region or a group of regions or at global level
- Regional marginal CO_2 abatement cost (depends on cap-and-trade policy and emission trading)
- Endogenous (global) technology learning
- Climate module
  - Limit the atmospheric CO_2 concentration
  - Limit the temperature changes

Disadvantages

- Very complex
- Less detailed energy system (UK)

Model ‘hardlinking and soft-linking

- Hard-linking models for continuous operation
  - MARKAL-Macro
  - TIAM-UCL integrated assessment
  - (But always reduced form depictions)
- Soft-linking capture best aspects of models at achievable analytical time and cost
  - Data availability?
  - Generate new insights?
  - Examples
    - MARKAL MED and UKDCM - Energy 2050
    - MARKAL MED and MRIO – indirect emissions
    - MARKAL and GIS – infrastructure and resources
    - *MARKAL MED and MDM-E3 – detailed energy-economic hybrid*

Closing thoughts

- UCL-EI are modelling omnivores!
- Range of model types
- Key model issues
  - technology, behaviour, scale, time, uncertainty, economic linkages, environmental linkages
- Model to generate insights