Energy-economic modelling of UK energy scenarios

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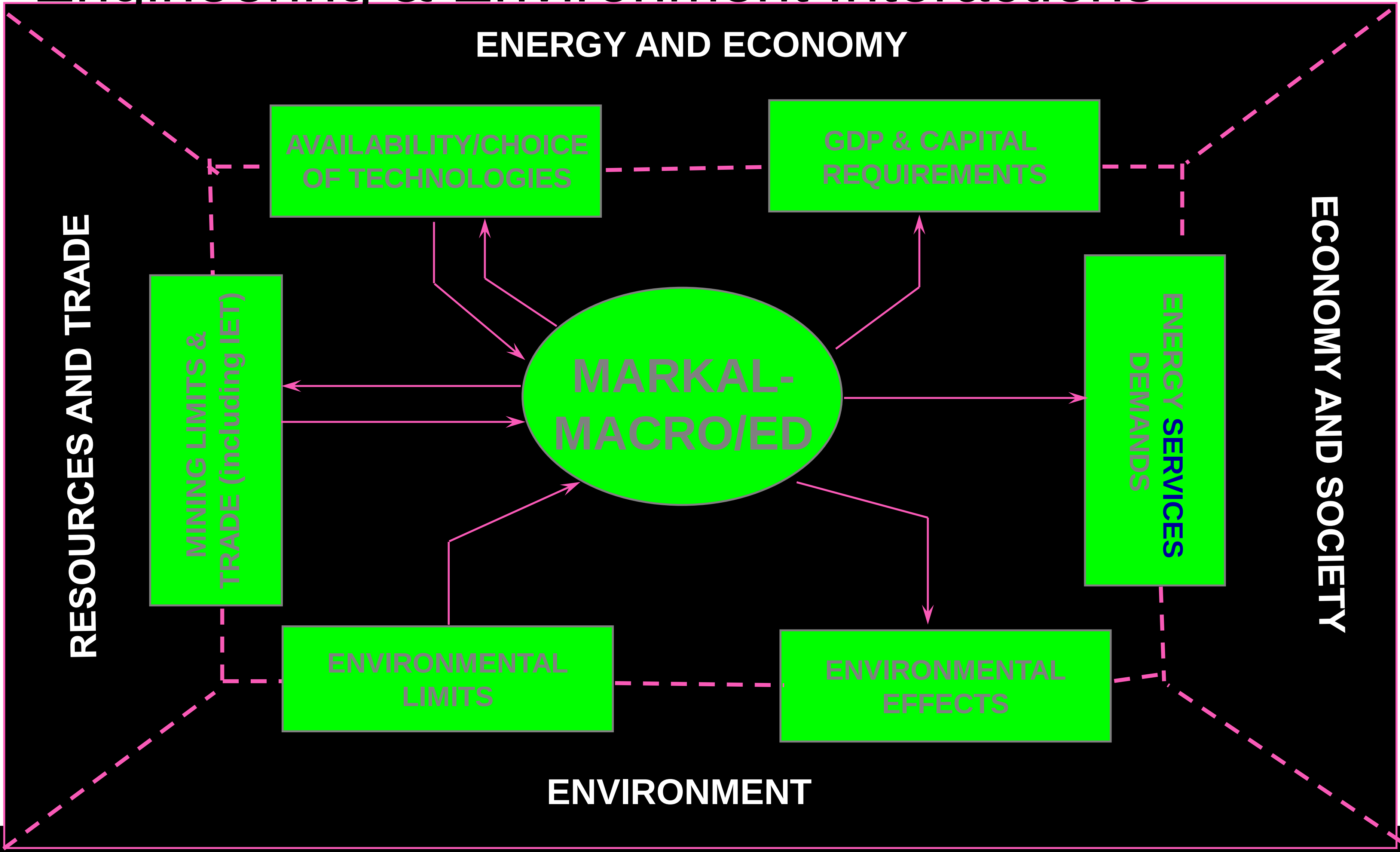
Seminar Overview

- Abstract
  – This talk will explore energy-economic modelling of long term UK energy scenarios, with particular emphasis on the core policy goals of decarbonisation and energy security.
- Outline
  1. Overview of E4 modelling
     - Energy-Economic-Engineering-Environment
  2. Overview of UK MARKAL model family
  3. Modelling-Policy Output –
     - MARKAL-Macro and the Energy White Paper 2007

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
- *“As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know”.* Donald Rumsfeld, 2002

Assessing Energy, Economy, Engineering & Environment Interactions



What is a mathematical model?

- … a simplification of reality
- … a series of equations that either solve a real-world problem or represent a physical phenomenon
- ...based on observed and/or inferred data and insights

Uses:

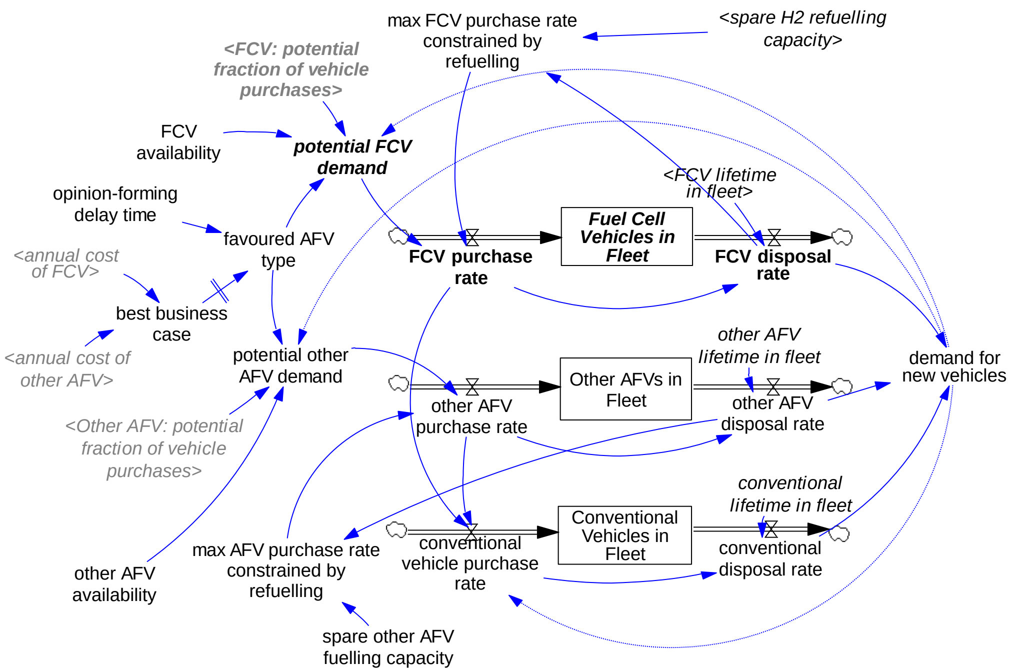
- Predictive: used to predict the future; requires calibration.
- Interpretive: Used as a framework for analysing a system and/or organizing field data; may not require calibration

- A model generally contains only the significant features or aspects of the system in question
- Two models of the same system or phenomenon may differ quite significantly.

Modelling stages:
e.g., London H_2 demand prediction (Hart et al.)

(1) Conceptual model

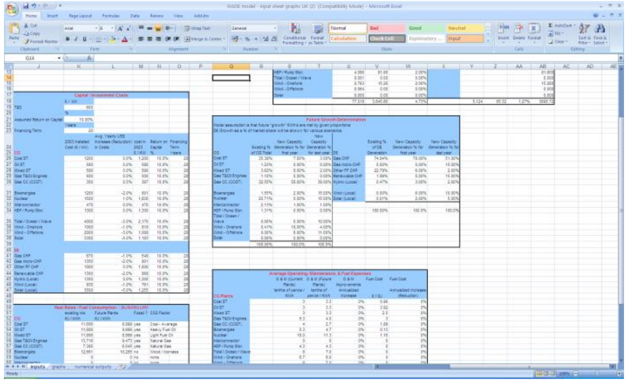
Fleets View



(2) Write equations

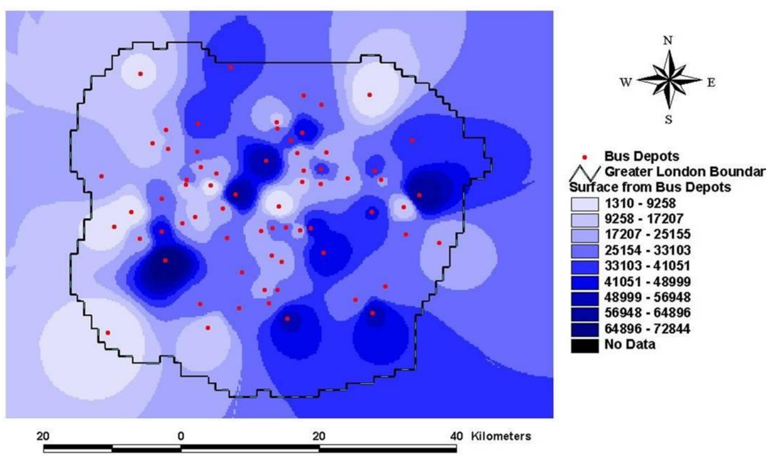
FC vehicles in Fleet (t) = FC vehicles in Fleet (t-1)*Purchase rate*(1-Disposal rate)

(3) Programme in software (e.g. Excel)



(4) Interpret results

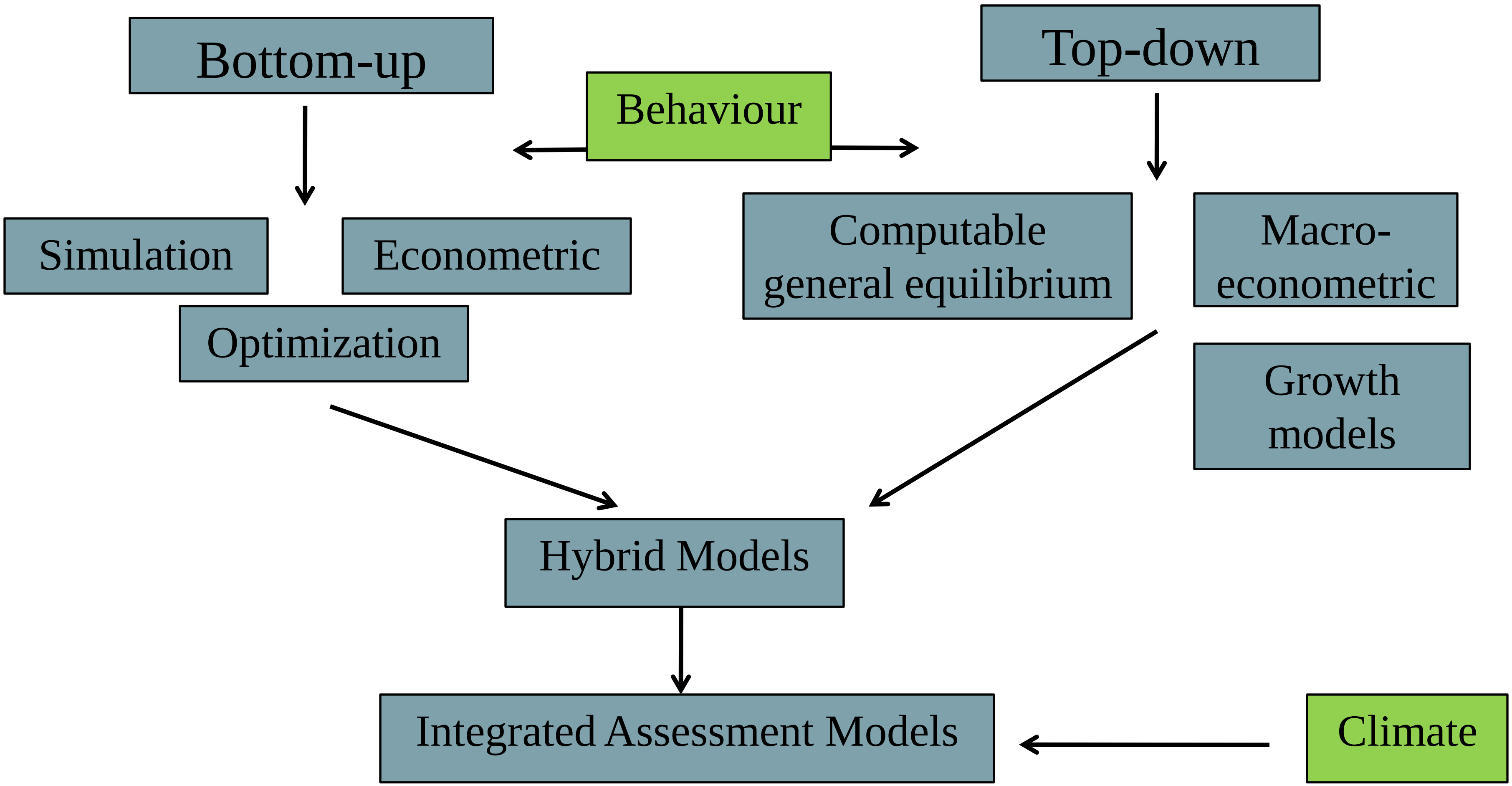
Hydrogen Demand (interpolation)



Model typology and examples

- 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 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)
- 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)

Energy Modelling typology



Always a trade-off in model type, focus and implementation

Top-down

- Macro-economic approaches
- Originally, had little detail on energy-consumption side of economy
- Technologies dealt in aggregate in production function
- A general equilibrium framework which addresses the feedback between the energy sector and other sectors

Bottom-up

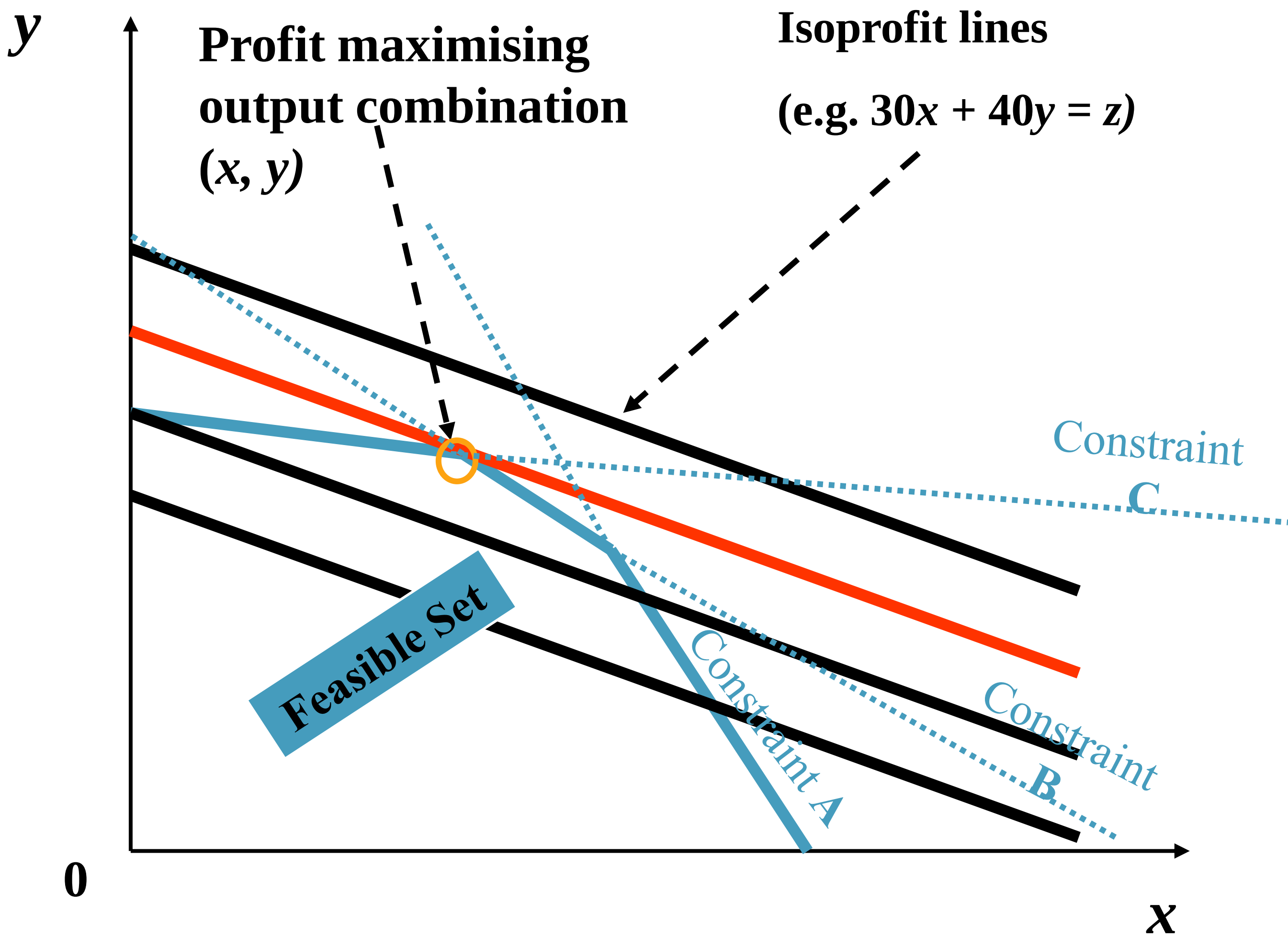
- Engineering approaches
- Focuses on how energy is supplied and used
- Rich technological detail
- Previously generated relatively lower mitigation costs
- Focus on detailed analysis of technical and economic dimensions of specific policy options

Optimisation models

- Seeking to optimise some goal or objective (termed the 'objective function') subject to specified constraints
  - Many examples – e.g., MARKAL, TIAM-UCL, Osemosys, ETI-ESME
- Two common types:
  - Minimisation (over given time period) of costs for energy supply system in meeting demands for a sector or region
  - Optimisation in operation of an energy system (e.g., electricity systems dispatch – e.g. use of merit order for least-cost operation*)*
- Starting point is just a representation of a system (i.e., a simulation). Then add in:
  - 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 minimum or maximum (e.g. linear programming)

Optimisation example

- A firm produces X and Y which yield a profit of £30 and £40 per unit respectively
- The firm wants to find the combination *(x, y)* that <u>maximises</u> its daily profit but that is also <u>feasible</u> with its three departments:
  - Max $30x + 40y$ (daily profit)
  - Subject to
    $3x + 2y \leq 44$ (A)
    $x + y \leq 16$ (B)
    $x + 2y \leq 24$ (C)



Simulation models

- Partial Equilibrium (usually)
- Most common type of energy model
- e.g. POLES
- Attempting to simulate a ‘system’ of interest by representing the relationships between key parts of it
  - Usually used to simulate future developments (e.g. IPCC)
- Can range from simple relationships between a few ‘actors’ or factors of interest
  - e.g., demand for energy = Some function of GDP and population (an econometric function, as previously)
- To complex representations of many factors interacting
  - e.g. ‘System Dynamics’, or ‘Reference Energy Systems’
- And can seek ‘general or partial equilibrium’ (where inputs are automatically adjusted to be consistent with calculated outputs) or rely on external manipulations to make inputs & outputs consistent

Econometric models

- Use of statistical techniques applied to determine parameter values based on analysis of historical relationships with other (input) parameters
  - Most commonly used for demand projections, based on parameters such as population, incomes, assumed technical progress (AEEI)
  - Are in essence simulation models
  - Typically use Regression to determine influence of a set of parameters on the dependent variable
- Range from simple models with few parameters to those with many variables (e.g., energy sources, sectors, energy uses etc)
- Usually requires long historical time-series of data for all input parameters

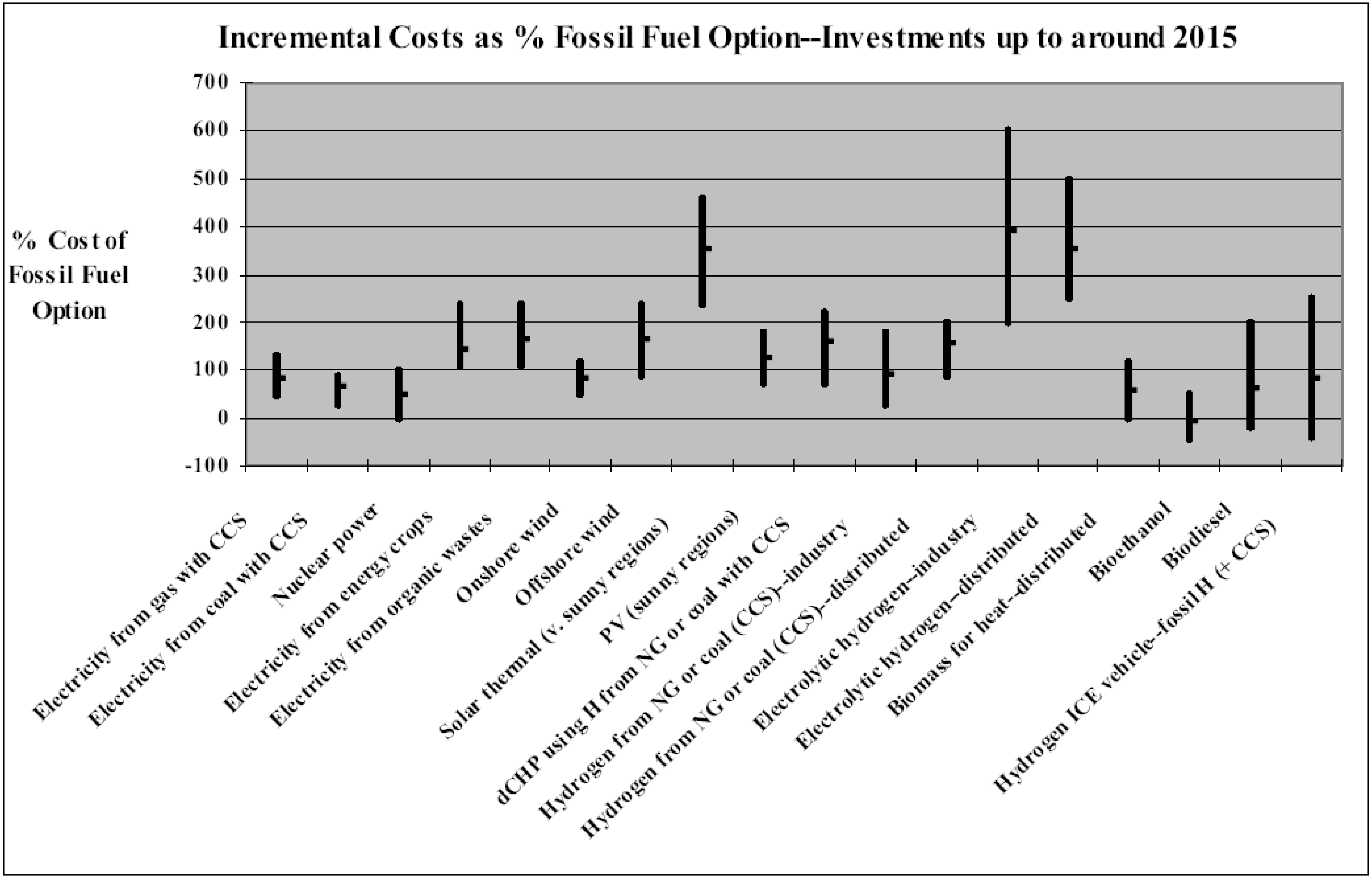
CGE models

- General equilibrium (static or dynamic)
- Many examples – EPPA, MERGE, SGM, AIM etc
- A CGE model consists of:
  - Tables of transaction values, input-output table or as a social accounting matrix.
  - Production function (labour, capital, materials, energy, other)
  - Elasticities: dimensionless parameters that capture behavioural response (e.g., price, demand, trade, income elasticities etc)
- Include government and foreign trade, use equations that specify supply and demand behaviour.
- Solve model with a set of exogenous (external) parameters (technology, wages, prices, and exchange rates) to bring all markets into equilibrium
- Not able to provide insights into the adjustment process between equilibrium
- Parameter are only partially statistically or econometrically calibrated (i.e., they are selected to fit one or few years of data)

Five critical modelling issues

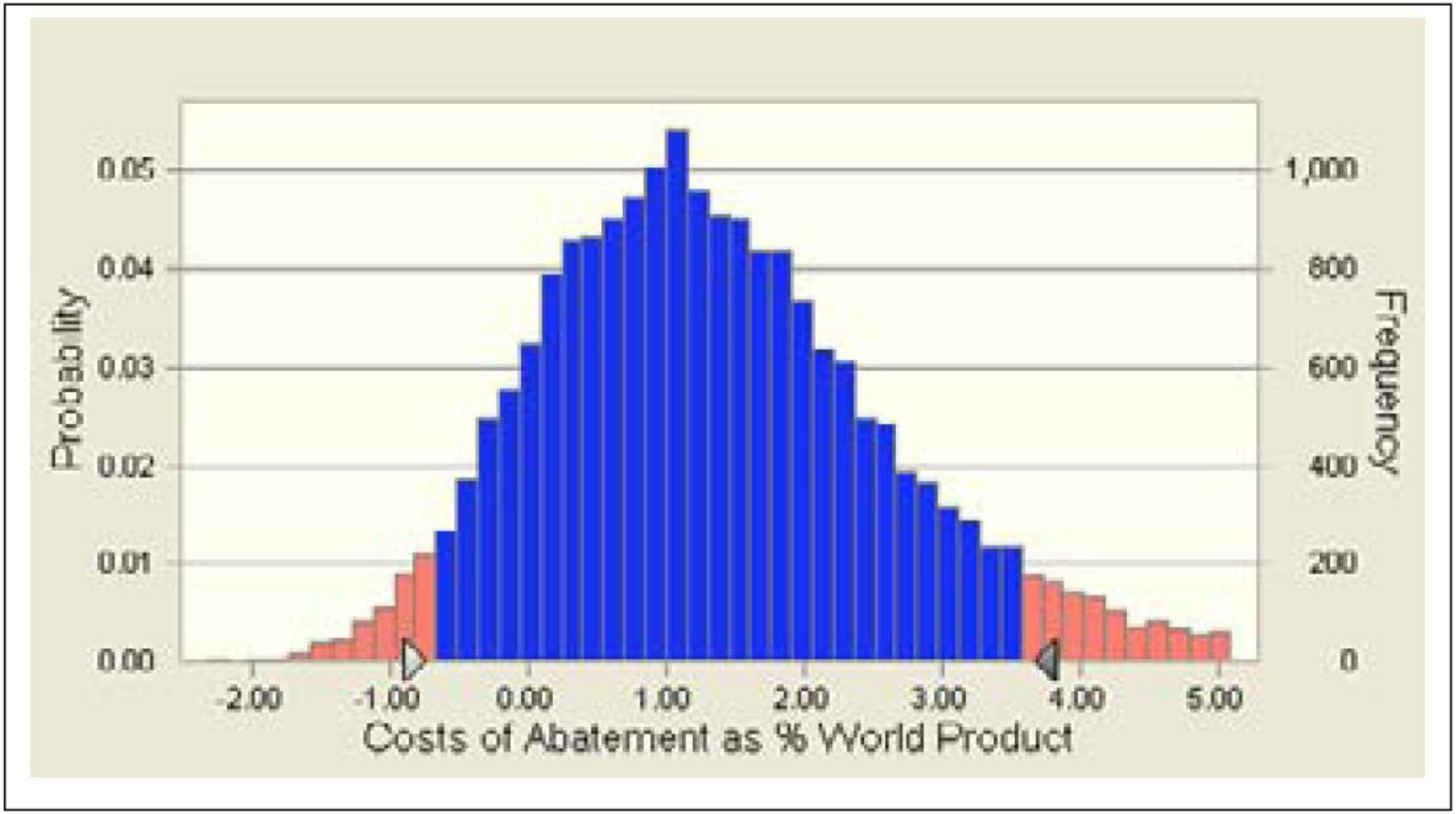
- Technology
  - Global drivers; national applicability; niche markets
  - Economies of scale, of learning, of scope
- Behaviour
  - Firms vs. individuals
  - Profit maximising and non price drivers?
  - Role of the state
- Scale
  - Global drivers vs. (EU) National policies vs. local planning vs. individual use
- Time
  - Instantaneous vs. short-, long- and very long-term
  - Non marginal changes (sideswipes)
- Uncertainty
  - Parametric – imperfect knowledge
  - Stochastic – inherent variability
  - Transparent model assumptions and dynamics

Sensitivity analysis of uncertainty
- range of cost estimates for mitigation options



Monte Carlo simulation analysis of uncertainty

- leads to probability distribution in modelled results



Definition of (E4) energy models

Energy-economic models are systematic tools to generate insights into the potential evolution of the energy system, and its interactions with the overall economy and the environment

But: E4 modelling as Science or Art or Both ?

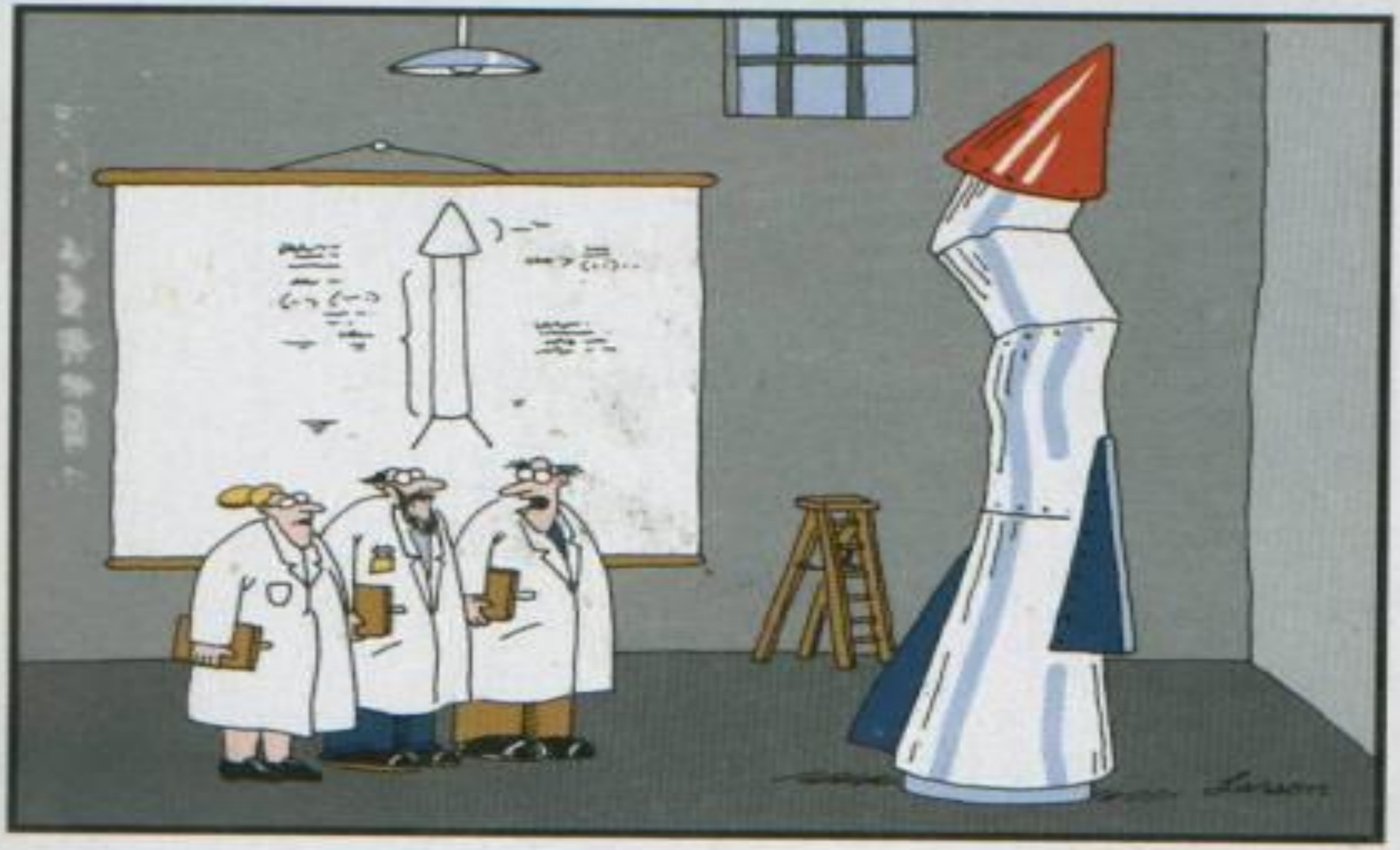
Conclusions for good E4 modelling

- Let the research issue drive the model
- Different categories of models all have strengths and weaknesses
  - Consider a consistent combination of models (linked or not)
- Worry about
  - Technology, Behaviour, Macro impacts, Scale, Time,
- Be explicit in regards to Uncertainty
- But increasing computing power can lead to over-complication, beyond ability to understand and critique

Model to generate insights, not just numbers

SEMINAR BREAK

Constructing an (E4) energy-economic model



"It's time we face reality, my friends. … We're not exactly rocket scientists."

Diversity in UK energy policy approaches

- Regulatory (command and control)
  - Building regulations
  - Renewables Obligation (link to market mechanisms, e.g., ROCs market)
- Subsidy
  - Capital grants (e.g., offshore wind)
  - Enhanced Capital Allowances
- Economic instruments
  - Climate Change Levy (=> Climate Change Agreements)
  - Emissions trading (EUETS)
  - Taxation (e.g., road duties)
- Voluntary agreements
  - negotiated agreements with Energy Intensive Industry
- RD&D and innovation policy

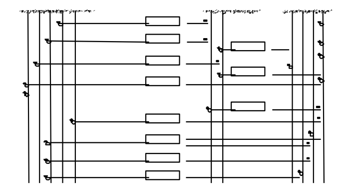
Introduction to UK MARKAL model

- A **least cost optimization** model based on life-cycle costs of competing technology pathways (to meet **energy demand services)**
- **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**
- **Extension** to MARKAL-Macro (M-M), elastic demand (MED), stochastic, mixed integer, multi-region, global TIAM-UCL model, other variants

Components of MARKAL

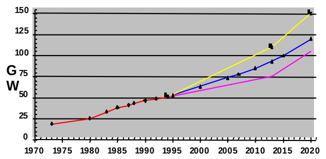
Components of an Energy System Model

* Energy system topology & organization



RES

* Numerical data



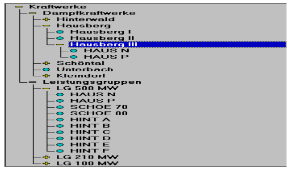
Time Series

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

$$P_{BHKW\_S} = \eta_{BHKW} \cdot P_{Coal\_BHKW}$$
$$O_{BHKW\_CO_2} = \varepsilon \cdot P_{Coal\_BHKW}$$
$$Q_{BHKW\_H} = \eta_{2\_BHKW} \cdot P_{Coal\_BHKW}$$

GAMS Model

* Scenarios and strategies



Cases

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

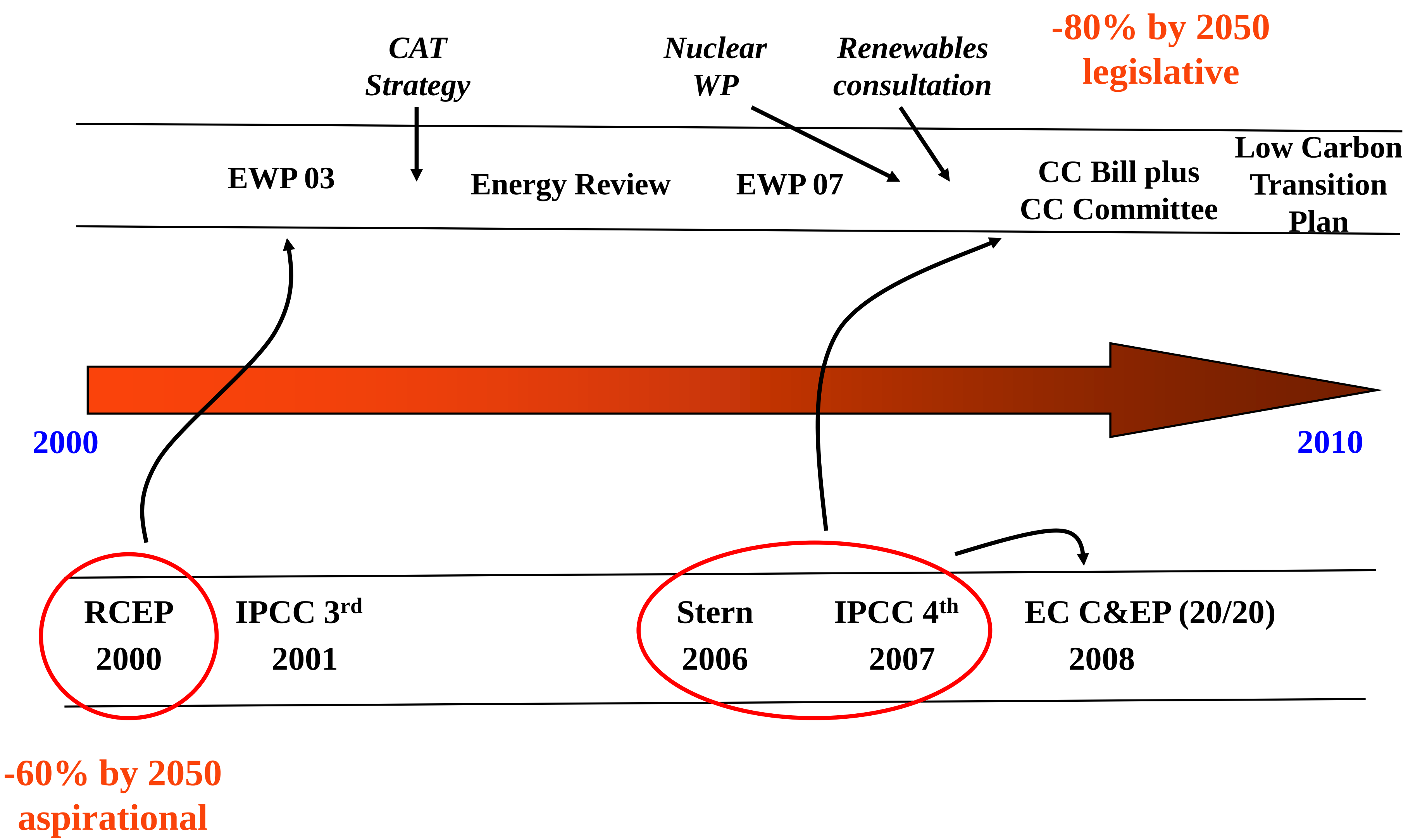
1. **System configuration** - potential energy pathways and interactions
2. **Resource supply curves** - imports and domestic production
3. **Energy service demands** - to a detailed sub-sectoral level
4. **Technology characterisation** - capital costs, O&M costs, efficiencies, availabilities etc
5.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

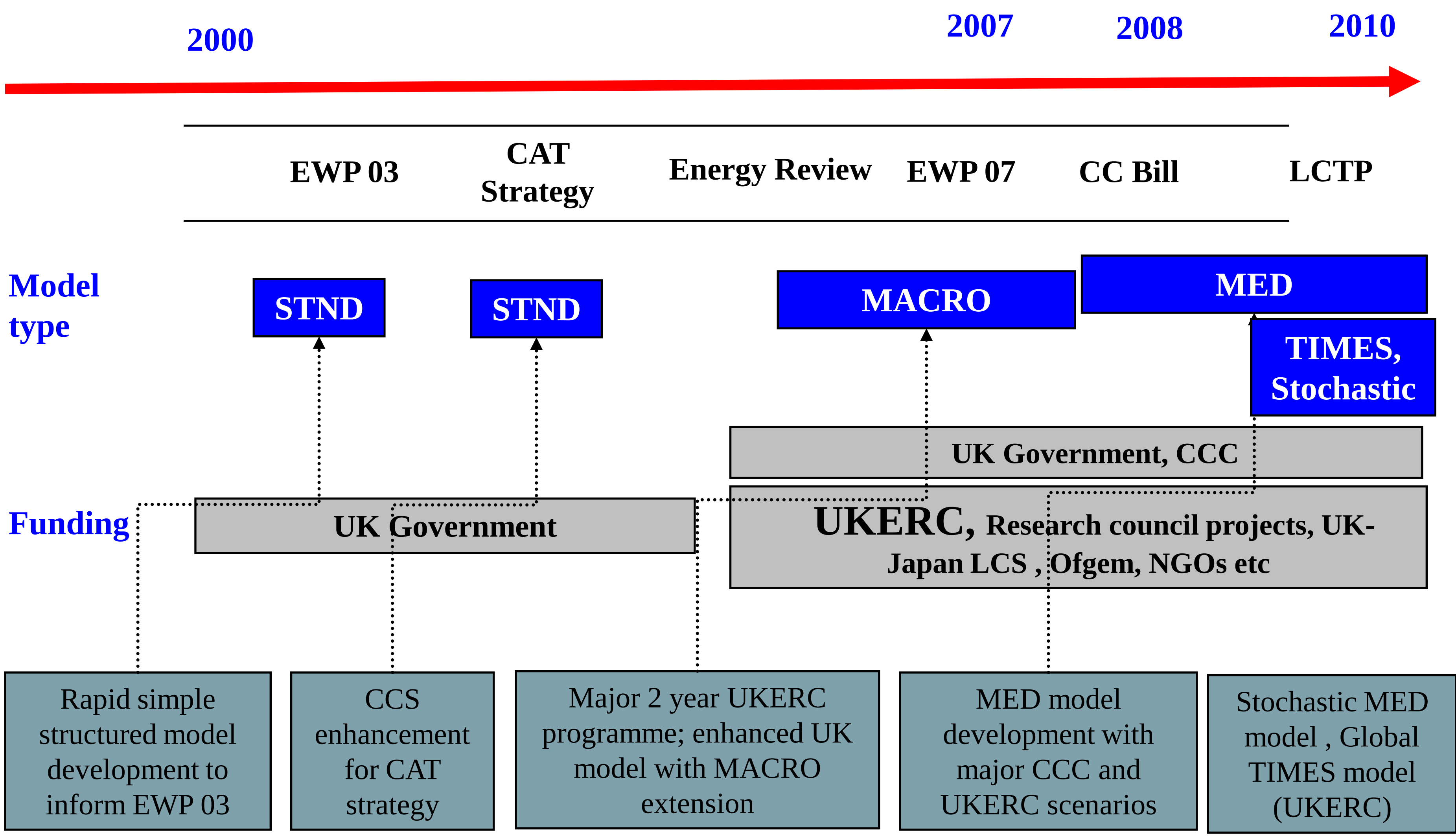
MARKAL
(Selected Advantages and Disadvantages)

- 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

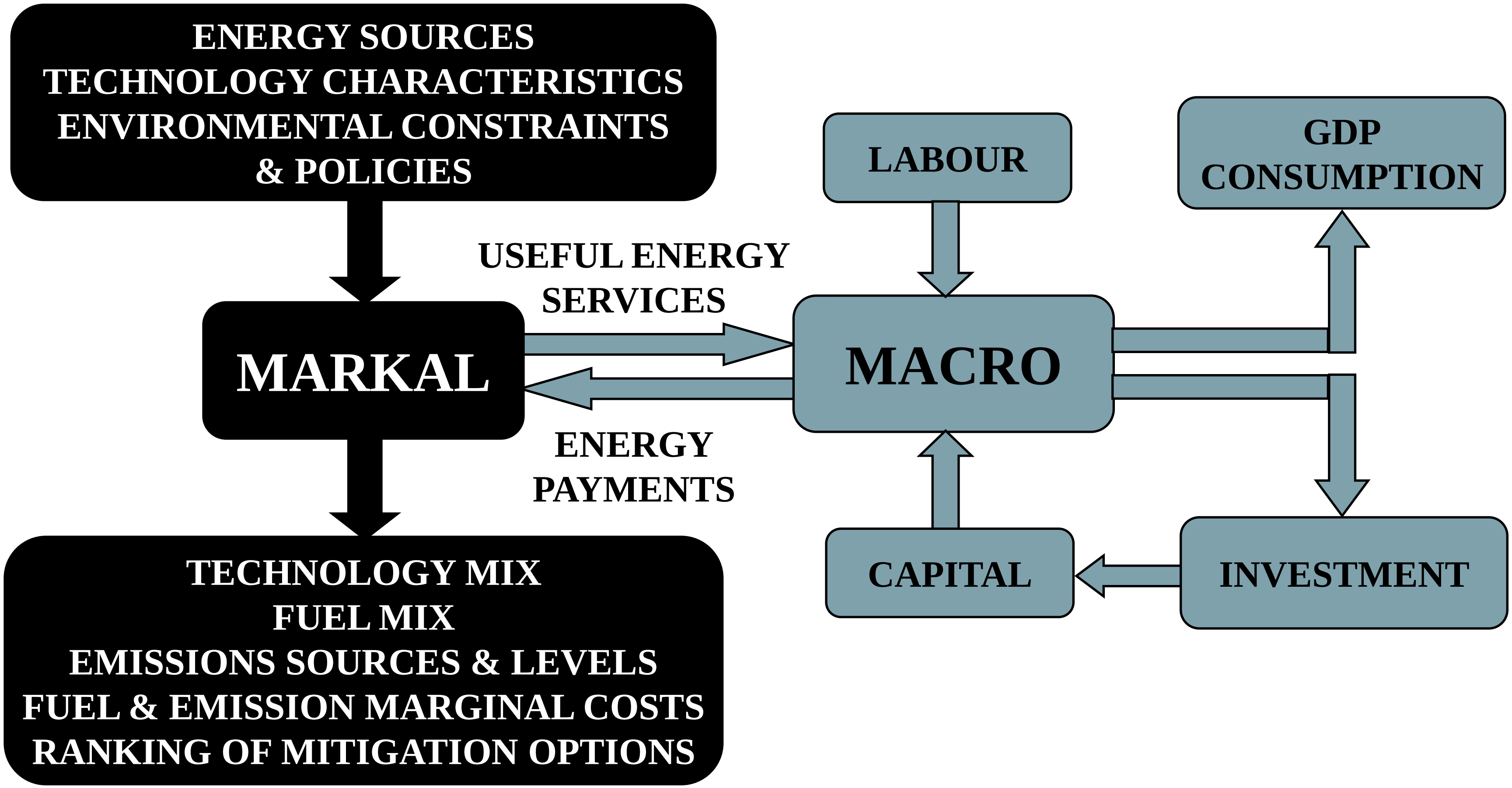
UK energy policy timeline



MARKAL modelling for UK policy



UK MARKAL Macro (M-M) model



M-M equations

$$UTILITY = \sum_{t=1}^{T-1} (udf_t)(\log C_t) + (udf_T)(\log C_T)/[1 - (1 - udr_T)^{ny}],$$

$$udf_t = \prod_{\tau=0}^{t-1} (1 - udr_\tau)^{ny},$$

$$udr_t = (kpvs)/(kgdp) - depr - grow_t,$$

$$PRD: \quad Y_t = \left[akl(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum b_{dm}(D_{dm,t})^{\rho}\right]^{1/\rho},$$

$$L_0 = 1, \quad L_t = (1 + grow_{t-1})^{ny} L_{t-1},$$

$$\alpha = kpvs,$$

$$\rho = 1 - 1/ESUB,$$

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

$$CAP: \quad K_{t+1} = tsrvK_t + (ny/2)(tsrvI_t + I_{t+1}),$$

$$tsrv = (1 - depr)^{ny},$$

$$I_0 = (grow_0 + depr)K_0,$$

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

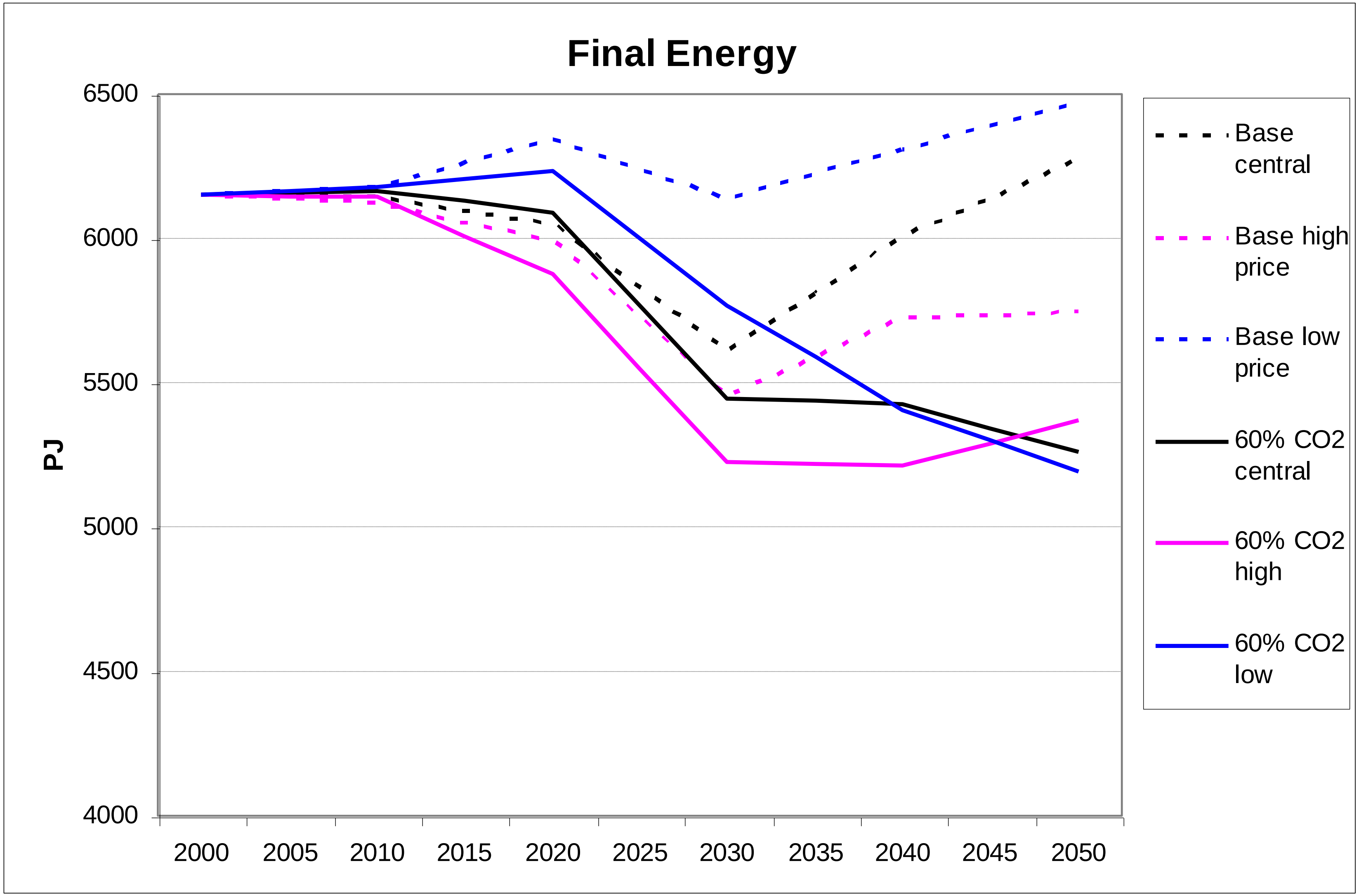
M-M features

- Macro-economic growth model hard-linked to a energy systems model
  - Explicit calculation of GDP, consumption and investment
  - Aggregated demand feedbacks from changes in energy prices
  - Autonomous demand changes for scenario analysis where energy demands are decoupled from economic (GDP) growth
  - Detailed technological change and energy interactions as before
- But…
  - No sectoral competitiveness and other trade issues
  - No information on transition costs
  - No revenue recycling from taxation or auctioning permits
  - Non-formal estimation of aggregated parameters (e.g. ESUB)
  - Consumer preferences are unchanging through the model horizon

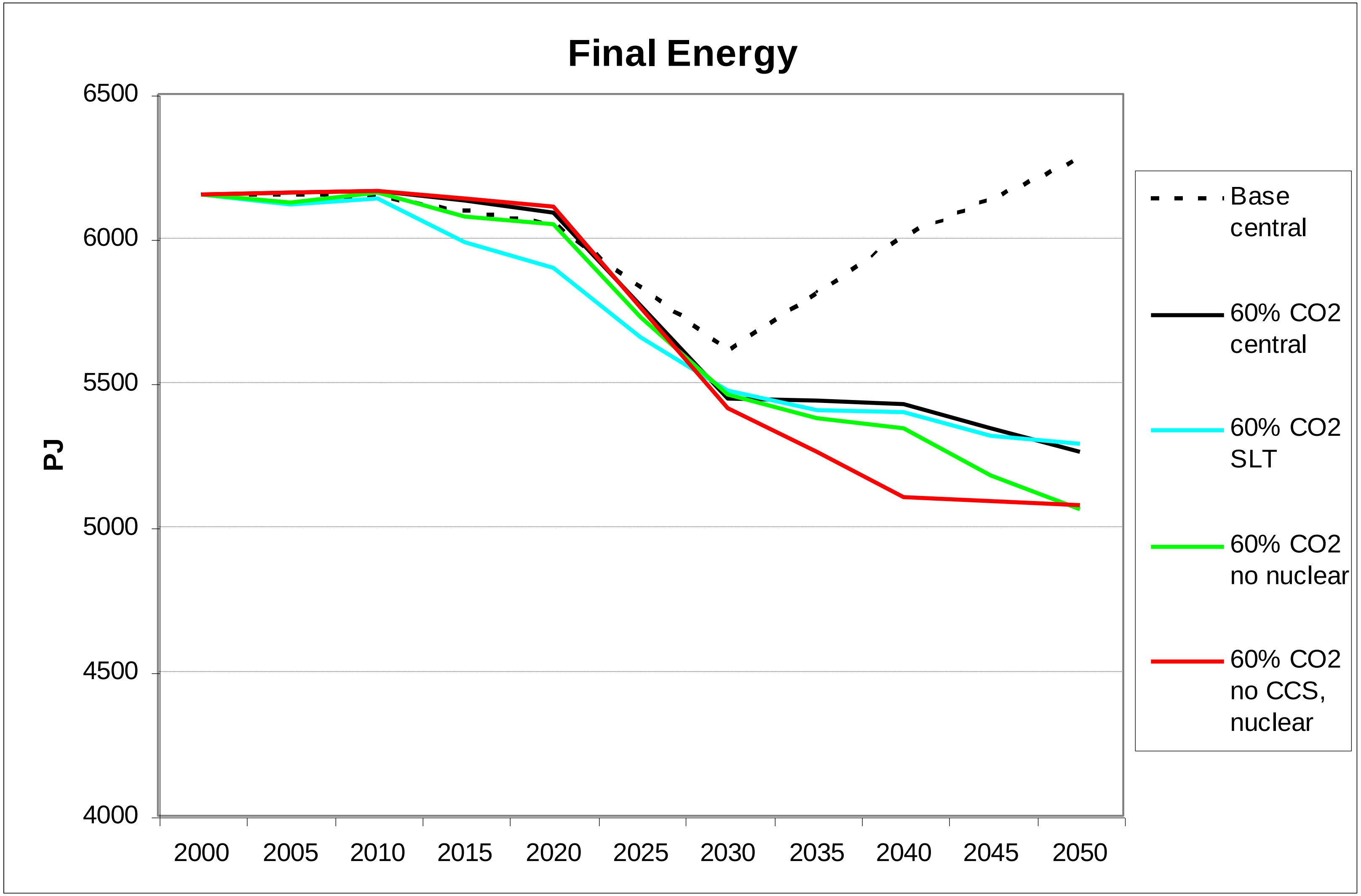
2007 Energy White paper
53 scenario sets in total

- UKERC vs. DTI assumptions
  - Technology costs, efficiency potential, transport hybrid penetration, uranium costs
- Standard vs. M-M model
  - With/without demand flexibility, LP vs. NLP optimization etc
- Scenarios
  - Constraint stringency: 20%, 40%, 60% CO_2 reductions
  - **60% CO_2 constraint trajectory: 2030+, 2010+ (SLT)**
  - **Low and high global fuel prices**
  - Restricted innovation (2020 and 2010 levels)
  - High and low technology cost estimates (by technology class)
  - **No nuclear**
  - **No nuclear / no CCS**
  - Renewable sensitivity (RO and technology costs)
- Based on key policy drivers, NOT a formal uncertainty analysis

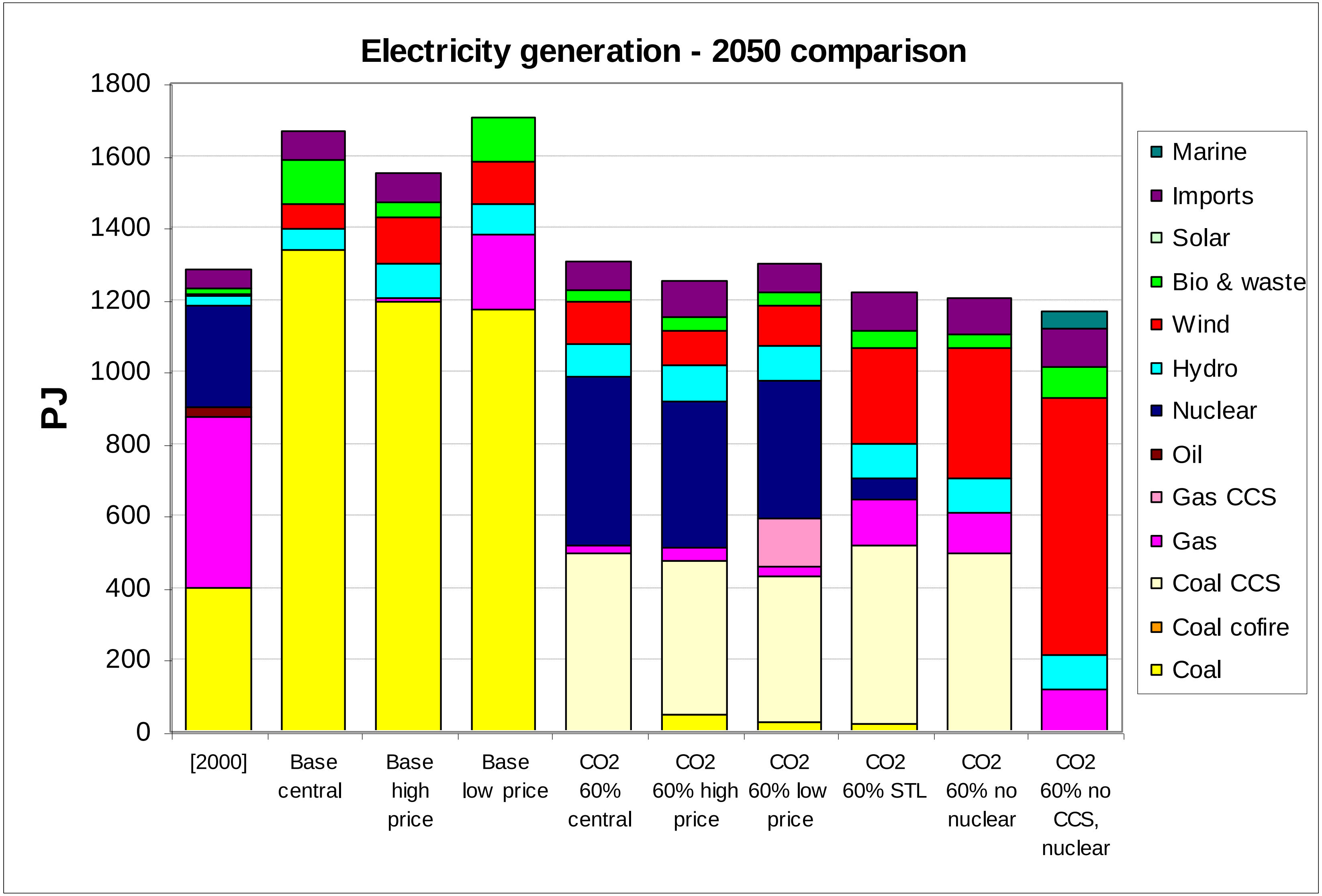
Final energy – resource price scenarios



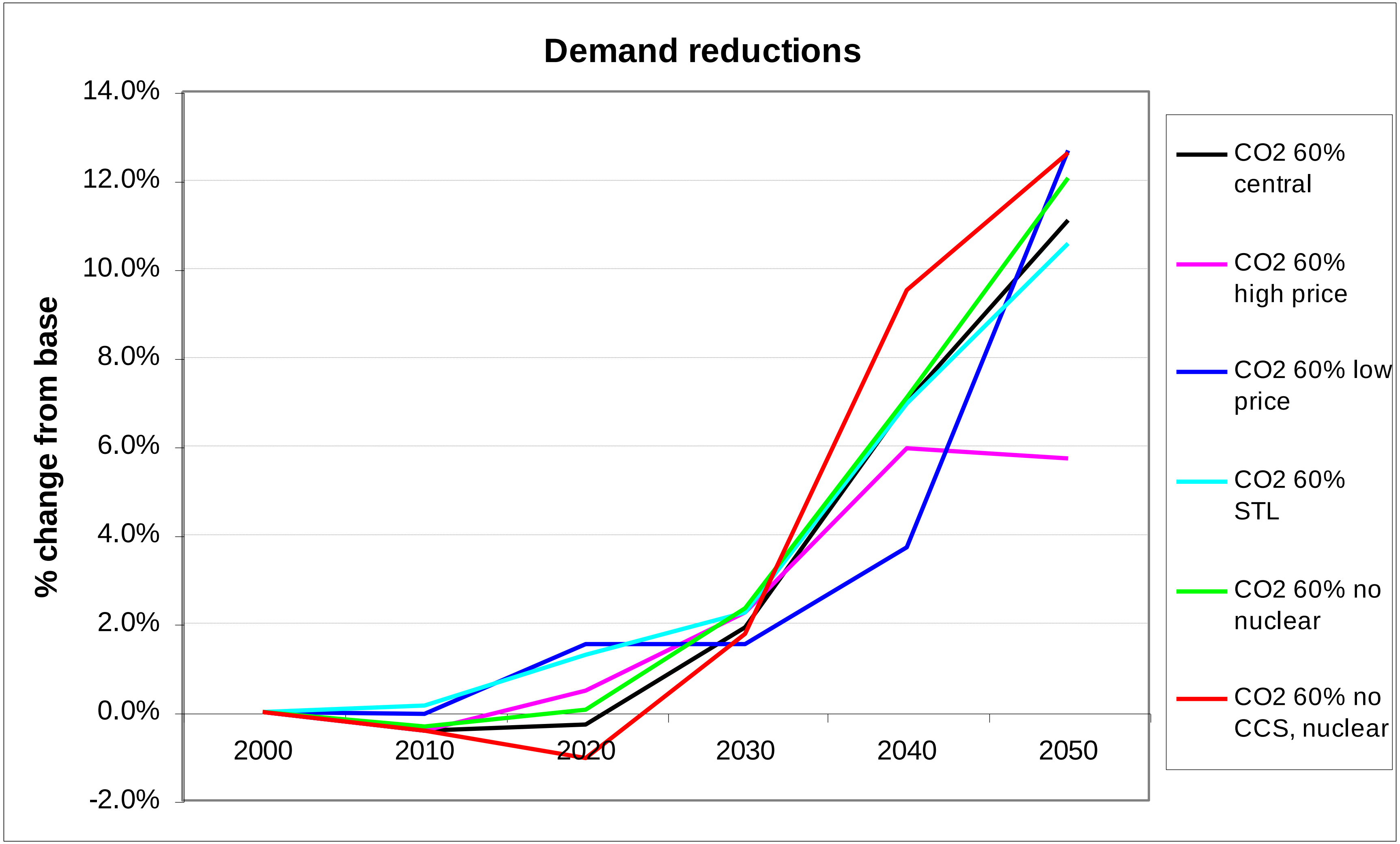
Final energy – alternate constraint and restricted technology scenarios



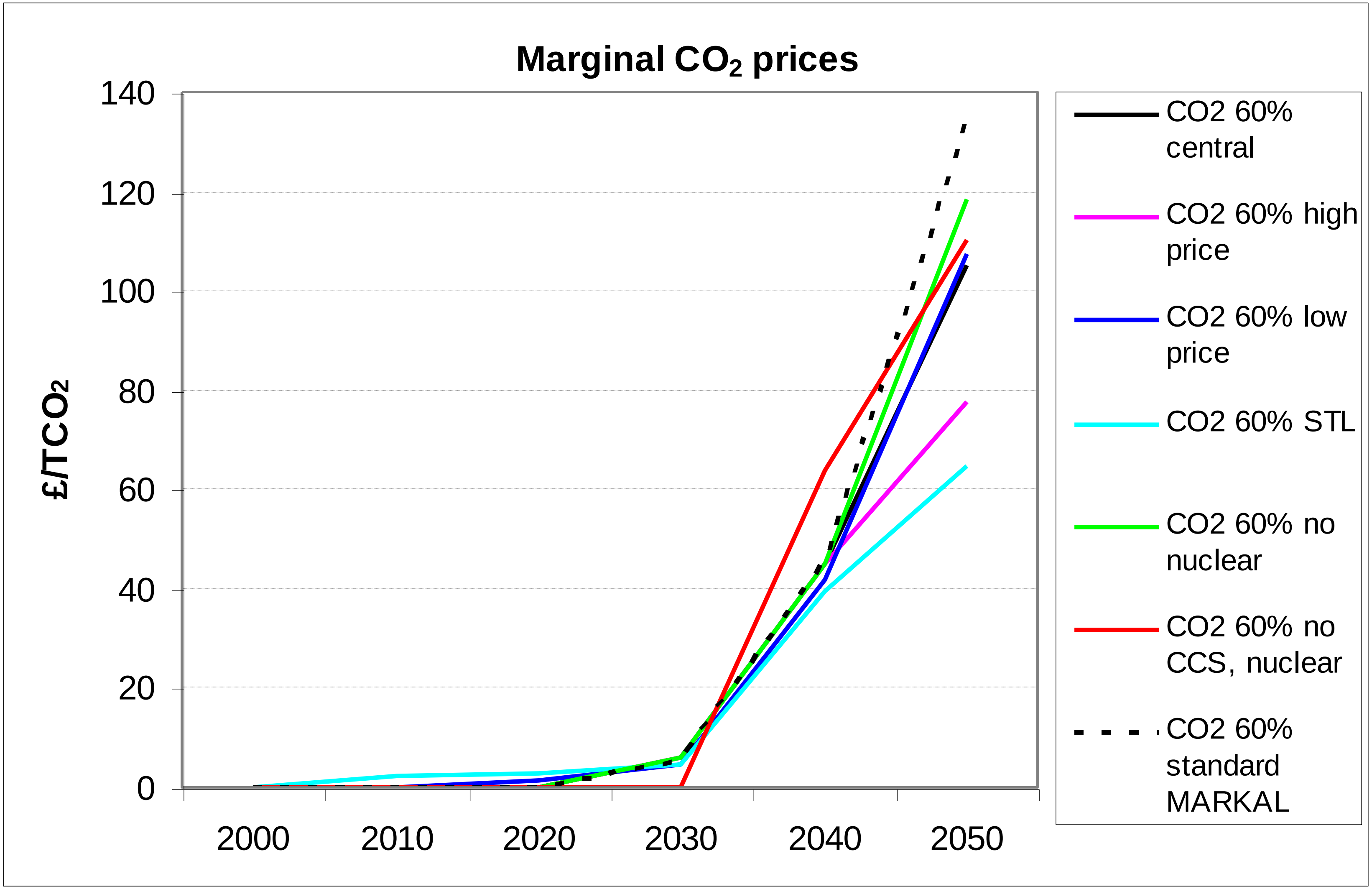
Electricity generation: 2050 comparison



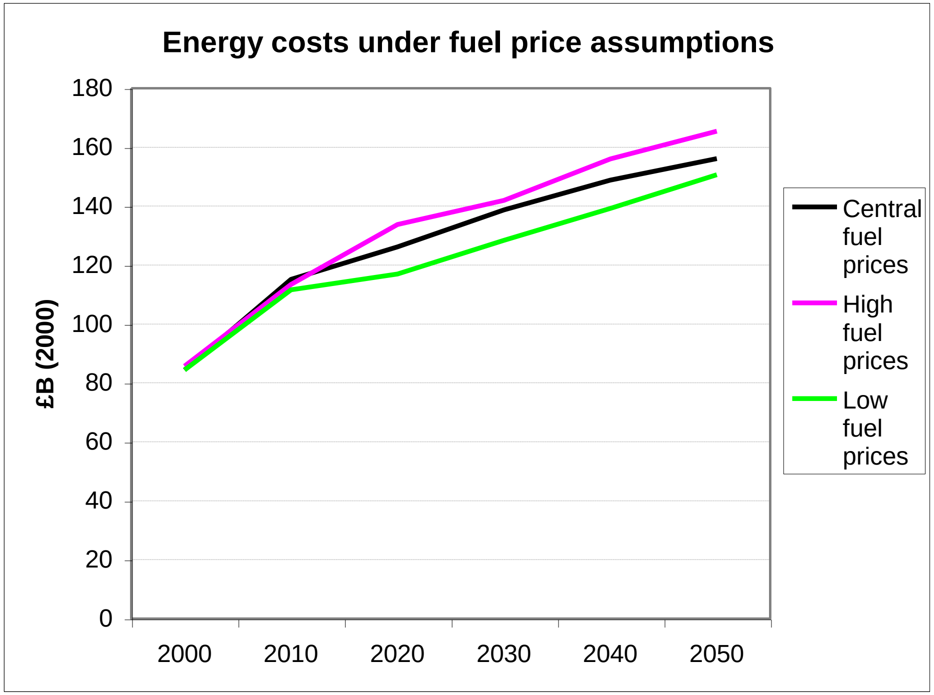
Energy service demand reductions

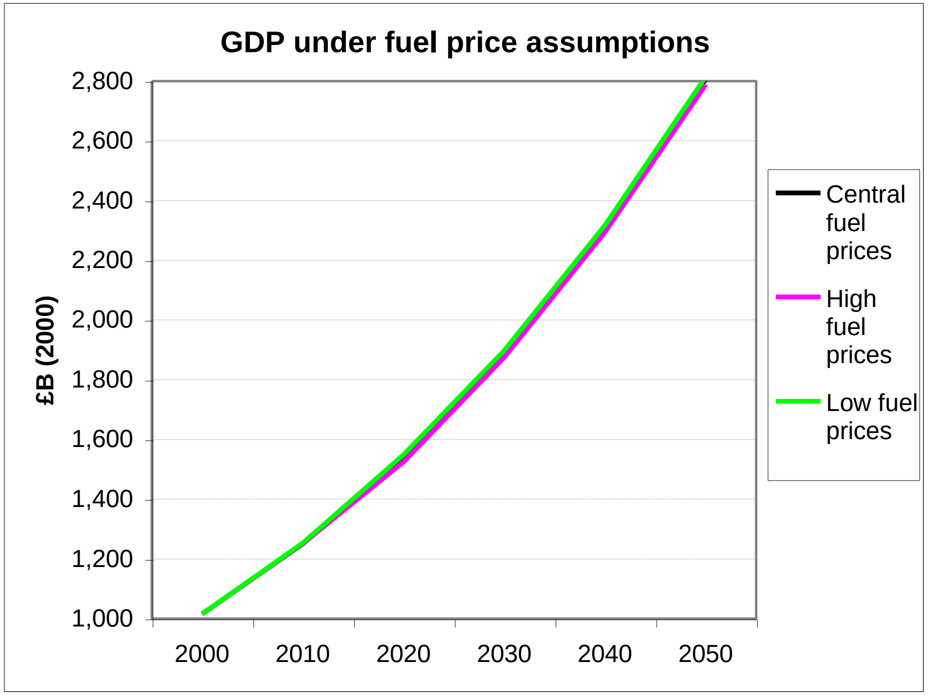


CO_2 marginal prices

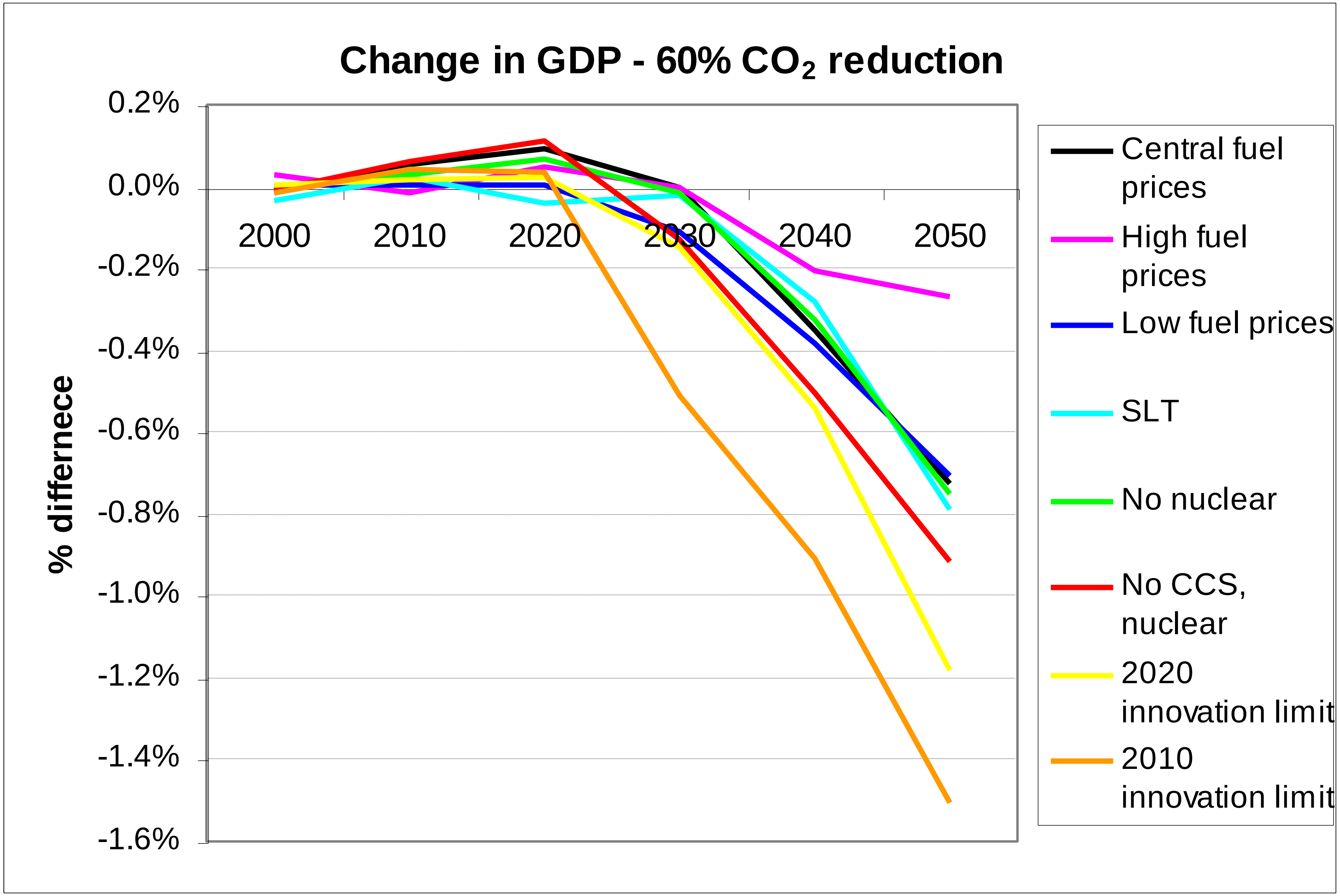


UKERC M-M fuel price sensitivity
Base-case energy costs and GDP

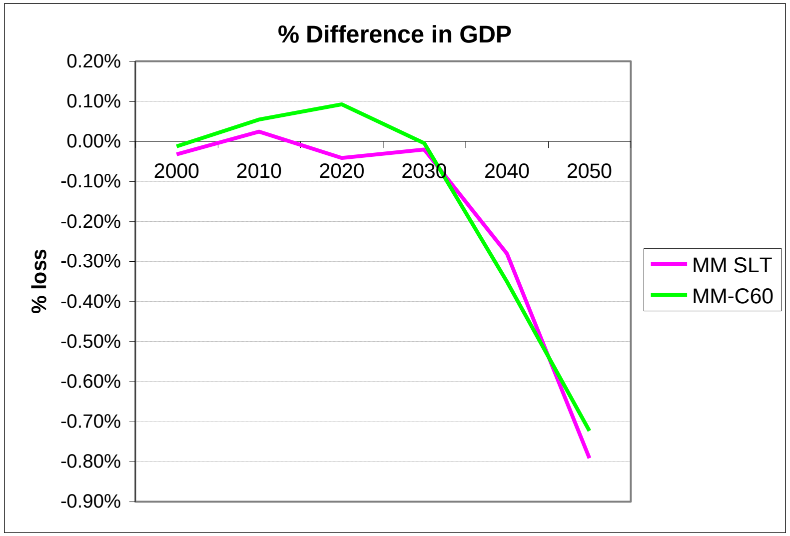


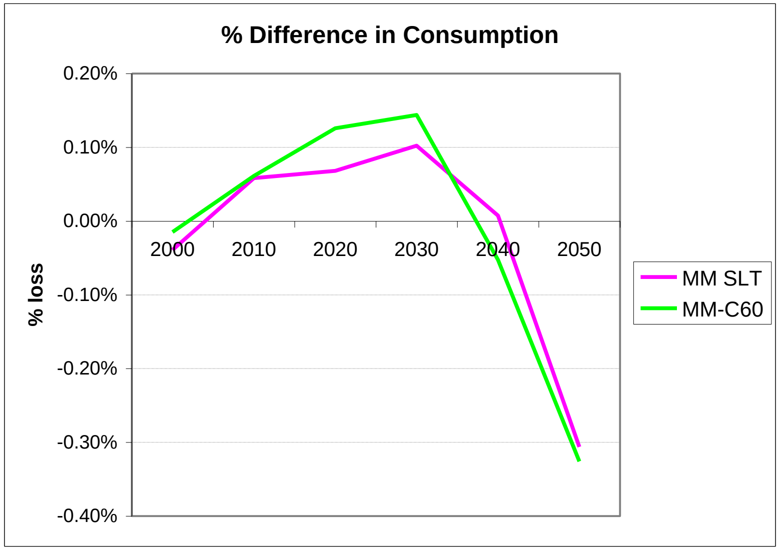


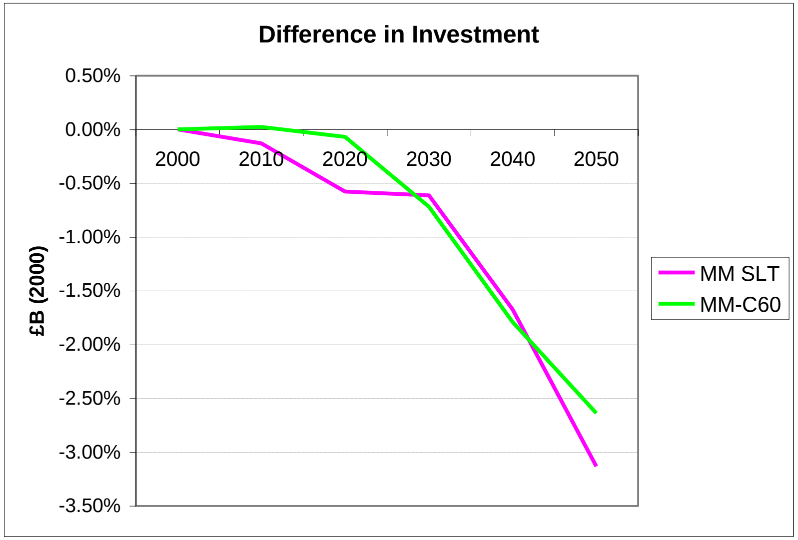
GDP % changes

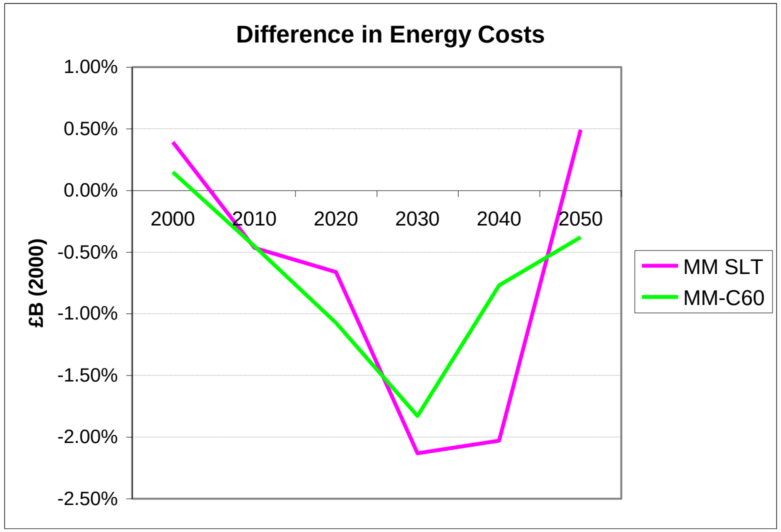

Change in GDP - 60% CO_2 reduction
0.2%
0.0%
-0.2%
-0.4%
-0.6%
-0.8%
-1.0%
-1.2%
-1.4%
-1.6%
% differnece
2000
2010
2020
2030
2040
2050
Central fuel prices
High fuel prices
Low fuel prices
SLT
No nuclear
No CCS, nuclear
2020 innovation limit
2010 innovation limit

UKERC M-M: CO_2 constraints
Macro parameters % differences









Principal findings given to EWP 2007

- A 60% reduction in UK CO_2 emissions entails radical changes in technology portfolios, resources and infrastructure use
- This long-term transition requires a strong CO_2 price signal with a central M-M model estimate of £105/TCO_2 by 2050
  - within a scenario range of £65/TCO_2 to £176/TCO_2
- The resultant impacts on the UK economy are more modest
  - range of annual GDP losses in 2050 from 0.3% to 1.5% (equivalent to £B7.5 to £B42.0).
  - Higher cost estimates are strongly influenced by pessimistic low-carbon technology assessments
- Numerous trade-offs illustrate the very considerable uncertainties in future UK low-carbon scenarios
  - e.g., no dominant technology class within the future electricity portfolio (i.e., coal CCS vs. nuclear vs. large scale renewables)