Energy system modelling to inform energy and climate policies

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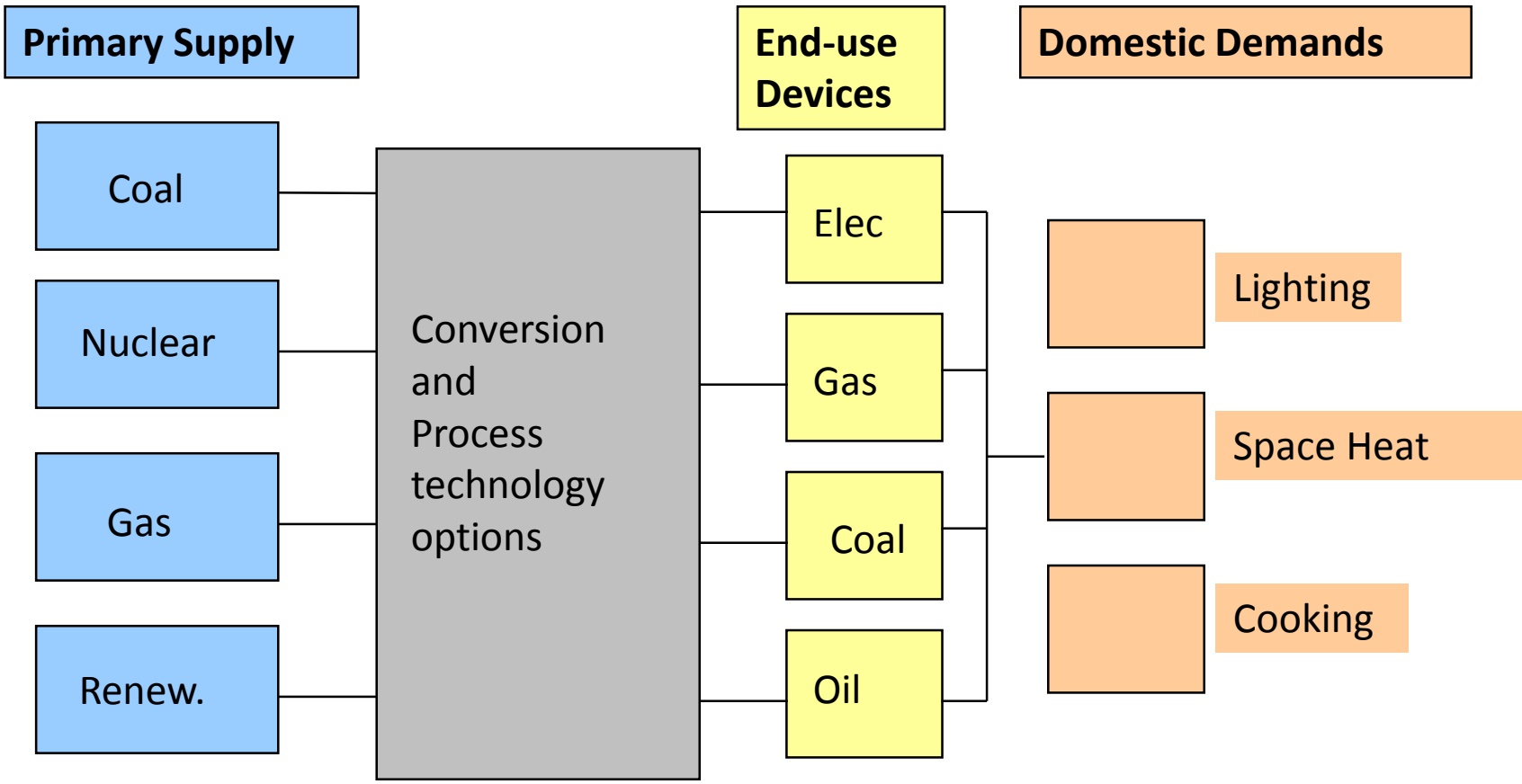
Content

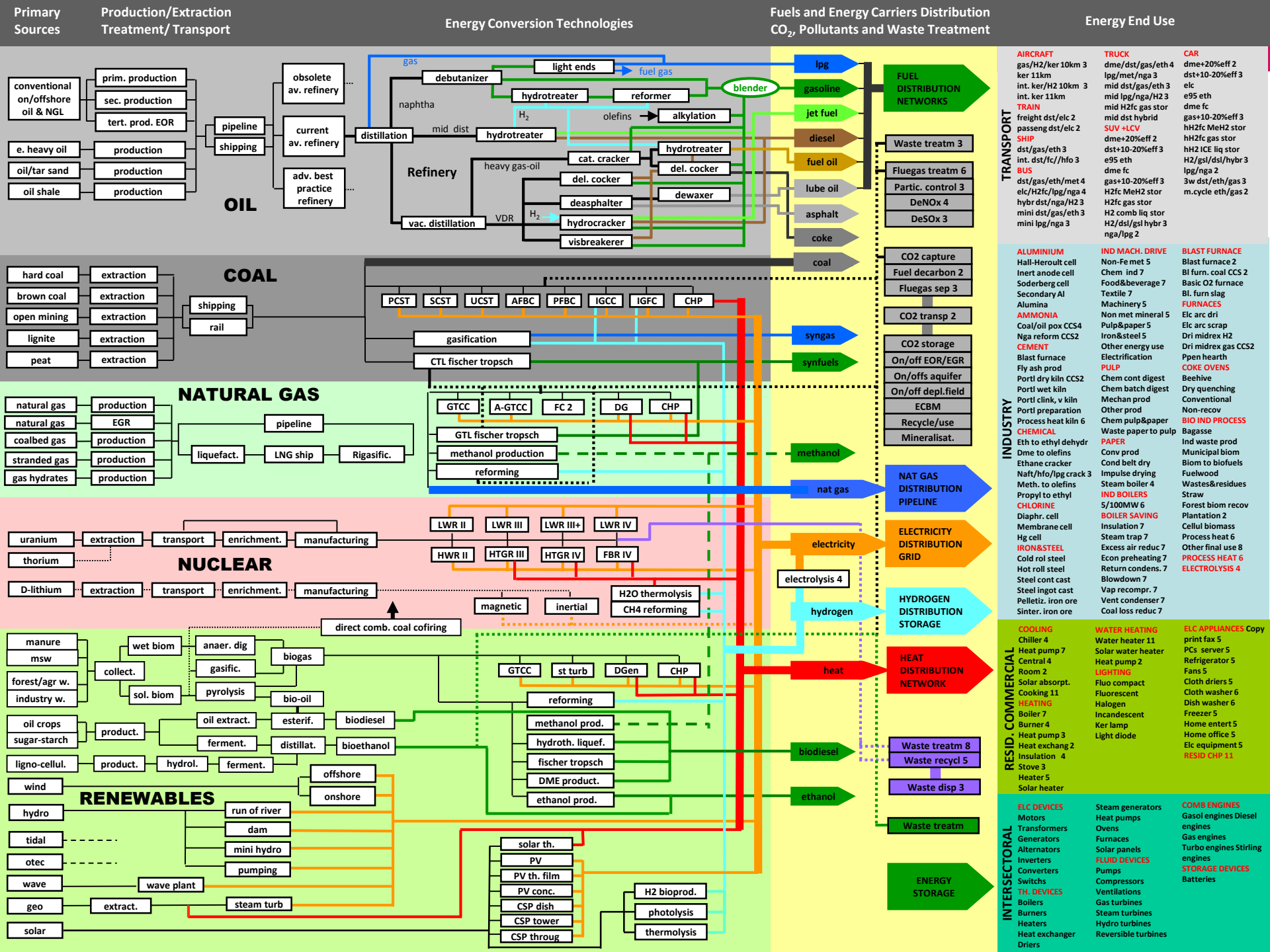
- Reference energy system
- Energy system models and policy interactions
- LEAP model
- TIMES modelling: UK Scenarios and results

Reference energy system

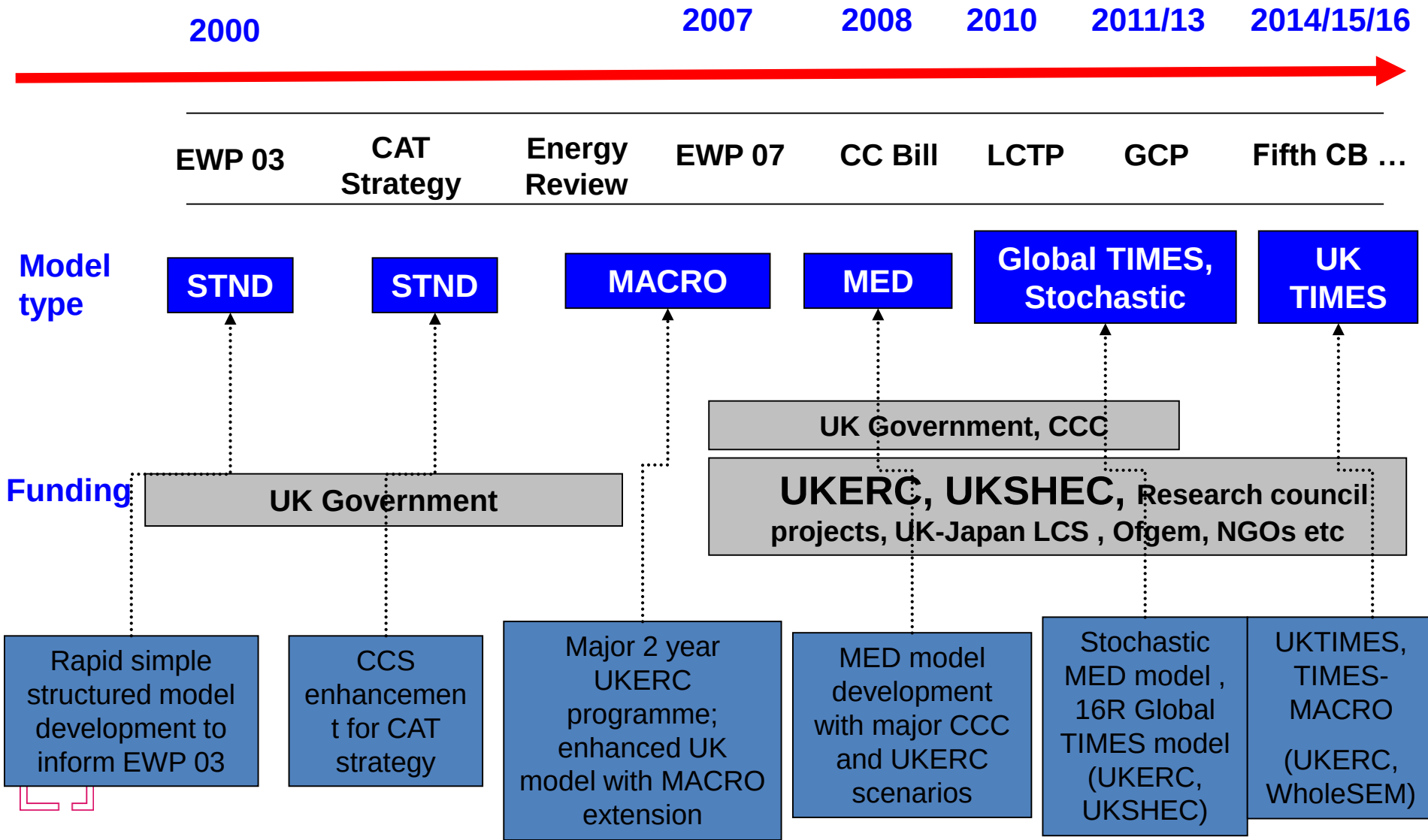
- Energy system is made up of:
  - Demands for energy services (vkms, lighting) by users
  - Sources of energy (imports / mining—domestic resources)
- A reference energy system describes the 'pathway' of energy sources to demands – like a network flow diagram
- It represents the 'pathway' through the system from sources to demand using:
  - Commodities - energy carriers e.g. coal, emissions
  - Technologies - conversion (e.g. coal to electricity) or process

Reference energy system – Example




Primary Sources
Production/Extraction Treatment/ Transport
Energy Conversion Technologies
Fuels and Energy Carriers Distribution
CO_2, Pollutants and Waste Treatment
Energy End Use
OIL
conventional on/offshore oil & NGL
e. heavy oil
oil/tar sand
oil shale
prim. production
sec. production
tert. prod. EOR
production
production
production
pipeline
shipping
obsolete av. refinery
current av. refinery
adv. best practice refinery
distillation
gas
debutanizer
light ends
fuel gas
naphtha
hydrotreater
reformer
blender
mid dist
hydrotreater
olefins
alkylation
Refinery
heavy gas-oil
cat. cracker
hydrotreater
del. cocker
del. cocker
dewaxer
deasphalter
vac. distillation
VDR
hydrocracker
visbreakerer
lpg
gasoline
jet fuel
diesel
fuel oil
lube oil
asphalt
coke
FUEL DISTRIBUTION NETWORKS
Waste treatm 3
Fluegas treatm 6
Partic. control 3
DeNOx 4
DeSOx 3
TRANSPORT
AIRCRAFT
gas/H2/ker 10km 3
ker 11km
int. ker/H2 10km 3
int. ker 11km
TRAIN
freight dst/elc 2
passeng dst/elc 2
SHIP
dst/gas/eth 3
int. dst/fc//hfo 3
BUS
dst/gas/eth/met 4
elc/H2fc/lpg/nga 4
hybr dst/nga/H2 3
mini dst/gas/eth 3
mini lpg/nga 3
TRUCK
dme/dst/gas/eth 4
lpg/met/nga 3
mid dst/gas/eth 3
mid lpg/nga/H2 3
mid H2fc gas stor
mid dst hybrid
SUV +LCV
dme+20%eff 2
dst+10-20%eff 3
e95 eth
dme fc
gas+10-20%eff 3
H2fc MeH2 stor
H2fc gas stor
H2 comb liq stor
H2/dsl/gsl hybr 3
nga/lpg 2
CAR
dme+20%eff 2
dst+10-20%eff 3
elc
e95 eth
dme fc
gas+10-20%eff 3
hH2fc MeH2 stor
hH2fc gas stor
hH2 ICE liq stor
H2/gsl/dsl/hybr 3
lpg/nga 2
3w dst/eth/gas 3
m.cycle eth/gas 2
COAL
hard coal
brown coal
open mining
lignite
peat
extraction
extraction
extraction
extraction
extraction
shipping
rail
PCST
SCST
UCST
AFBC
PFBC
IGCC
IGFC
CHP
gasification
CTL fischer tropsch
coal
syngas
synfuels
CO2 capture
Fuel decarbon 2
Fluegas sep 3
CO2 transp 2
CO2 storage
On/off EOR/EGR
On/offs aquifer
On/off depl.field
ECBM
Recycle/use
Mineralisat.
NATURAL GAS
natural gas
natural gas
coalbed gas
stranded gas
gas hydrates
production
EGR
production
production
production
pipeline
liquefact.
LNG ship
Rigasific.
GTCC
A-GTCC
FC 2
DG
CHP
GTL fischer tropsch
methanol production
reforming
methanol
nat gas
NAT GAS DISTRIBUTION PIPELINE
INDUSTRY
ALUMINIUM
Hall-Heroult cell
Inert anode cell
Soderberg cell
Secondary Al
Alumina
AMMONIA
Coal/oil pox CCS4
Nga reform CCS2
CEMENT
Blast furnace
Fly ash prod
Portl dry kiln CCS2
Portl wet kiln
Portl clink, v kiln
Portl preparation
Process heat kiln 6
CHEMICAL
Eth to ethyl dehydr
Dme to olefins
Ethane cracker
Naft/hfo/lpg crack 3
Meth. to olefins
Propyl to ethyl
CHLORINE
Diaphr. cell
Membrane cell
Hg cell
IRON&STEEL
Cold rol steel
Hot roll steel
Steel cont cast
Steel ingot cast
Pelletiz. iron ore
Sinter. iron ore
IND MACH. DRIVE
Non-Fe met 5
Chem ind 7
Food&beverage 7
Textile 7
Machinery 5
Non met mineral 5
Pulp&paper 5
Iron&steel 5
Other energy use
Electrification
PULP
Chem cont digest
Chem batch digest
Mechan prod
Other prod
Chem pulp&paper
Waste paper to pulp
PAPER
Conv prod
Cond belt dry
Impulse drying
Steam boiler 4
IND BOILERS
5/100MW 6
BOILER SAVING
Insulation 7
Steam trap 7
Excess air reduc 7
Econ preheating 7
Return condens. 7
Blowdown 7
Vap recompr. 7
Vent condenser 7
Coal loss reduc 7
BLAST FURNACE
Blast furnace 2
Bl furn. coal CCS 2
Basic O2 furnace
Bl. furn slag
FURNACES
Elc arc dri
Elc arc scrap
Dri midrex H2
Dri midrex gas CCS2
Ppen hearth
COKE OVENS
Beehive
Dry quenching
Conventional
Non-recov
BIO IND PROCESS
Bagasse
Ind waste prod
Municipal biom
Biom to biofuels
Fuelwood
Wastes&residues
Straw
Forest biom recov
Plantation 2
Cellul biomass
Process heat 6
Other final use 8
PROCESS HEAT 6
ELECTROLYSIS 4
NUCLEAR
uranium
thorium
D-lithium
extraction
transport
enrichment.
manufacturing
extraction
transport
enrichment.
manufacturing
LWR II
LWR III
LWR III+
LWR IV
HWR II
HTGR III
HTGR IV
FBR IV
electricity
electrolysis 4
hydrogen
ELECTRICITY DISTRIBUTION GRID
HYDROGEN DISTRIBUTION STORAGE
magnetic
inertial
H2O thermolysis
CH4 reforming
direct comb. coal cofiring
RENEWABLES
manure
msw
forest/agr w.
industry w.
collect.
wet biom
sol. biom
anaer. dig
gasific.
pyrolysis
biogas
bio-oil
oil crops
sugar-starch
product.
oil extract.
ferment.
esterif.
distillat.
biodiesel
bioethanol
ligno-cellul.
product.
hydrol.
ferment.
wind
hydro
tidal
otec
wave
geo
solar
offshore
onshore
run of river
dam
mini hydro
pumping
wave plant
extract.
steam turb
GTCC
st turb
DGen
CHP
reforming
methanol prod.
hydroth. liquef.
fischer tropsch
DME product.
ethanol prod.
solar th.
PV
PV th. film
PV conc.
CSP dish
CSP tower
CSP throug
H2 bioprod.
photolysis
thermolysis
heat
biodiesel
ethanol
HEAT DISTRIBUTION NETWORK
Waste treatm 8
Waste recycl 5
Waste disp 3
Waste treatm
ENERGY STORAGE
RESID. COMMERCIAL
COOLING
Chiller 4
Heat pump 7
Central 4
Room 2
Solar absorpt.
Cooking 11
HEATING
Boiler 7
Burner 4
Heat pump 3
Heat exchang 2
Insulation 4
Stove 3
Heater 5
Solar heater
WATER HEATING
Water heater 11
Solar water heater
Heat pump 2
LIGHTING
Fluo compact
Fluorescent
Halogen
Incandescent
Ker lamp
Light diode
ELC APPLIANCES Copy
print fax 5
PCs server 5
Refrigerator 5
Fans 5
Cloth driers 5
Cloth washer 6
Dish washer 6
Freezer 5
Home entert 5
Home office 5
Elc equipment 5
RESID CHP 11
INTERSECTORAL
ELC DEVICES
Motors
Transformers
Generators
Alternators
Inverters
Converters
Switchs
TH. DEVICES
Boilers
Burners
Heaters
Heat exchanger
Driers
Steam generators
Heat pumps
Ovens
Furnaces
Solar panels
FLUID DEVICES
Pumps
Compressors
Ventilations
Gas turbines
Steam turbines
Hydro turbines
Reversible turbines
COMB ENGINES
Gasol engines Diesel engines
Gas engines
Turbo engines Stirling engines
STORAGE DEVICES
Batteries

MARKAL/TIMES modelling for UK policy



MARKAL/TIMES Contributions

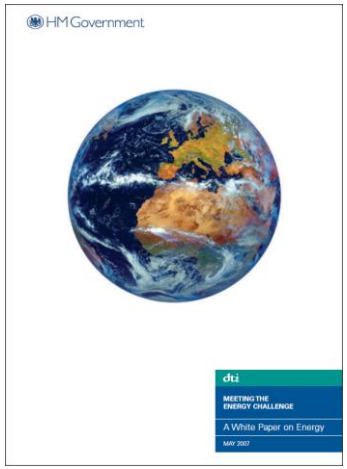
- Energy White Paper 2003 (Standard MARKAL)
- Energy White Paper 2007 (MARKAL MACRO)
- Climate Change Bill, 2008 (MED)
- Low Carbon Transition Pathways (MED)
- Fourth Carbon Budget, 2010 (Stochastic MARKAL)
- Global Carbon Pathways, 2012 (TIAM-UCL)
- Fourth Carbon Budget Review, 2013 (TIAM-UCL)
- DECC have undertaken UKTIMES as core tool
- Fifth Carbon Budget, 2015 (UK TIMES)

Models have been used to inform UK climate & energy strategy since 2003

RCEP 2000

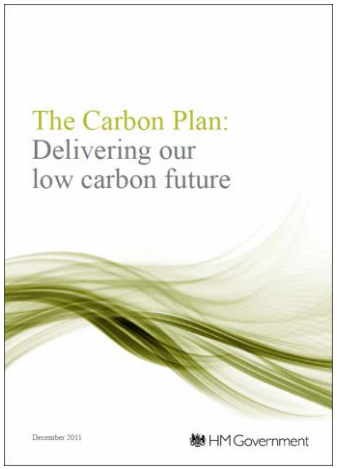
EWP 2003

EWP 2007



CCB 2008

DECC 2011

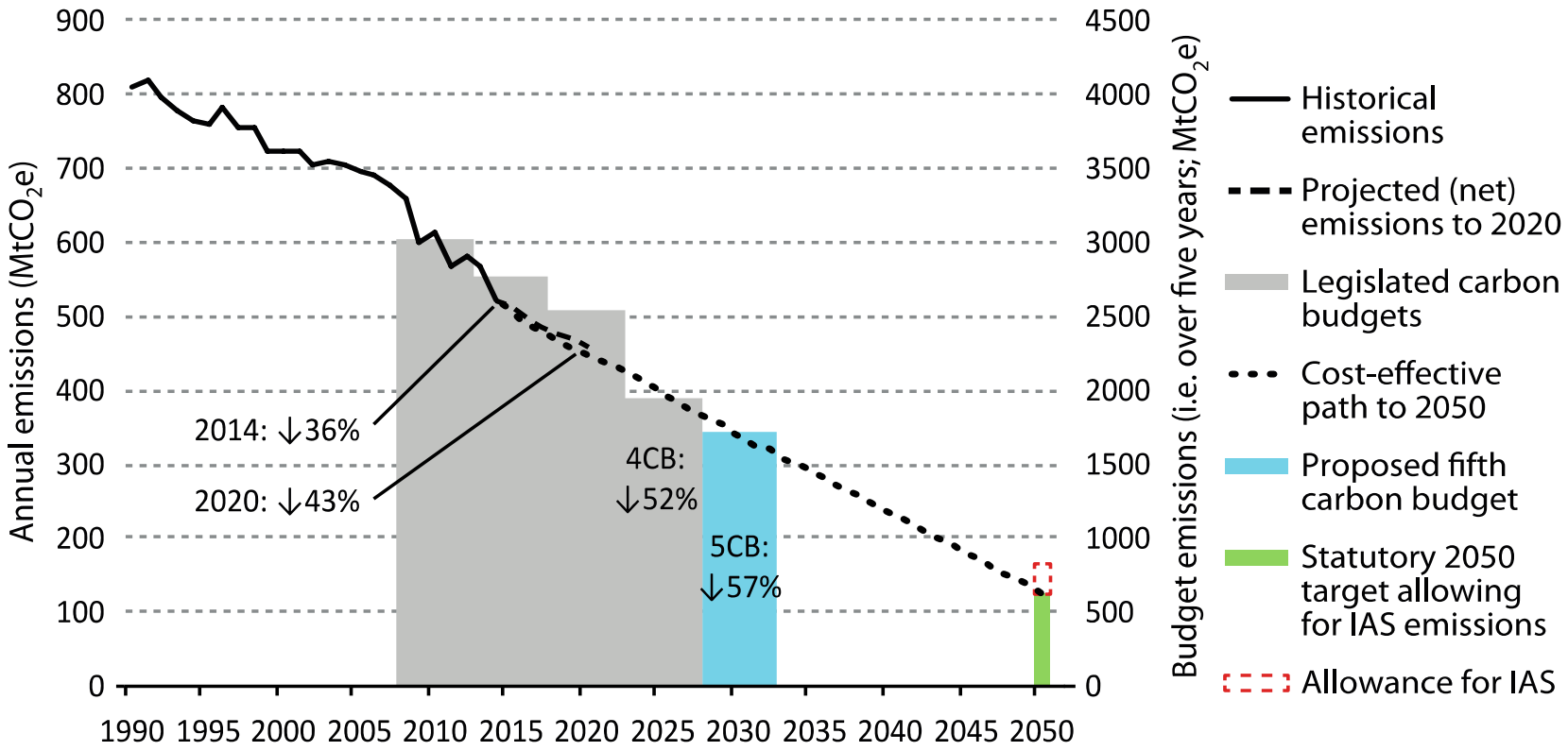


Proposed targets → **Building evidence base and political consensus** → **Legislative framework and targets** → **Implementation framework**

The Climate Change Act and UK regulations

- The Climate Change Act was passed in 2008 and established a framework to develop an economically credible emissions reduction path. The act commits the UK to reducing emissions by at least 80% in 2050 from 1990 levels.
- **Department for Energy and Climate Change (DECC)** leads on the UK's policy to reduce emissions.
- **Carbon Budgets.** The Act requires the Government to set legally binding 'carbon budgets'. A carbon budget is a cap on the amount of greenhouse gases emitted in the UK over a five-year period.
- **The Committee on Climate Change (CCC)** was set up to advise the Government on emissions targets, and report to Parliament on progress made in reducing greenhouse gas emissions.
- In 2016, **BREXIT**, Department for Business, Energy and Industrial Strategy (**BEIS**)

UK GHG Emission pathway



Source: DECC (2015) *Final UK greenhouse gas emissions national statistics: 1990-2013*; DECC (2015) Provisional UK greenhouse gas emissions national statistics; DECC Energy Model; CCC analysis.
Notes: Data labels show reductions in annual emissions relative to 1990. Historical emissions are on a 'gross' basis (i.e. actual emissions). Projections and carbon budgets are on the current budget accounting basis: net carbon account excluding international aviation and shipping (IAS), but allowing for IAS to be included in the 2050 target.

LEAP

LEAP Modeling Capabilities

- **Energy Demand**
  - Hierarchical accounting of energy demand (activity levels x energy intensities).
  - Choice of methodologies.
  - Optional modeling of stock turnover.
- **Energy Conversion**
  - Simulation of any energy conversion sector (electric generation, transmission and distribution, CHP, oil refining, charcoal making, coal mining, oil extraction, ethanol production, etc.)
  - Electric system dispatch based on electric load-duration curves.
  - Exogenous and endogenous modeling of capacity expansion.
- **Energy Resources:**
  - Tracks requirements, production, sufficiency, imports and exports.
  - Optional land-area based accounting for biomass and renewable resources.
- **Costs:**
  - All system costs: capital, O&M, fuel, costs of saving energy, environmental externalities.
- **Environment**
  - All emissions and direct impacts of energy system.
  - Non-energy sector sources and sinks.

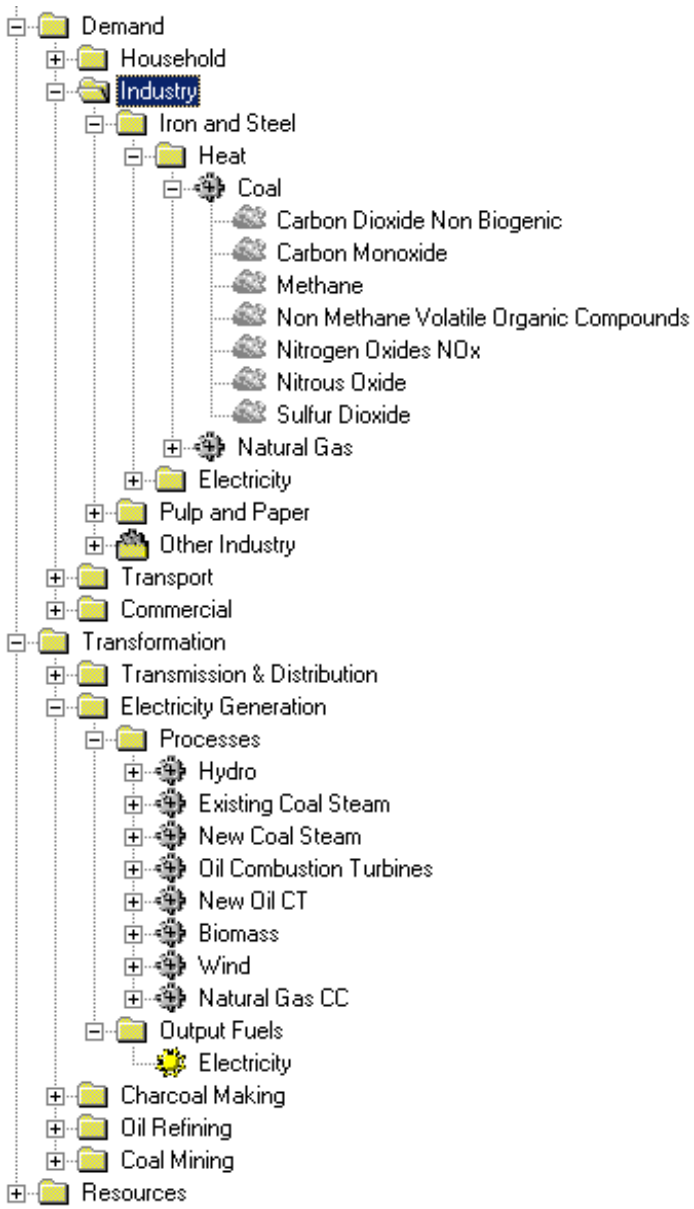
Demand Modeling Methodologies (1)

1. Final Energy Analysis: $e = a \times i$
   - Where e=energy demand, a=activity level, i=final energy intensity (energy consumed per unit of activity)
   - **Example:** energy demand in the cement industry can be projected based on tons of cement produced and energy used per ton. *Each can change in the future.*
2. Useful Energy Analysis: $e = a \times (u / n)$
   - Where u=useful energy intensity, n = efficiency
   - Example: energy demand in buildings will change in future as (1) more buildings are constructed [+a] (2) people get richer and heat and cool buildings more [+u], or building insulation improves [-u], or as people switch from less efficient oil boilers to electricity or natural gas [+n].

Demand Modeling Methodologies (2)

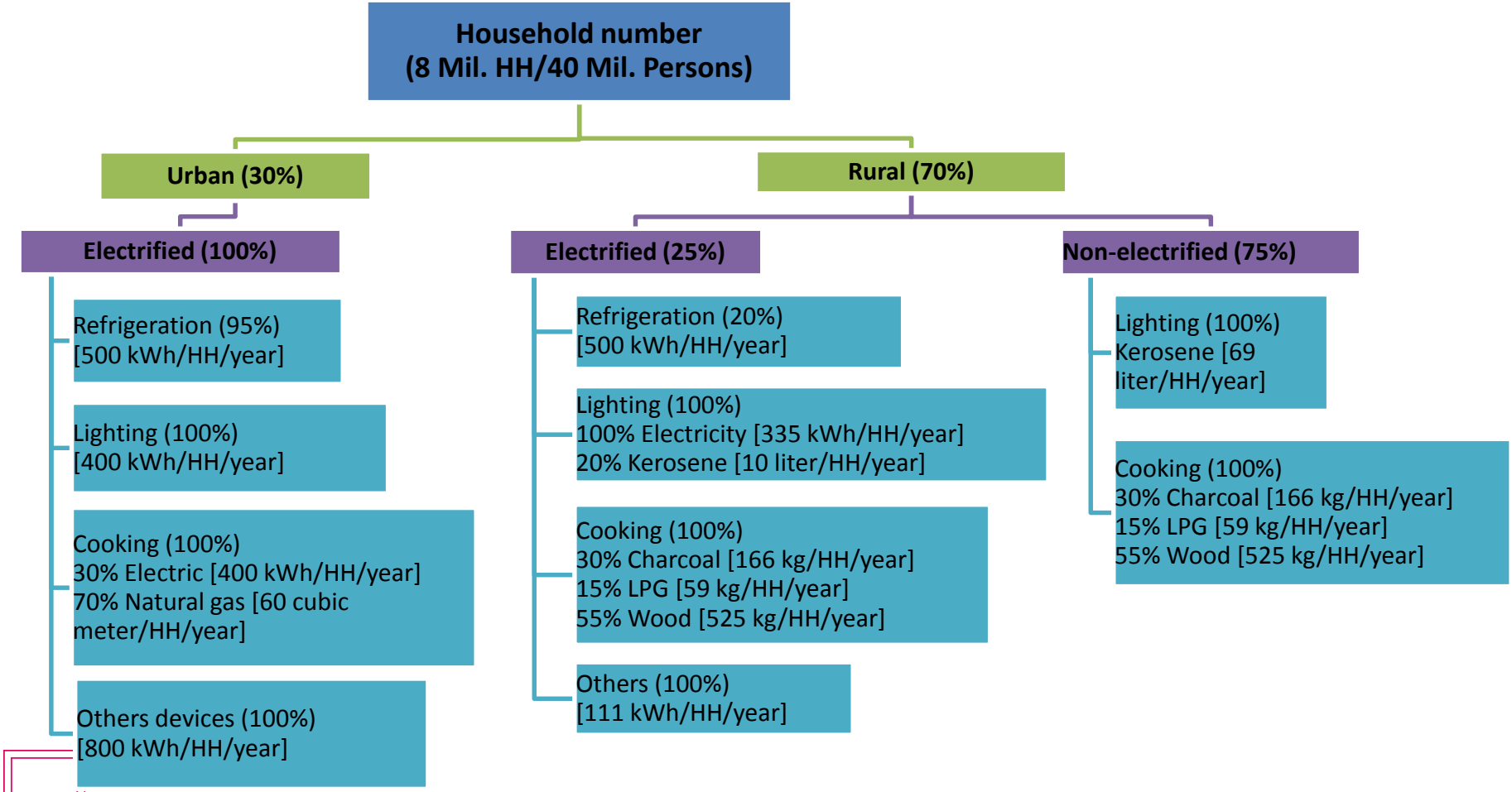
3. Stock Analysis: $e = s \times d$
   - Where s=stock, d=device intensity (energy use per device). Stock is modeled endogenously based on existing vintage of devices, sales of new devices and survival profile for devices.
   - Example: how quickly will a new energy efficiency standard for refrigerators lead to energy savings based on penetration of new devices and turnover of existing stock?
4. Transport Analysis: $e = s \times m / fe$
   - Where m = vehicle miles, fe = fuel economy (MPG)
   - Allows modeling of vehicle stock turnover.
   - Also allows pollutant emissions to be modeled as function of vehicle miles
   - Example: model impact of new vehicle fuel economy or emissions standards.

The Tree

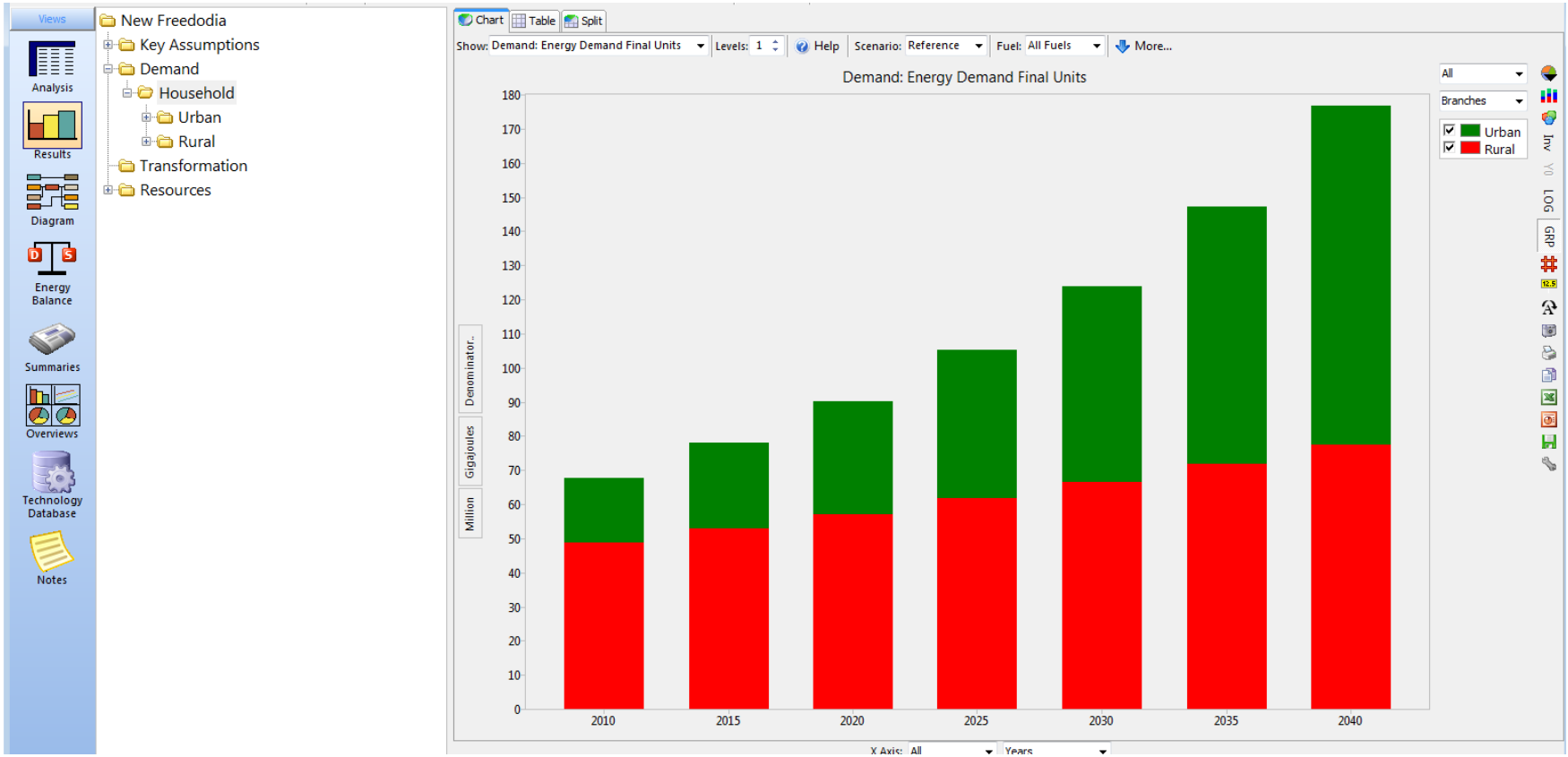


- The tree, which appears in the Analysis View, the Results View, and the Notes View is a hierarchical outline used to organize and edit the main data structures in a LEAP analysis.
- The main data structure used for organizing data and models, and reviewing results
- Icons indicate types of data (e.g., categories, technologies, fuels and effects)
- User can edit data structure.
- Supports standard editing functions (copying, pasting, drag & drop of groups of branches)

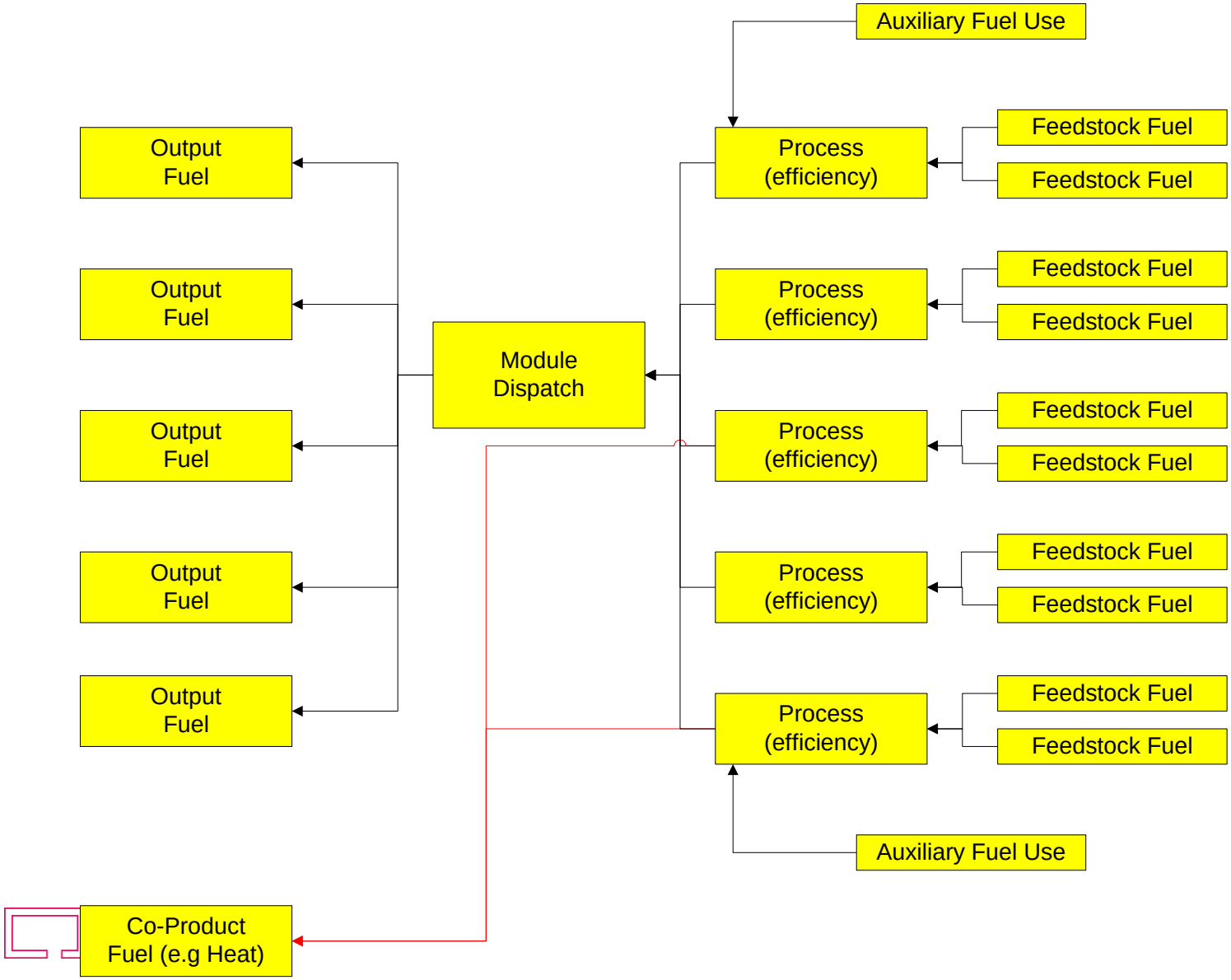
Current Account: Household sector



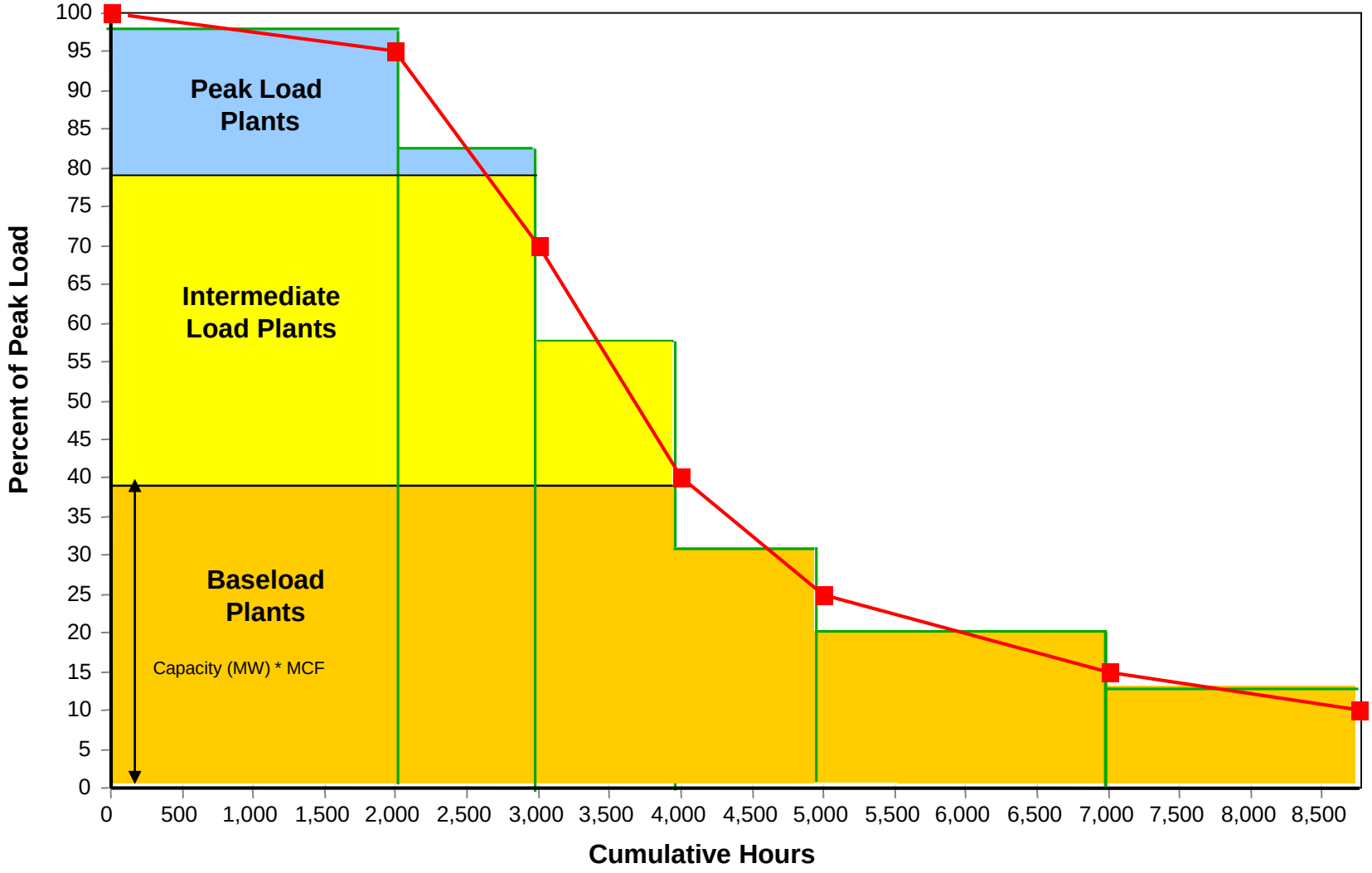
View the results



Transformation Modules



Load Curves and Electric Dispatch



OSeMOSYS (Open Source Energy Modelling System)

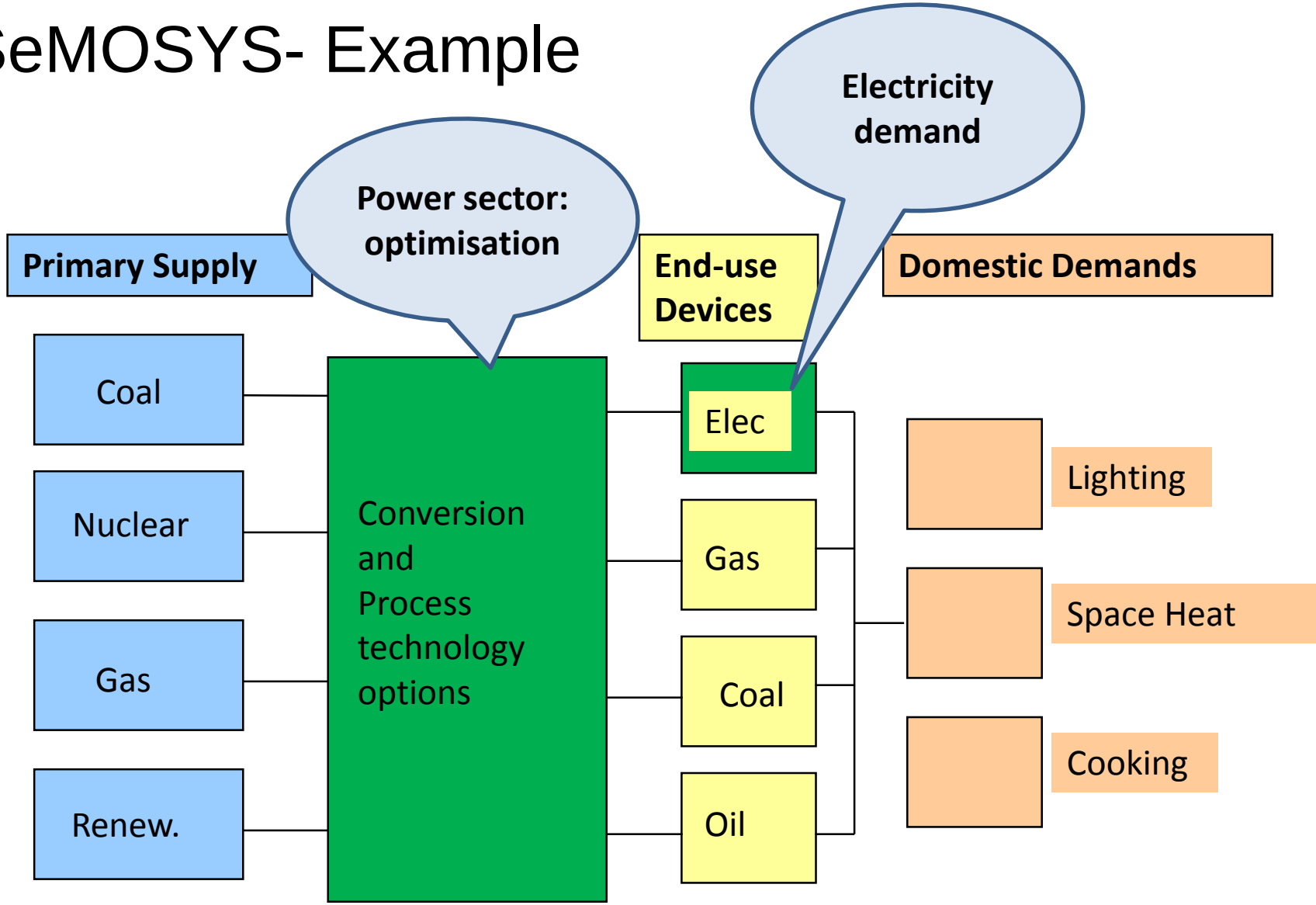
LEAP

- Demand
  - Household
  - Industry
    - Iron and Steel
      - Heat
        - Coal
          - Carbon Dioxide Non Biogenic
          - Carbon Monoxide
          - Methane
          - Non Methane Volatile Organic Compounds
          - Nitrogen Oxides NOx
          - Nitrous Oxide
          - Sulfur Dioxide
        - Natural Gas
      - Electricity
    - Pulp and Paper
    - Other Industry
  - Transport
  - Commercial
- Transformation
  - Transmission & Distribution
  - Electricity Generation
    - Processes
      - Hydro
      - Existing Coal Steam
      - New Coal Steam
      - Oil Combustion Turbines
      - New Oil CT
      - Biomass
      - Wind
      - Natural Gas CC
    - Output Fuels
      - Electricity
  - Charcoal Making
  - Oil Refining
  - Coal Mining
- Resources

Residential sector (Urban/Rural; Electrified/non-electrified

Optimised power sector with OSeMOSYS

OSeMOSYS- Example



UK Scenarios

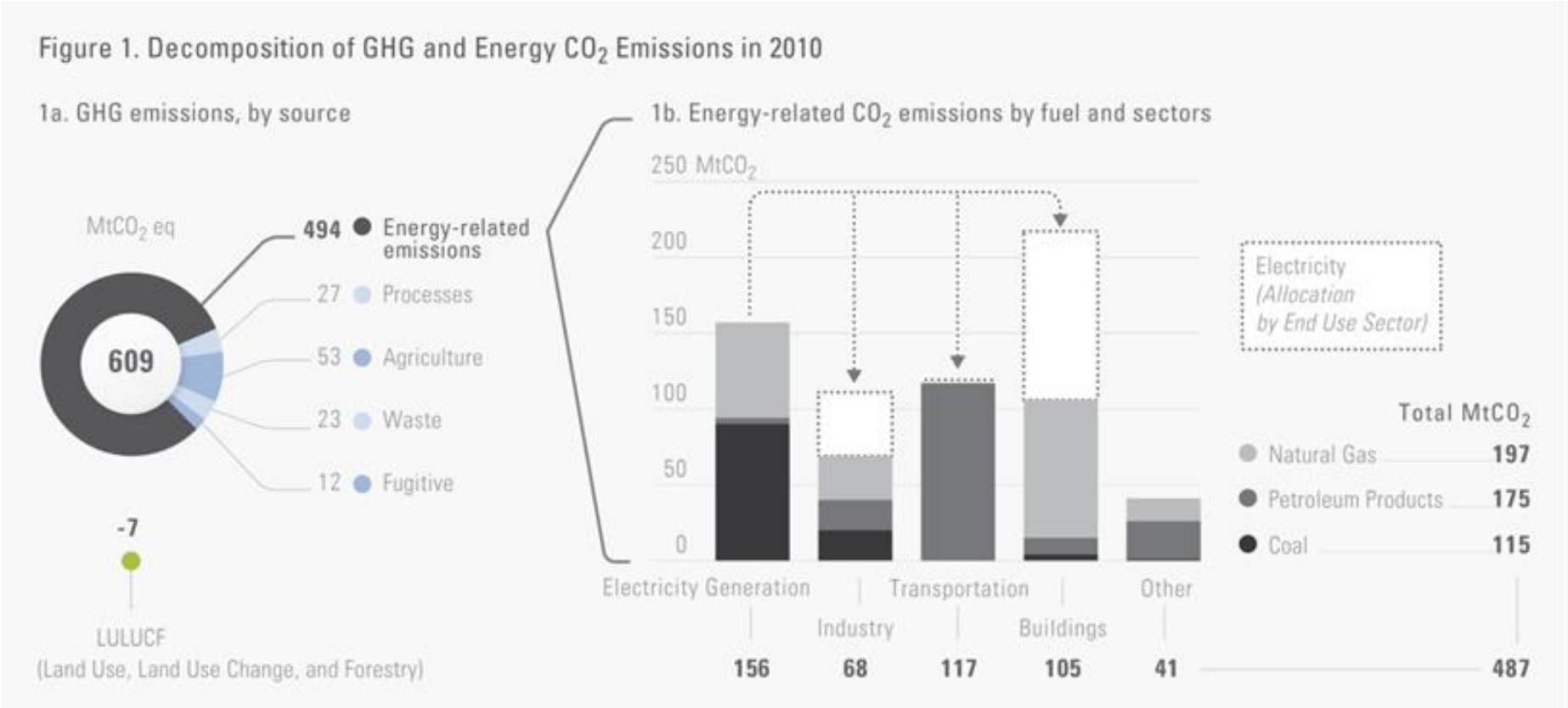
Deep Decarbonisation Pathways Project (DDPP)

- Backed by the UN and French Government.
- Interim report delivered to Ban Ki-moon in July 2014, in support of the Leaders' Climate Summit, and to the French Foreign minister.

- Final report published in summer 2015 – and key publication in run up to COP21.
- While not informing INDCs, ensure 2 °C target is in the frame, and provides robust analysis.

The situation today: CO_2 from energy use is critical, accounting for 82% of total GHG emissions

- Largest emitting sector is power generation; however, emission contributions across all sectors point to need for system wide action.



Scenario overview: high-level description

D-EXP: 'decarbonise and expand'

- Early power sector decarbonisation, followed by expansion to enable electrification of end use sectors.
- Relies on strong early development of low carbon technologies (R&D, policy, financing).

M-VEC: 'multi-vector pathways'

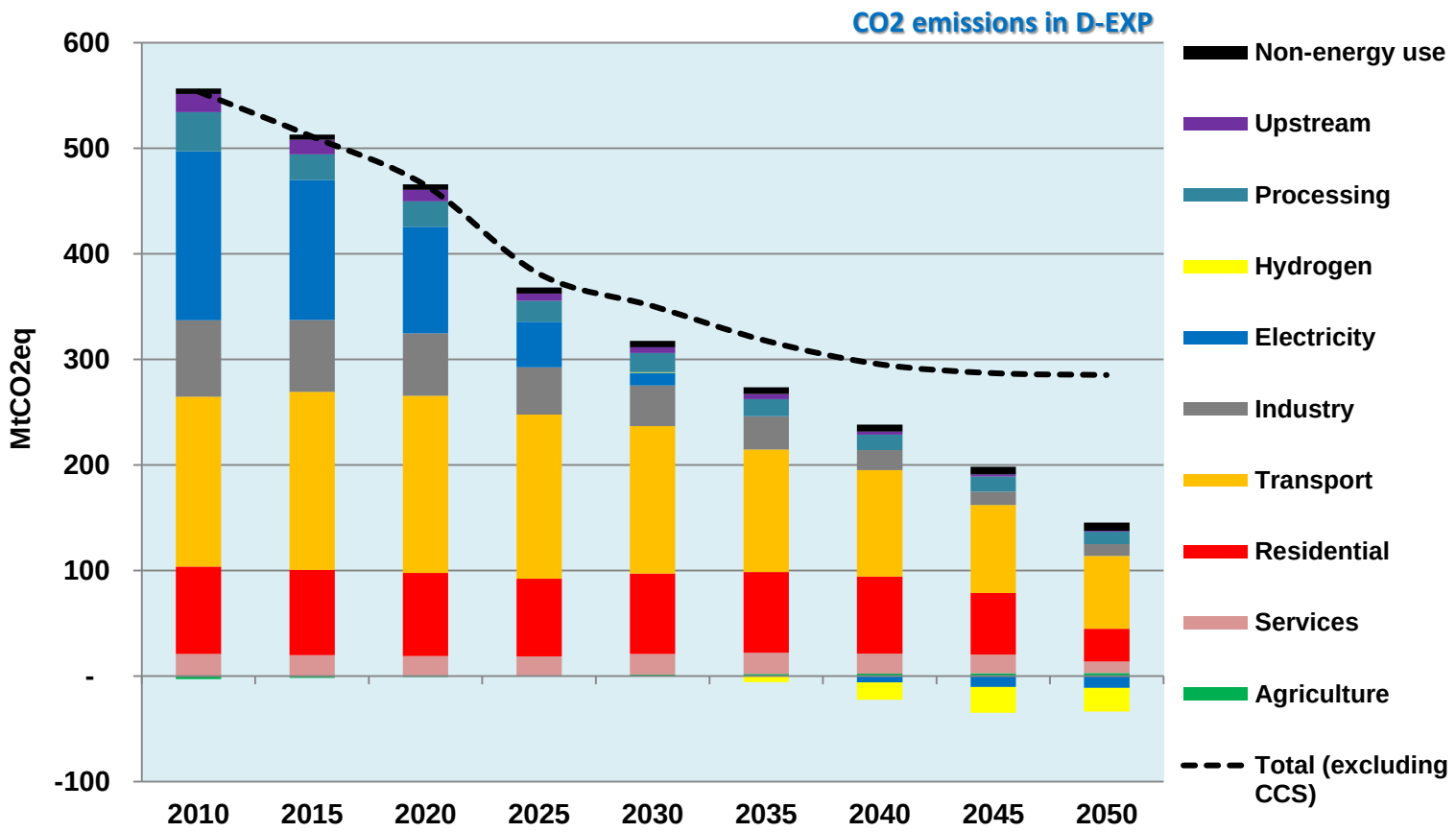
- A more limited deployment of CCS / nuclear for range of reasons and public acceptability concerns.
- Stronger growth of wind (and a more intermittent system); lower electrification due to system integration issues and more cost-competitive alternatives – bioenergy and H2 play a stronger role.
- Highlights system operation challenge and higher costs of lower & delayed deployment.

R-DEM: 'reduced demand'

- Stronger focus on local solutions, with area-based building retrofit programmes and local transport measures.
- In addition, transport demand does not grow as forecast (saturation effects) and international aviation reduces due to high costs.

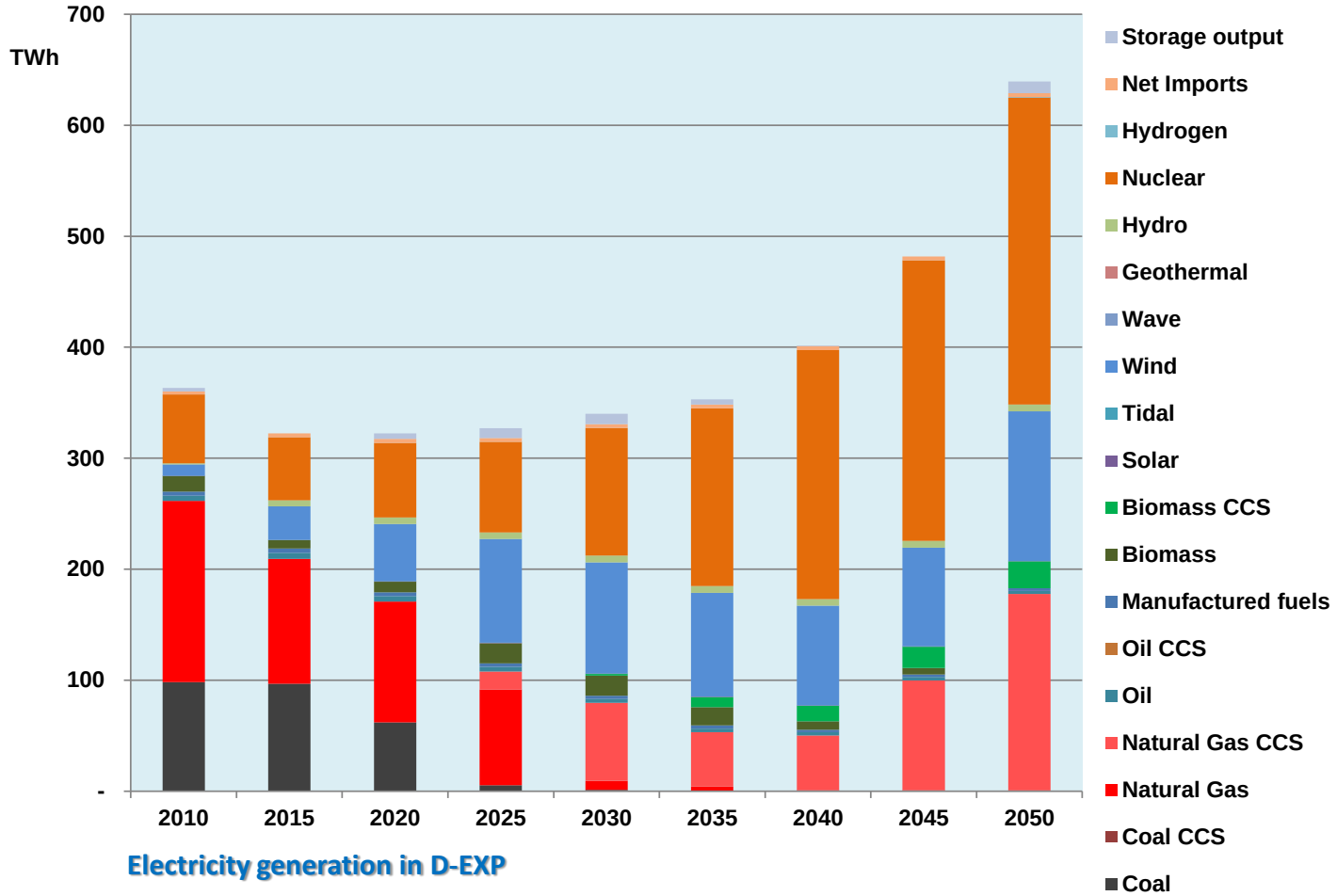
Decarbonisation pathways characterised by strong action in power sector

- Post 2030, end use sector decarbonisation follows in transport, industry and buildings.
- Critical role for CCS (and negative emissions).



Rapid power sector decarbonisation followed by expansion

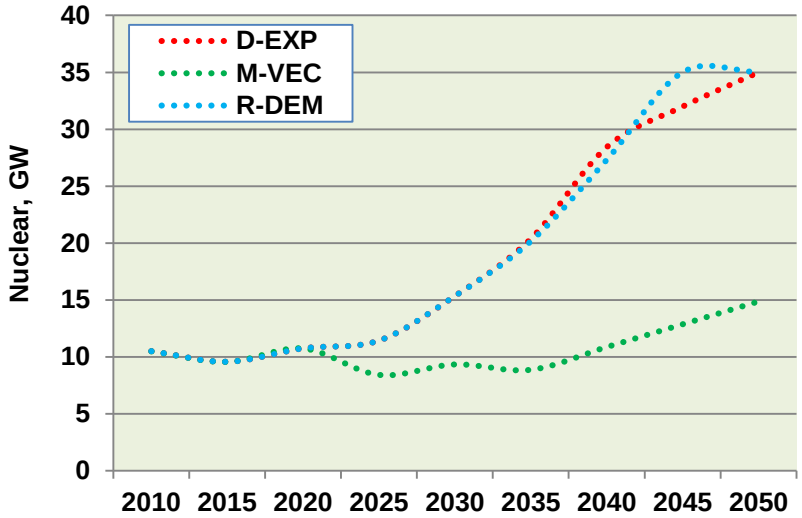
- By 2030, CI of 0 gCO_2/kWh, and low carbon technology dominated.
- Strong increase in generation post 2030, due to end use electrification.

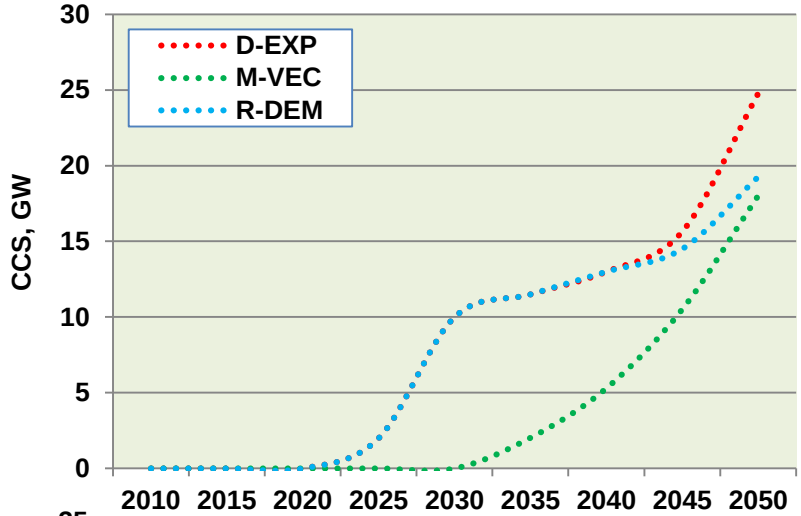


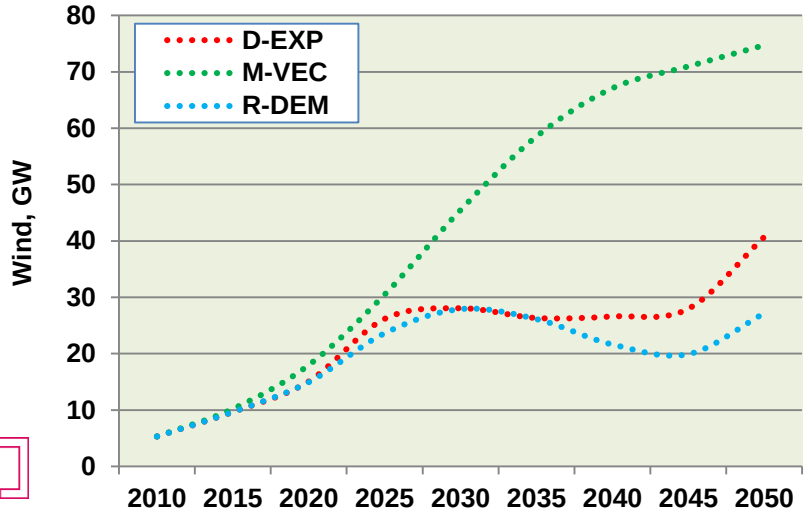
Electricity generation in D-EXP

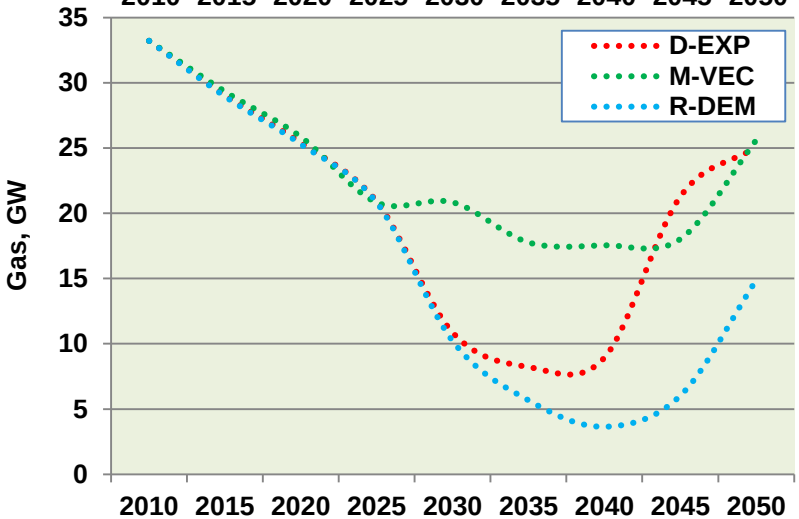
Lower deployment of key technologies impacts solution

- Low deployment of nuclear, and delay in CCS means stronger wind capacity uptake.
- Strong role for gas capacity in LT as back-up capacity.



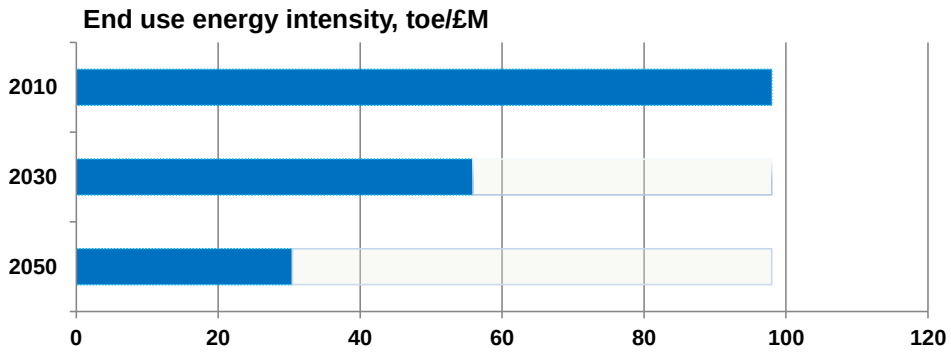




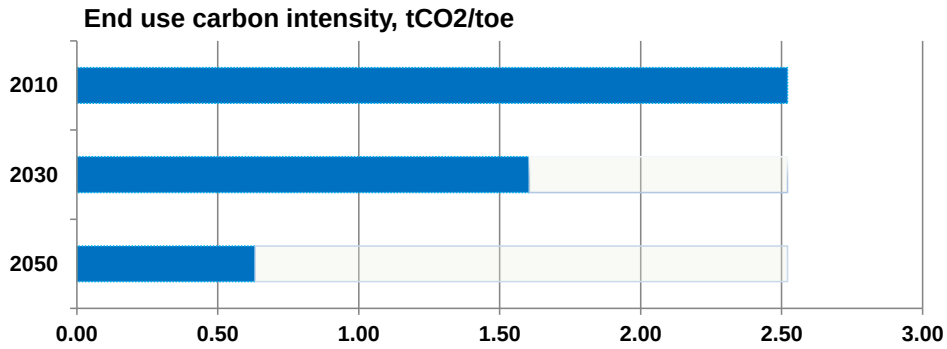


Energy /carbon intensity of final energy consumption falls by over 70%

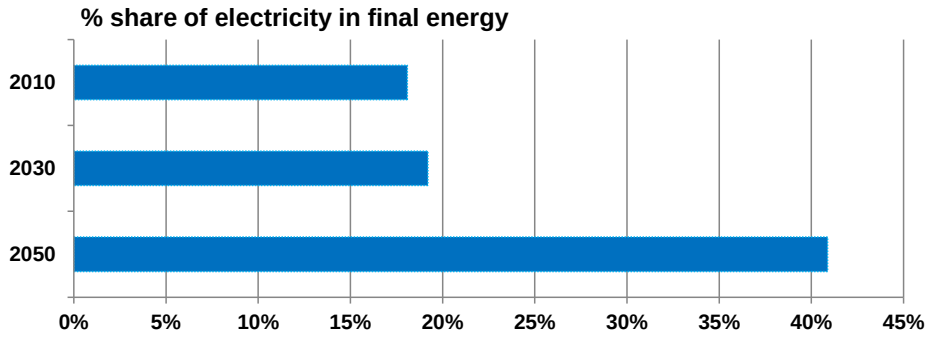
- Increased efficiency seen across all pathways.



- Decarbonisation of energy mix also critical.

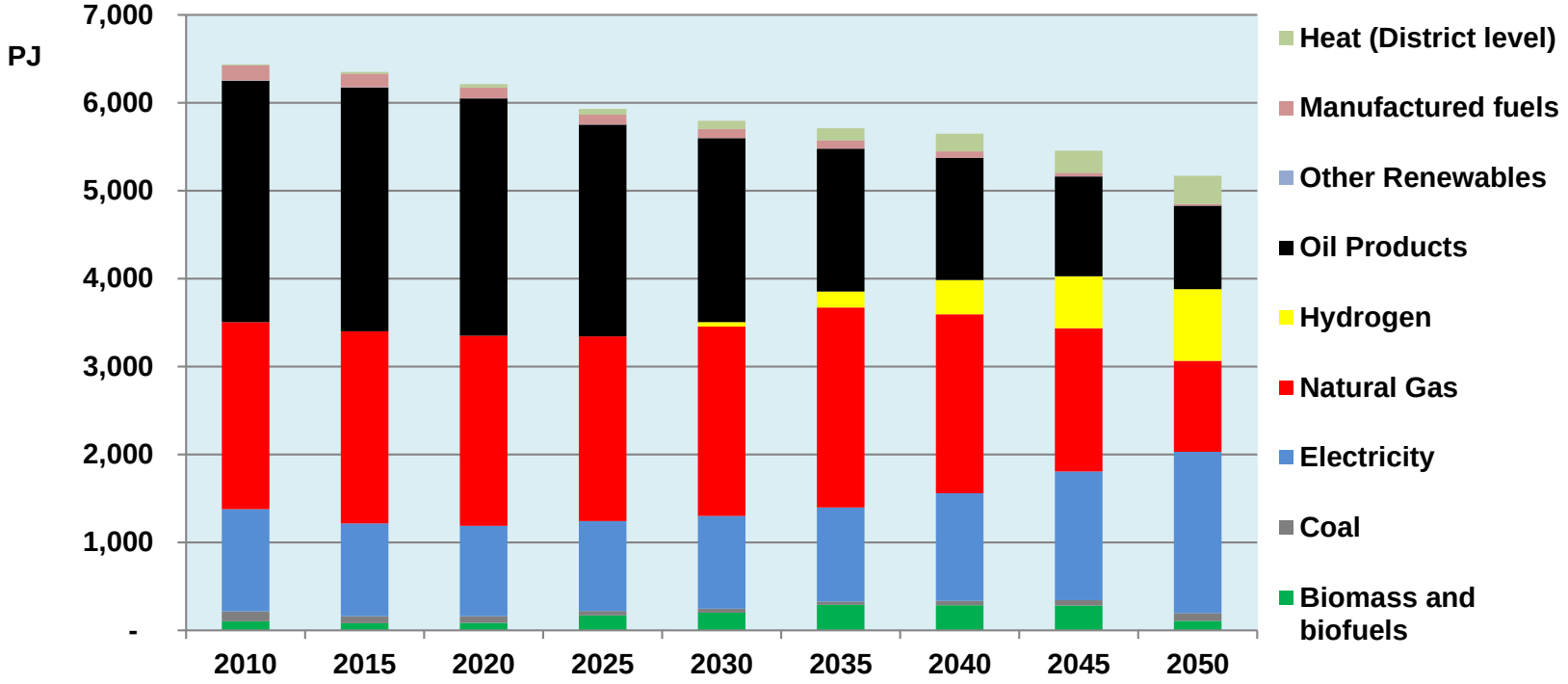


- Strong role for electricity, (although lower under M-VEC ~30%).



Increased efficiency and move towards a lower carbon energy mix

- Emergence of hydrogen for transport and industry from 2030 onwards.
- Strong reductions in oil and gas use in end use sectors – and growth in electricity use.



Final energy demand in D-EXP

Transport sector transitions: car travel demand (bvkm)

D-EXP:

Car stock transition between 2025 – 2035; large-scale take-up of PHEV/EVs

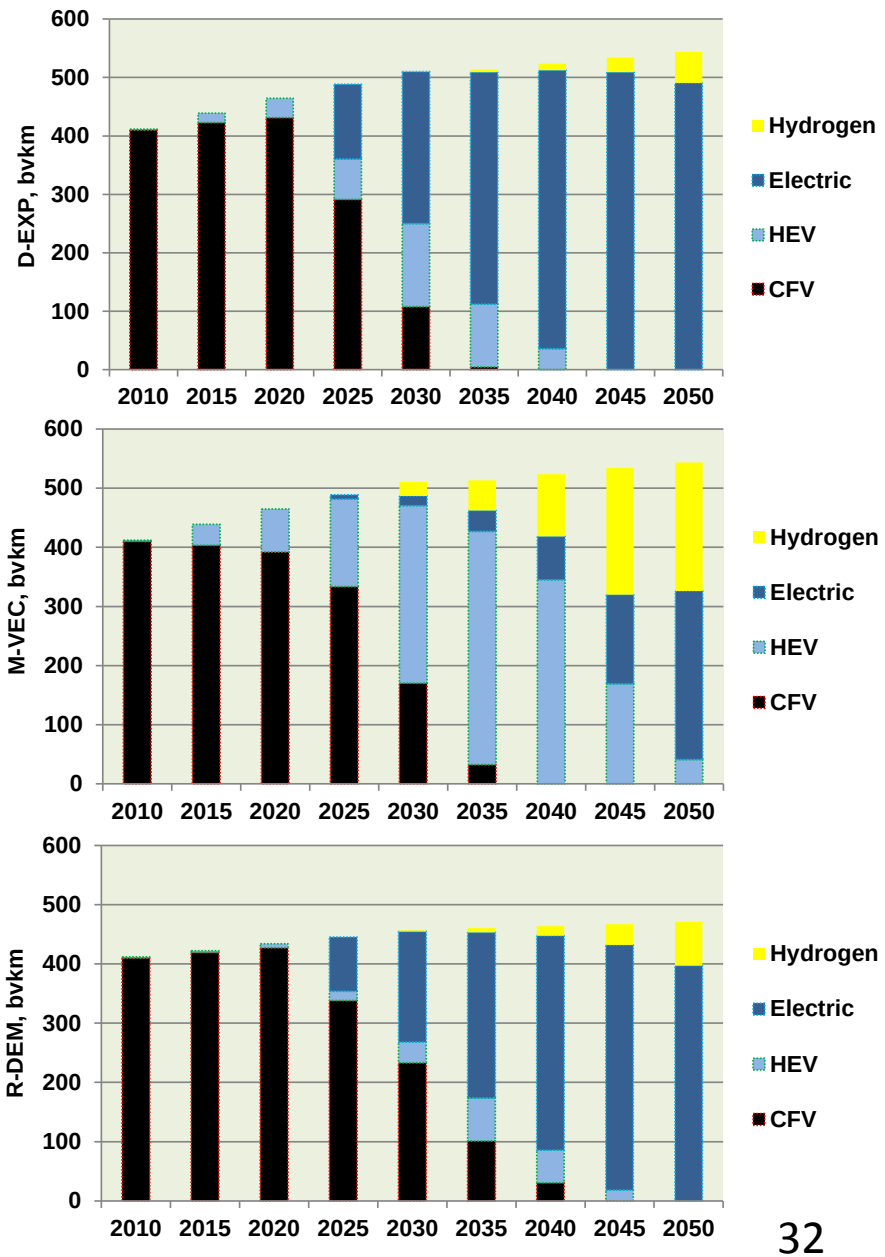
M-VEC:

Longer transition phase with HEVs

More limited uptake of electric, and stronger role for hydrogen

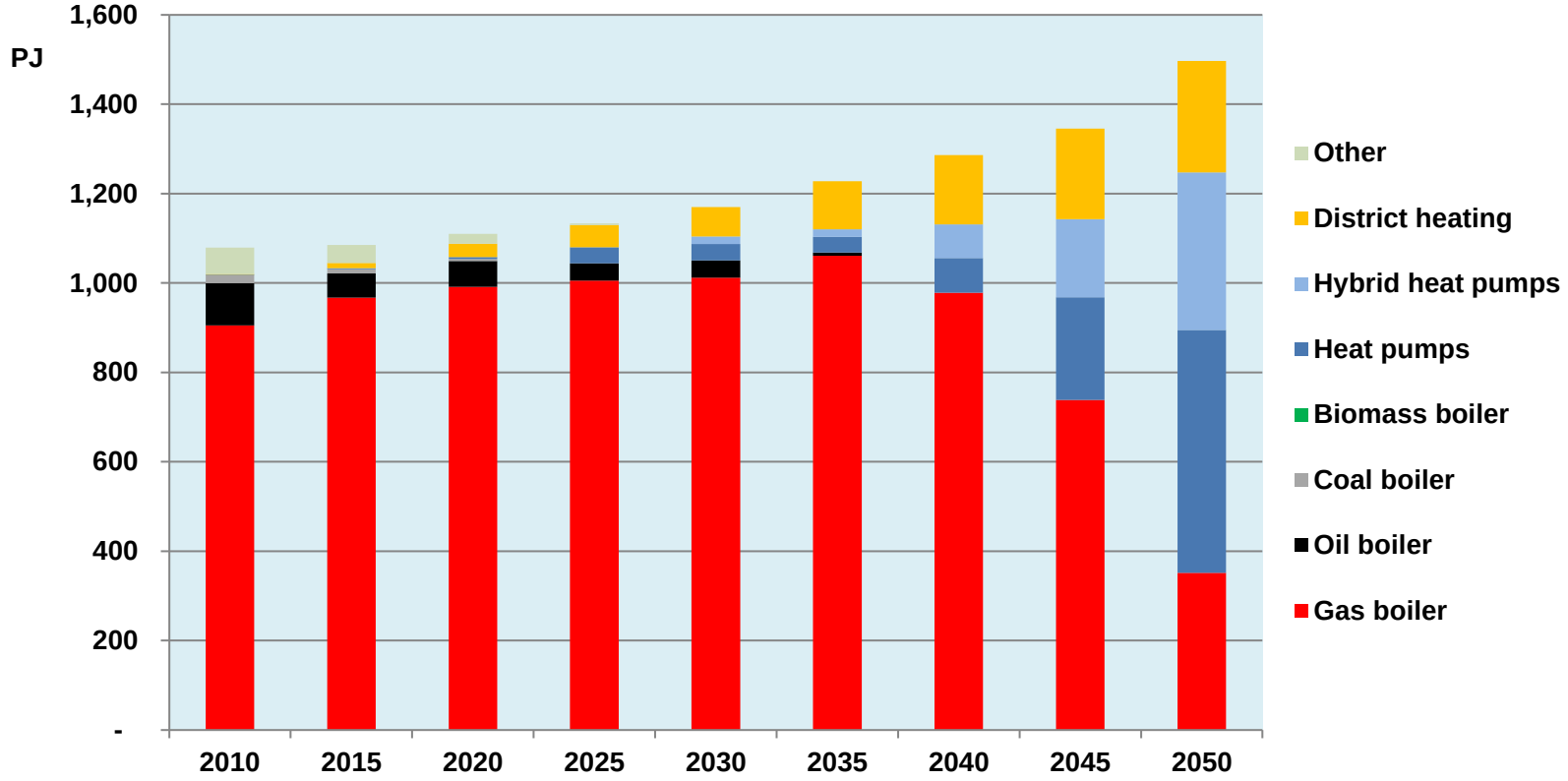
R-DEM:

Reduced growth in car demand allows for slower transition that D-EXP



Residential sector transition a key challenge

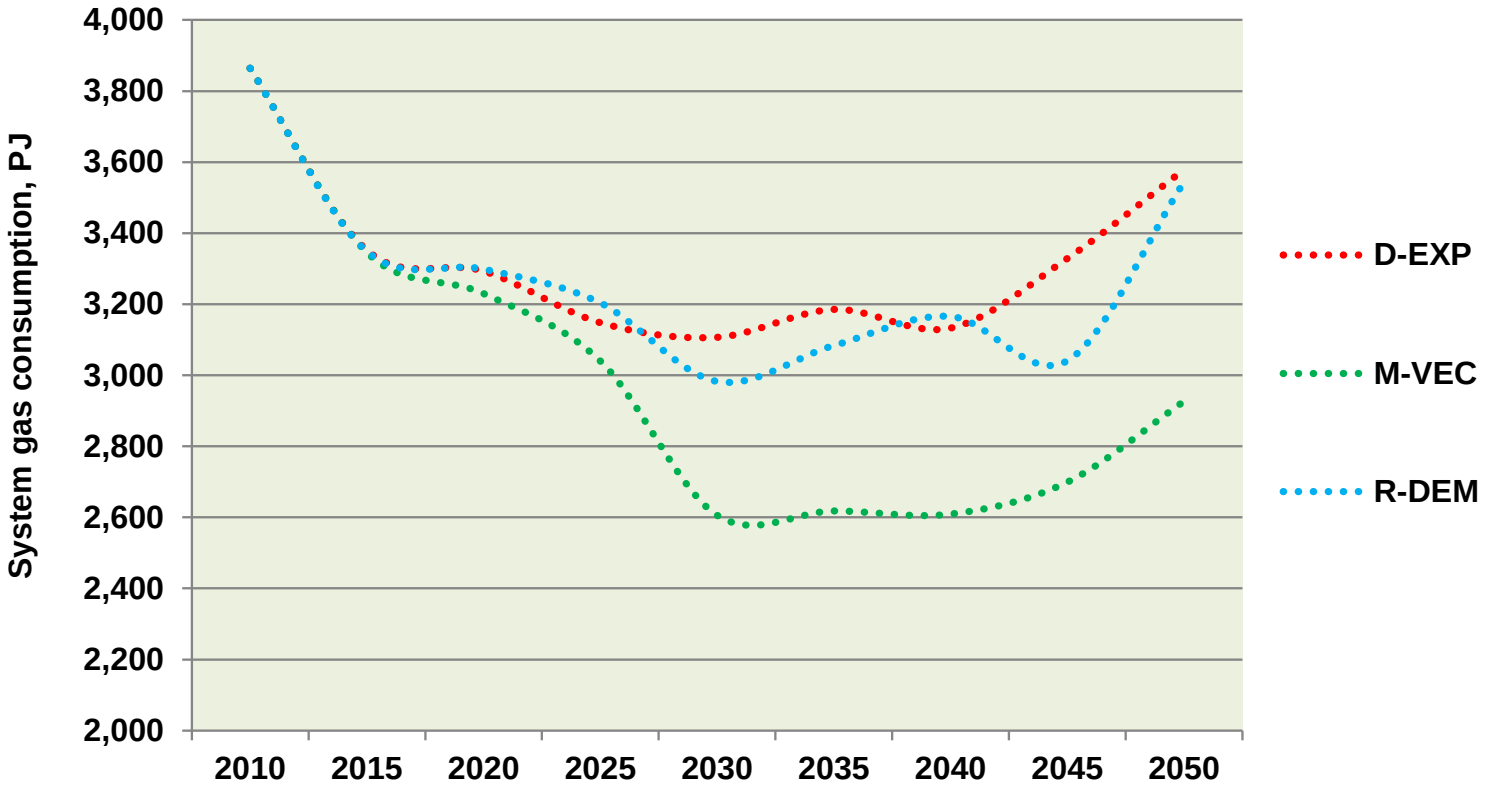
- Central heating is excellent, and copes with high winter peak demand.
- Later mitigation in sector compared to transport; strong role for heat pumps – but gas use continues to deal with heating peak.
- Role for district heating, providing additional storage in strongly electrified sector.



Residential heat demand in D-EXP

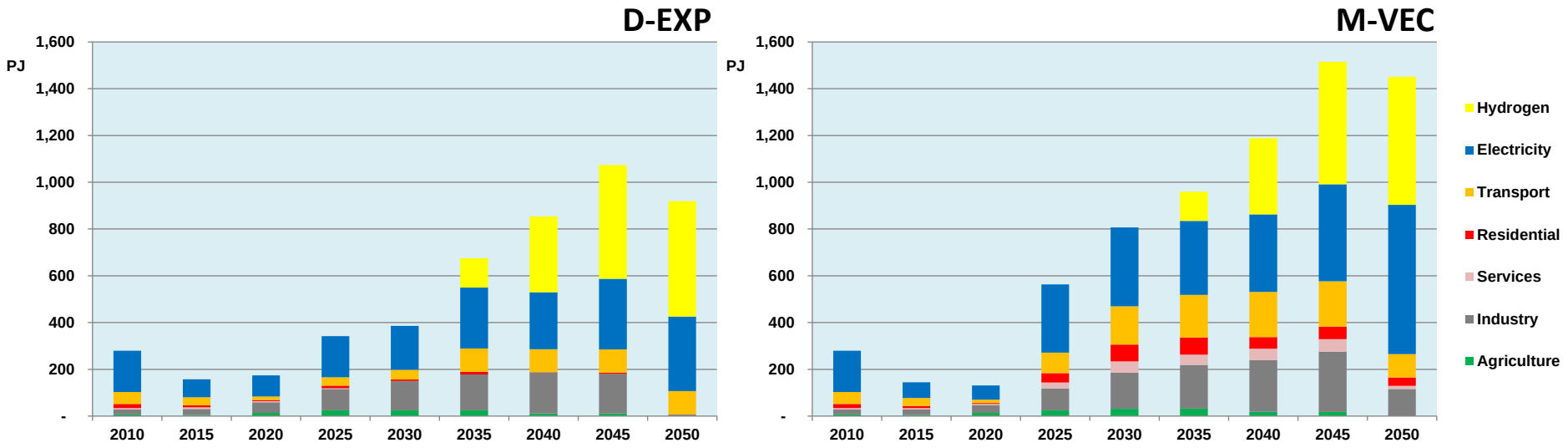
Energy supply transition: the role of gas

- Increase in gas in later periods due to use in electricity and H2 production, both with CCS.
- Lower deployment level of electricity CCS in M-VEC, and more electricity use for H2 production (rather than gas).



Energy supply transition: optimal allocation of bioenergy

- Higher bioenergy potential in M-VEC case, due to lower electrification.
- More direct use in end use sectors under M-VEC – but in general allocation for use in combination with CCS, particularly H2 / electricity.



Some conclusions…

- Most cost-effective mitigation is in the power sector; ‘decarbonise and expand’ is fairly well recognised.
- Lower deployment of key generation technologies increases costs, and increases challenge for system operation.
- CCS (incl. negative emissions) provides significant headroom in later years to continue using some fossil fuels in end use sectors.
- Bioenergy assumptions are critical; strong use in hydrogen and electricity production w/ CCS.

….and implications

- Re-orientation of how we deliver energy services necessary (system operation, policy incentives, new infrastructure, supply chain capacity).
- Society has to be engaged!
- Key role for government on policy frameworks, R&D etc.; markets cannot deliver this alone (high capital investment and perception of risk).
- Action has to happen now; in 15 years, power system decarbonized and large market in electric vehicles and heat pumps.
- International cooperation essential to make this happen; UK is a price taker in the main but can influence some technologies (CCS, offshore wind).
- Key uncertainties include role and price of gas, CCS performance / deployment, and use of bioenergy.

Thank you