www.eti.co.uk

Energy system modelling in an uncertain world

Manchester University Summer School 07/6/2016

Adam Thirkill

adam.thirkill@eti.co.uk

What is the ETI?

- The Energy Technologies Institute (ETI) is a public-private partnership between global industries and UK Government

Delivering...

- Targeted development and demonstration of new technologies
- Shared risk
- System level strategic planning

ETI members

bp
CATERPILLAR®
EDF ENERGY
Rolls-Royce
Shell
EPSRC Pioneering research and skills
Department of Energy & Climate Change
Department for Business Innovation & Skills
Innovate UK Technology Strategy Board

ETI programme associate

HITACHI Inspire the Next

See www.eti.co.uk for more details on our projects

energy technologies institute

The ETI works with:

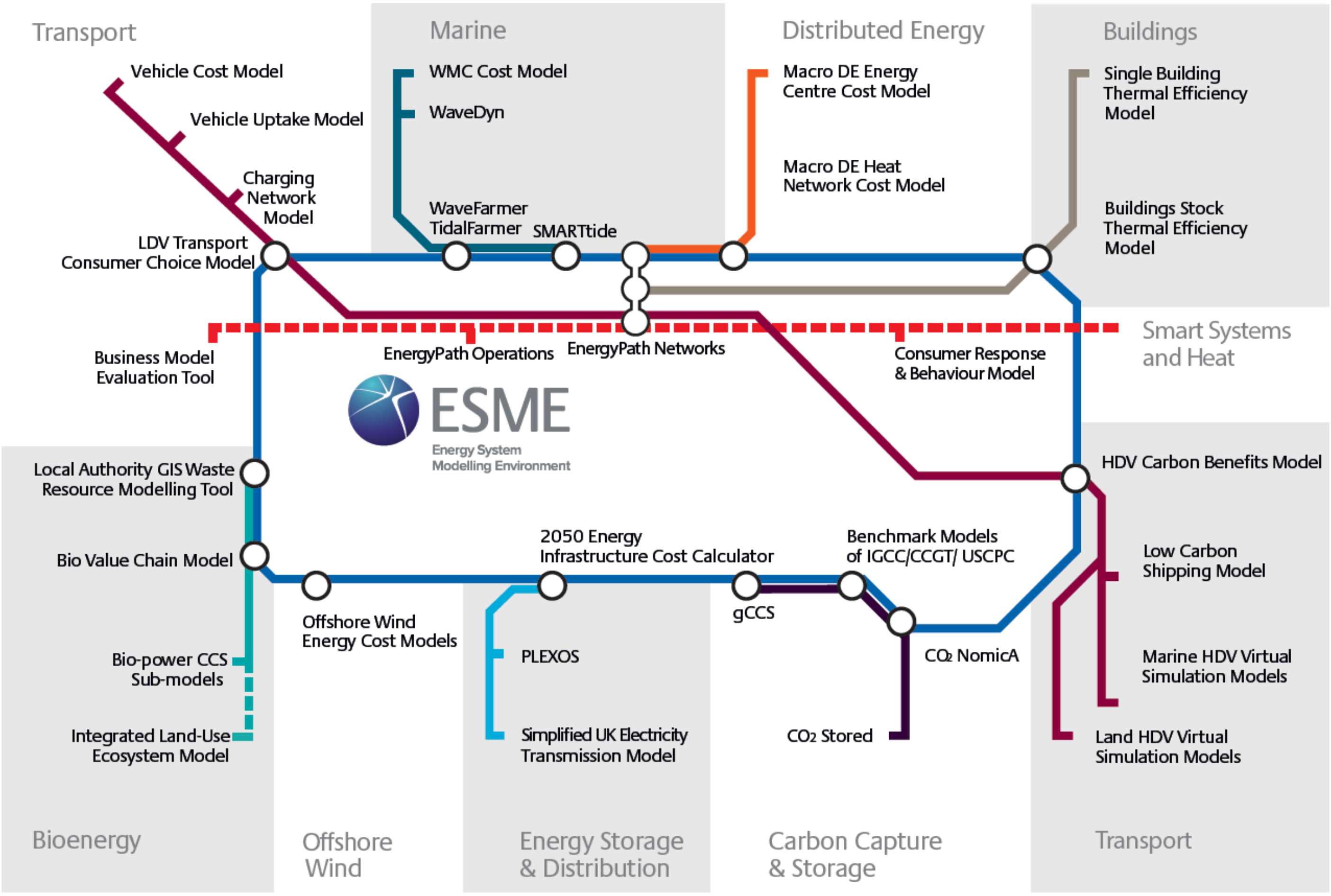
Why do energy system modelling?

- Energy systems are complex and inter-dependent, made more so by emissions reduction objectives:
  - Efforts to cut emissions are substitutable across power, heat, transport, industry and infrastructure
  - There are key decision points and choices are long lived
- Energy governed by well-understood physical laws, so quantitative modelling is capable of representing system interactions and capturing dynamics that would otherwise not be understood

Types of Debate that ESME is used to inform

- What might be ‘no regret’ technology choices and pathways to 2050?
- What is the total system cost of meeting the energy targets?
- What are the opportunity costs of individual technologies?
- What are the key constraints? e.g. resources, supply chains etc.
- How does uncertainty influence system design choices?

Knowledge from across ETI programme areas is integrated in ESME



ESME in use by the ETI, its members and partners

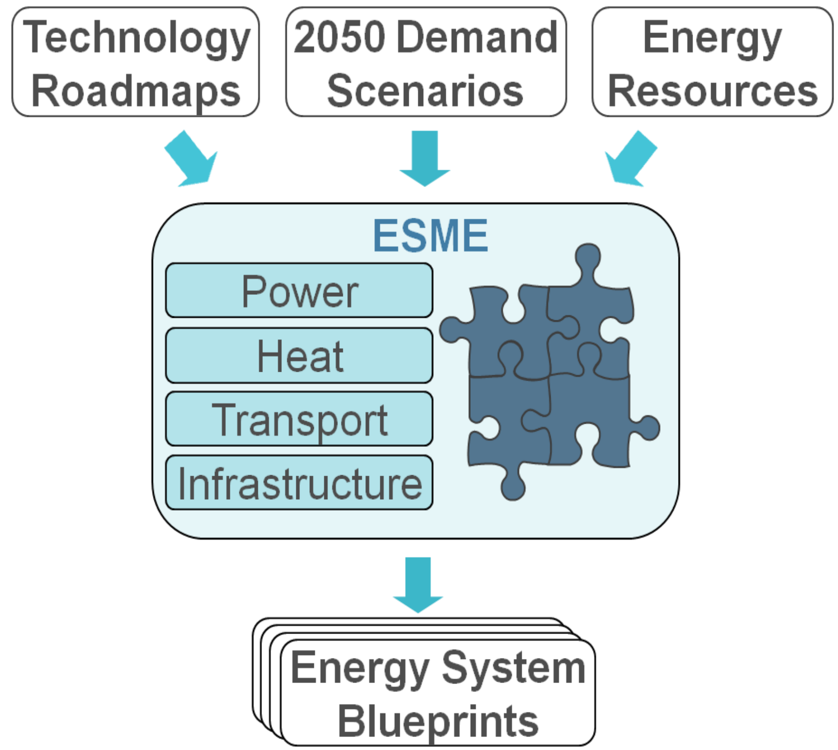
- ESME developed to inform technology development choices and targets for ETI & members
- ESME used to inform policy work by DECC* and CCC+ on a range of issues
- ETI Members are developing own versions for specific countries of interest
- Academic research projects ongoing. Licences to use ESME for academic research are available.

* UK Government Department of Energy & Climate Change
+ Committee on Climate Change, a statutory UK body

The ESME model and approach

The ESME modelling approach

- Least cost optimisation, policy neutral
- Deployment & utilisation of >250 technologies
- Probabilistic treatment of key uncertainties
- Pathway and supply chain constraints to 2050
- Spatial and temporal resolution sufficient for system engineering



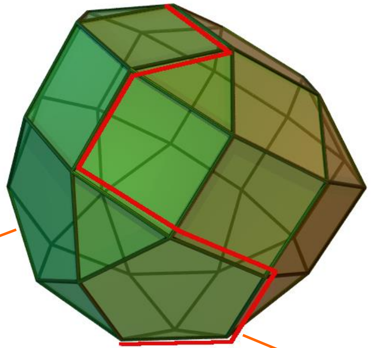
The resulting mathematical optimisation

Decision variables:

- Deployment: per technology, per decade, per region
- Operation: per technology, per decade, per region, per timeslice

Constraints:

- Mass balances and operational constraints
- Meet demand
- Meet CO_2 emissions targets
- Limits on rate of deployment
- Security of supply constraints



Feasible space for a 3d Linear Program

Path followed by Simplex algorithm

A typical ESME optimisation has ~200,000 variables & constraints

In ESME the optimisation is formulated as a Linear Program:

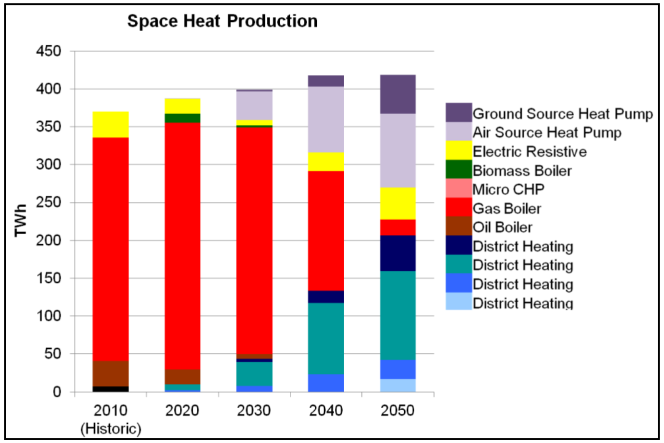
- All constraints are strictly linear
- All variables are continuous
- ... a key approximation

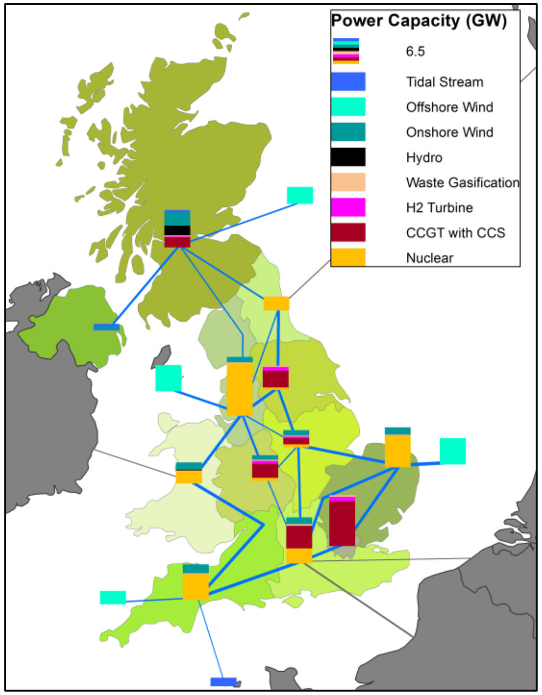
In matrix / vector notation:

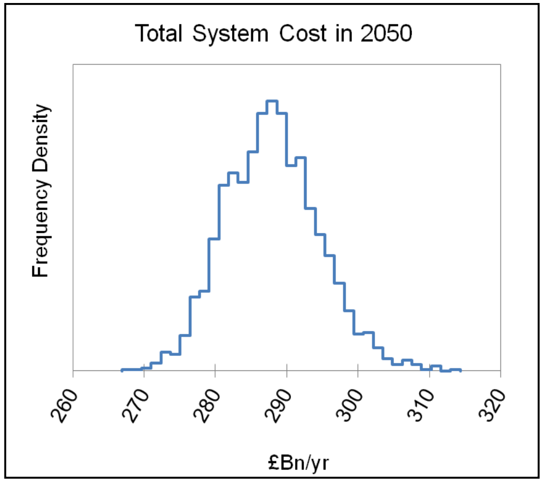
minimise $f(\mathbf{x}) = \mathbf{c}^t\mathbf{x}$

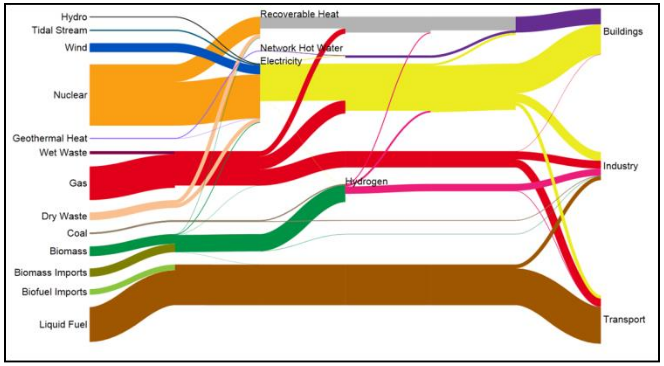
such that $\mathbf{Ax} \leq \mathbf{b}$ and $\mathbf{x} \geq 0$

Typical ESME Outputs



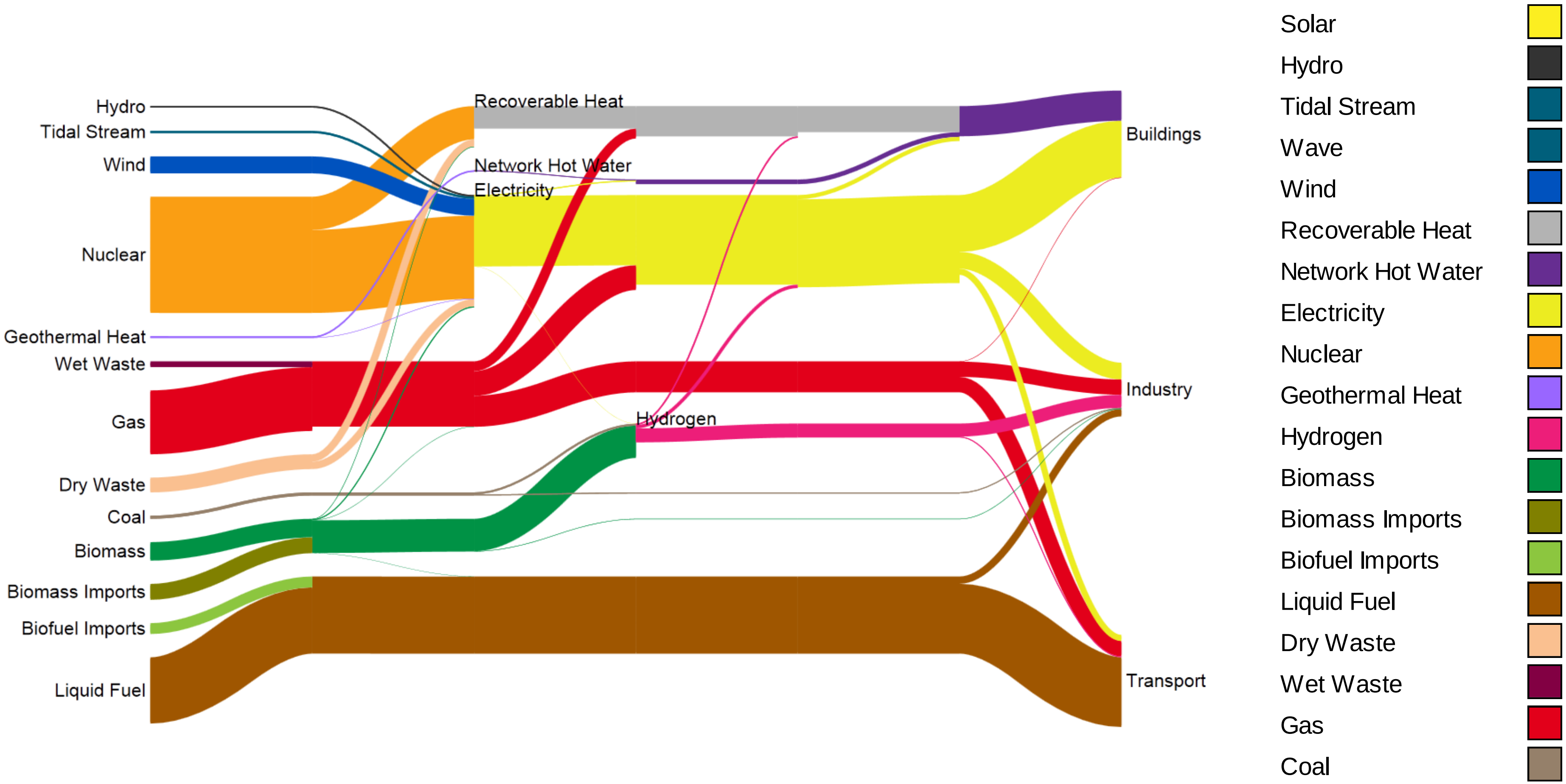






Energy System Sankey Diagram

A Typical 2050 Case



ESME uncertainty analysis

Examples of the assumptions used in ESME which are highly uncertain

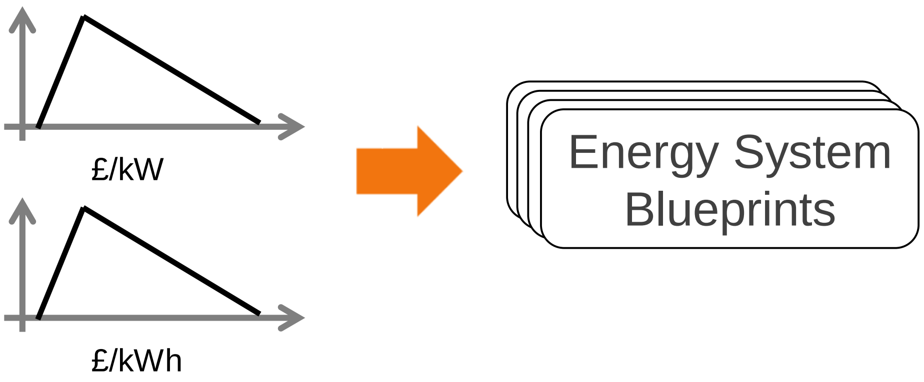
1. Technology costs e.g. CCS power stations, Hydrogen Cars
   Cost improvement for novel technologies, efficiency improvements, safety, ...

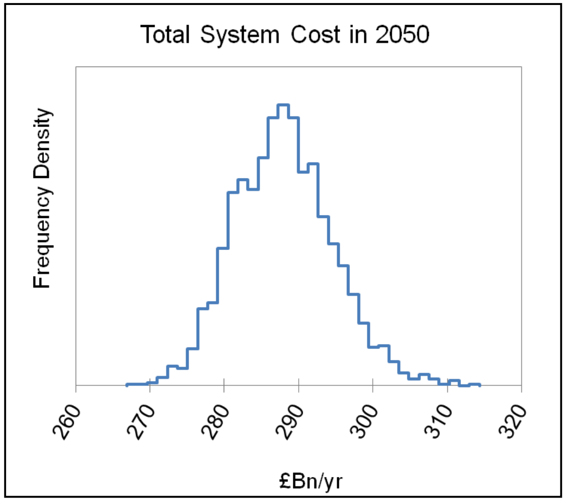
2. Fuel prices e.g. gas price, oil price, imported biomass price
   International supplies, demand from other countries, shale gas, ...

3. Maximum UK resource for Biomass
   Sustainability questions, public acceptance, farmer acceptance, yields, ...

ESME uncertainty analysis

- ESME is a Monte Carlo model
  - Ranges and probability distributions on uncertain inputs
  - Results are an ensemble of least-cost energy systems

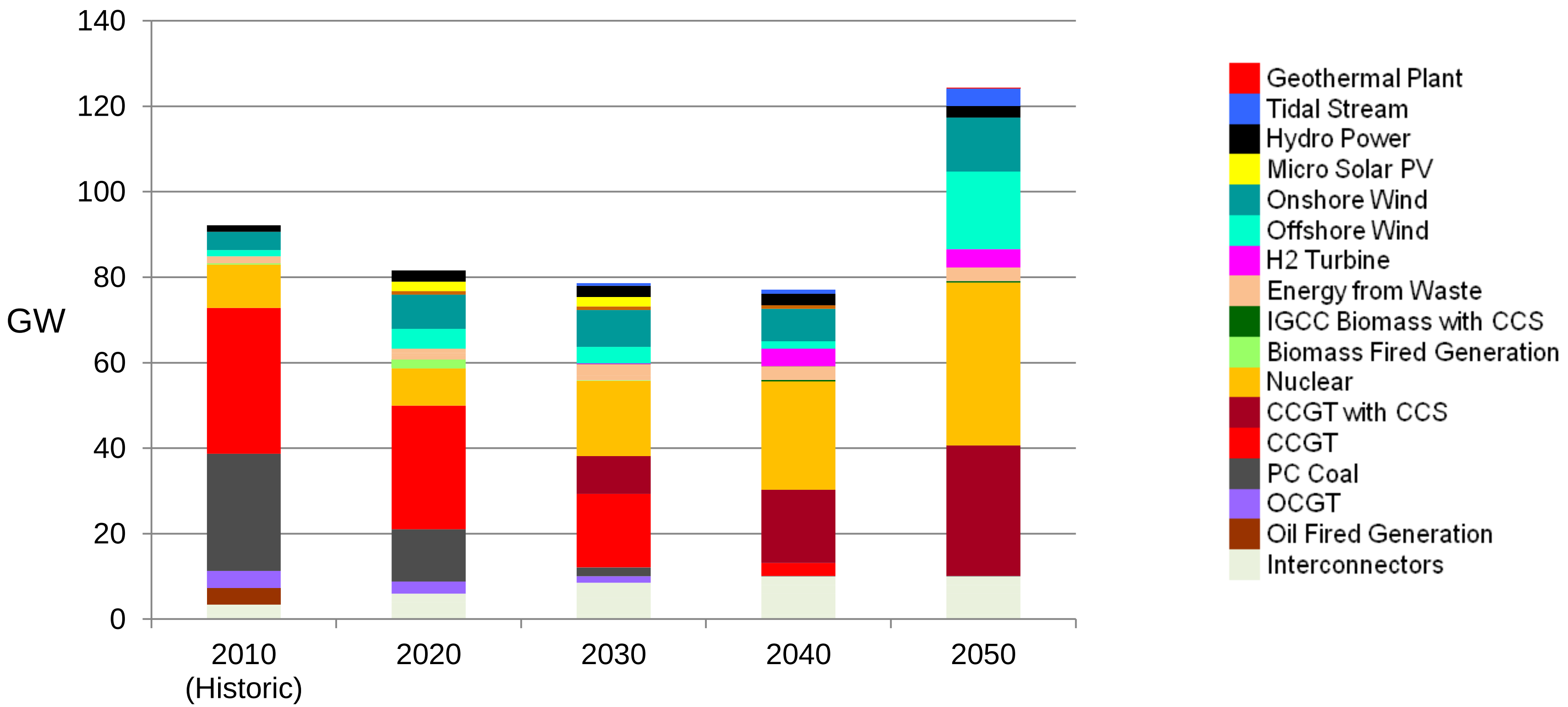




- This effectively automates a large amount of sensitivity analysis

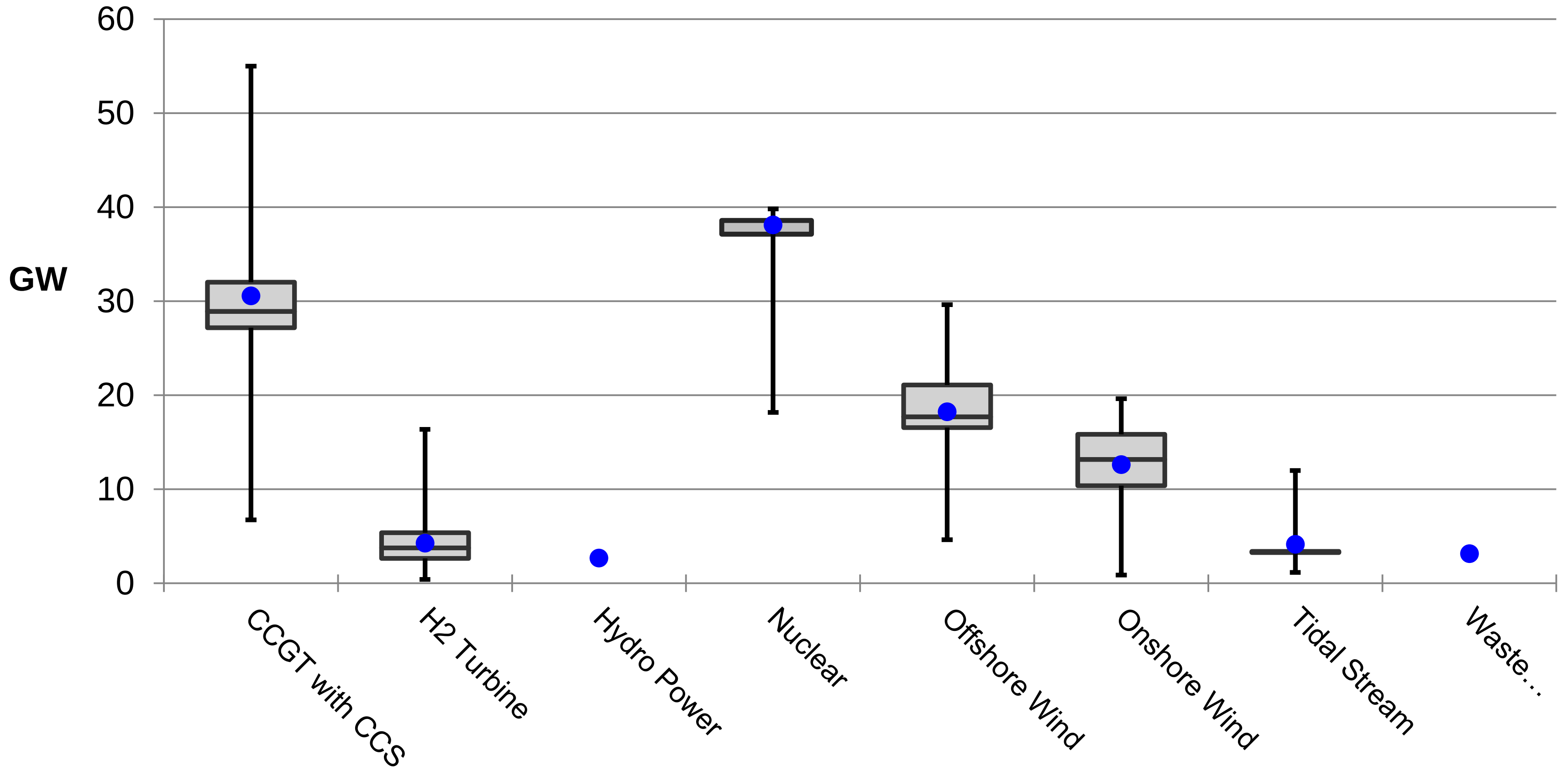
Electricity Generation Capacity

Average case



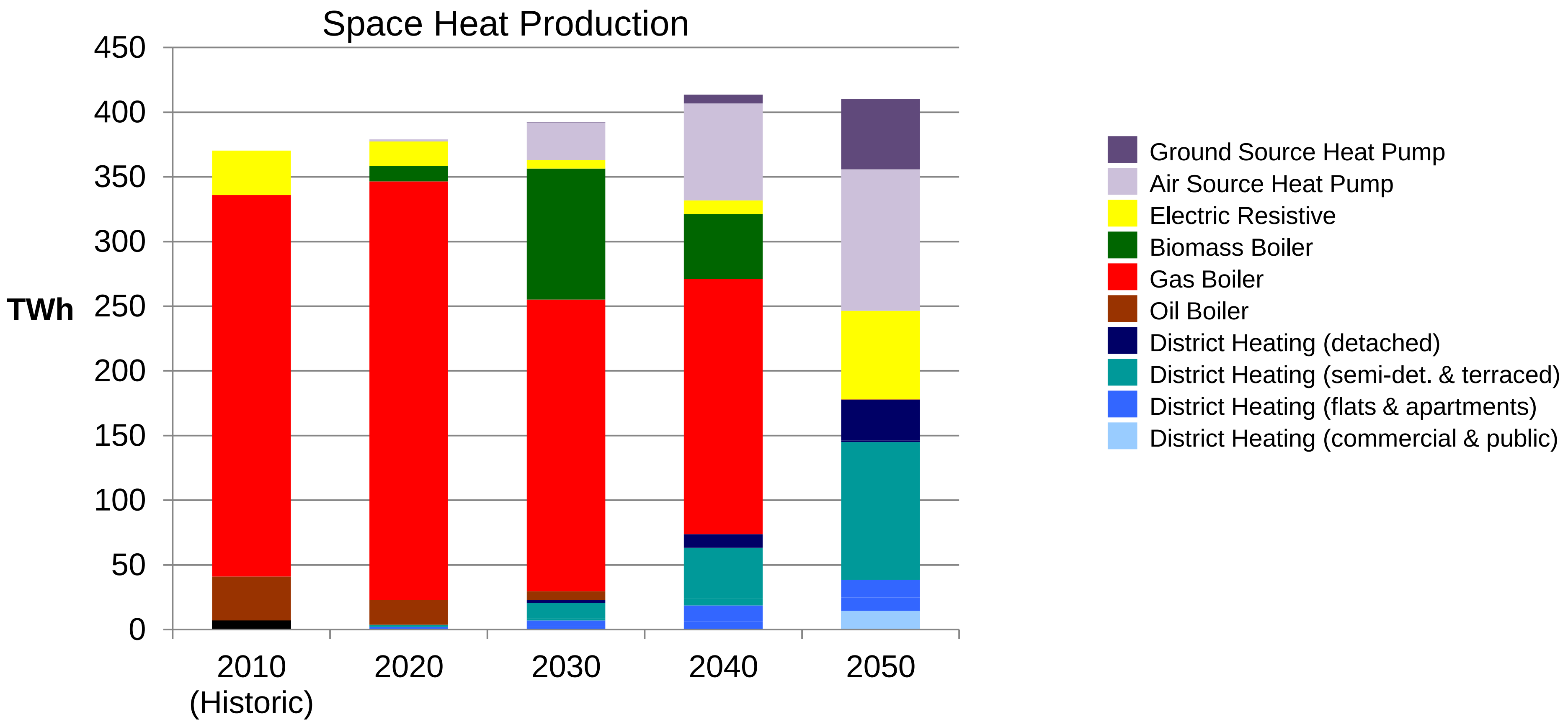
Data 2014DC / Optimiser v3.4

Spread of ESME results for 2050 power capacity



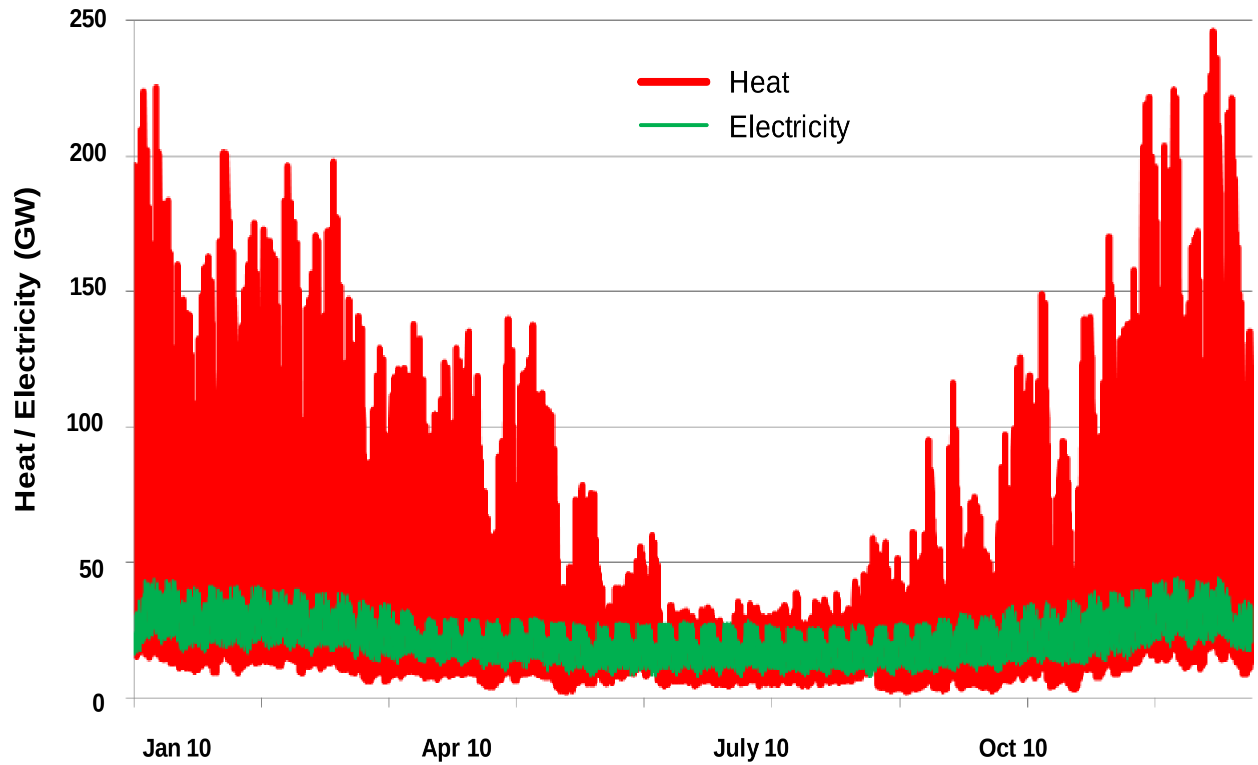
Space heating results from ESME

Average case



Heat demand variability in 2010

UK system has to cope with 6x heat demand swing
Existing gas distribution grid supports this

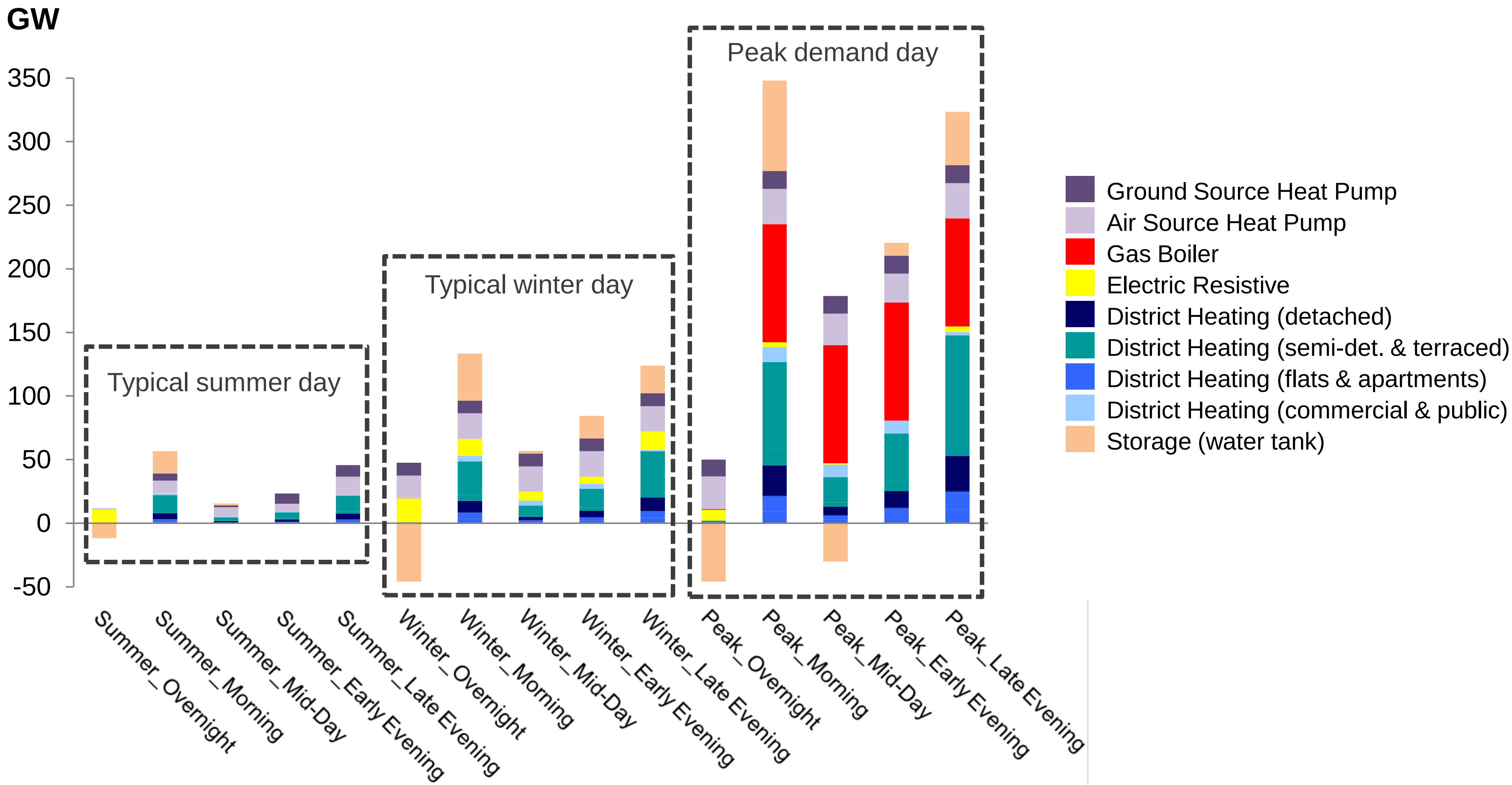


Design point for a GB heat delivery system

Design point for a GB electricity delivery system

GB 2010 heat and electricity hourly demand variability - commercial & domestic buildings
R. Sansom, Imperial College

ESME space heating results: typical vs peak

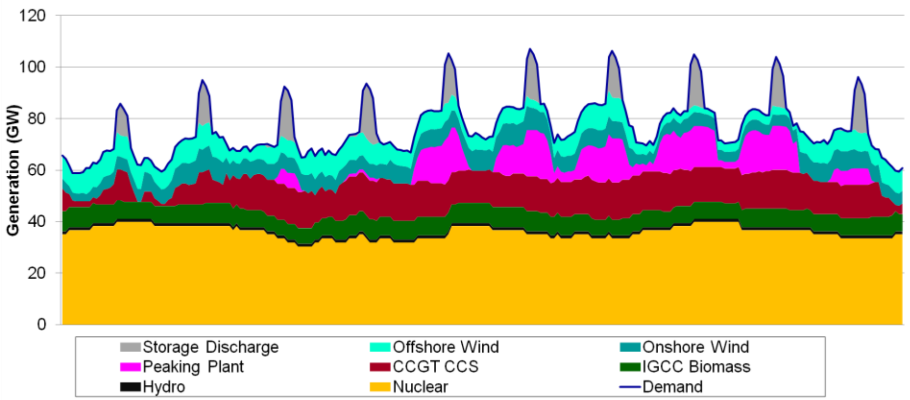


Sensitivity analysis

- Monte Carlo results – 'no-regret' options, marginal choices
- 3 future UK demand cases – alternative socio-economic pathways for the UK
- Long list of "No technology X" sensitivities – opportunity cost metric
- Sensitivity to different CO_2 targets
- Sensitivity to improved/accelerated technology development

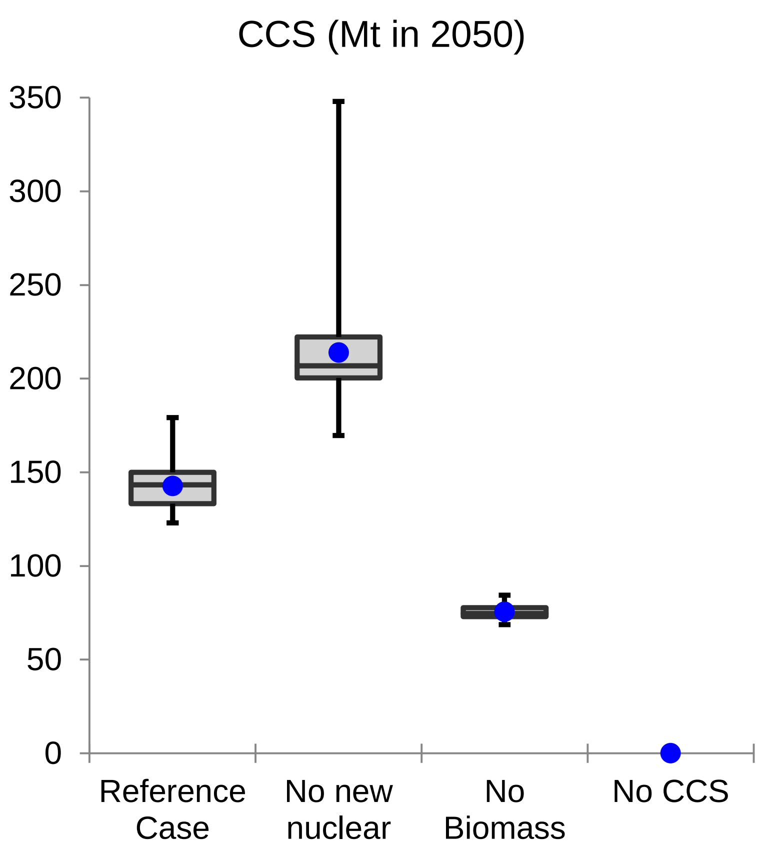
Testing with more detailed tools

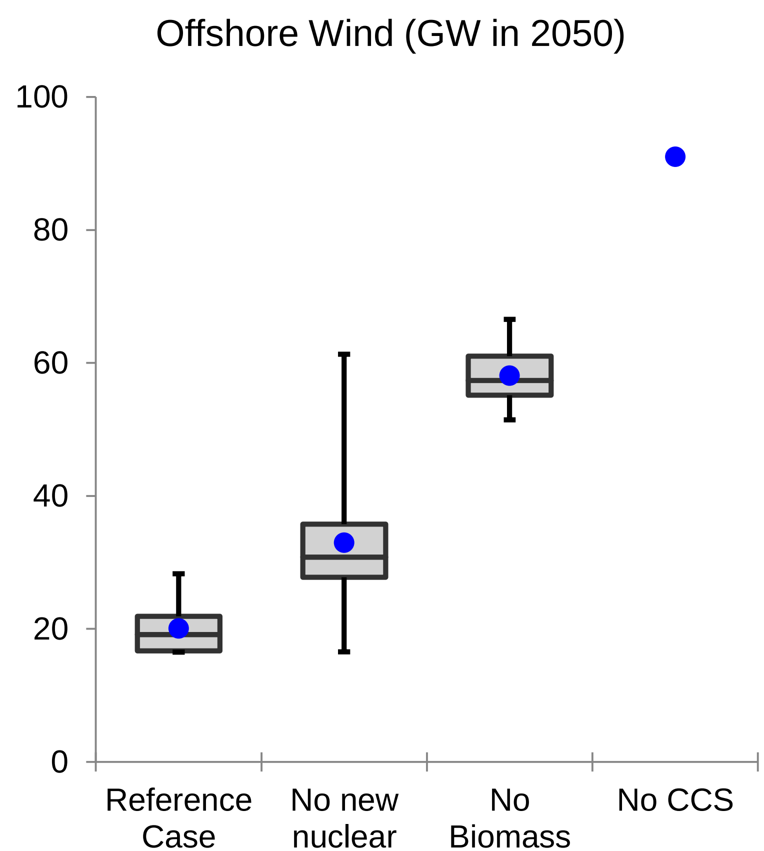
- Dispatch of the ESME electricity system is studied in PLEXOS
- More detailed buildings & heat optimisation
- More detailed peak day optimisation



Technology deployment

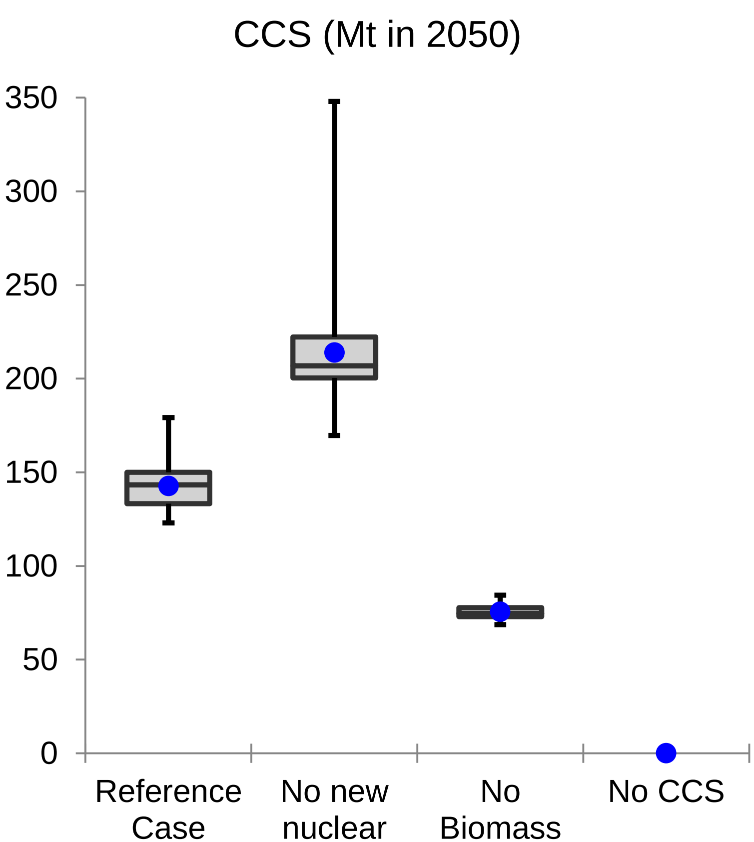
CCS appears a mainstay, offshore wind more variable

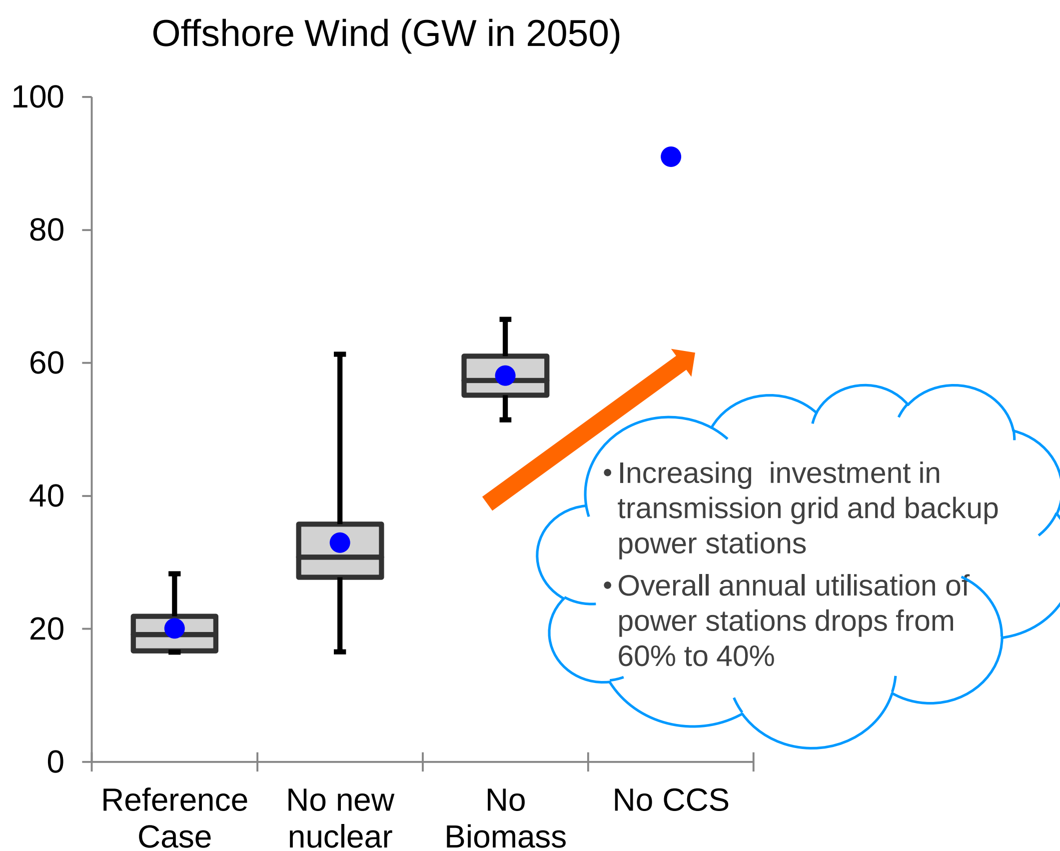




Technology deployment

CCS appears a mainstay, offshore wind more variable





Using ‘opportunity cost’ to measure role of a technology in the system

Opportunity cost of technology X is defined by two alternative scenarios:

A. The least-cost energy system design using standard assumptions
B. The least-cost energy system design if technology X unavailable

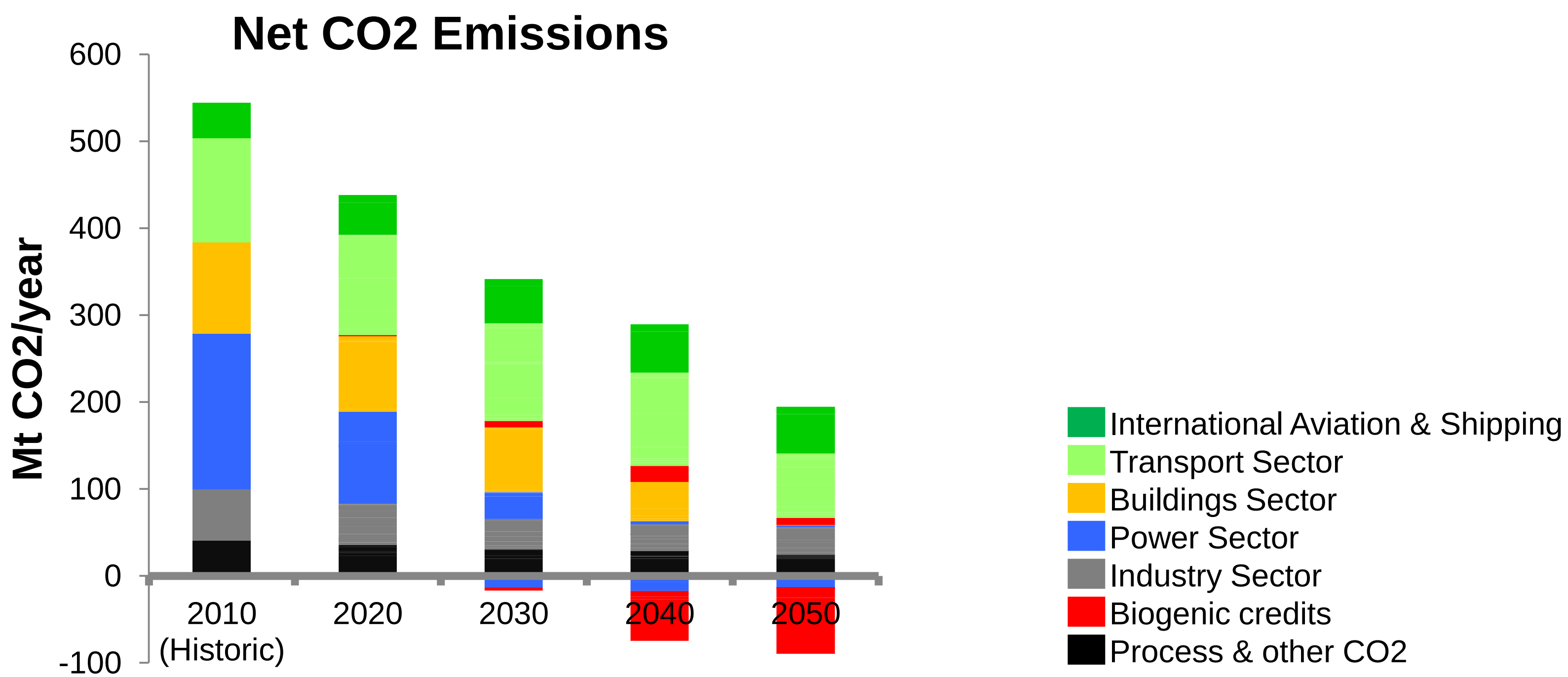
Opportunity cost = Total Cost (B) –Total Cost (A)

= 0 if technology X is not present in the reference case (System A)

> 0 if technology X is present in System A.

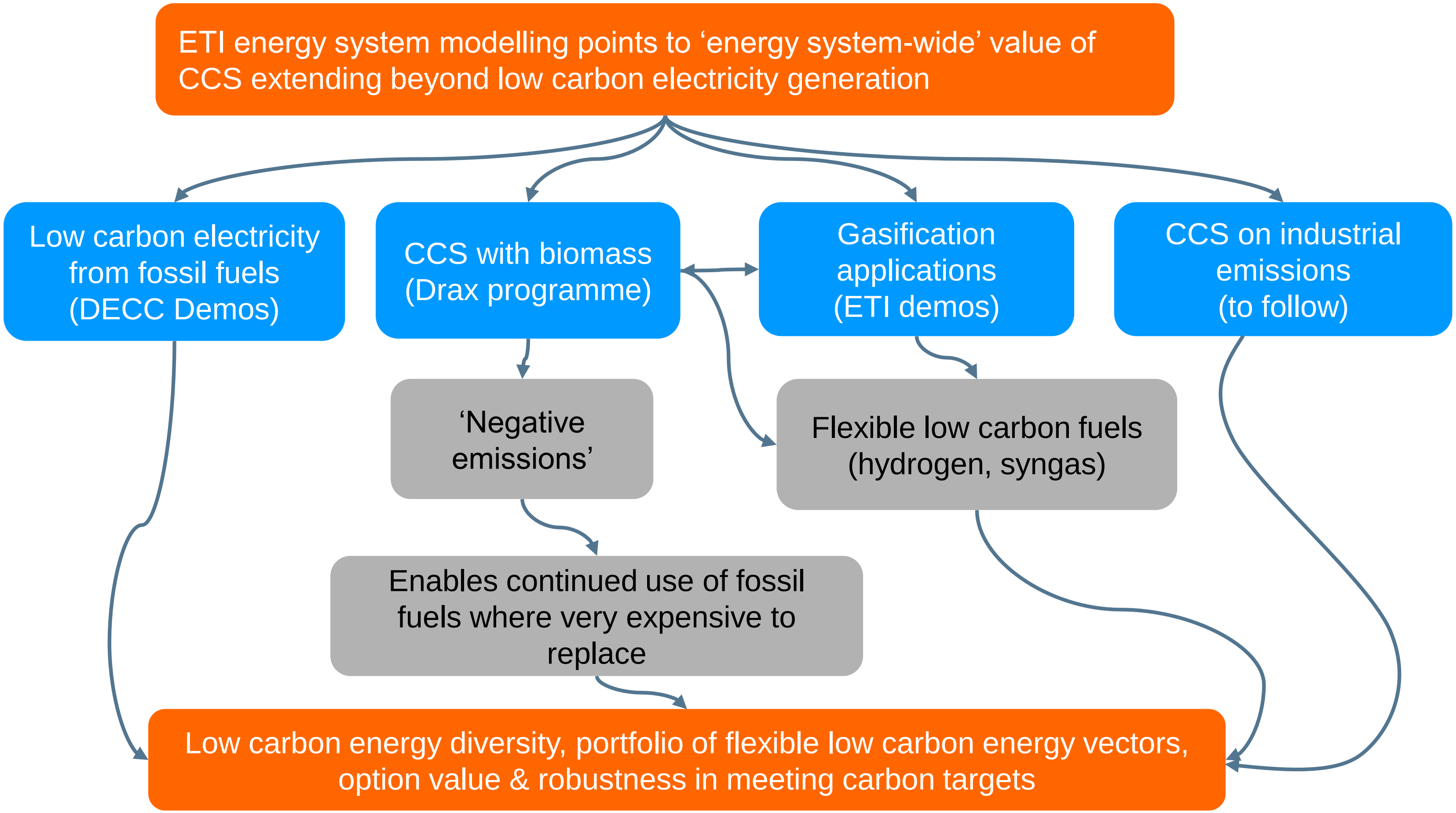
Magnitude of the opportunity cost depends on the relationship between System A and System B: ‘substitution’ or ‘reconfiguration’

CCS and Biomass consistently have the highest opportunity costs



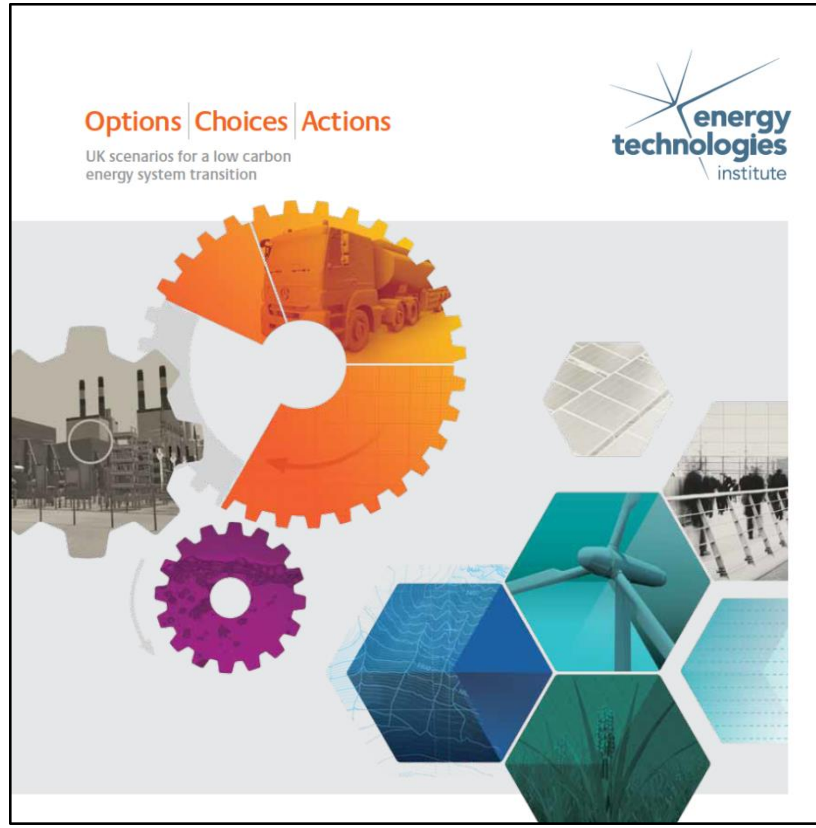
CCS is high value as it creates options

application of the same infrastructure for power, industry, enabling bioenergy usage and H2 production



ETI Scenarios

- UK energy system – power, heating, transport, industry & infrastructure
- Bound by Climate Change Act – 80% emissions reduction by 2050
- Building on several years of modelling, analysis and scenario development using ESME
- Devised in consultation with ETI members and stakeholders
- Launched March 2015



ETI Scenarios

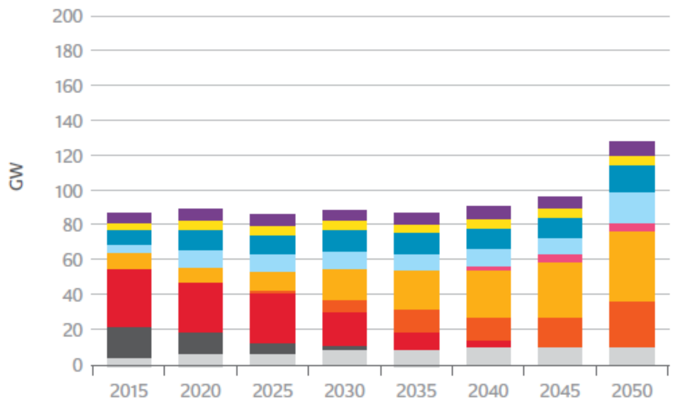
CLOCKWORK

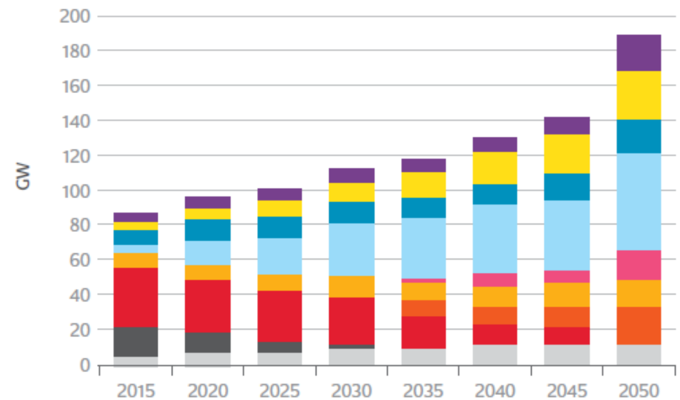
Well-coordinated, long term investments allow new energy infrastructure to be installed like clockwork. The regular build of new nuclear, CCS plants and renewables ensures a steady decarbonisation of the power sector. National-level planning enables the deployment of large-scale district heating networks, with the local gas distribution network retiring incrementally from 2040 onwards. By contrast, due to a strong role for emissions offsetting, the transportation system remains in the earlier stages of a transition and people and companies continue to buy and use vehicles in a similar way to today, albeit with regulation and innovation continuing to improve their efficiency.

PATCHWORK

With central government taking less of a leading role, a patchwork of distinct energy strategies develops at a regional level. Society becomes more actively engaged in decarbonisation, partly by choice and partly in response to higher costs. Popular attention is paid to other social and environmental values, influencing decision-making. There is a more limited role for emissions offsetting, meaning more extensive decarbonisation across all sectors, including transport. Cities and regions compete for central support to meet energy needs which is tailored to local preferences and resources. Over time central government begins to integrate the patchwork of networks to provide national solutions.

ELECTRICITY CAPACITY





CLOCKWORK

- Nuclear provides 40GW of capacity by 2050
- Existing pipeline of renewables built out to 2020, then maintained, with some further uptake of wind in 2040s
- Gas plants retrofitted/replaced with CCS from 2020s
- Hydrogen takes over from gas for peaking capacity from 2030s
- Total capacity of ~130GW by 2050. Balance between nuclear, CCS and renewables

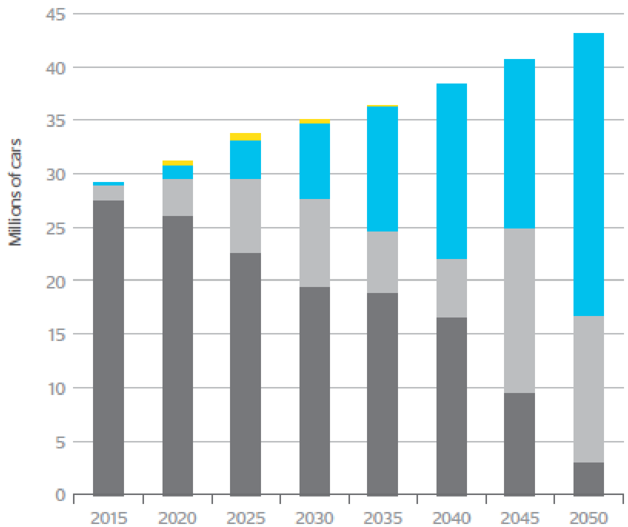
PATCHWORK

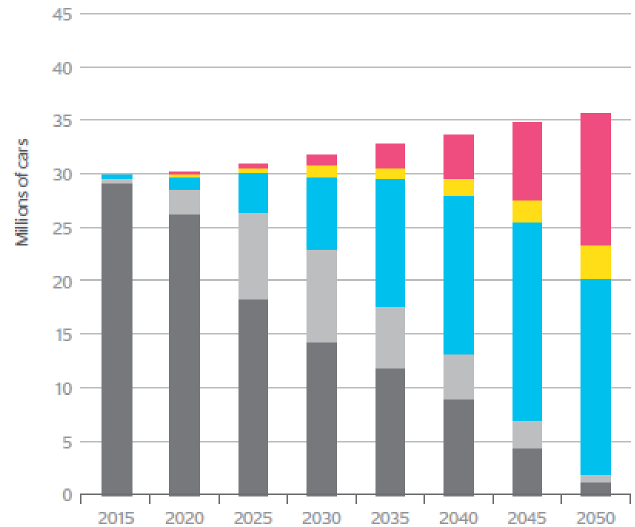
- Nuclear replacement of existing capacity only (16GW)
- CCS delayed until 2030s before replacing unabated gas plants
- Wind power capacity reaches 75GW by 2050, mostly from offshore
- Significant capacity of hydrogen turbines (17GW) required to balance intermittent supply
- Solar provides 28GW, Tidal 10GW and Wave 4GW of capacity by 2050
- Total capacity of ~190GW by 2050, dominated by renewables

TRANSPORT: CAR FLEET

Hydrogen FCV
Battery EV
Plug-in Hybrid EV
Hybrid ICE
Conventional ICE

energy technologies institute





CLOCKWORK

- In Clockwork the car fleet grows to 42m vehicles by 2050
- The continued tightening of vehicle emissions standards drives the uptake of low carbon vehicles from 2020, with conventional ICEs being switched out in favour of hybrids and plug-in hybrids
- Pure electric vehicles make a contribution to these earlier targets but over time consumers choose in favour of the range associated with plug-in hybrids
- The average range of plug-in hybrids increases over time, further encouraging take up until these make up the majority of the car fleet in 2050

PATCHWORK

- Vehicle demand grows more slowly in Patchwork, rising to 35m cars by 2050
- More progressive vehicle emissions standards from 2020 onwards drive a higher adoption of low carbon vehicles, including hybrid, battery electric, plug-in hybrid and hydrogen fuel cell vehicles
- The need for a more comprehensive decarbonisation of the transport sector leads to a large share of FCVs in the car fleet by 2050 supported by long range plug-in hybrids and some battery electric vehicles

Key Messages

1

The UK can achieve an affordable transition to a low carbon energy system over the next 35 years. Our modelling shows abatement costs ranging from 1-2% of GDP by 2050, with potential to achieve the lower end of this range through effective planning

2

The UK must focus on developing and proving a basket of the most promising supply and demand technology options. Developing a basket of options (rather than a single system blueprint) will help to limit inevitable implementation risks

3

Key technology priorities for the UK energy system include: bioenergy, carbon capture and storage, new nuclear, offshore wind, gaseous systems, efficiency of vehicles and efficiency/heat provision for buildings

4

It is critical to focus resources in the next decade on preparing these options for wide-scale deployment. By the mid-2020s crucial decisions must be made regarding infrastructure design for the long-term

5

CCS and bioenergy are especially valuable. The most cost-effective system designs require zero or even "negative" emissions in sectors where decarbonisation is easiest, alleviating pressure in more difficult sectors

6

High levels of intermittent renewables in the power sector and large swings in energy demand can be accommodated at a cost, but this requires a systems level approach to storage technologies, including heat, hydrogen and natural gas in addition to electricity

Registered Office
Energy Technologies Institute
Holywell Building
Holywell Park
Loughborough
LE11 3UZ

For all general enquiries telephone the ETI on 01509 202020.

For the latest ETI news and announcements email info@eti.co.uk

For more information about the ETI visit www.eti.co.uk

The ETI can also be followed on Twitter @the_ETI