Spatio-temporal energy system models

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wholeSEM DECC Stakeholder Workshop
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Outline

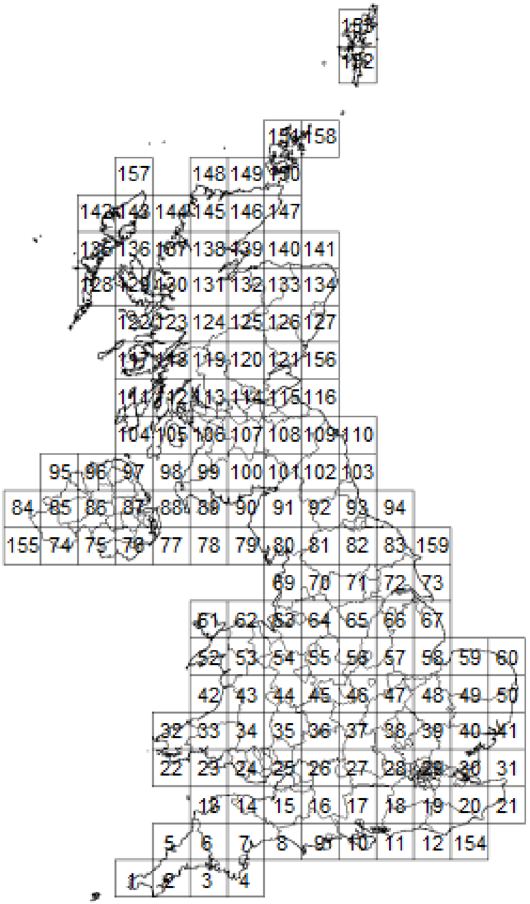
- Introduction
- Examples
  - Biomass
  - Hydrogen
- Conclusions

Key elements

- Space
- Time
- Resources
- Technologies
- Infrastructure

Key elements

- Space
  - cellular representation
  - defined by centroid and area
  - cell-level information: demand, land cover, built environment, technologies, resource availability
- Time
- Resources
- Technologies
- Infrastructure



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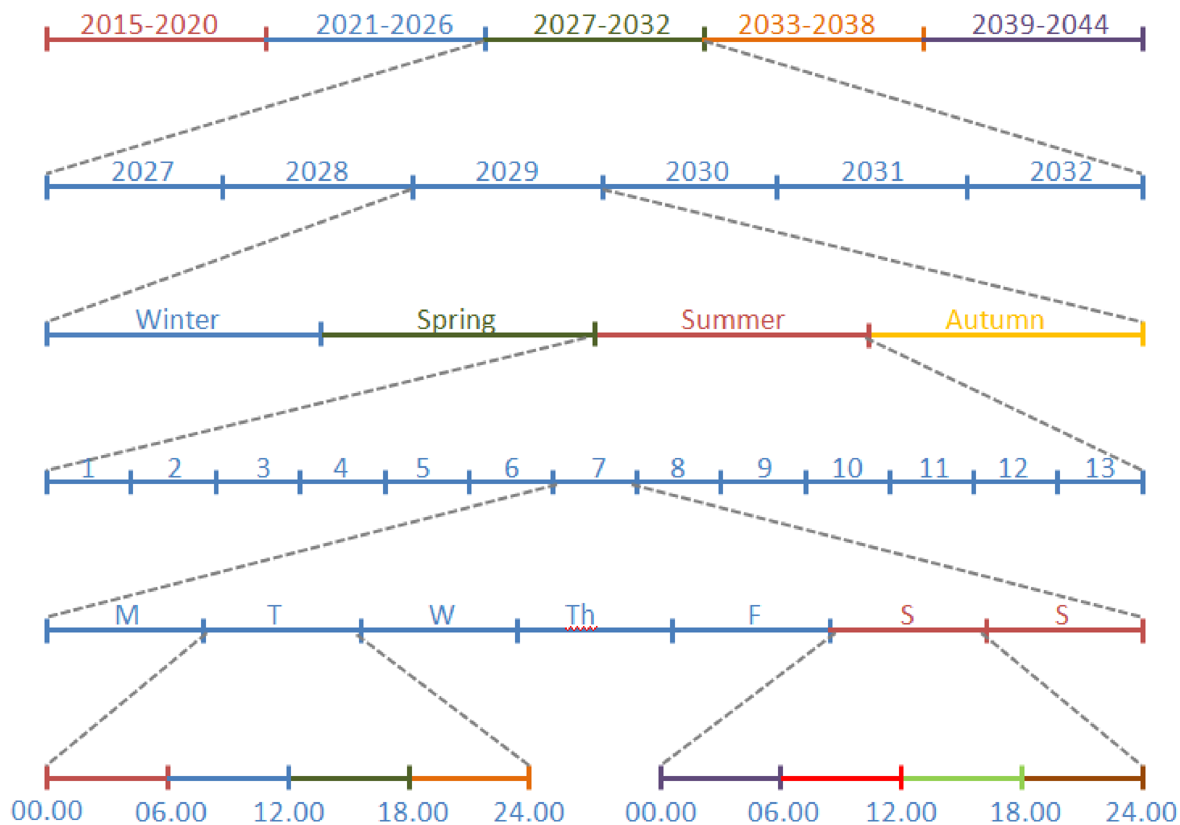
Key elements

- Space
- Time
  - Multiscale concept
    - Decades for investment
    - Annual/seasonal to capture seasonal variations
    - Day/night to capture diurnal variations
    - Within day for system balancing
- Resources
- Technologies
- Infrastructure



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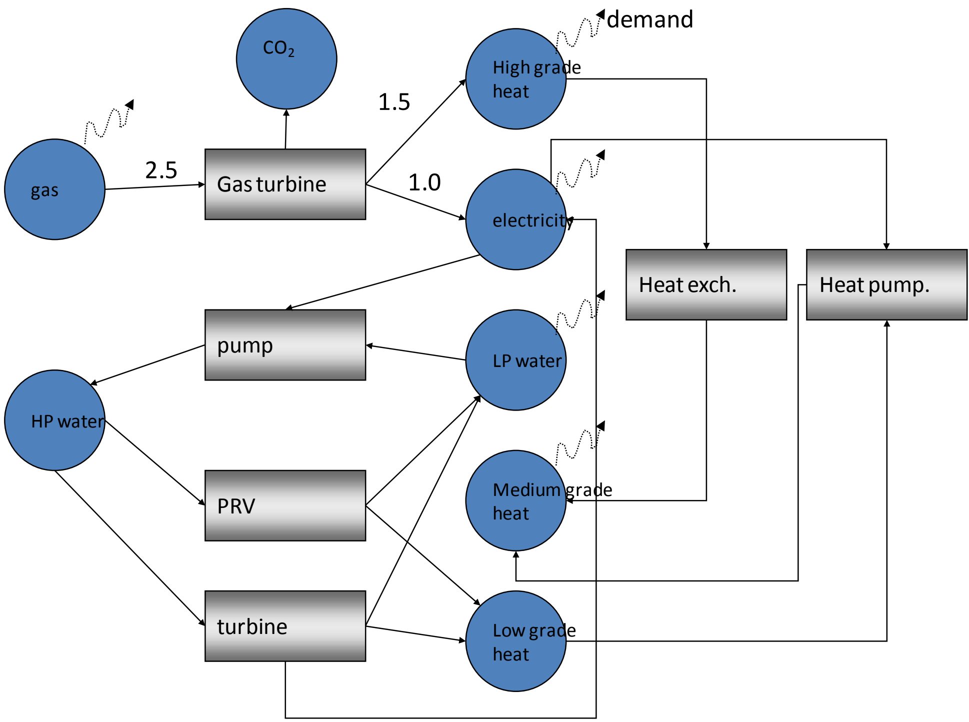
Key elements

- Space
- Time
- Resources
  - Primary raw materials and energy sources (e.g. biomass, petroleum, natural gas, sunlight)
  - Intermediate resources (e.g. torrefied pellets, syngas, pyrolyis oil, biogas)
  - End use energy vectors (e.g. power, heat, transport fuel)
  - Wastes (e.g. CO_2, NO_x, waste heat)
- Technologies
- Infrastructure



Resource-technology network

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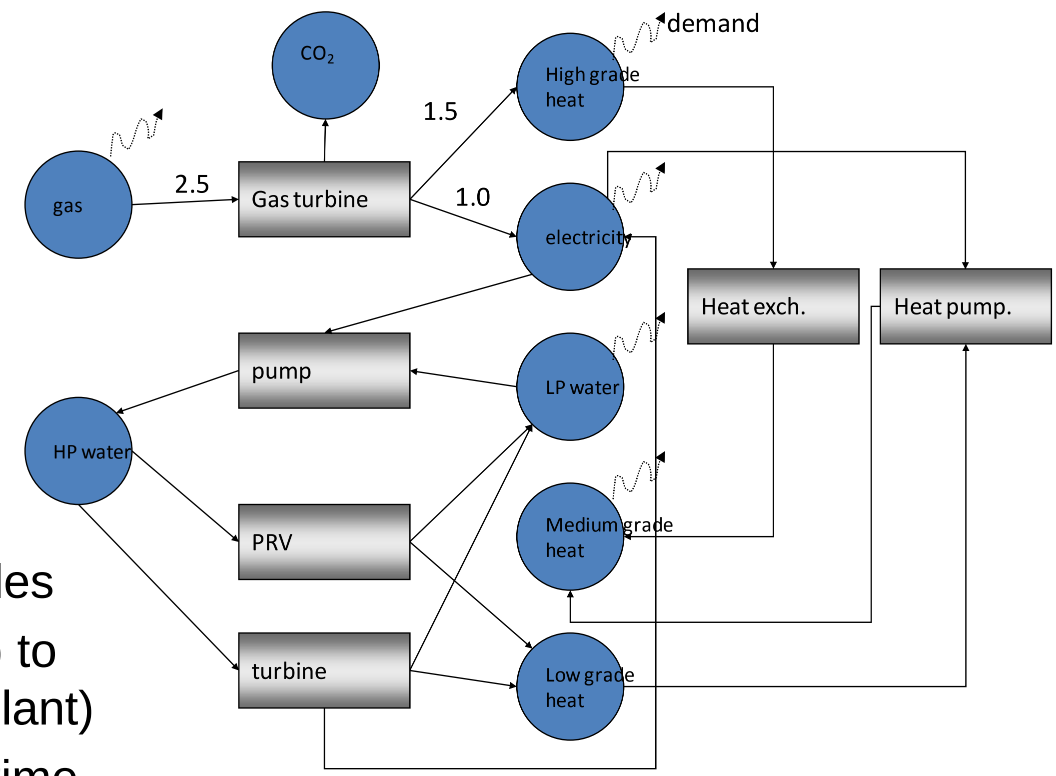
Key elements

- Space
- Time
- Resources
- Technologies
  - Interconvert resources
  - Multiple operating modes
    - Different inputs and outputs
    - Different efficiencies
  - May be available at different scales
  - Vary from household (e.g. boiler) to centralised (e.g. nuclear power plant)
  - Performance may improve over time
- Infrastructure



Resource-technology network

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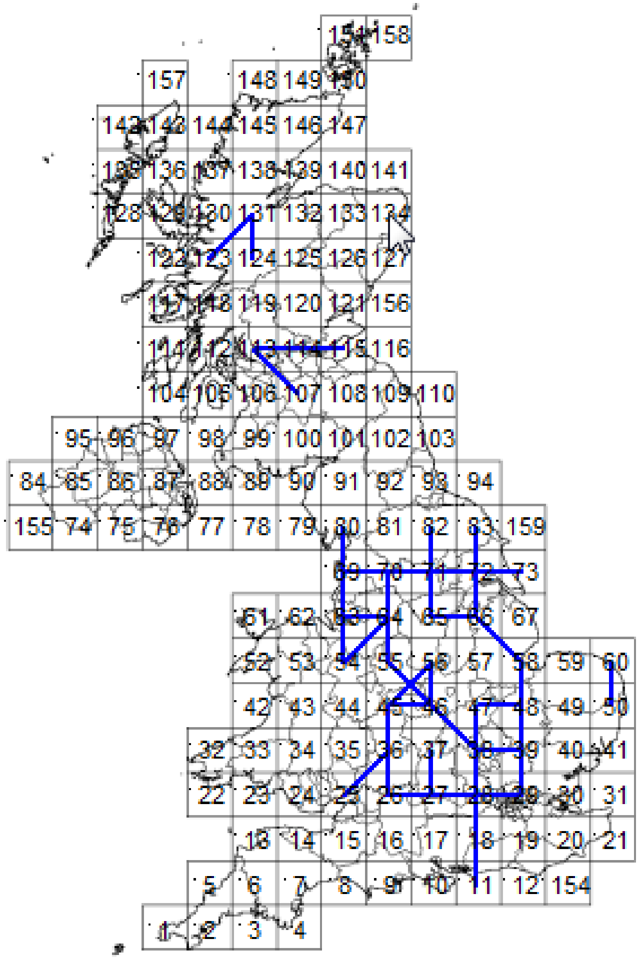
Key elements

- Space
- Time
- Resources
- Technologies
- Infrastructure
  - Used to move resources
    - Transport network for biomass
    - Power grid
    - Gas grid
    - Heat network
    - H2, CO2, syngas pipelines
  - May exist or need to be built



Inland waterways network

Optimisation model

- Given
  - Spatially and temporally distributed resource demands and availability
  - Coefficients and metrics (cost, GHG etc) data, economies of scale
- Determine
  - Network construction
    - What technologies?
    - What scales?
    - Where?
    - Storage facilities
    - Transport networks
  - Network operation
    - Rates of production
    - Transport flows
- Objective
  - Minimise cost or maximise profit
  - Minimise GHG emissions
  - Maximise energy/exergy production

Optimisation model

- Typical variables
  - Which technologies to purchase (and resources to use)
    - Where, when, what size
  - What transport networks to build
  - Resource flow and conversion
- Typical constraints
  - Resource balances
  - Demand satisfaction
  - Cost/GHG constraints
  - Build rate constraints
- Typical platforms
  - JAVA linked to solvers
  - AIMMS
  - GAMS

Example: Biomass Value Chain Model (BVCM)

BVCM

- Objectives
  - To determine bioenergy value chains for efficient/low cost/low carbon provision of energy
  - To assist with spatial planning and demonstration of technologies
  - To identify one or two technology demonstrators and assess their benefits

What is BVCM?

- A UK-wide optimisation model
- Models pathway-based bioenergy systems over five decades (from 2010 to 2050)
- Based on spatially explicit, flexible modelling methodology

Biomass resource data

Technology options

Energy vector demand data

Logistics

→

Optimal bioenergy value chain structures

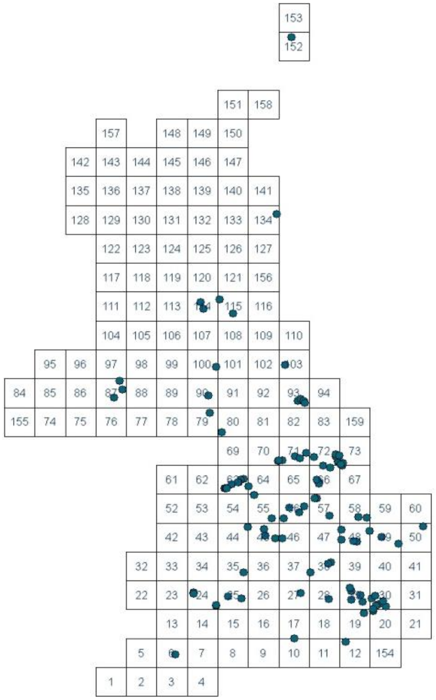
- allocation of crops to available land
- choice of technologies
- energy provision (electricity, heat, hydrogen, biofuels, biomethane)
- transport networks required

Model Elements: Time, Space and Climate

- Time
  - 5 decades
  - Up to 4 seasons per year

- Spatial representation
  - United Kingdom divided into 157 square cells of length 50km

- Climate scenarios
  - Low and medium based on UKCP09



Model Elements: Land Use

Four levels of land "aggression"

- Level 1 as "easy, established technology"
  - Arable land
  - Heterogeneous agricultural land (e.g. Non-permanent crops associated with permanent crops)
- Level 2 as "pioneering plant establishment"
  - Shrub and/or herbaceous vegetation association, e.g. natural grassland
  - Open spaces with little or no vegetation
- Level 3 as "challenging techno-ecological and economic land use change"
  - Permanent crops, e.g. fruit trees and berry plantations
  - Pastures
- Level 4 as "last resort"
  - Forests
  - Artificial non-agricultural vegetated areas (e.g. green urban areas and parks)

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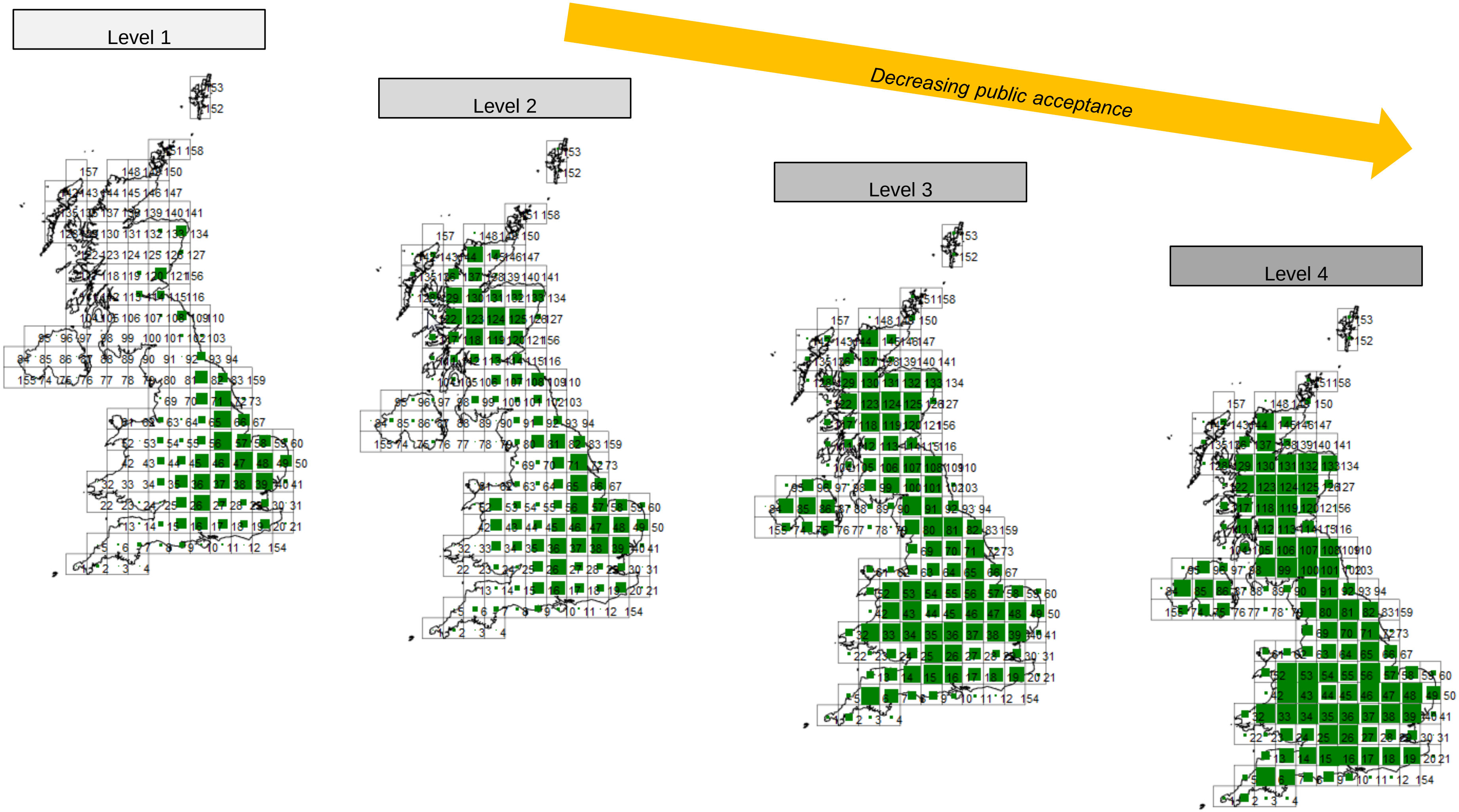
Model Elements: Land Use



Model Elements: Bioresources

- Miscanthus
- Short Rotation Coppice (SRC) – willow
- Winter wheat
- Oilseed rape
- Sugar beet
- Short Rotation Forestry (SRF)
- Long Rotation Forestry (LRF)

The BVCM currently includes 94 resources, comprising bioresources, intermediates, final products, by-products and wastes.

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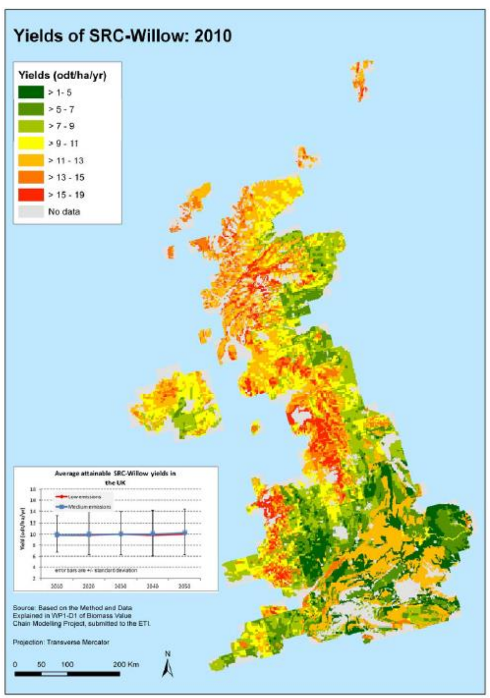
Model Elements: Bioresources

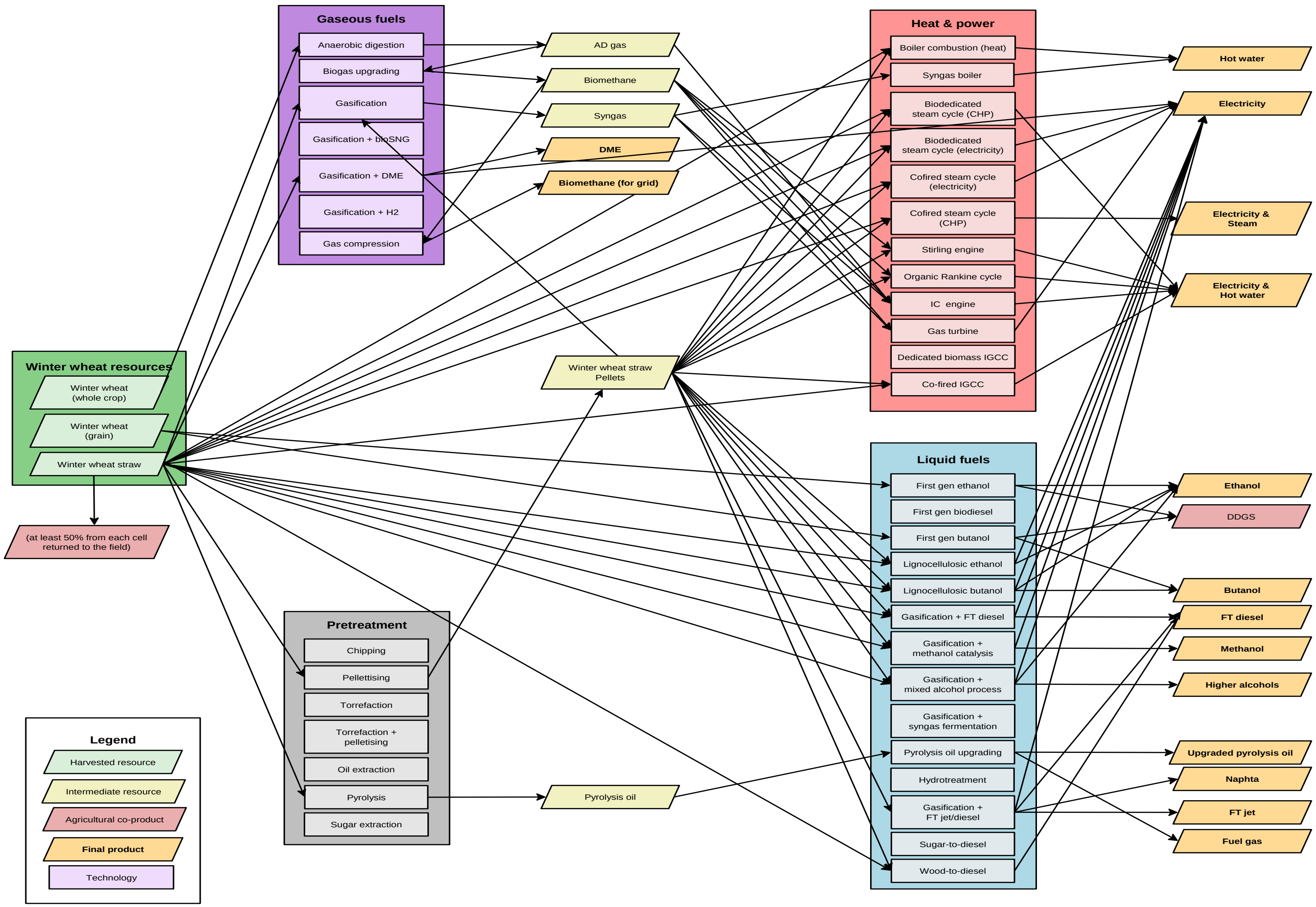
- Biomass data (yield, cost, and emissions) have been typically estimated at high resolution (1x1km)
- High resolution data have been aggregated at a scale adequate for optimisation (50x50km)



Model Elements: Technologies

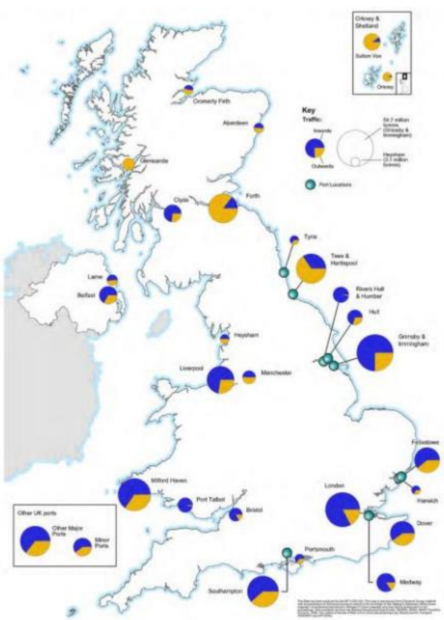
- 72 distinct technologies, some with multiple scales, for more than 100 technology instances, including:
  - pre-treatment and densification technologies
  - technologies for gaseous fuel production
  - technologies for liquid fuel production
  - technologies for heat, power, and combined heat and power generation
  - waste to energy technologies
  - carbon capture technologies

Example of a Resource-Technology Chain: Winter Wheat

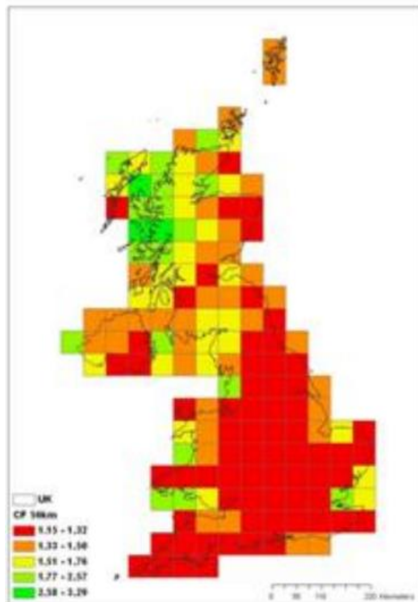


Model Elements: Logistics

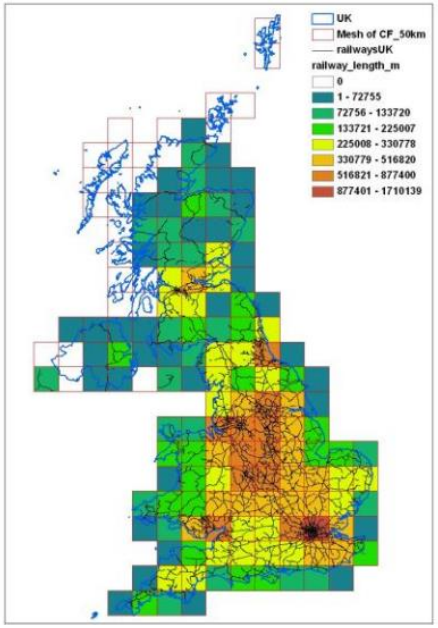
- 4 transport modes: Ship, Road, Rail, Inland waterways



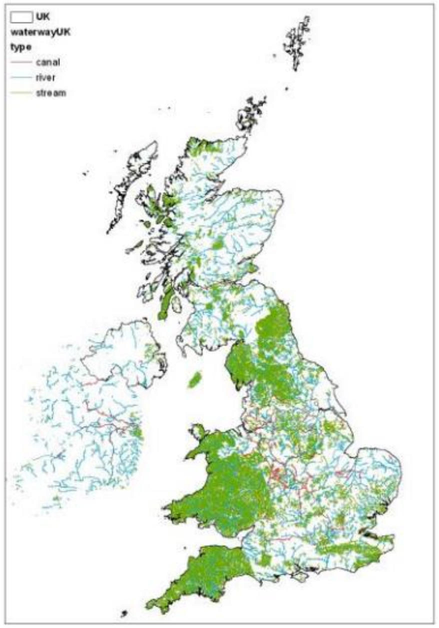
UK Ports



Road Tortuosity



Railway Length



Inland Waterways

Key Model Drivers

- Potential yields
- Costs
- Demands for different bioenergy end-uses (heat, power, biodiesel, bioethanol, biogas, etc.)

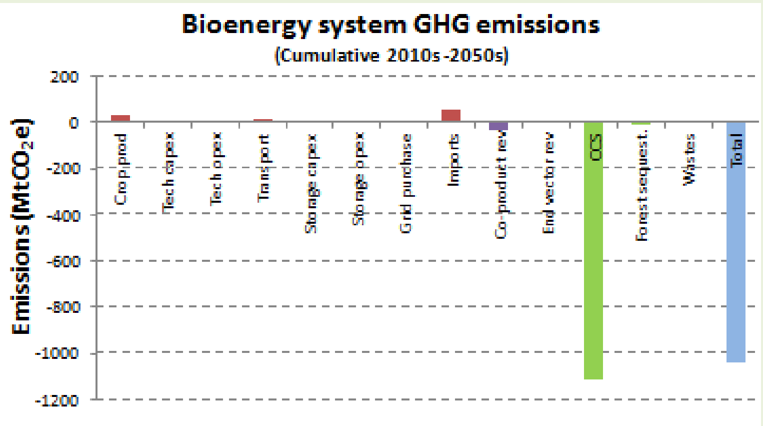
  – Each can be specified spatially or in aggregate by decade to generate alternative scenarios
  – One of the major uses of the tool is to explore the impacts of different penetration levels of bioenergy vectors

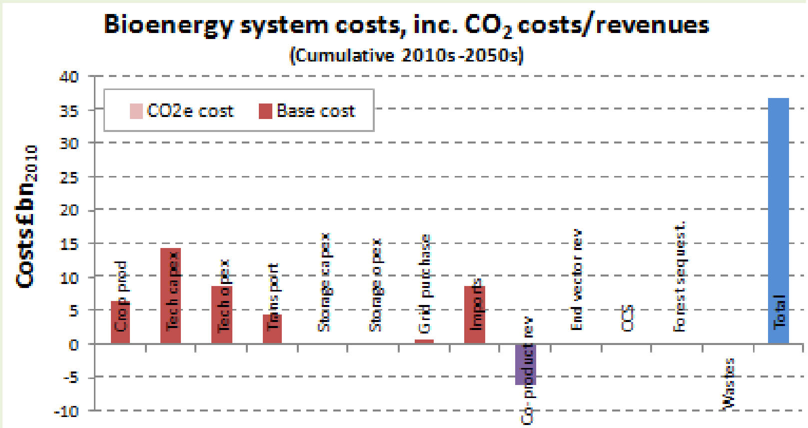
Key Model Outputs

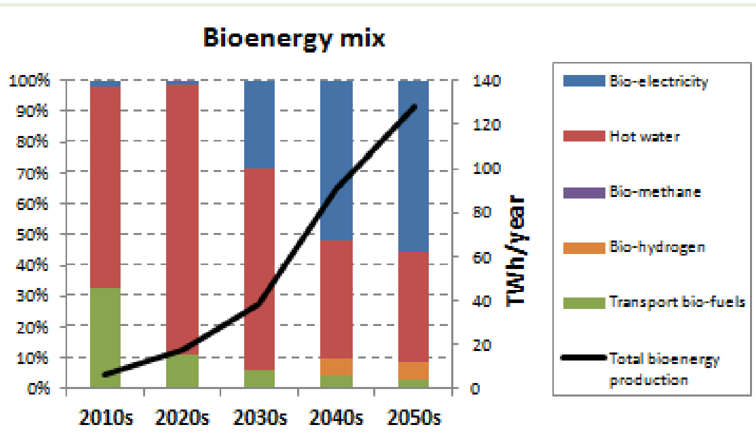
- Total system cost
- Total system bioenergy production (primary and end-use)
- Total system greenhouse gas emissions
- Production of biomass *b* in cell *c*, decade *d* and season *t*
- Number and capacity of technologies of type *j* invested in in decade *d* and cell *c*
- Number and capacity of technologies of type *j* available in decade *d* and cell *c*
- Production rate of technology of type *j* in decade *d*, season *t* and cell *c*
- Amount of resource *r* stored at the end of season *t* of decade *d* in cell *c*
- Amount of resource *r* transported from *c* to *c*' during season *t* of decade *d* using link type *l*

Example case study

Least-cost bioenergy system that meets an average level of energy demand and desirable GHG emission savings required from the UK bioenergy sector, derived from the ETI Energy Systems Modelling Environment (ESME), using up to ~10% of UK land (2% of Level 1 and 15% of Levels 2-4)





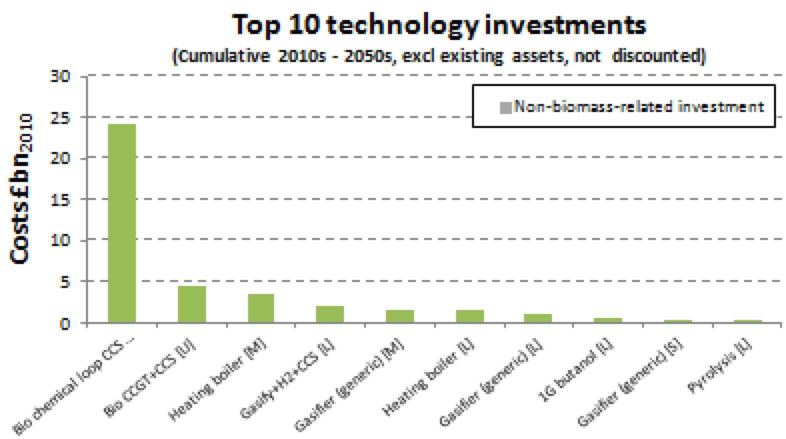


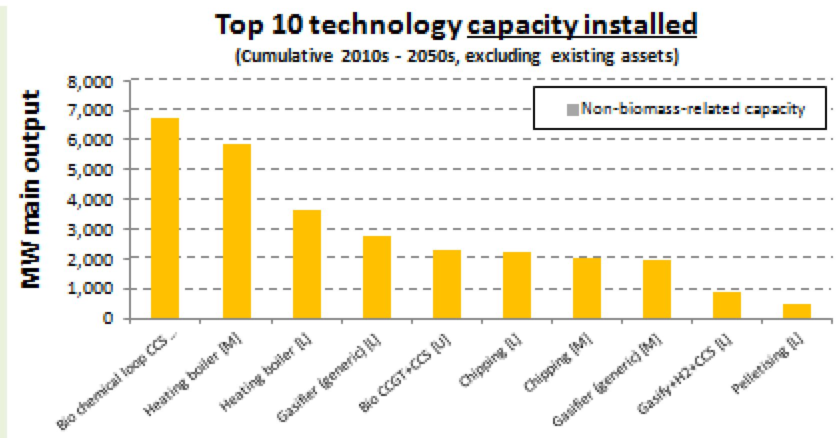
(TWh/yr)	2010s	2020s	2030s	2040s	2050s
Bio-electricity	0.13	0.21	10.97	47.14	71.15
Hot water	3.95	15.72	25.45	34.54	45.88
Bio-methane	0.00	0.00	0.00	0.00	0.00
Bio-hydrogen	0.00	0.00	0.00	5.35	6.88
Transport bio-fuels	1.96	2.04	2.27	3.71	4.02
Total	**6.05**	**17.97**	**38.70**	**90.75**	**127.94**

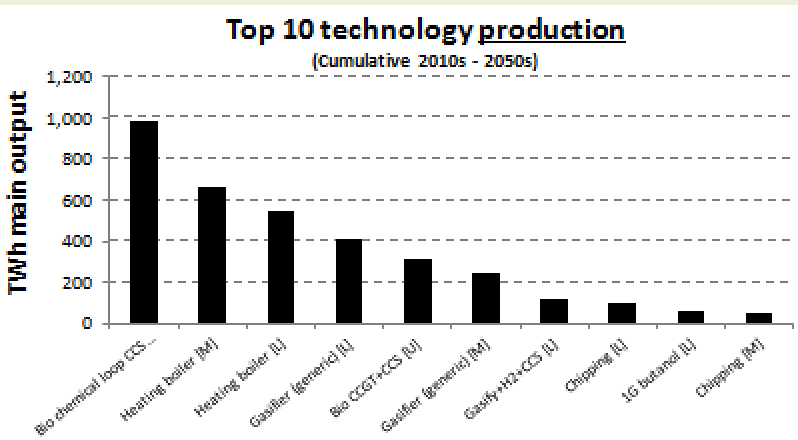
($MtCO_2e$/yr)	2010s	2020s	2030s	2040s	2050s
Total GHG emissions	0.08	0.29	-9.15	-38.75	-56.10

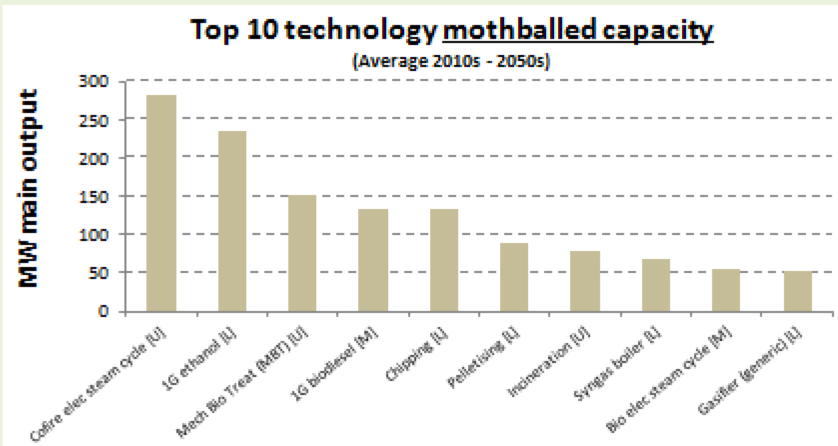
Total system cost	7.3 £bn/decade	41.5 £/MWh
Total GHG emissions	-20.7 $MtCO_2e$/yr	-368 $kgCO_2e$/MWh

Example case study

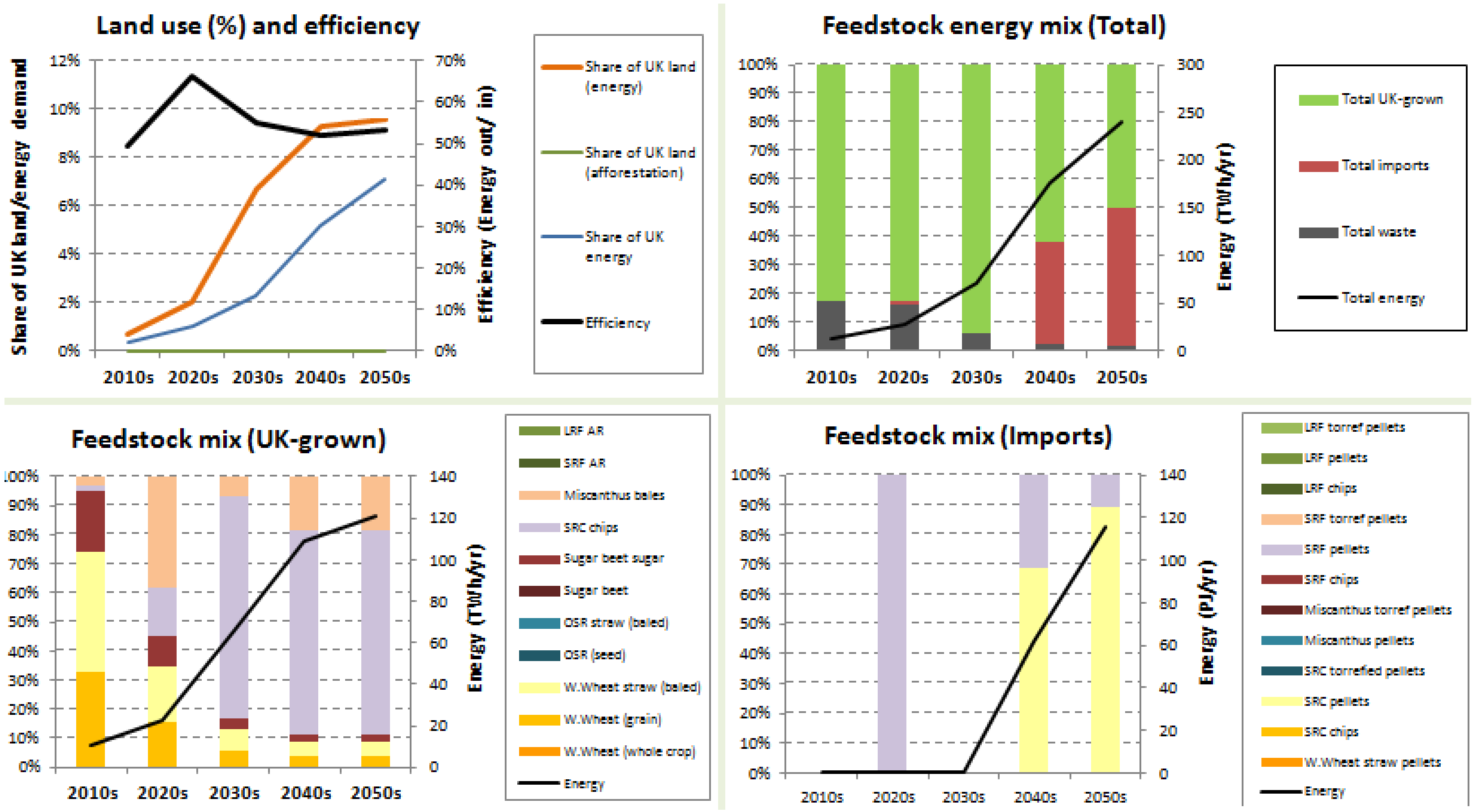








Example case study



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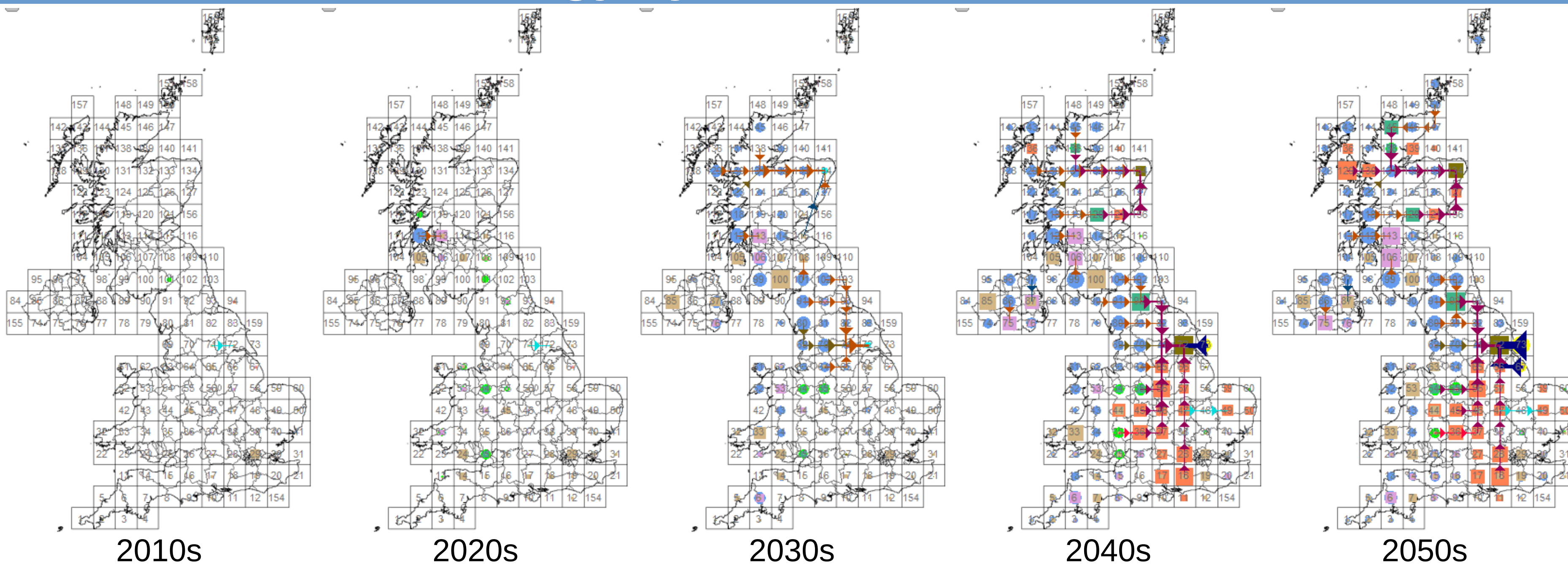
Evolution of bioenergy system



Figures show top 6 most utilised technologies and top 3 grown crops

Biomass growth

- Miscanthus - AR (baled)
- SRC (Willow) - chips
- Winter wheat (grain)

Imported resources

- SRF - pellets
- SRC (Willow) - pellets

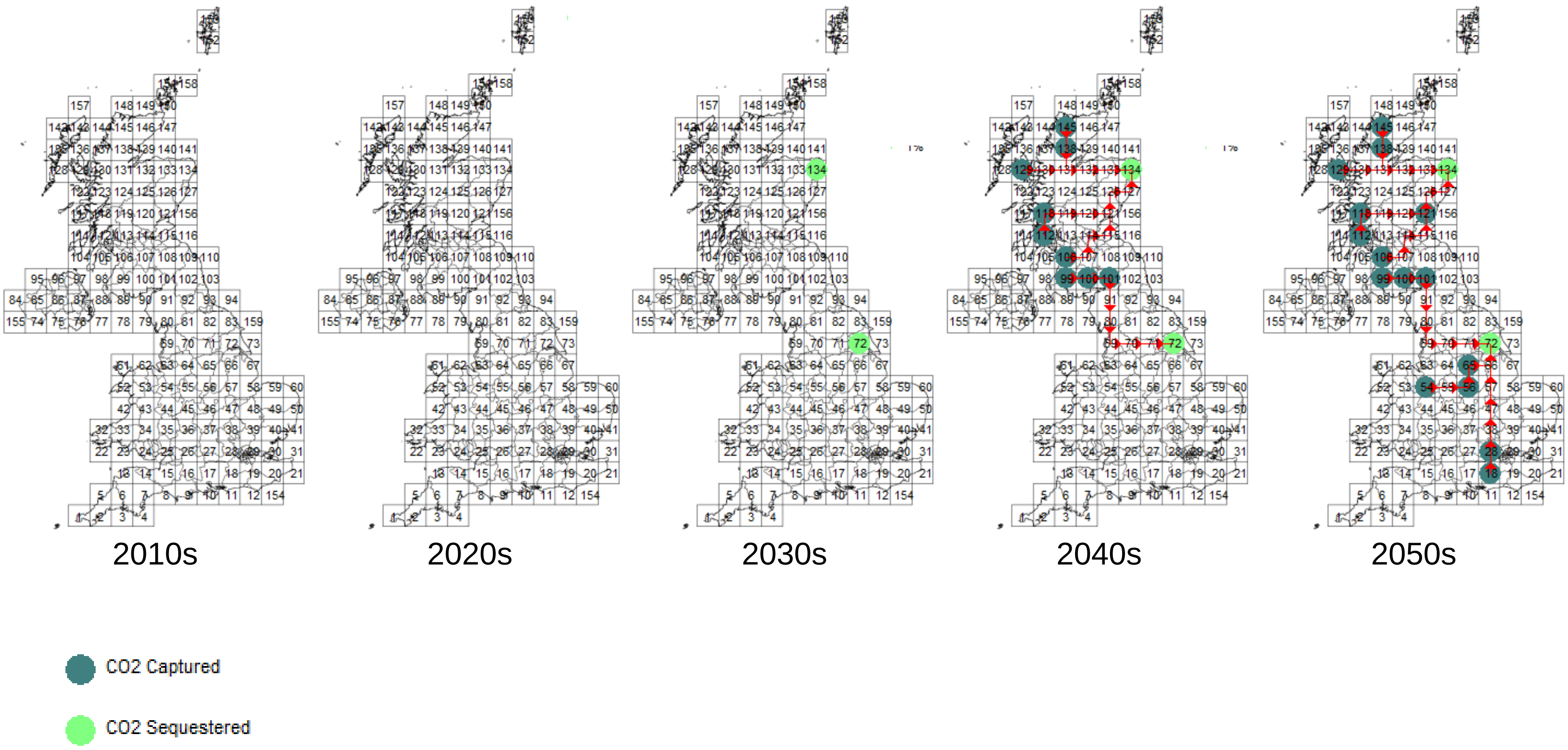
Technology utilisation

- Gasification (generic) - Medium
- Gasification (generic) - Large
- Boiler combustion (heat) - Medium
- Boiler combustion (heat) - Large
- Biodedicated chemical looping CCS - Large
- Biodedicated CCGT with CCS - Unique

Transport	Truck	Rail	Barge	Ship
LRF - chip	✓	✓	✓	✓
Waste - Wood - chips	✓	✓	✓	✓
Miscanthus - pellets	✓	✓	✓	✓
SRF - pellets	✓	✓	✓	✓
SRC (Willow) - chips	✓	✓	✓	✓
SRC (Willow) - pellets	✓	✓	✓	✓
Waste - Wood - pellet	✓	✓	✓	✓
SRC (Willow) - torrefied pellets	✓	✓	✓	✓
Miscanthus - torrefied pellets	✓	✓	✓	✓
Pyrolysis oil	✓	✓	✓	✓
Syngas	✓	✓	✓	✓
Winter wheat (grain)	✓	✓	✓	✓

Evolution of CCS infrastructure

Maximise profit with low CO_2 price scenario



Strengths

- Very detailed representation of bioenergy systems
  - High spatial resolution
  - Large number of resources and technologies
  - Constraints capture all “what if” scenarios
- Flexible
  - Data driven architecture
  - Can add new resources and technologies very easily
  - Applicable to other countries
- Very user friendly interface

Weakness

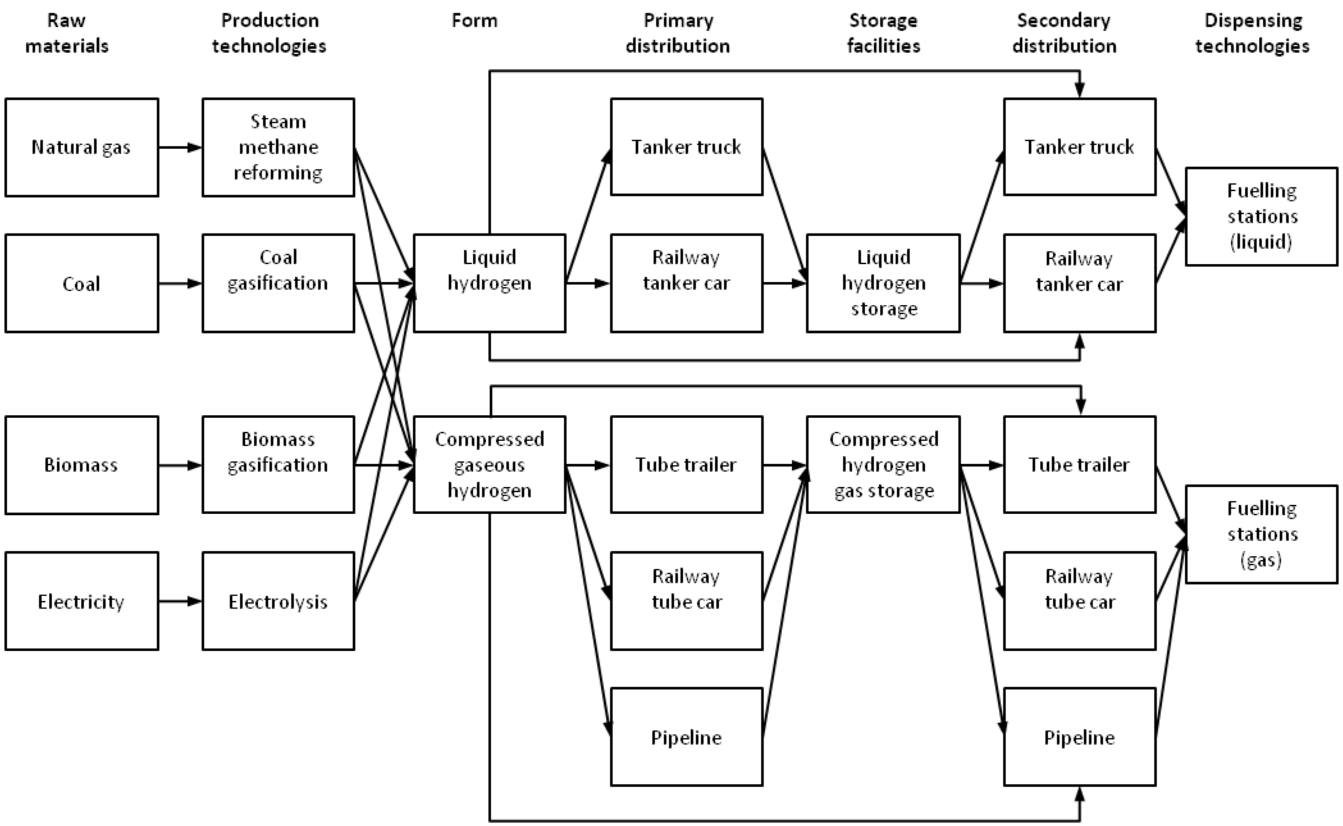
- Limited to bioenergy
  - Interaction with rest of energy system cannot be examined

Example: Hydrogen Supply Chain (HSC) Model

What is HSC?

- A pathway-based model of a future hydrogen supply chain network that is capable of producing, distributing, storing and dispensing hydrogen to end users
- Spatially-dependent and includes different time scales
- A MILP optimisation problem implemented in AIMMS
- Finds the least-cost hydrogen supply network

Hydrogen supply network pathways



The various options for production, distribution and storage lead to many possible hydrogen supply pathways

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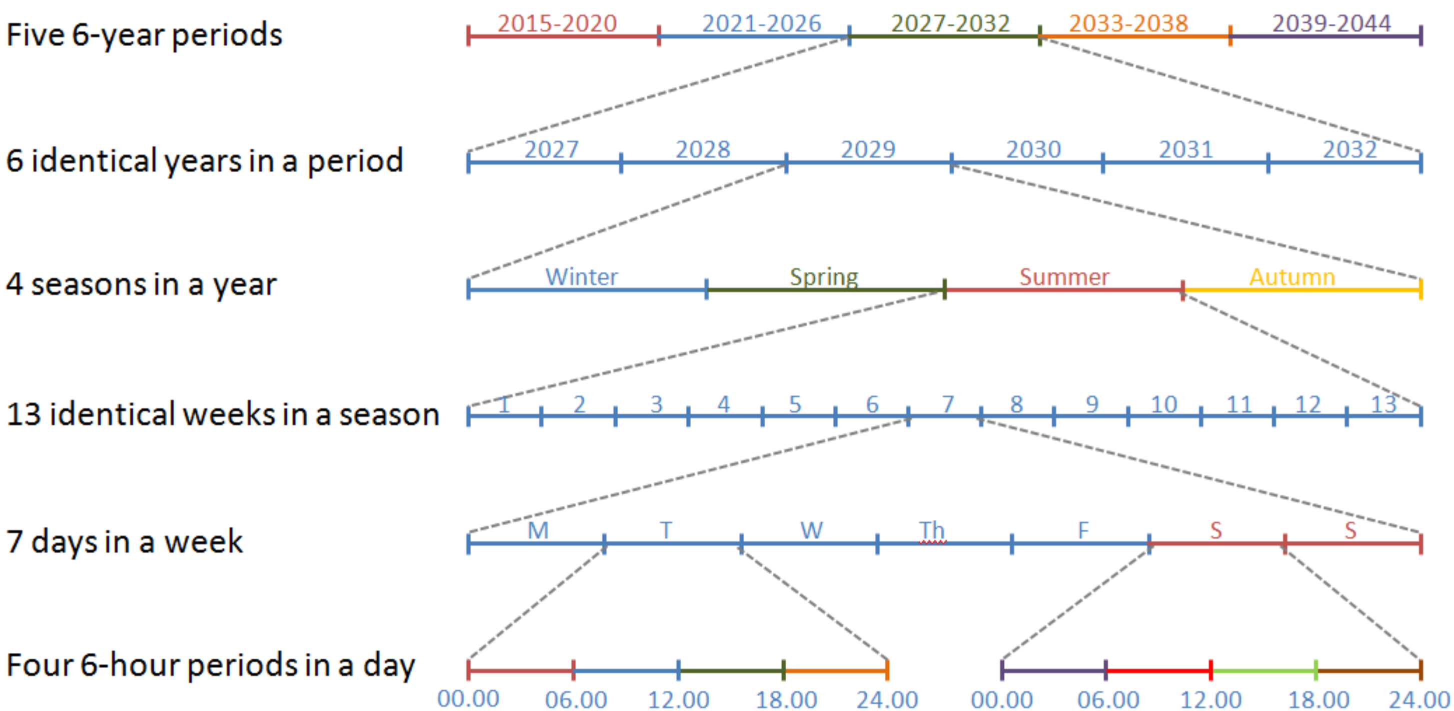
Model Elements: Space and Time

- Spatial representation
  - Great Britain divided into 34 grid squares of 108 km length
- Time
  - Modelled using hierarchical non-uniform time discretisation



Model Elements: Production and Storage Facilities

- Production facilities
  - Steam methane reforming, coal gasification, biomass gasification, electrolysis
  - Decisions: number, location, and capacity of each plant type and hydrogen production rates in each grid square at every time period

- Storage facilities
  - Cryogenic storage, compressed gas storage
  - Decisions: number, location and capacity of each storage type and hydrogen inventory in each grid square at every time period

Model Elements: H_2 Forms and Primary Energy Sources

- Hydrogen physical forms
  - Liquid or gas
  - Determines the transportation mode and storage type

- Primary energy sources
  - Natural gas, oil, coal, biomass, solar power, etc.
  - Determines the size, type and location of production plants
  - Decisions: amount of raw materials utilised and rate of import (from neighbouring grid square or abroad)

Model Elements: Transport and Dispensing

- Transportation modes
  - Pipeline, truck and rail
  - Cost of transport mode vs. establishing a new production plant
  - Decisions: whether to establish a link between different grids and the flow rate of hydrogen
- Fuelling stations
  - Type and size are determined by the demand and form of hydrogen to dispense
  - Decision: number of fuelling stations in each grid square in each time period

Key Model Drivers and Outputs

- Key model drivers:
  - Costs
  - Hydrogen demand
- Key model outputs:
  - Number, location, type and size of plants and storage facilities built in each grid square in each time period
  - H_2 production rate and inventory in each grid square at different times
  - Transportation links established, transport mode and rate of H_2 transport at different times
  - Number of fuelling stations installed in each grid square in each time period
  - Raw material consumption and import in each grid square at different times

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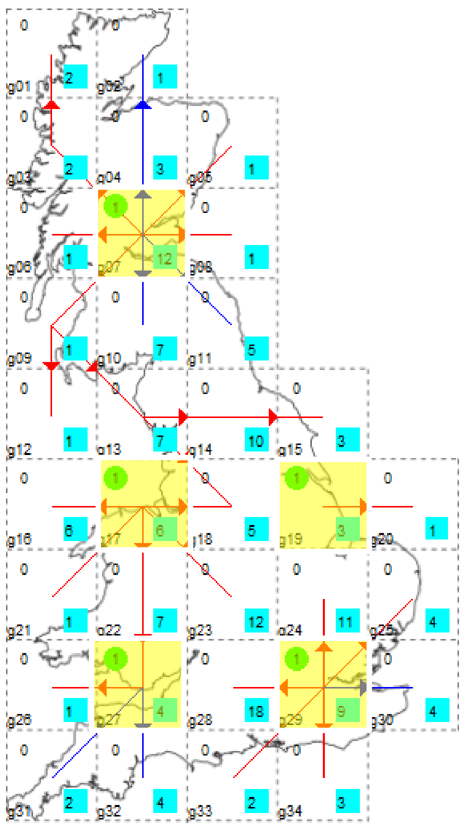
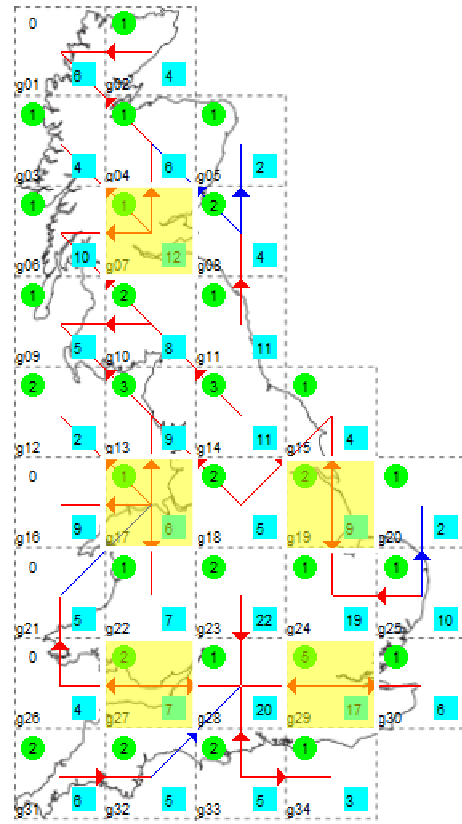
Case Study: Possible Optimal Network Structure



Summer 2015-2020



Summer 2039-2044

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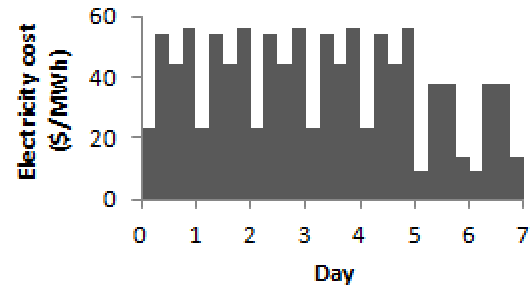
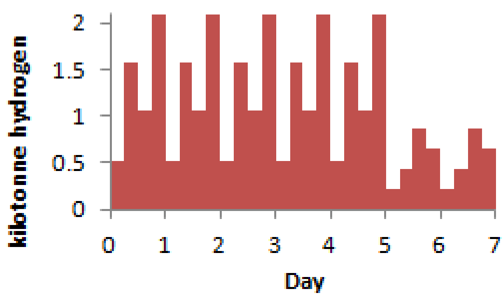
Case Study: Hydrogen as Electricity Storage

Electrolysers and hydrogen storage can take advantage of daily price variations in electricity



Electricity cost



Hydrogen demand

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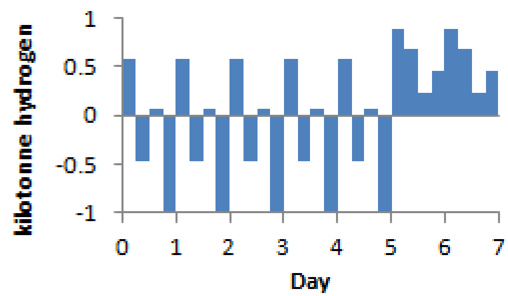

Hydrogen surplus

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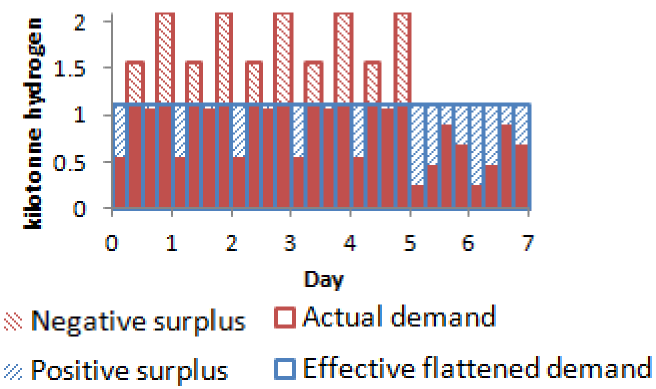

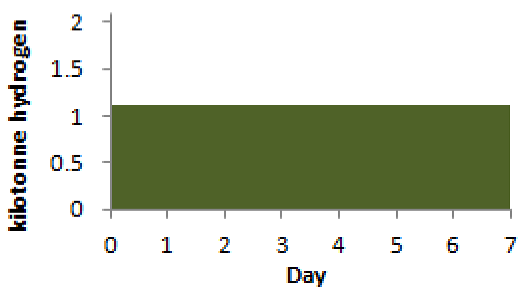

Hydrogen production

Advantages:

Flattening of the effective demand

Reduced requirement for peaking generators

Enhanced operating efficiency of production plants

Strengths

- Different time scales allow study of
  - Intermittent renewables
  - Storage
- Storage is modelled in detail
- Large number of scenarios can be investigated

Weakness

- Formulation has been made more efficient but full MIP solution takes a long time (~3 days)

Conclusions

- Spatio-temporal energy system models have been developed.
- The common features are:
  - The use of optimisation
  - The use of multiperiod time representation to develop a "pathway" and avoid myopic solutions
  - The use of spatial discretisation to capture spatial effects
- Enhancements
  - The integration between models
  - Algorithms for tractability
  - Better representation of stochastics and options
  - "Individual actor" perspective rather than centralised optimisation