Modelling integrated multi-vector energy systems capturing spatial dependencies and hourly operation over a long-term planning horizon

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Outline

1. Motivation
2. Problem statement
3. Deterministic model (STeMES)
4. Uncertainty
5. Conclusion

Motivation

- Why integrated multi-vector networks?
  - Traditionally evolved separately: not necessarily optimal
  - New networks (e.g. H_2) are emerging
  - More interactions between these networks
  - Integrating the networks may increase overall efficiency

- Why do we need a spatio-temporal model
  - Energy demands are not uniformly distributed and exhibit significant variations with time
  - Primary energy resources (particularly renewables) are often localised and intermittent in availability
  - Crucial for accounting properly for transport and storage of resources

Problem statement

Given:

- Spatio-temporal demands for resources and energy services
- Spatio-temporal availability of primary energy sources and raw materials
- Characteristics of each technology (e.g. CAPEX, O&M, efficiency, lifetime)

Determine:

- Network design
  - Location, number and capacity of generation/conversion and storage technologies
  - Structure of transport infrastructure network (transmission and distribution)
  - When and where to purchase/install
  - What interactions
- Network operation
  - Which resources to convert, store and transport (how much, where and when)
  - Which technologies to use at different times
  - Transport flows between different regions

Problem statement (cont…)

Subject to:

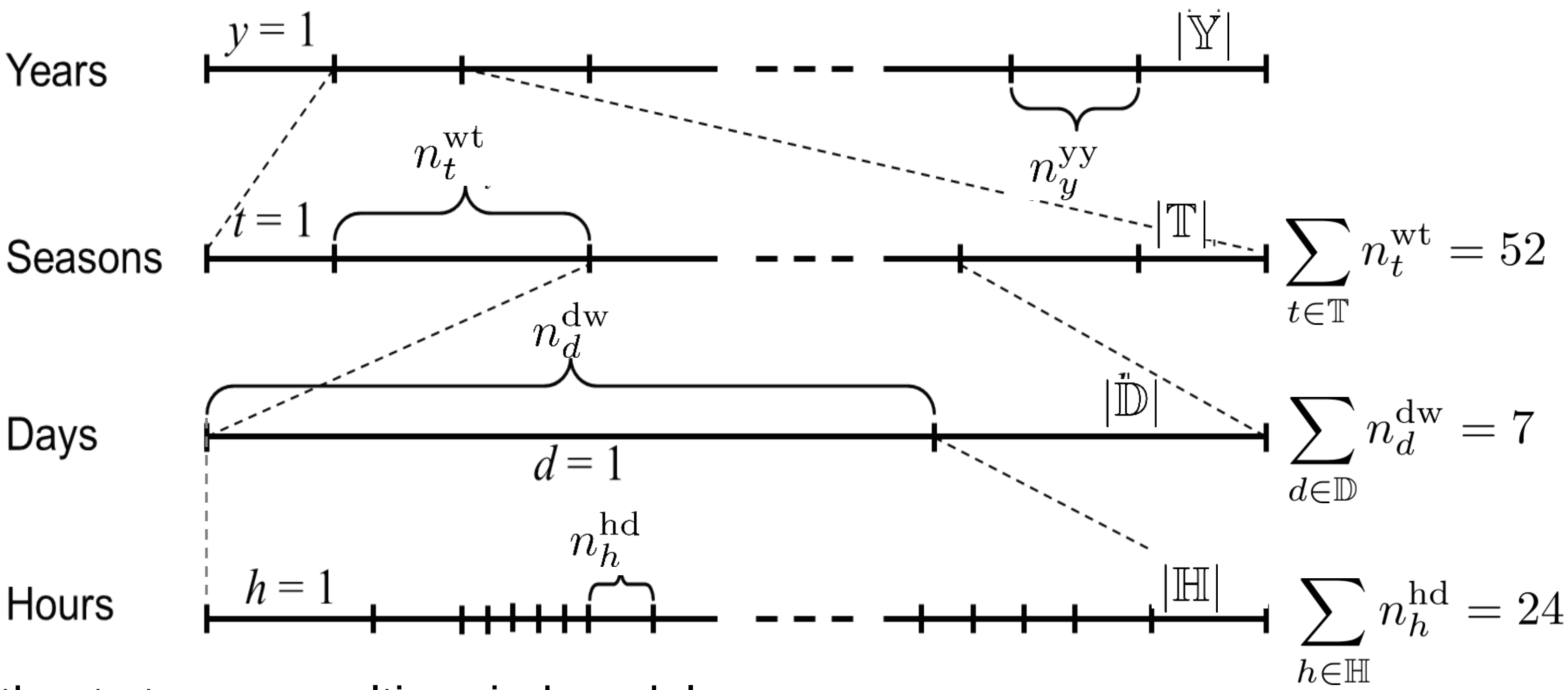
- Demand satisfaction
- Conservation and other physical laws
- Constraints on resources (e.g. land, water), costs and GHG emissions
- Technological constraints (e.g. tech. availability, build rates)
- Social and political constraints (e.g. siting of specific techs)

Objective:

- Minimise cost
- Minimise environmental impact (e.g. GHG emissions)
- Maximise value
- Any combination of the above

Temporal representation

- Long-term strategic decisions
- Short-term operational issues (intermittency, dynamics of energy storage)



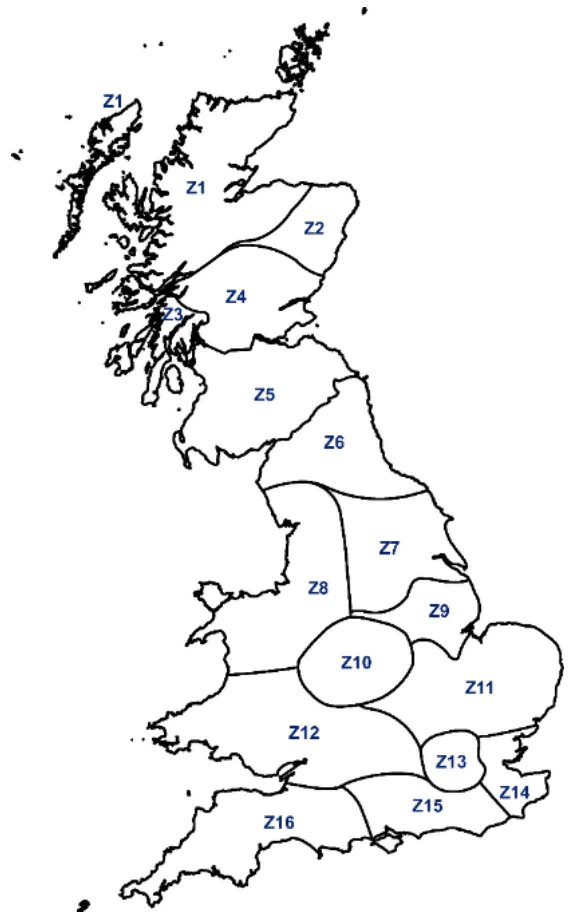
Without storage: multi-period model

With storage: dynamic model; extra variables for initial inventories; extra constraints to link inventories within and between time levels

S. Samsatli, N.J. Samsatli (2015). Computers & Chemical Engineering 80, 155-176, 0098-1354.

Spatial representation

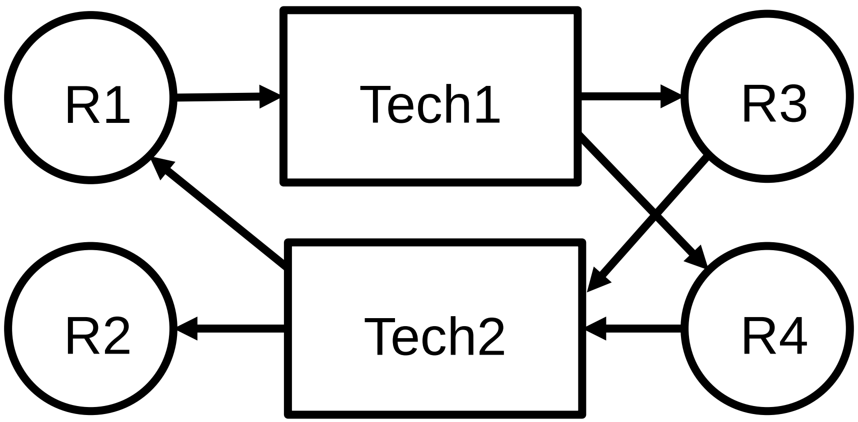
- The region under study divided into a number of zones
- Each zone may:
  - Be of any shape and size
  - Have dynamic demands for various resources
  - Contain some resources that are available in varying quantities
  - Host technologies for conversion and storage of resources
  - Be connected with other cells via transport infrastructures
  - Import or export resources

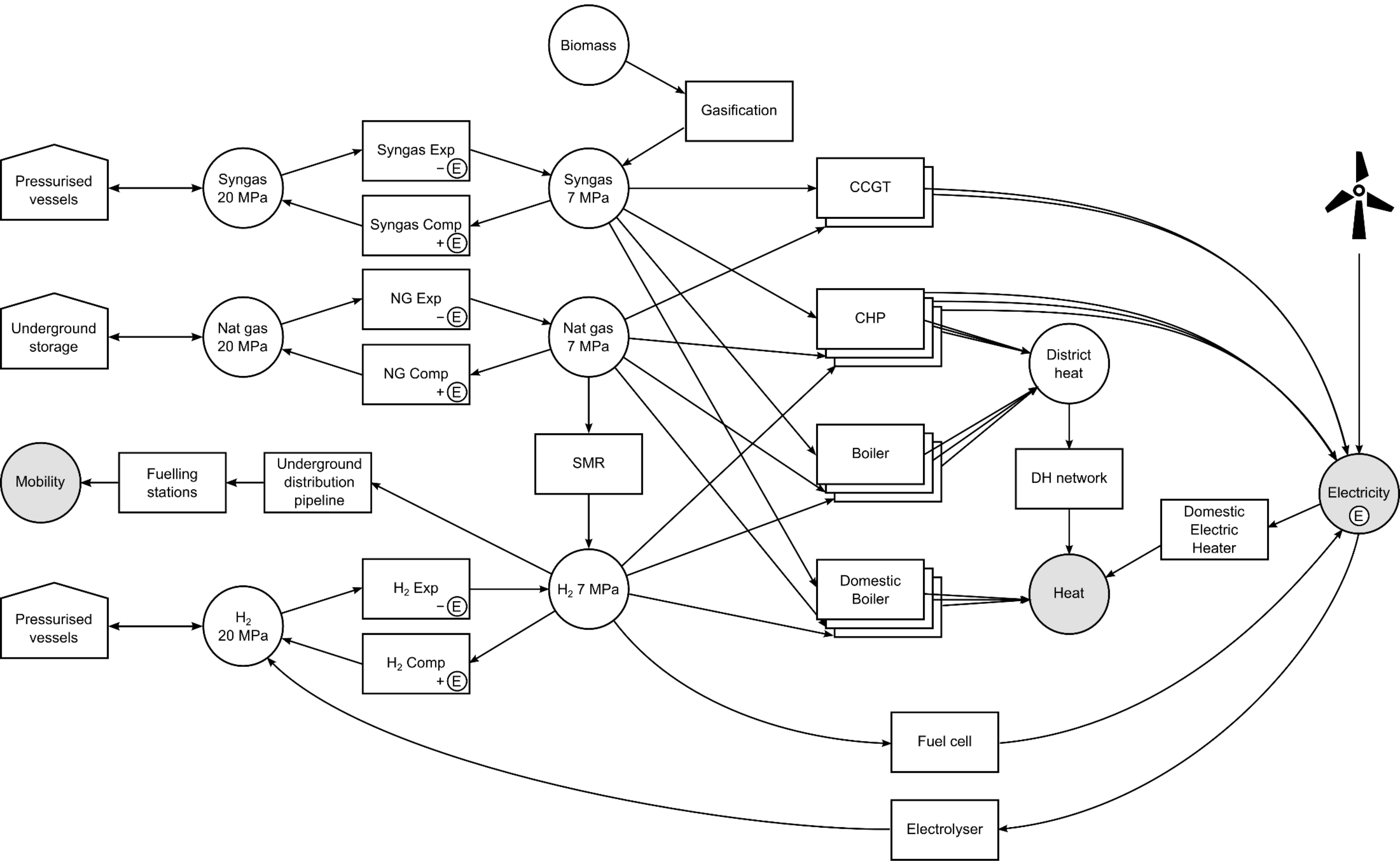


National Grid's SYS study zones

Integrated energy pathways

- Represented using Resource-Technology Networks (RTN)
- Able to model the most general situation
  - convert any resource to any other, including recycles (circular chains)
  - store and transport resources at any stage in the chain
- Consider a wide range of different feedstocks and technologies
  - different operating modes to generate different energy vectors
    - heat, electricity, transport fuel etc.

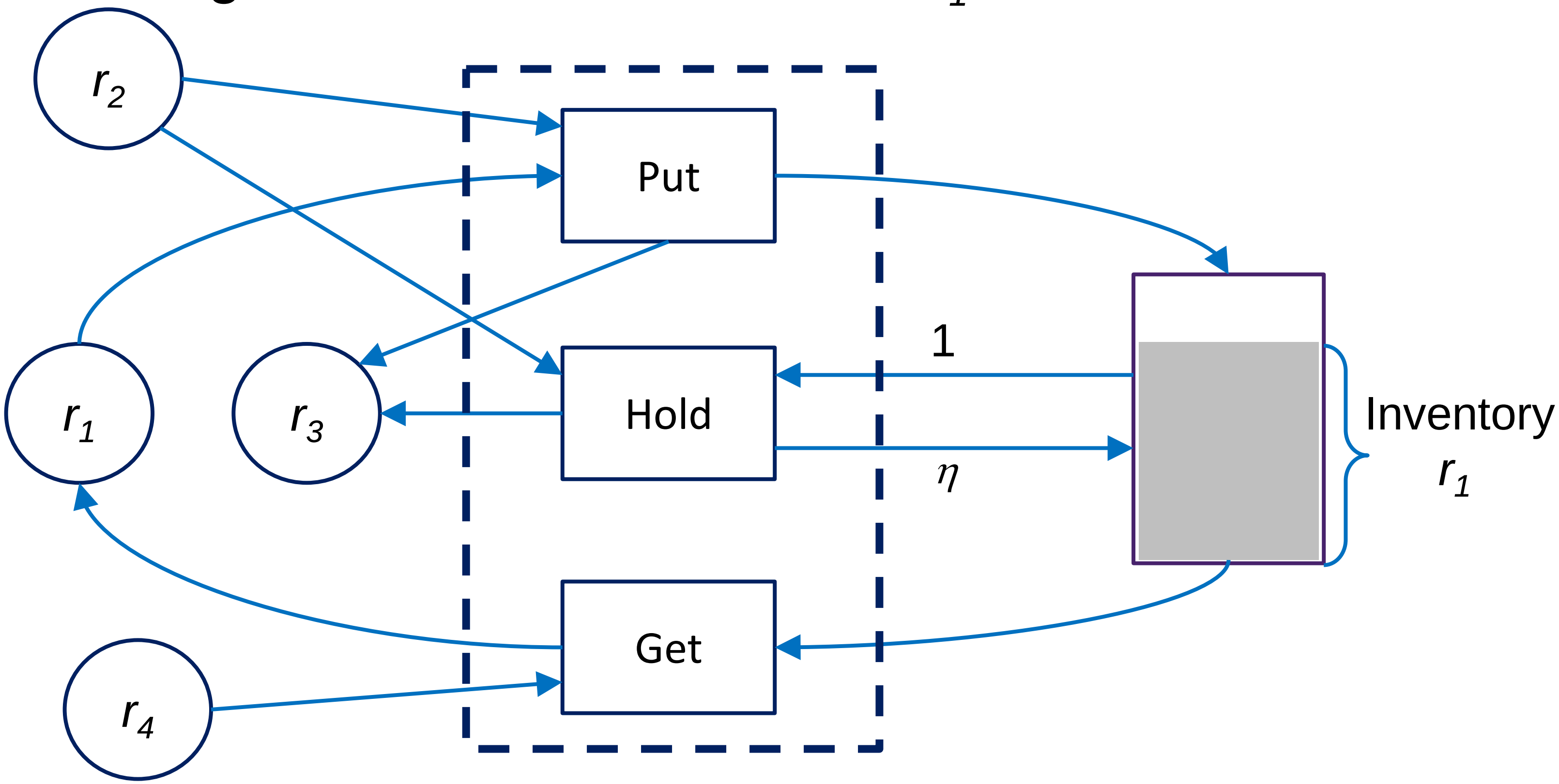




Biomass
Gasification
Pressurised vessels
Syngas 20 MPa
Syngas Exp −E
Syngas Comp +E
Syngas 7 MPa
CCGT
Underground storage
Nat gas 20 MPa
NG Exp −E
NG Comp +E
Nat gas 7 MPa
CHP
District heat
Mobility
Fuelling stations
Underground distribution pipeline
SMR
Boiler
DH network
Electricity E
Domestic Electric Heater
Pressurised vessels
H_2 20 MPa
H_2 Exp −E
H_2 Comp +E
H_2 7 MPa
Domestic Boiler
Heat
Fuel cell
Electrolyser

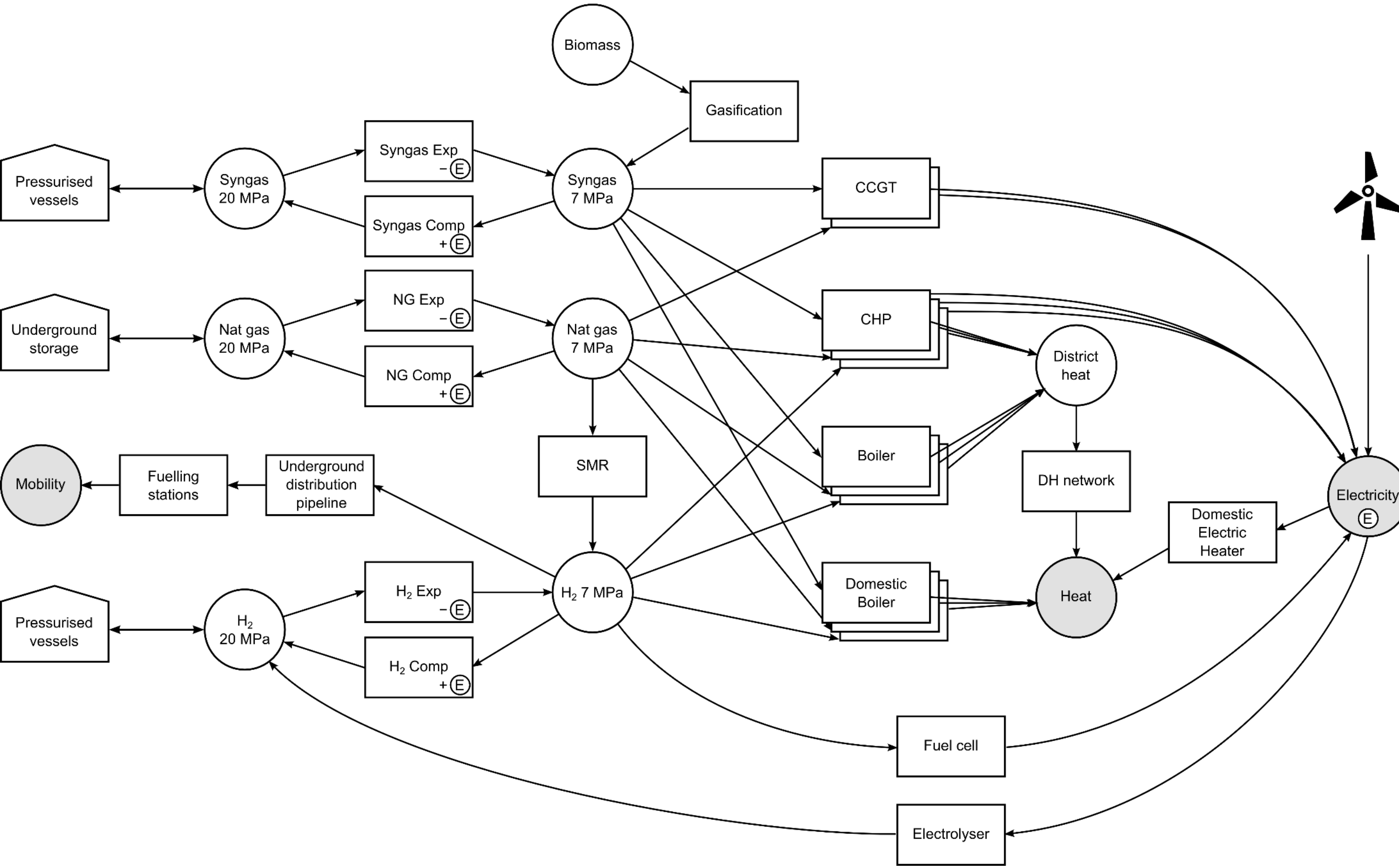
Modelling storage

Set of **storage tasks** to store resource r_1.



The “put” task transfers r_1 from the zone to the store, requiring some r_2 and producing some wastes r_3 (e.g. CO_2). The “hold” task maintains r_1 in storage which could be at less than 100% efficiency, the losses being converted to r_3 ; this task may also require some r_2. Finally, the “get” task retrieves r_1 from storage and delivers it to the zone, requiring some r_4.

S. Samsatli, N.J. Samsatli (2015). Computers & Chemical Engineering 80, 155-176, 0098-1354.



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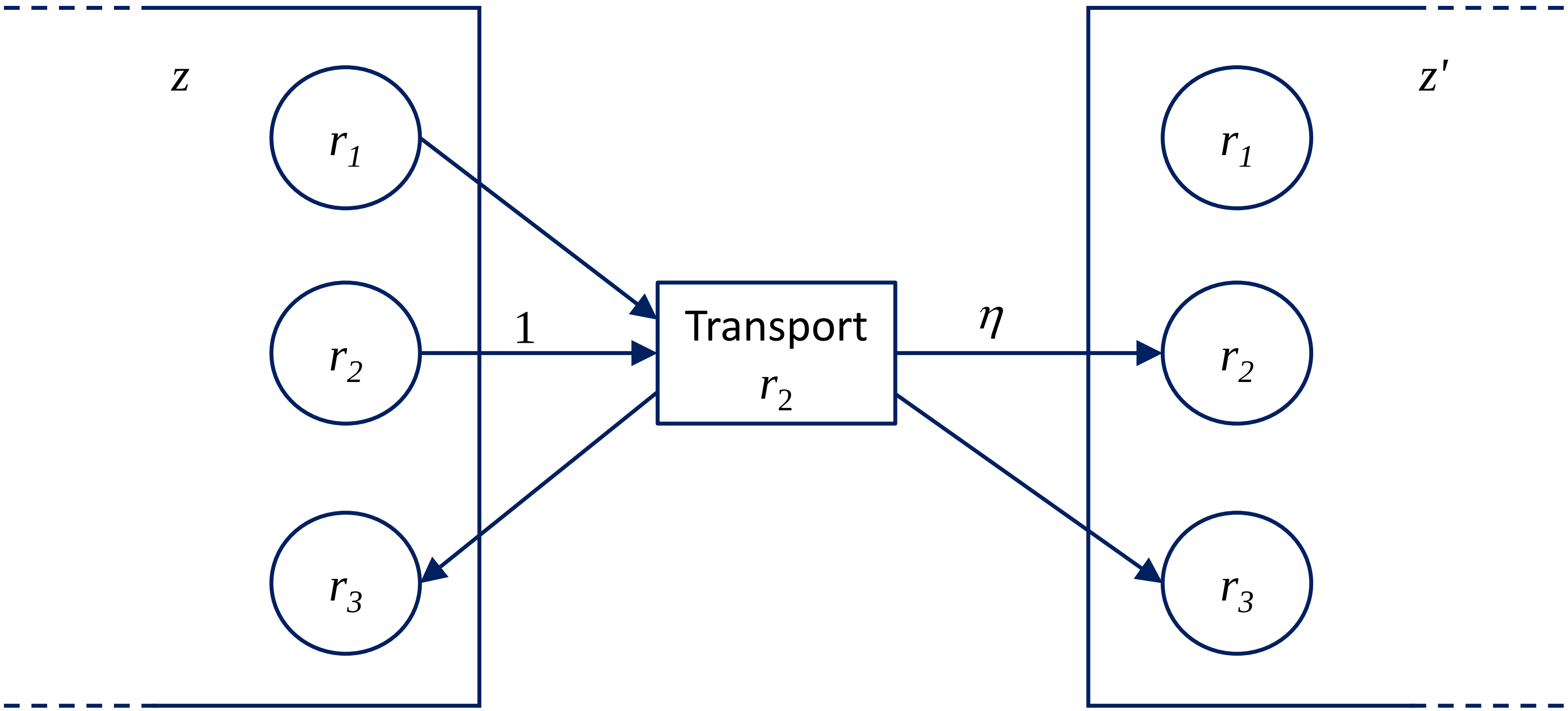
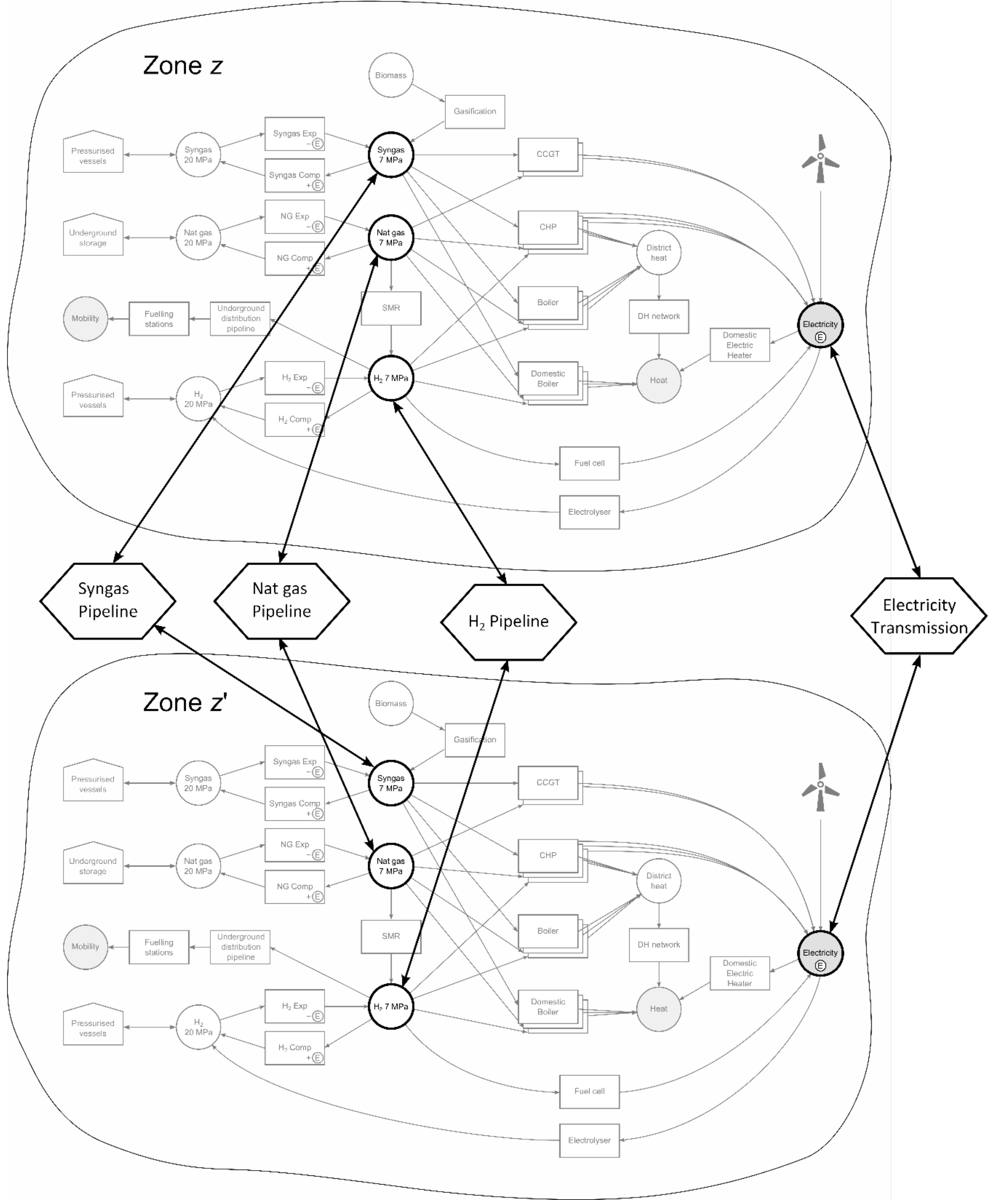
Modelling transport



Resource r_2 is transported from zone z to zone z', which requires r_1 from zone z and results in waste r_3 being generated in both zones

S. Samsatli, N.J. Samsatli (2015). Computers & Chemical Engineering 80, 155-176, 0098-1354.

Transmission technologies connect the networks between different zones



Pipeline model in gPROMS (used to determine max flow)

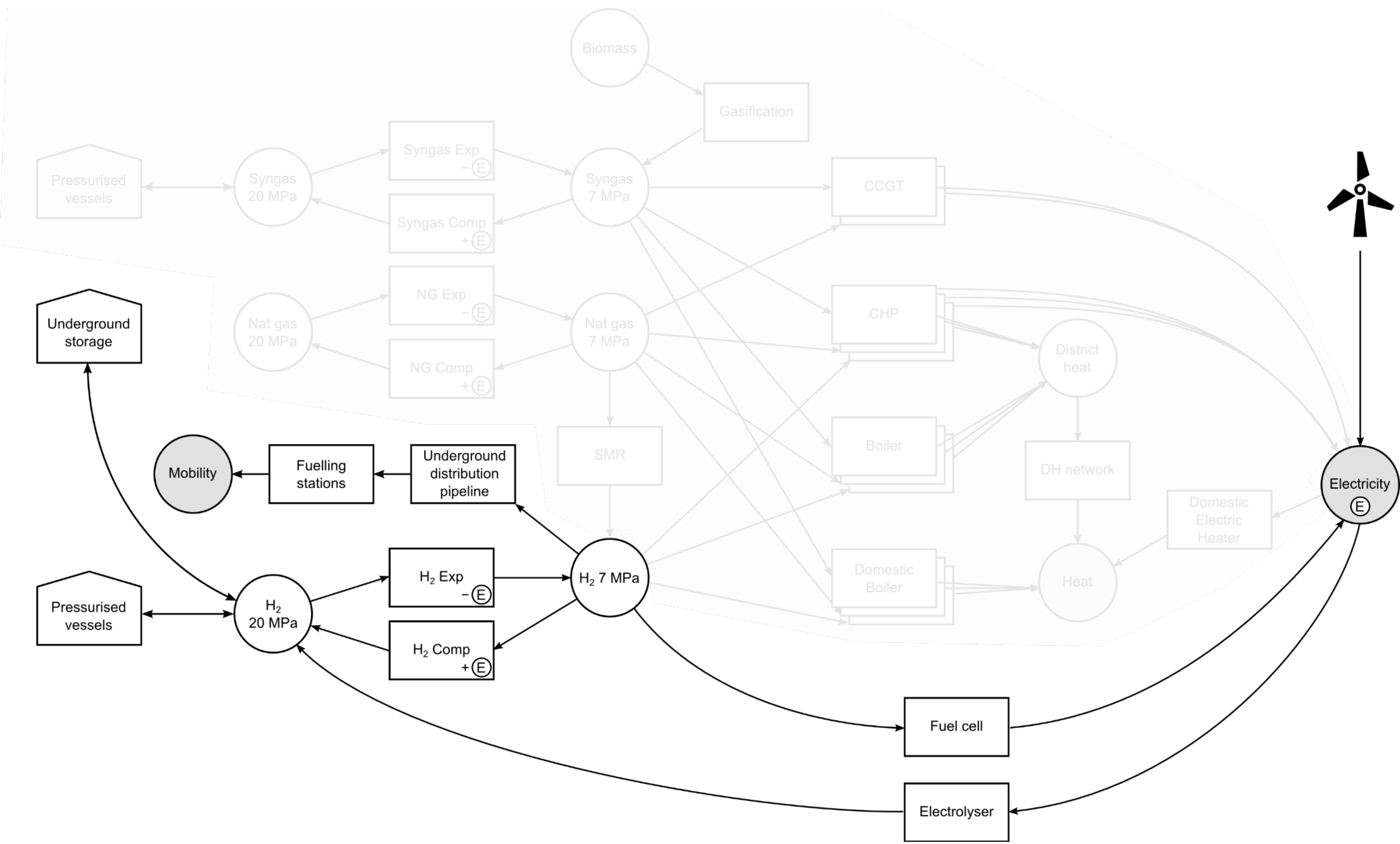
$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial z} = 0 \qquad \forall\ z \in (0, L]$$

$$\rho \frac{\partial w_i}{\partial t} + \rho v \frac{\partial w_i}{\partial z} = 0 \qquad \forall\ z \in (0, L],\ i = 1, \ldots, N_{\text{comp}}$$

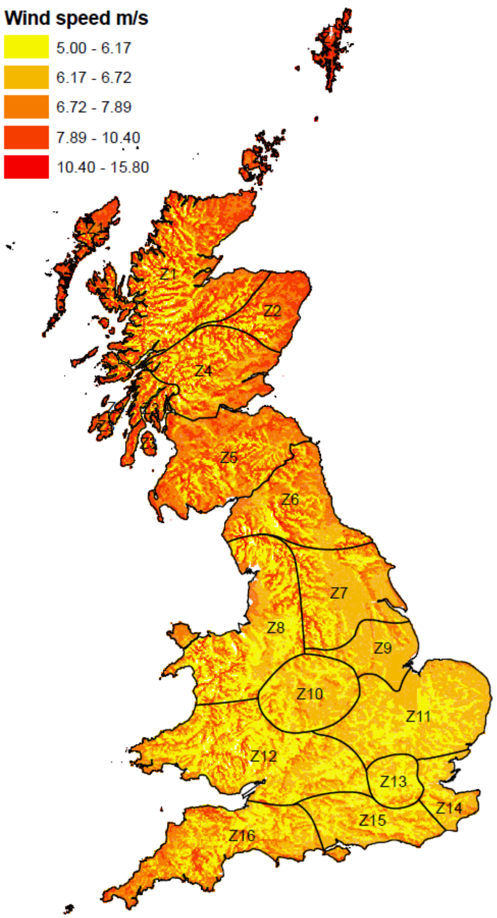
$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial z} = -\frac{\partial P}{\partial z} - \frac{4}{D} f \frac{\rho v |v|}{2} - \rho g \sin \alpha \qquad \forall\ z \in [0, L)$$

$$\frac{1}{\sqrt{f}} = -1.8 \log_{10} \left[\left(\frac{\varepsilon / D}{3.7} \right)^{1.11} + \frac{6.9}{\text{Re}} \right] \qquad \forall\ z \in [0, L]$$

$$\frac{\partial}{\partial t} \left[\rho (u + v^2/2) \right] + \frac{\partial}{\partial z} \left[\rho v (h + v^2/2) \right] + \rho g v \sin \alpha = \frac{4}{D} q \qquad \forall\ z \in (0, L]$$



Integrated wind-hydrogen-electricity network to decarbonise the domestic transport sector



Wind availability

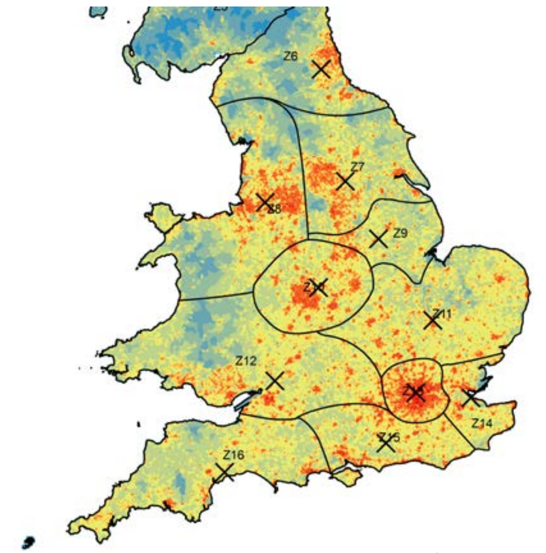
Distribution network

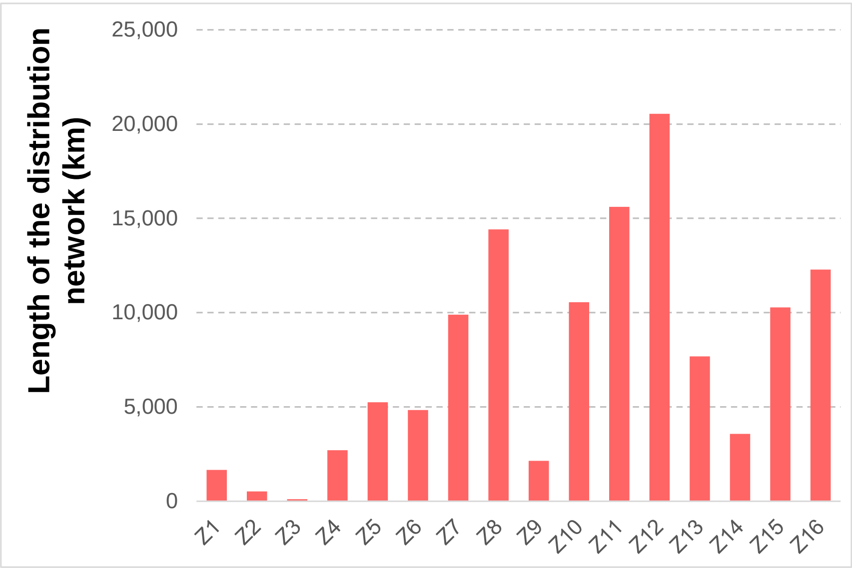
- Length of the distribution pipeline network

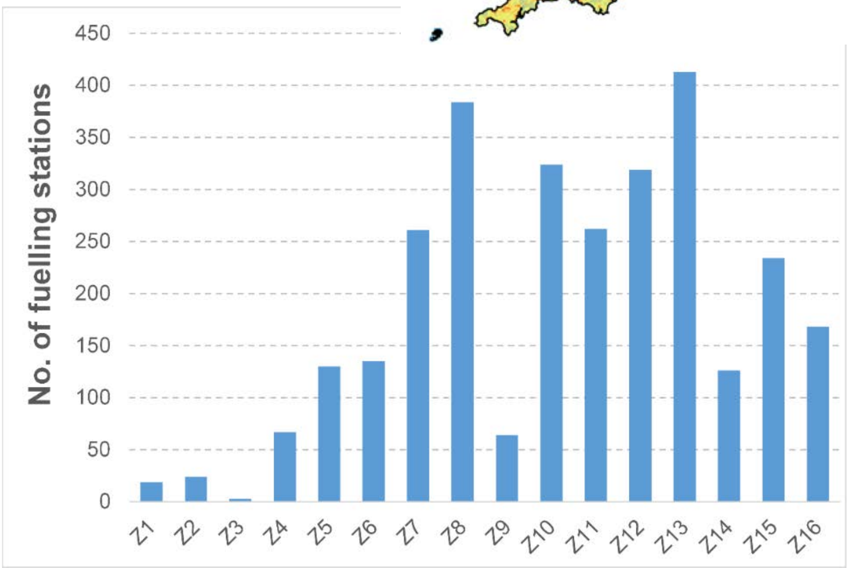
$$L_z^{network} = \iint_{S_z} \frac{D(x,y)}{C} \sqrt{(x-x_z)^2 + (y-y_z)^2}\, d$$

- Number of fuelling stations:

$$N_z^{stations} = \left\lceil \frac{1}{C} \iint_{S_z} D(x,y)\, dx\, dy \right\rceil$$







Wind turbine siting constraints

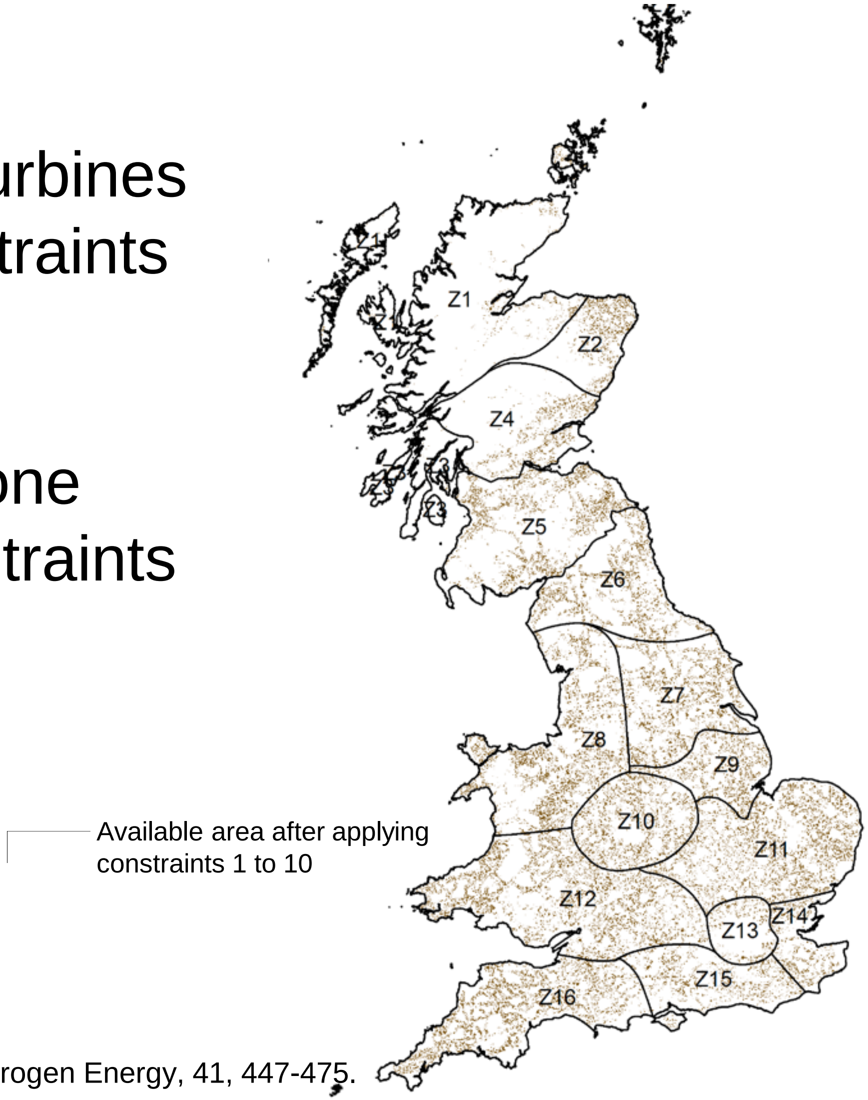
Criteria used to determine the total land area in each zone suitable for siting wind turbines

1. Average wind speed of at least 5m/s at 45m above ground level
2. Slope of less than 15%
3. Access: a minimum distance of 500m from minor road network
4. Connectivity to National Grid: at least 200m but not more than 1500m from major road network
5. Not in SSSI (Sites of Special Scientific Interest)
6. Population impacts: at least 500m from DLUA (developed land used area
7. Water pollution: at least 200m from river
8. Wildlife and interference: at least 250m from woodland
9. Safety: at least 5km from airports
10. Not occupied by existing wind turbines including spacing between turbines of 5 rotor diameters

Land footprint constraint

- Total available area for wind turbines
  - Intersection of the 10 constraints
  - 2% of total GB area

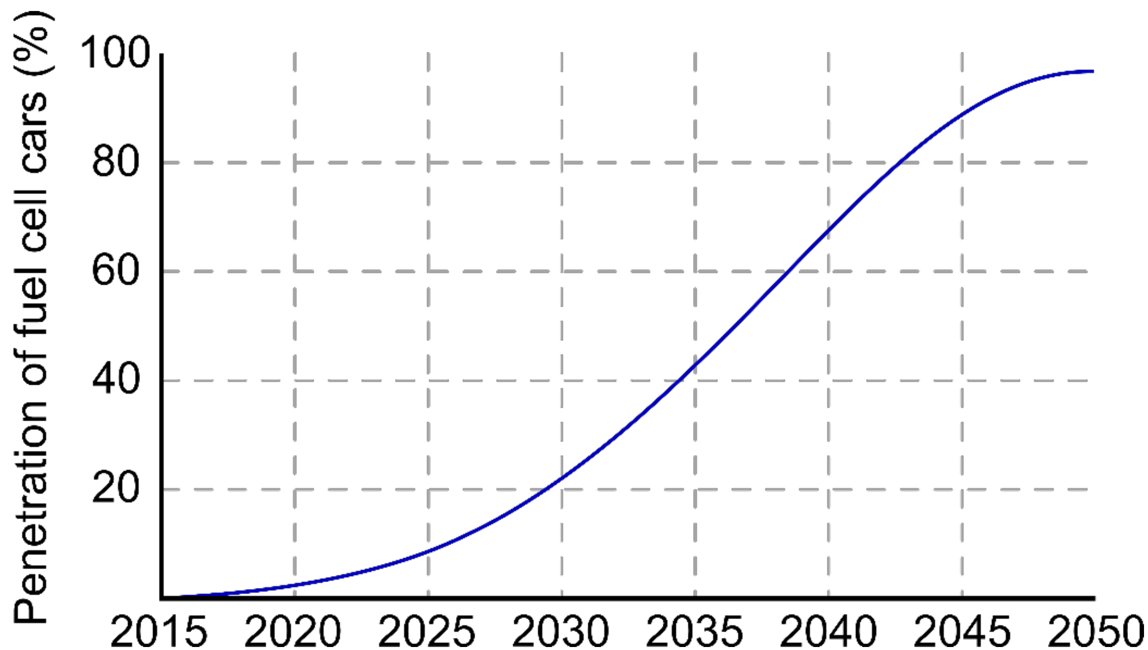
- Total available area in each zone defines the land footprint constraints in the model



S. Samsatli, I. Staffell, N.J. Samsatli (2016). International Journal of Hydrogen Energy, 41, 447-475.

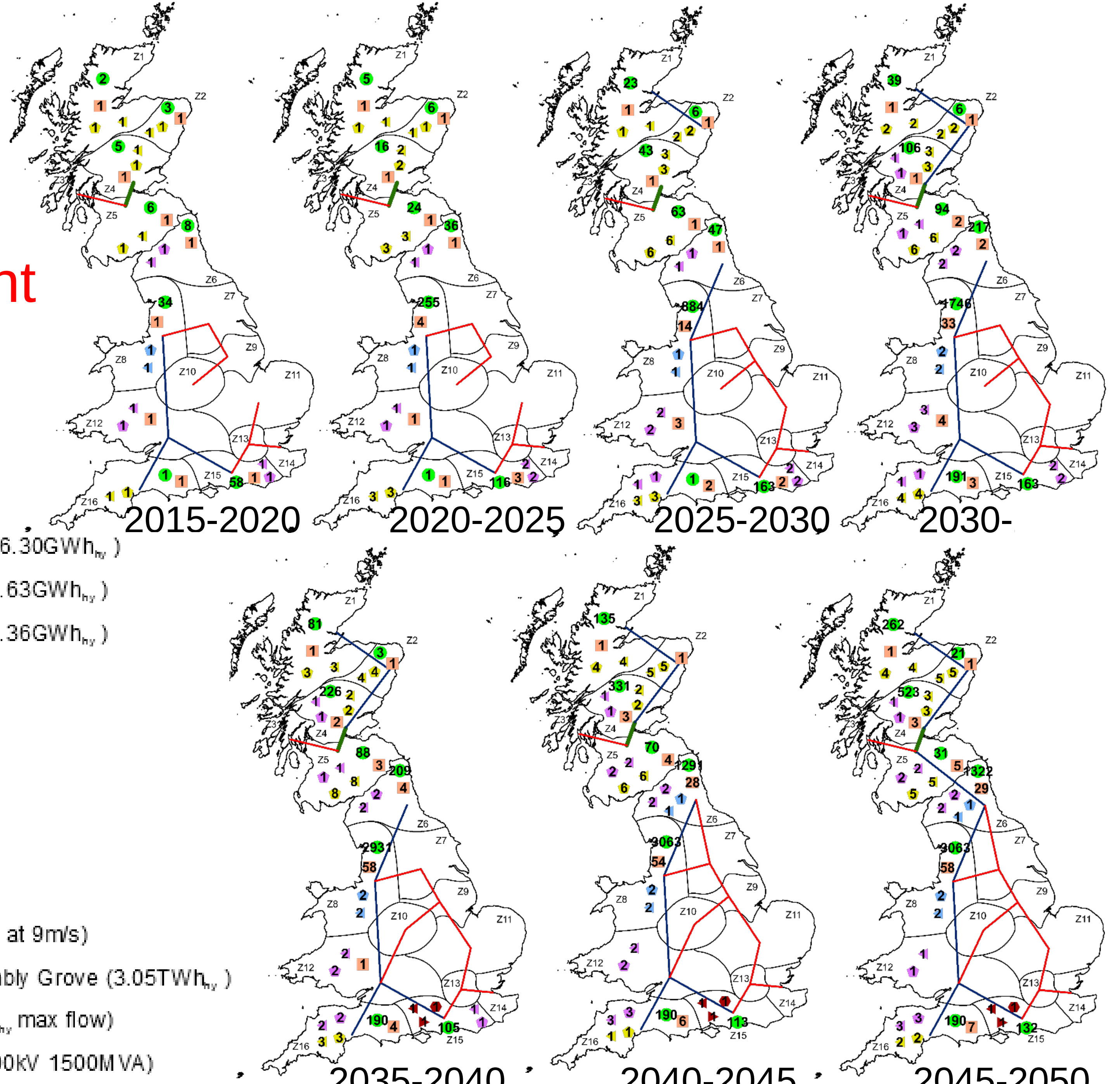
Spatio-temporal input data

- Hourly time-series wind data obtained from the Virtual Wind Farm Model*
- Future wind speed derived from the UKCP09
- Hourly demand time-series data from DfT data for vehicular usage
- Future demand data projected assuming a trajectory of penetration of fuel cell cars



* I. Staffell and R. Green. Renewable Energy, 66(0):775 – 786, 2014.

Network configuration for net present cost minimisation



Compressed gas storage (36.30GWh$_{hy}$)

Compressed gas storage (3.63GWh$_{hy}$)

Compressed gas storage (0.36GWh$_{hy}$)

Compressor (63.76MW$_{e}$)

Expander (13.17MW$_{el}$)

Expander (1.32MW$_{el}$)

Expander (0.13MW$_{el}$)

Expander (28.67MW$_{el}$)

Electrolyser (69.38MW$_{hy}$)

New wind turbine (1.23MW$_{e}$ at 9m/s)

Underground storage - Humbly Grove (3.05TWh$_{hy}$)

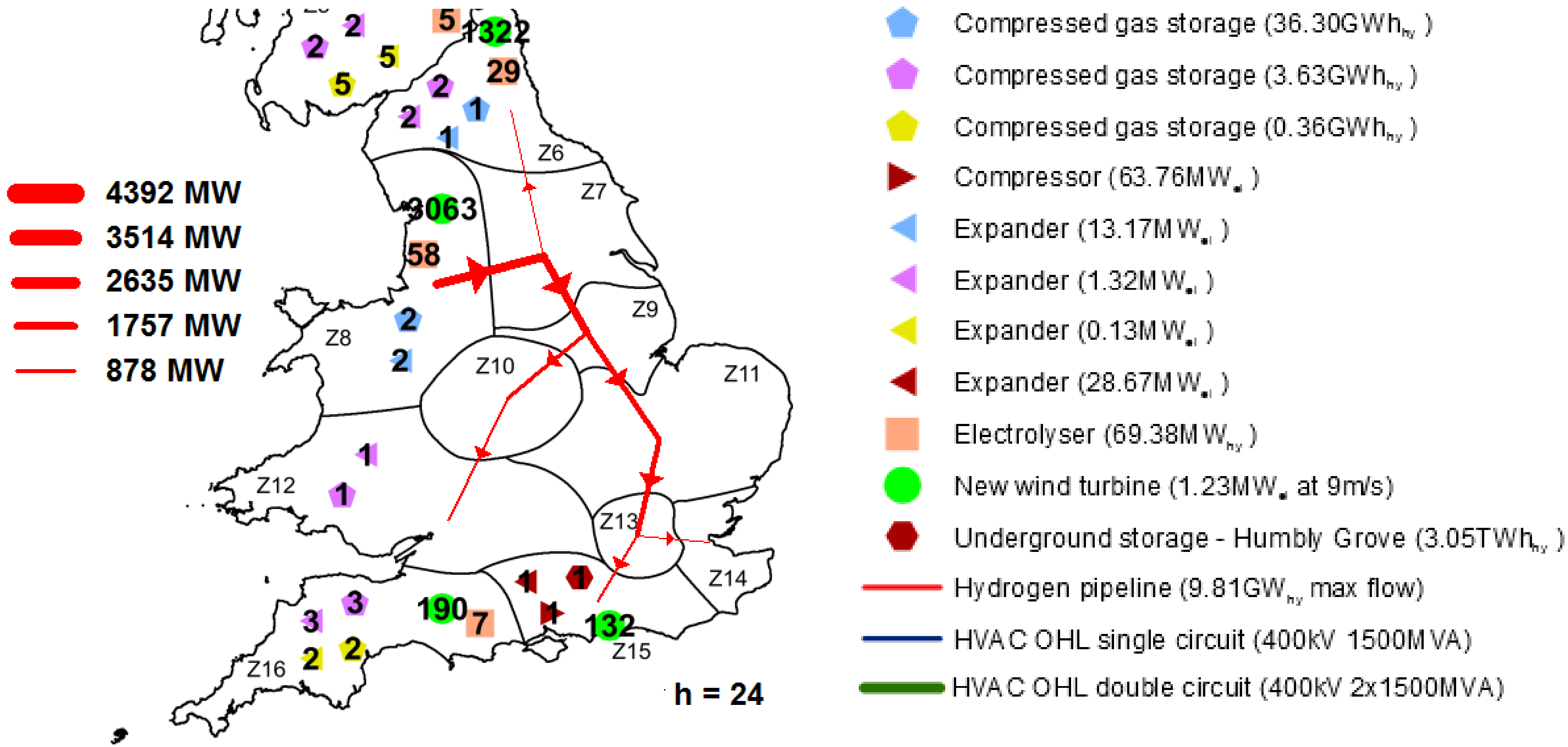
Hydrogen pipeline (9.81GW$_{hy}$ max flow)

HVAC OHL single circuit (400kV 1500MVA)

HVAC OHL double circuit (400kV 2x1500MVA)

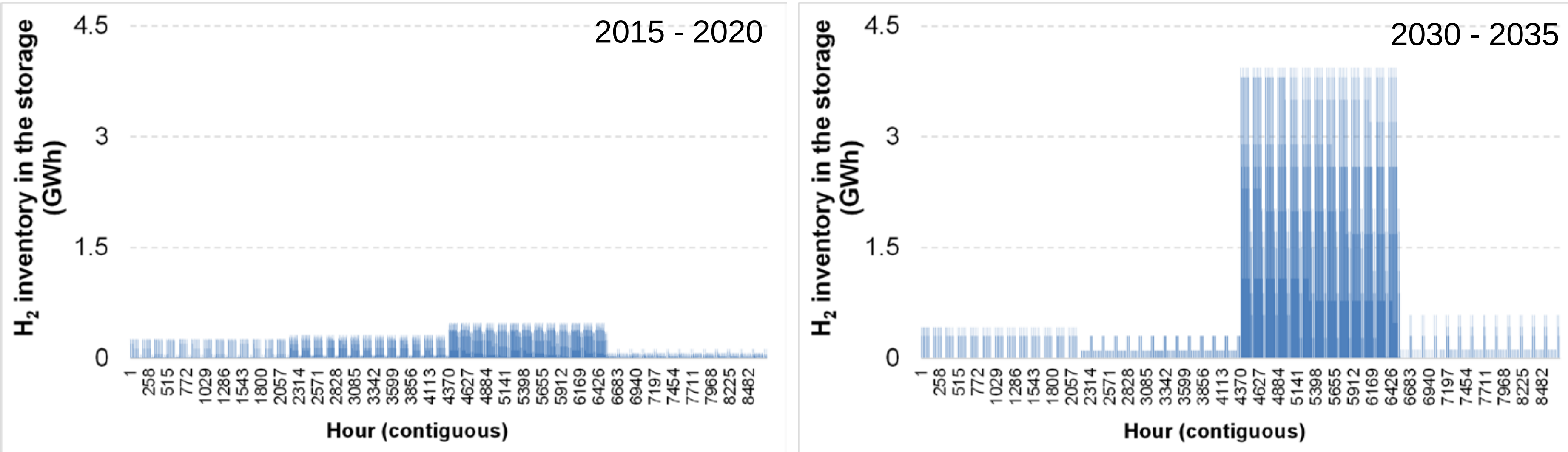
Operation of the hydrogen transmission network

Snapshot during weekdays in summer in 2045-2050

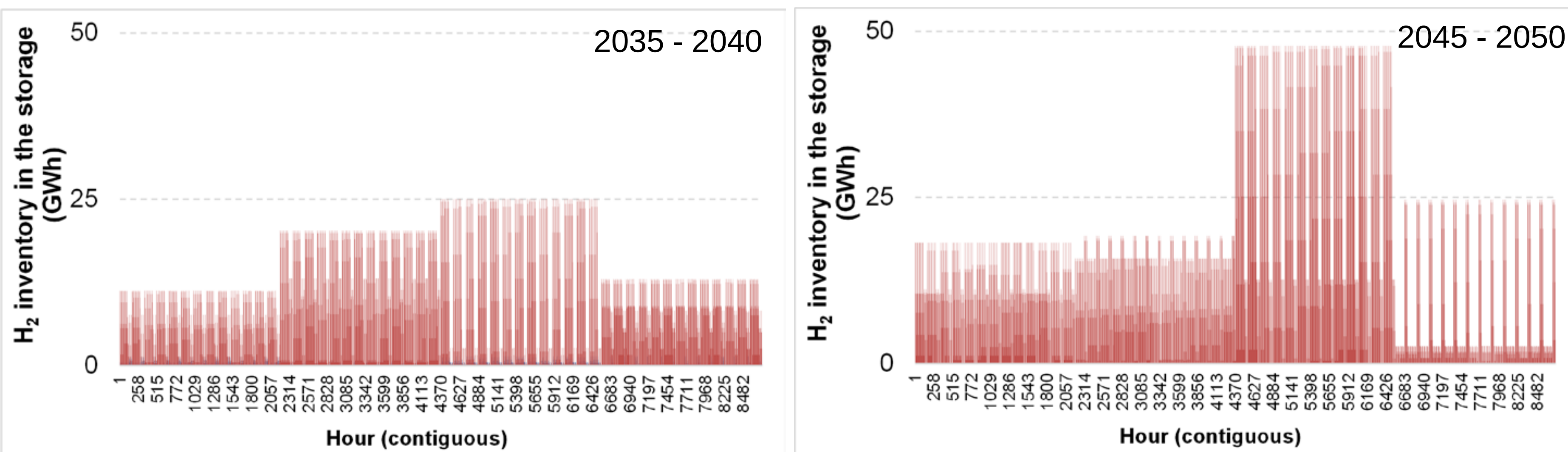


View in slide show mode for the animation

Hourly inventory of hydrogen in zone 15



H_2 gas storage in pressurised vessels from 2015 to 2035



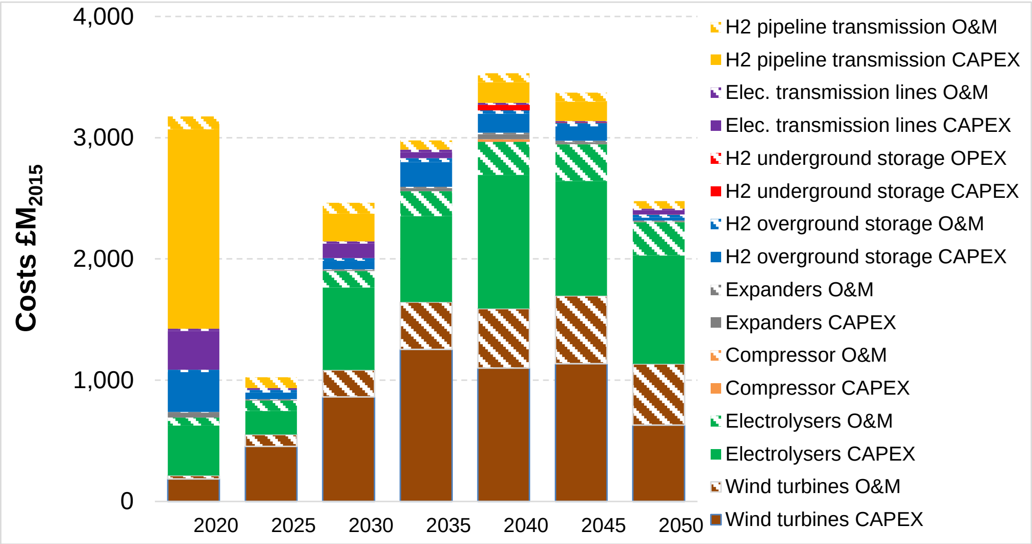
Switching to Humbly Grove underground storage until 2050

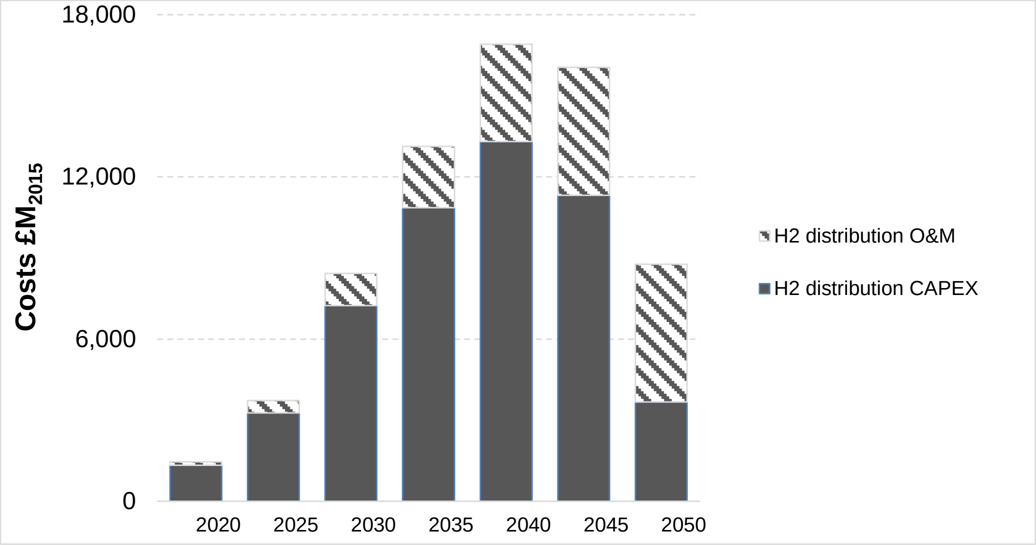
Costs

Net present cost = £87.5 bn

Total avoided CO_2 emissions = 2 bn t

Cost of avoided CO_2: £43.75/t

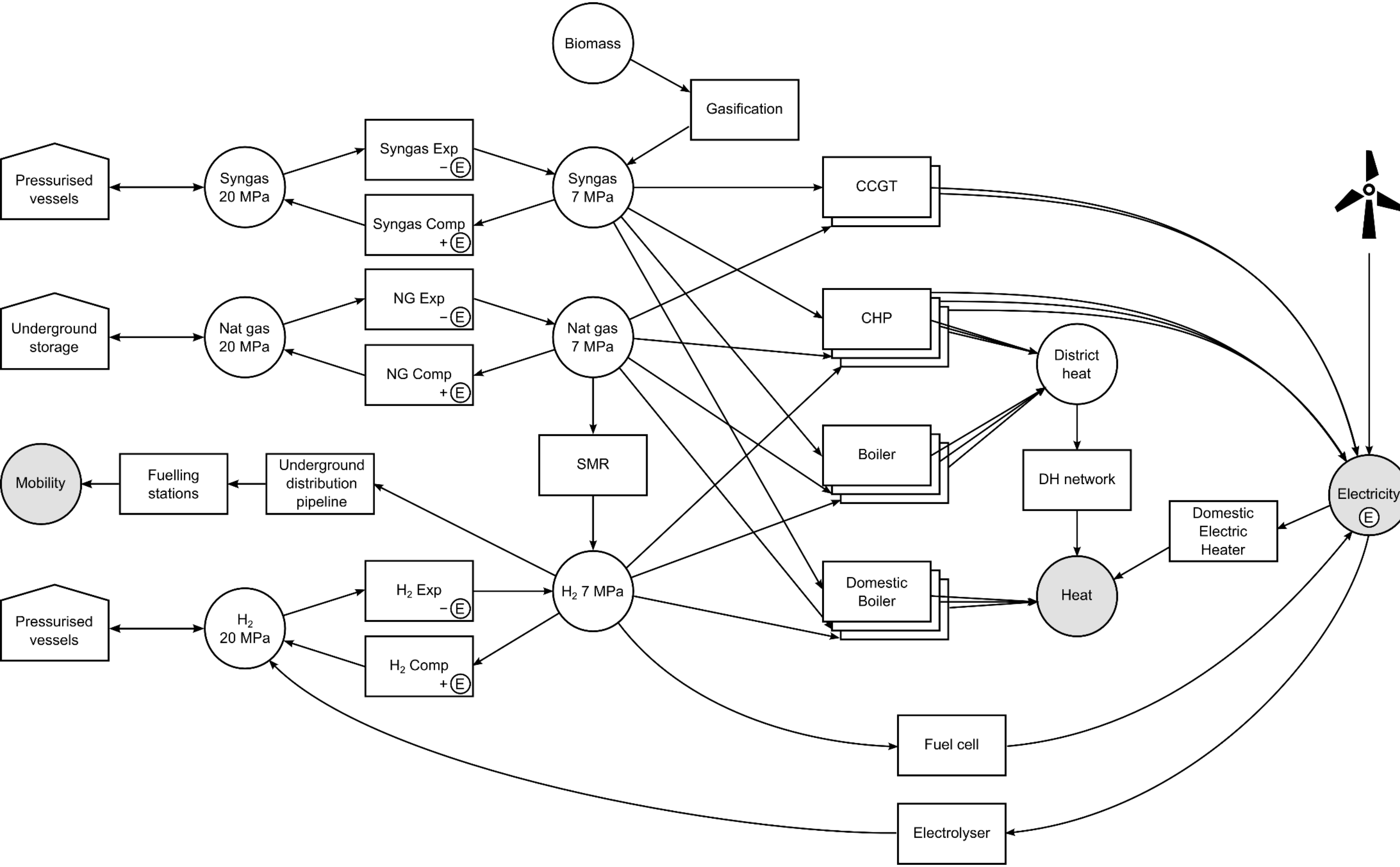




Computational statistics

- Number of variables: 1,500,000 (10,100 integers)
- Number of constraints: 3,350,000
- Full solution takes > 2 weeks
- With decomposition method* takes about 2 days

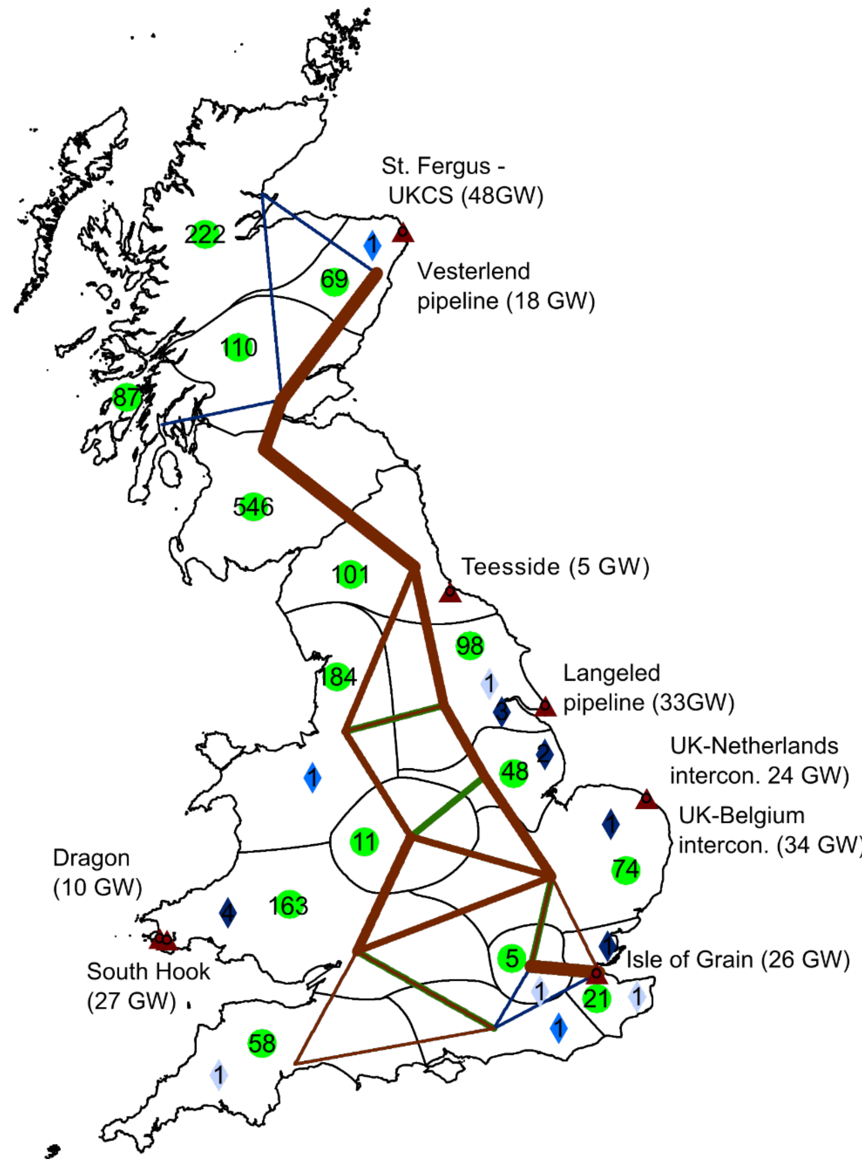
*S. Samsatli and N. Samsatli (2015). A general spatio-temporal model of energy systems with a detailed account of transport and storage. Computers and Chemical Engineering 80, 155-176, 0098-1354.



Multi-vector network to meet domestic heat, electricity and transport fuel (H_2) demands

Existing assets and natural gas availability

- Natural gas pipeline (14.3 GW max flow)
- HVAC OHL single circuit (400 kV 1500 MVA)
- HVAC OHL double circuit (400 kV 2x1500 MVA)
- CCGT - natural gas (1.5 GW)
- CCGT - natural gas (1 GW)
- CCGT - natural gas (0.5 GW)
- Wind turbine (1.23 MW at 9m/s)
- Natural gas terminal



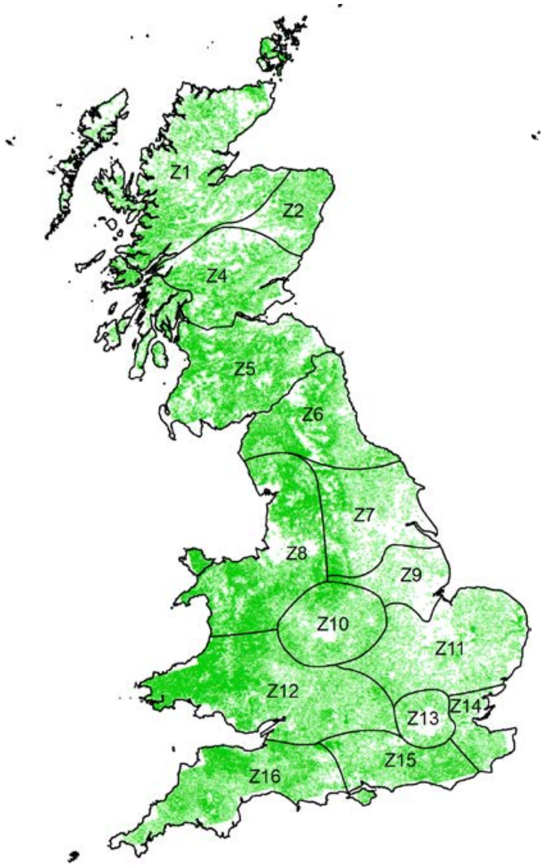
Assumptions:

- Natural gas availability decreases by 2% every year
- Existing wind turbine capacity retires over 15 years (1/3 every 5 years)
- Existing CCGT plants retire 30 years after they were built

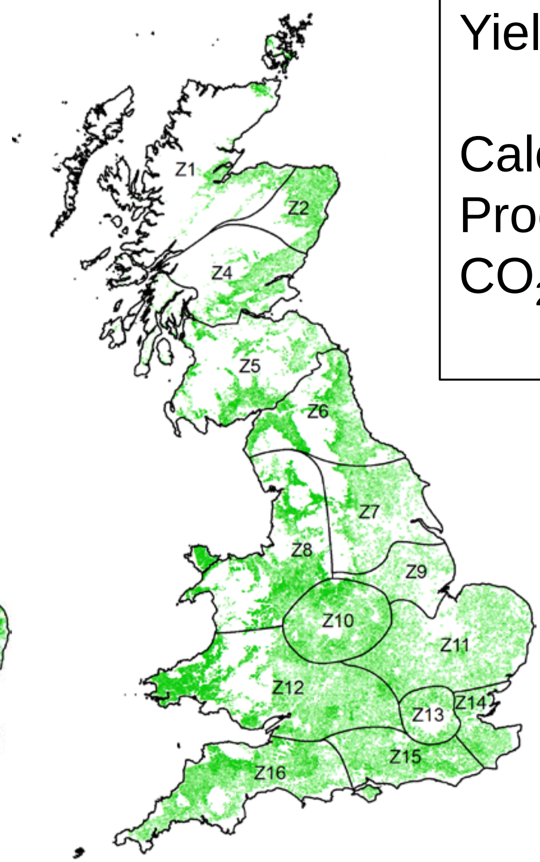
Biomass production

Miscanthus properties:

Yield potential: 5.34 odt/ha (Winter)
3.58 odt/ha (Spring)
Calorific value: 3.92 MWh/odt
Production cost: £41.59/odt
CO_2 emissions: 15 kg/MWh



All grassland in GB
32% of GB land area

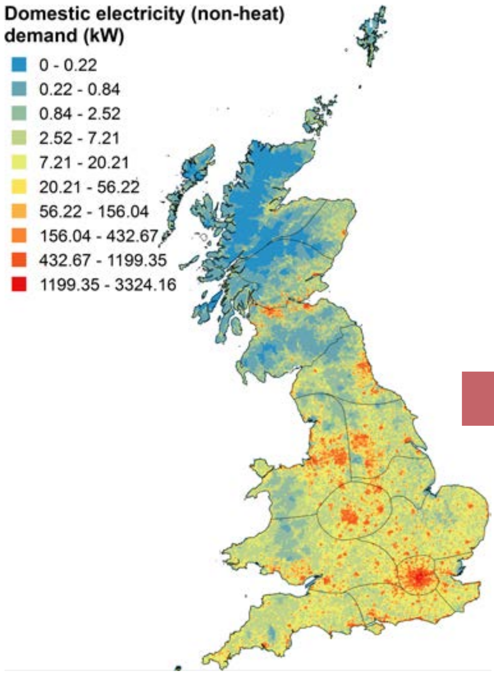


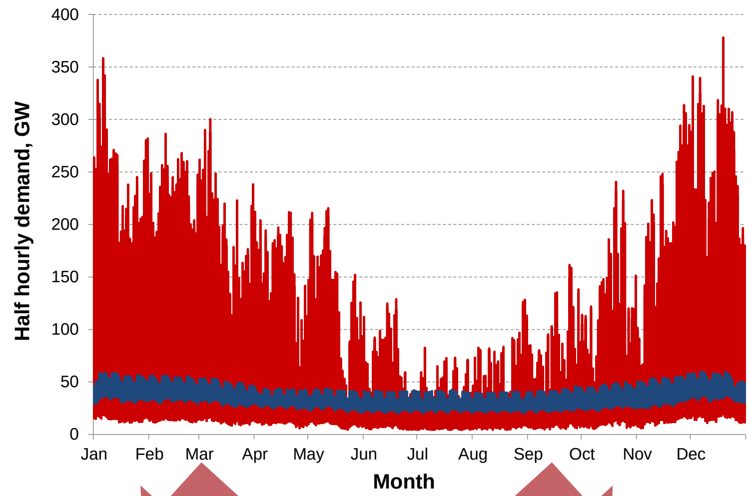
After excluding land area with

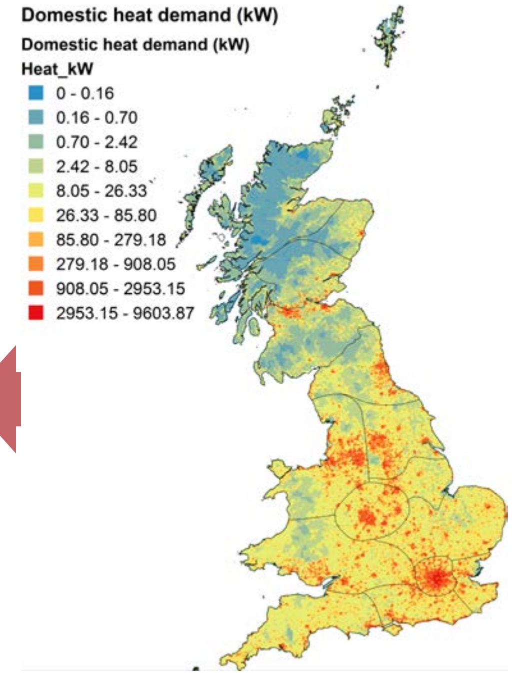
- Elevation > 250 m
- Slope > 15%
- Urban areas/roads/rivers, parks
- Protected areas, SSSI
- Area of outstanding beauty

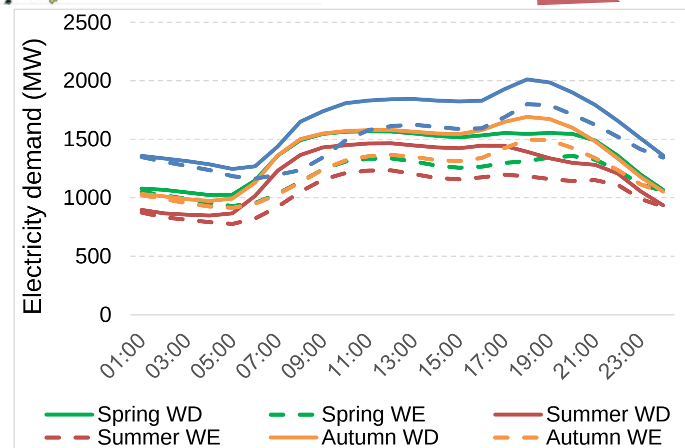
13% of total GB are

In the case study, further imposed that only 10% of this is available for biomass

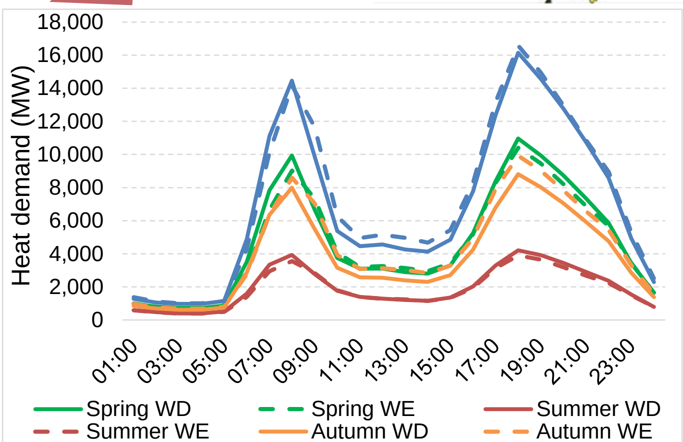






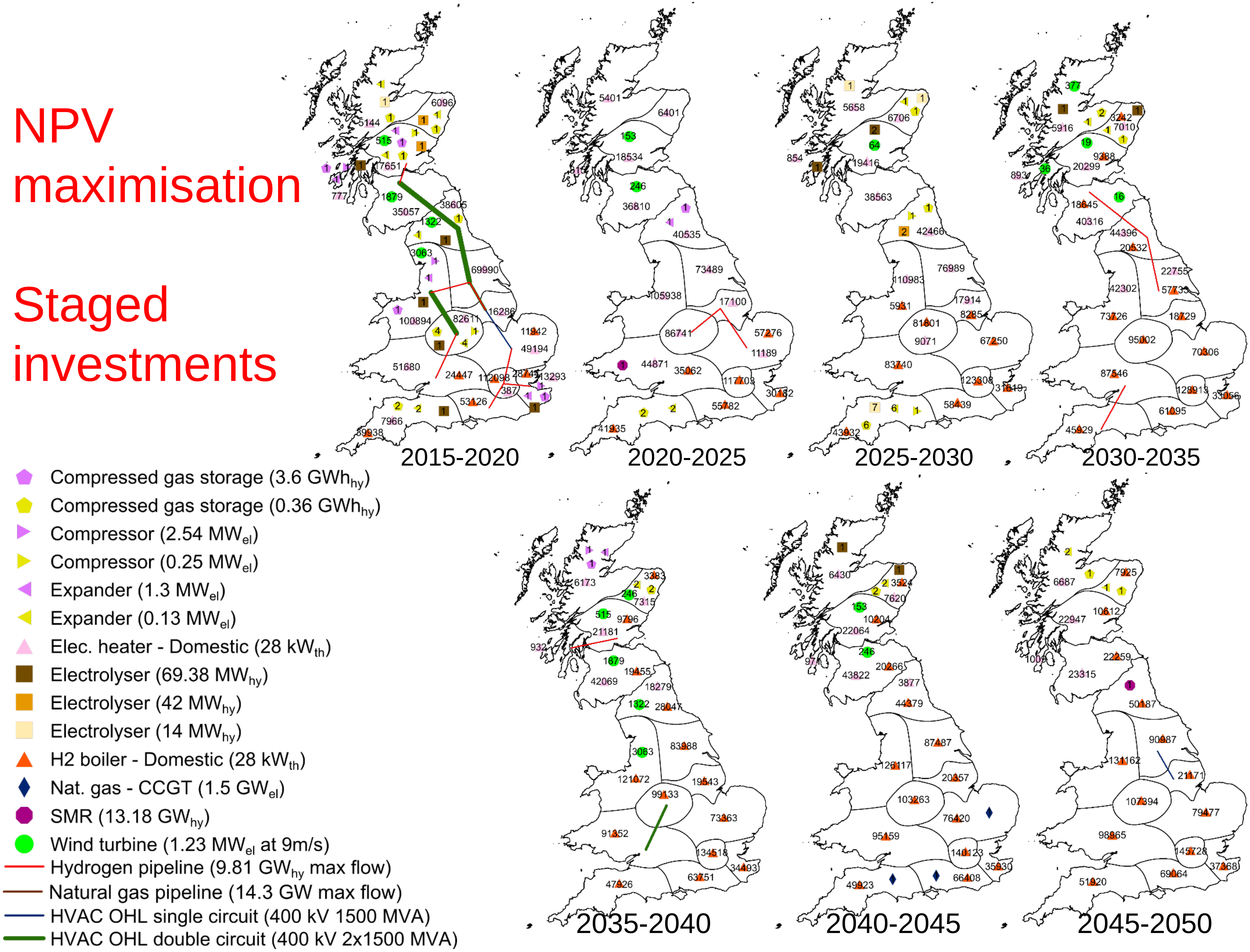


Electricity demands in Z13 (similar graphs were derived for the other zones)



Heat demands in Z13 (similar graphs were derived for the other zones)

- Demands in 2009; were projected into the future assuming a fixed growth rate



NPV maximisation
Staged investments
2015-2020
2020-2025
2025-2030
2030-2035
2035-2040
2040-2045
2045-2050
Compressed gas storage (3.6 GWh$_{hy}$)
Compressed gas storage (0.36 GWh$_{hy}$)
Compressor (2.54 MW$_{el}$)
Compressor (0.25 MW$_{el}$)
Expander (1.3 MW$_{el}$)
Expander (0.13 MW$_{el}$)
Elec. heater - Domestic (28 kW$_{th}$)
Electrolyser (69.38 MW$_{hy}$)
Electrolyser (42 MW$_{hy}$)
Electrolyser (14 MW$_{hy}$)
H2 boiler - Domestic (28 kW$_{th}$)
Nat. gas - CCGT (1.5 GW$_{el}$)
SMR (13.18 GW$_{hy}$)
Wind turbine (1.23 MW$_{el}$ at 9m/s)
Hydrogen pipeline (9.81 GW$_{hy}$ max flow)
Natural gas pipeline (14.3 GW max flow)
HVAC OHL single circuit (400 kV 1500 MVA)
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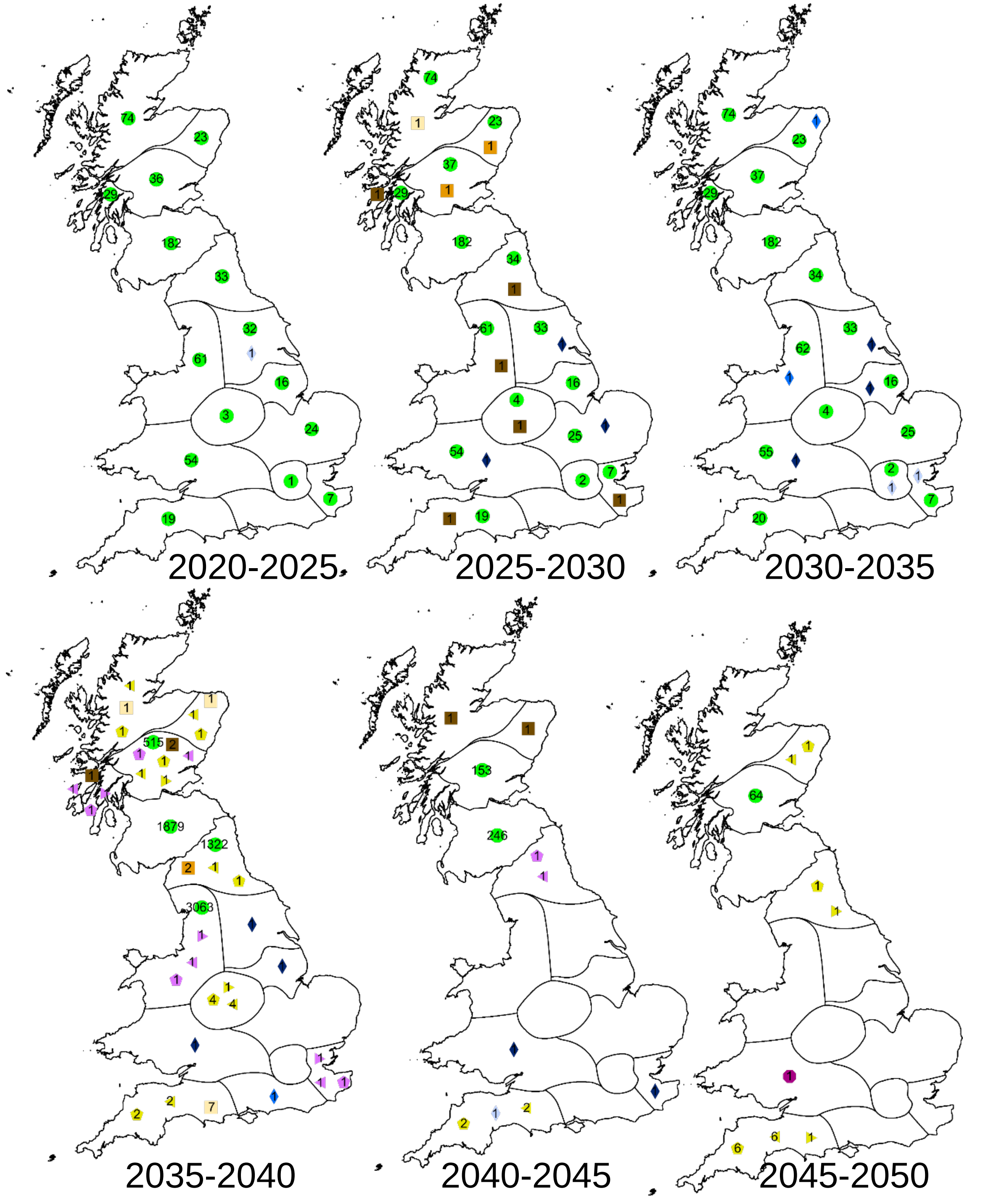
NPV maximisation

Technology retirements



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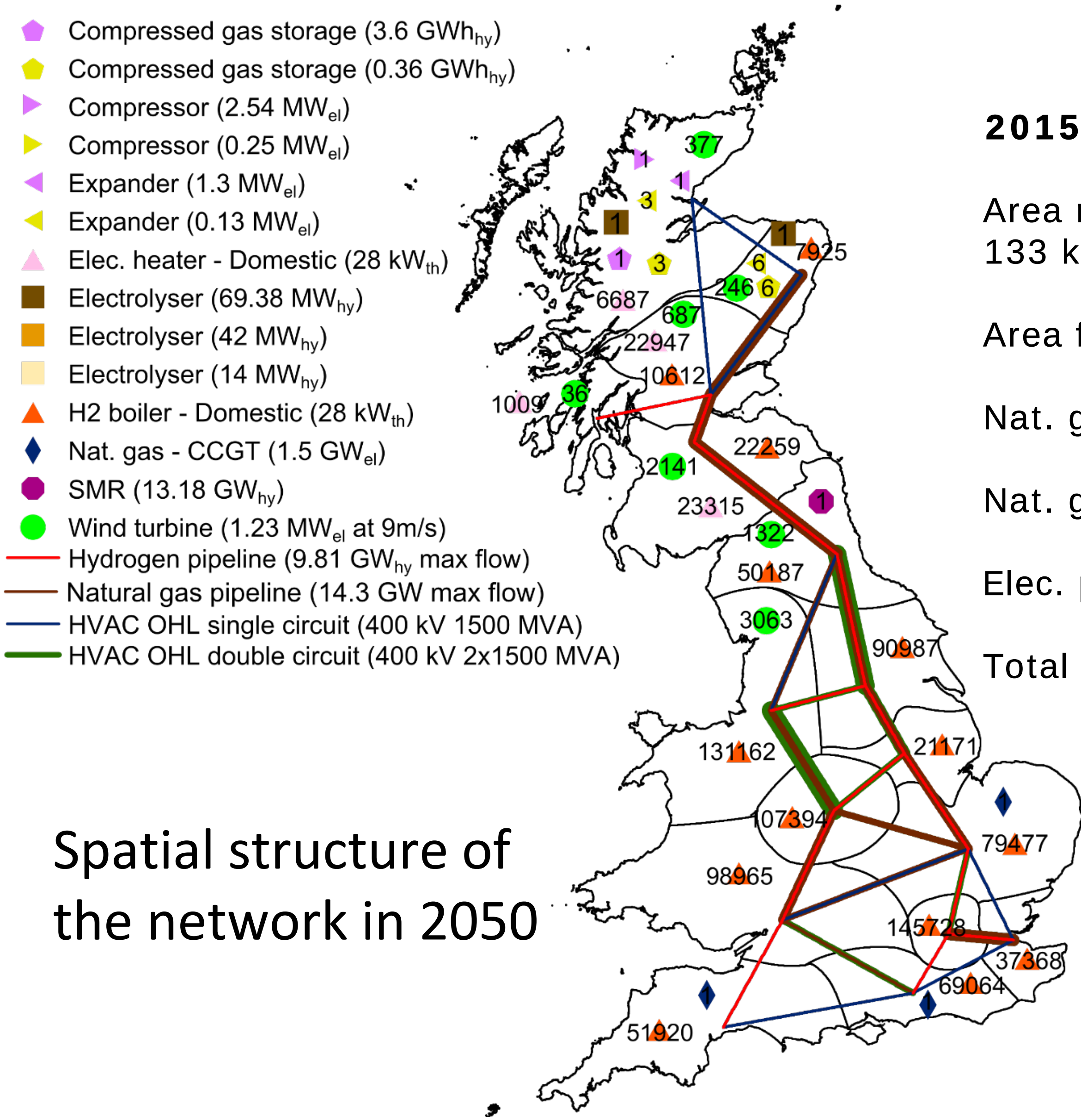
Maximise net present value



Spatial structure of the network in 2050

2015 to 2050:

Area required for new wind turbines = 133 kha increasing to 155 kha in 2050

Area for biomass = 0

Nat. gas. local prod. = 0

Nat. gas import = 9,113 TWh

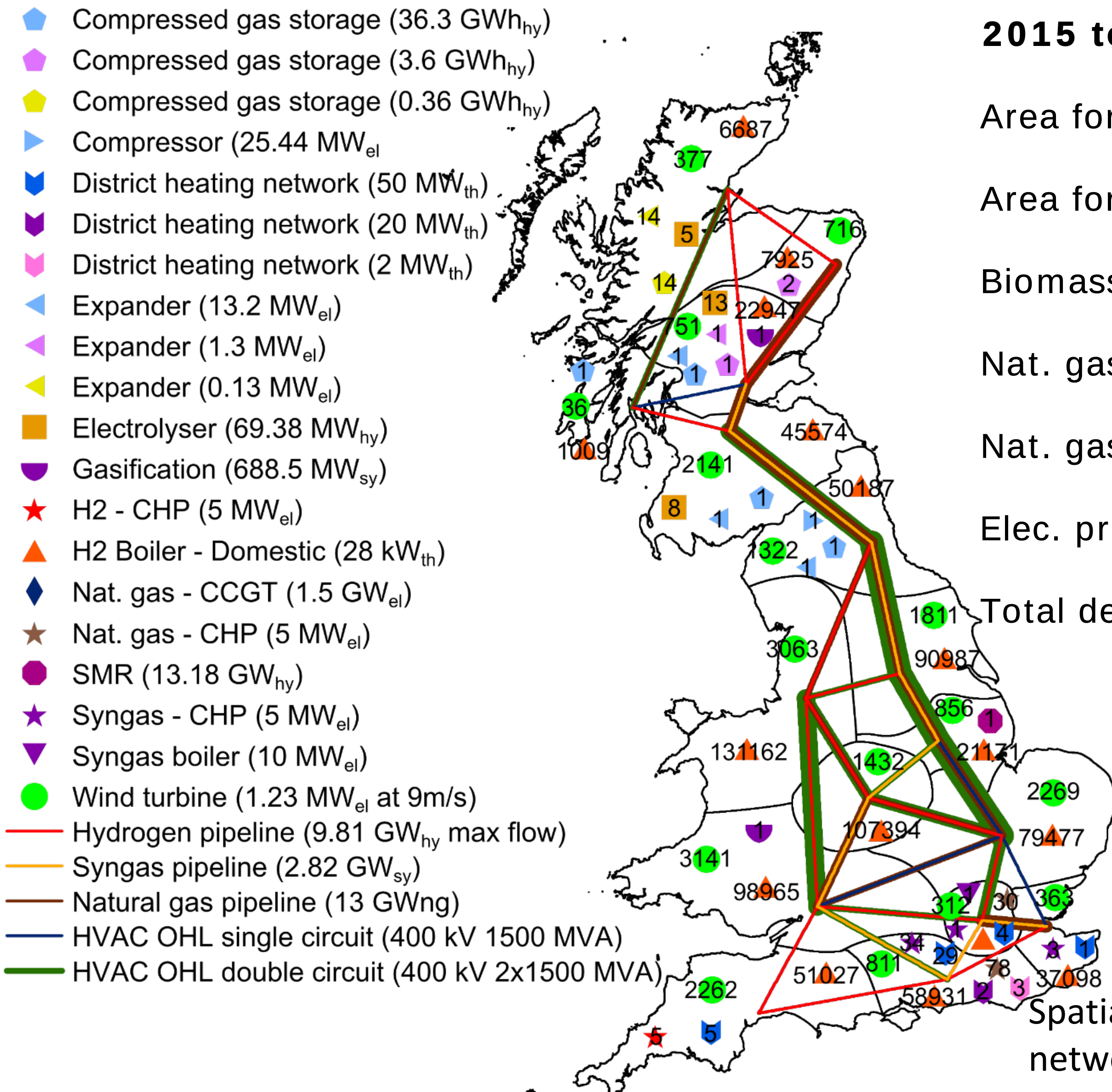
Elec. prod. by wind turbines = 3,536 TWh

Total demands satisfied = 10,083 TWh

NPV = £121 bn

CO_2 Emissions = 2.07 Gt

Minimise CO_2 emissions



2015 to 2050:

Area for new wind turbines = 425 kha

Area for biomass = 313 kha

Biomass production = 154 TWh

Nat. gas. local prod. = 0

Nat. gas import = 7,569 TWh

Elec. prod. by wind turbines = 4,564 TWh

Total demands satisfied = 10,083 TWh

NPV = £32 bn

CO_2 Emissions = 1.72 Gt

Spatial structure of the network in 2050

Dealing with uncertainty

- Stochastic analysis
  - Multiple *deterministic* optimisations
    - Each an independent scenario
    - Uncertain parameters sampled from a random distribution
  - Output is solution of every scenario
    - Calculate averages (and other moments of output distributions)
    - Examine histograms
  - No increase in complexity
  - Solution time roughly proportional to number of scenarios

Dealing with uncertainty

- Robust optimisation
  - Single optimisation with multiple scenarios
  - Optimise/constrain expectations
  - Significant increase in complexity
  - Solution time > linear in number of scenarios
  - Decisions can be made at different stages
    - Applied to all scenarios: “here and now”
      - Design/investment decisions
    - Applied to each scenario: “wait and see”
      - Operation
      - Staged investments

Types of uncertainty

Uncertainty	Techniques	Challenges
Availability of renewables	Robust	V. large no. of scenarios Not all independent – how to sample? Extreme events Control strategies
Policy	Stochastic analysis Robust	How to pick scenarios
Technological	Stochastic analysis Robust	How to allow for the appearance of a new (disruptive) technology
Demands	Robust only?	Future predictions Effect of network design on the future demands

Conclusion

- Developed a powerful modelling framework applicable to a wide range of integrated multi-vector energy networks
  - Simultaneously determines design and operation
  - Flexible temporal resolution simultaneously both:
    - Hourly intervals for operation
    - Long-term planning horizon (to 2050 or beyond)
  - Flexible spatial representation
    - Can be applied to any region/country
    - Trade off with temporal resolution (model size)
  - New networks can be easily added without changing mathematical formulation
- The level of detail in the model makes uncertainty analysis very challenging
  - Need for efficient methods

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Work in progress and future work

- Uncertainty analysis
- H_2 injection into the nat. gas grid
- Pipeline storage
- CO_2 value chains