Imperial College London

Modelling integrated multi-vector energy systems with a detailed account of transport and storage

Sheila Samsatli and Nouri Samsatli

wholeSEM workshop

Imperial College London

24 May 2016

Centre for Process Systems Engineering
Imperial College, London

wholeSEM

EPSRC
Engineering and Physical Sciences Research Council

Outline

Introduction

- 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

Imperial College London

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

Imperial College London

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)

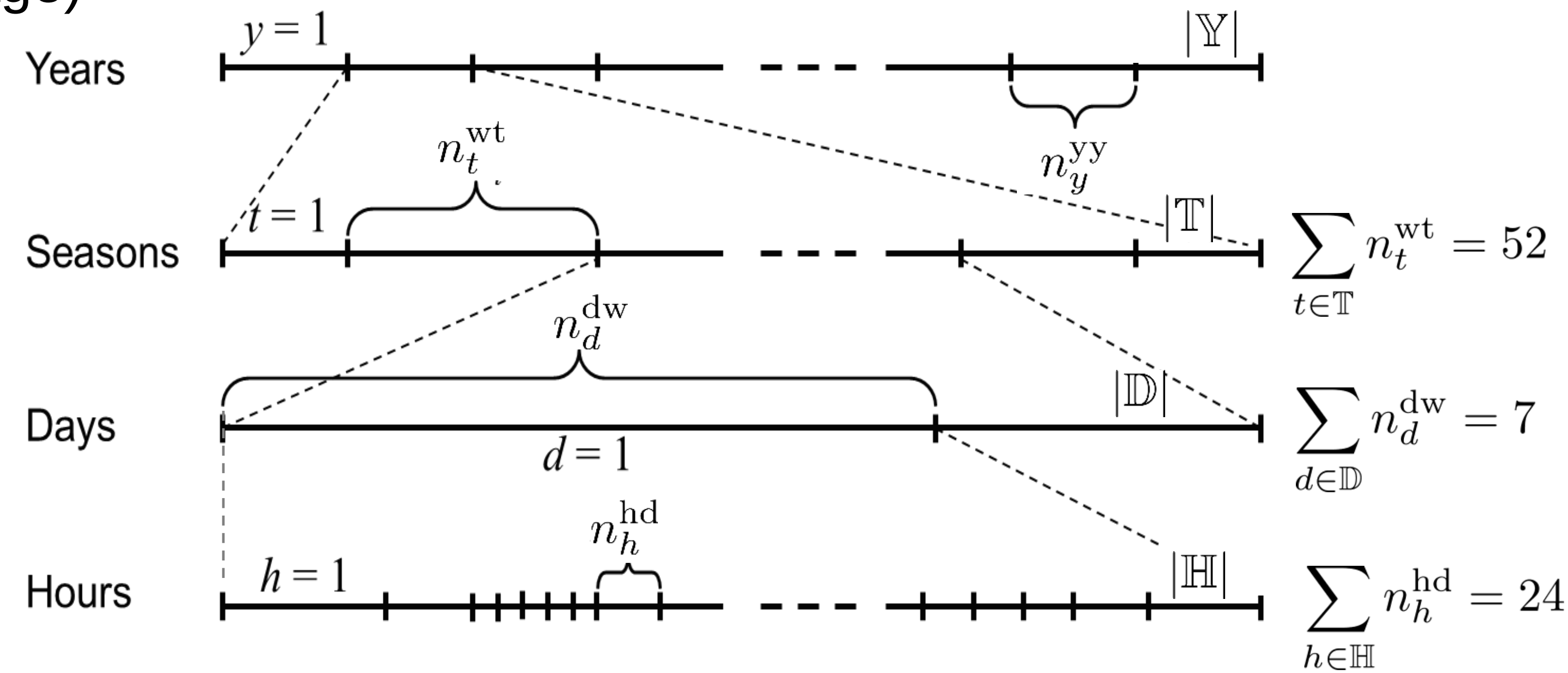
Objective:

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

Imperial College London

Temporal representation

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



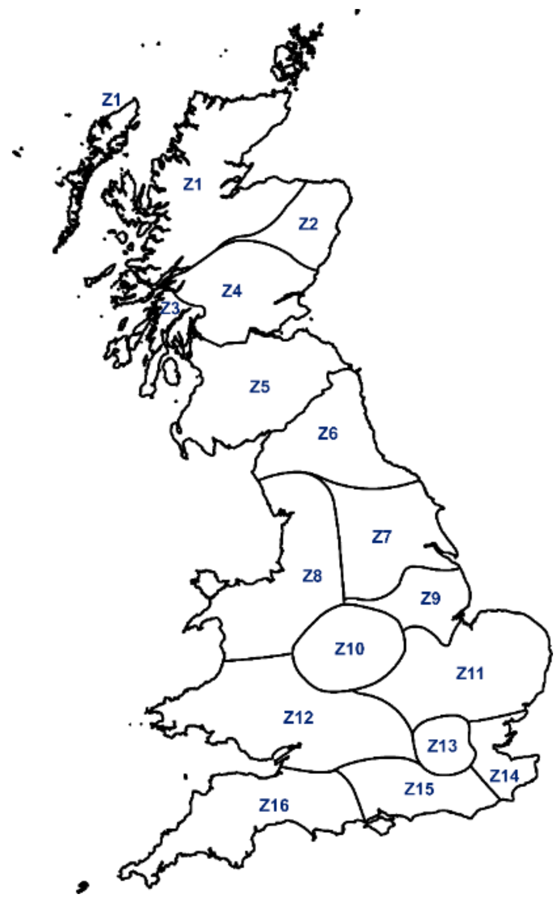
Without storage: multi-period model
With storage: dynamic model; extra variables for initial inventories; extra constraints to link inventories within and between time levels

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

Imperial College London

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

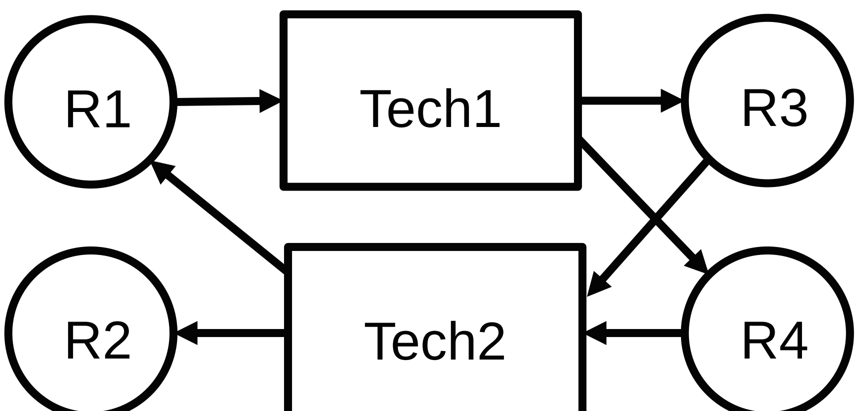


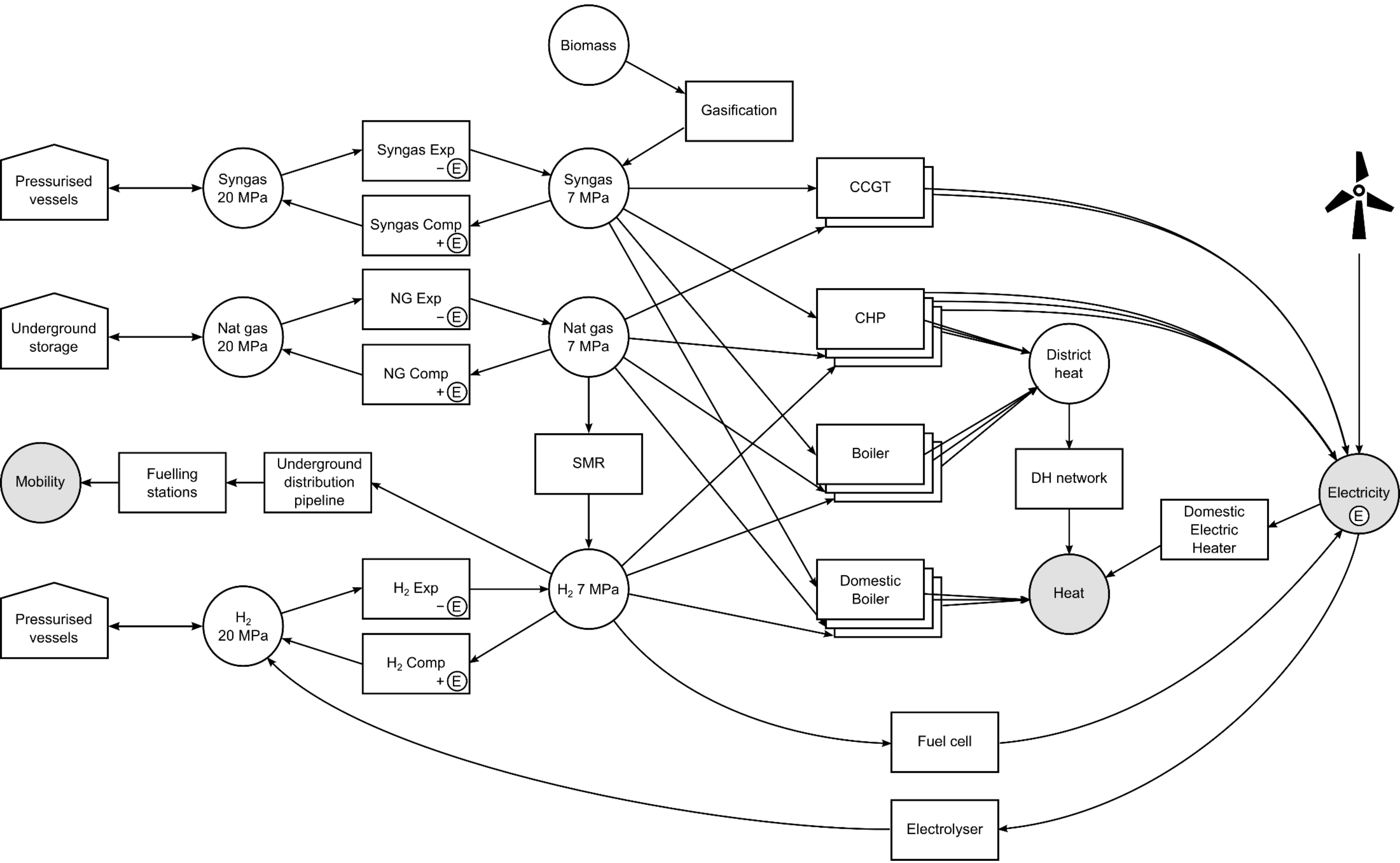
National Grid's SYS study zones

Imperial College London

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.



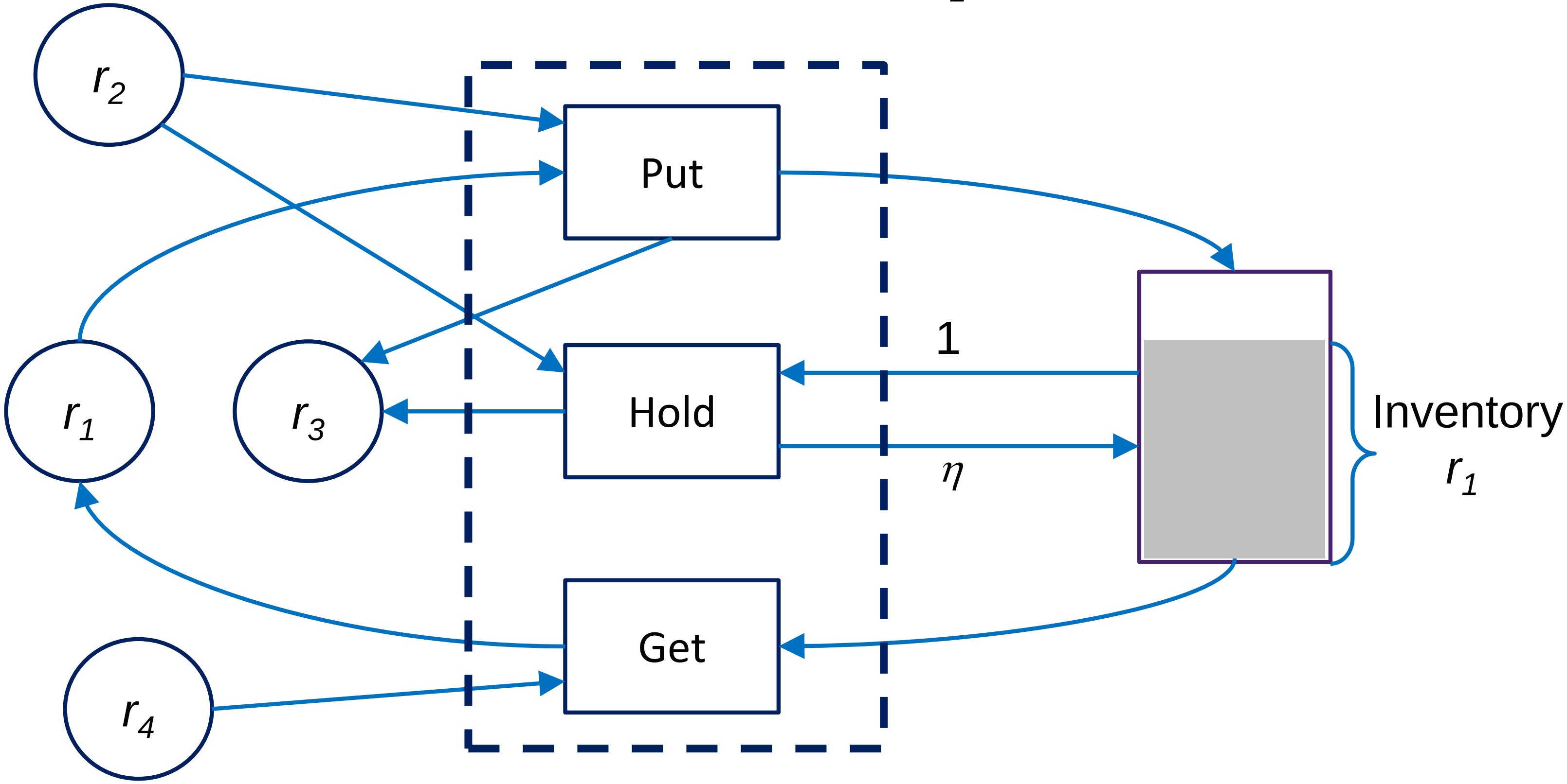


Biomass
Gasification
Pressurised vessels
Syngas 20 MPa
Syngas Exp −E
Syngas Comp +E
Syngas 7 MPa
CCGT
Underground storage
Nat gas 20 MPa
NG Exp −E
NG Comp +E
Nat gas 7 MPa
CHP
District heat
SMR
Boiler
DH network
Mobility
Fuelling stations
Underground distribution pipeline
Electricity E
Domestic Electric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

Imperial College London

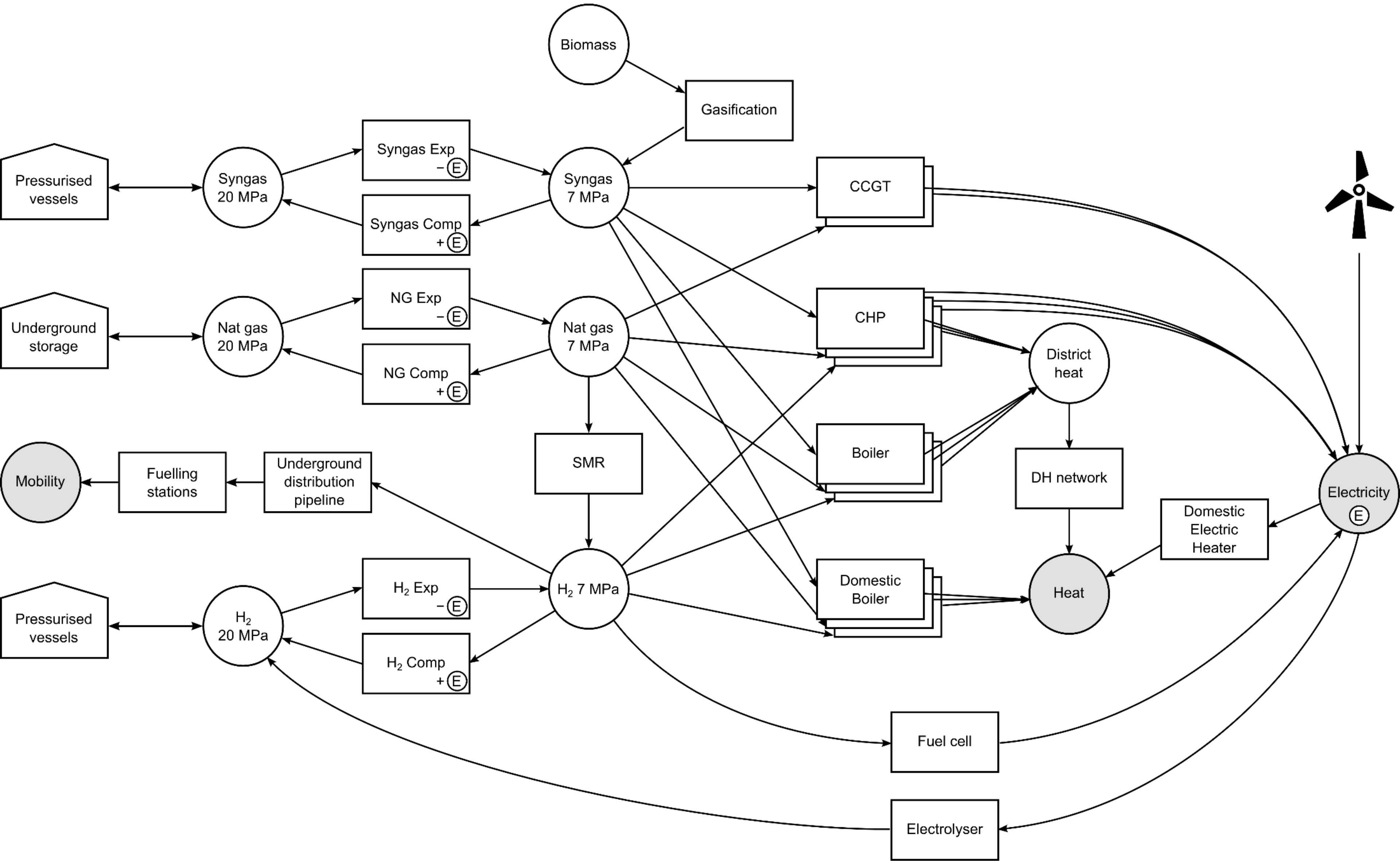
Modelling storage

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.

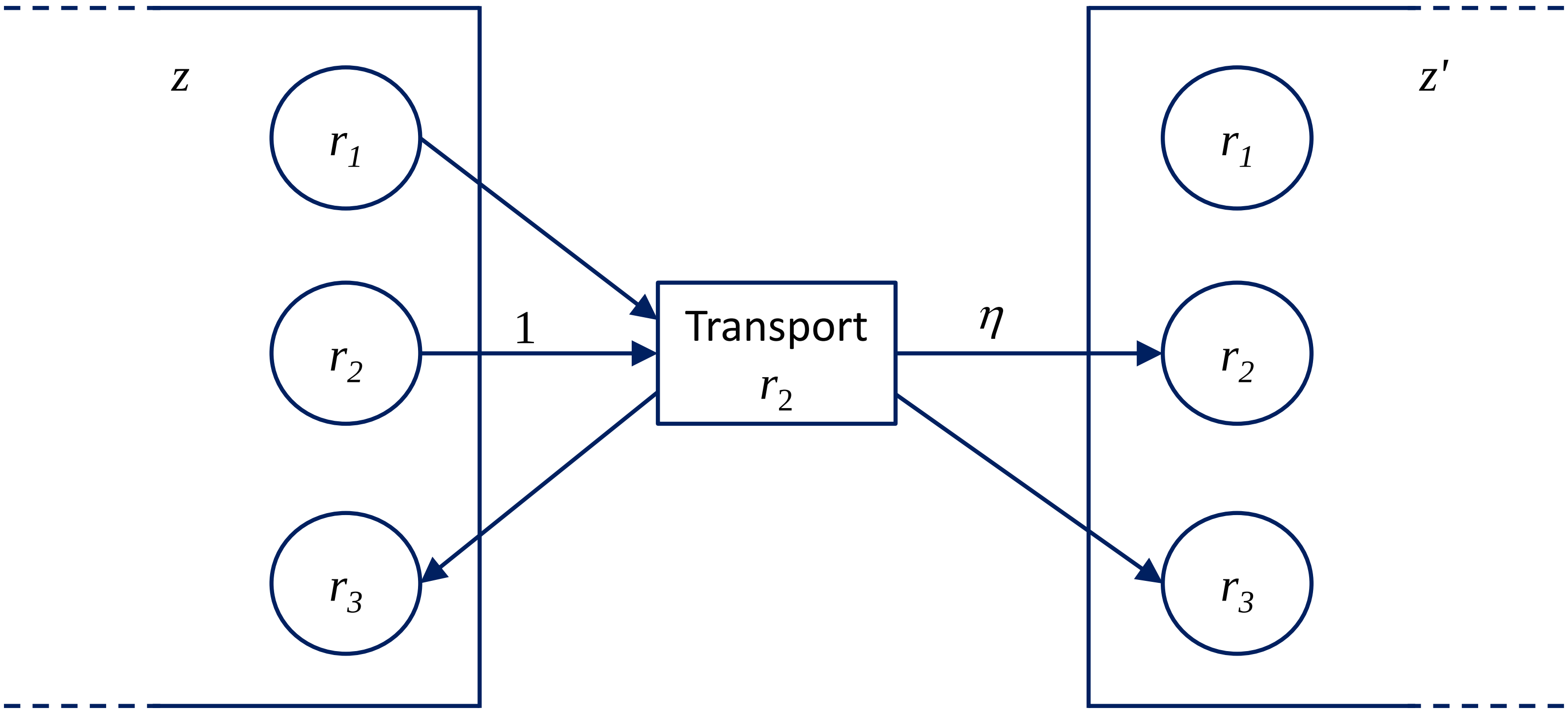
S. Samsatli, N.J. Samsatli (2015). Computers & Chemical Engineering 80, 155-176, 0098-1354.



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
H2 20 MPa
H2 Exp
− E
H2 Comp
+ E
H2 7 MPa
Domestic Boiler
Heat
Fuel cell
Electrolyser

Imperial College London

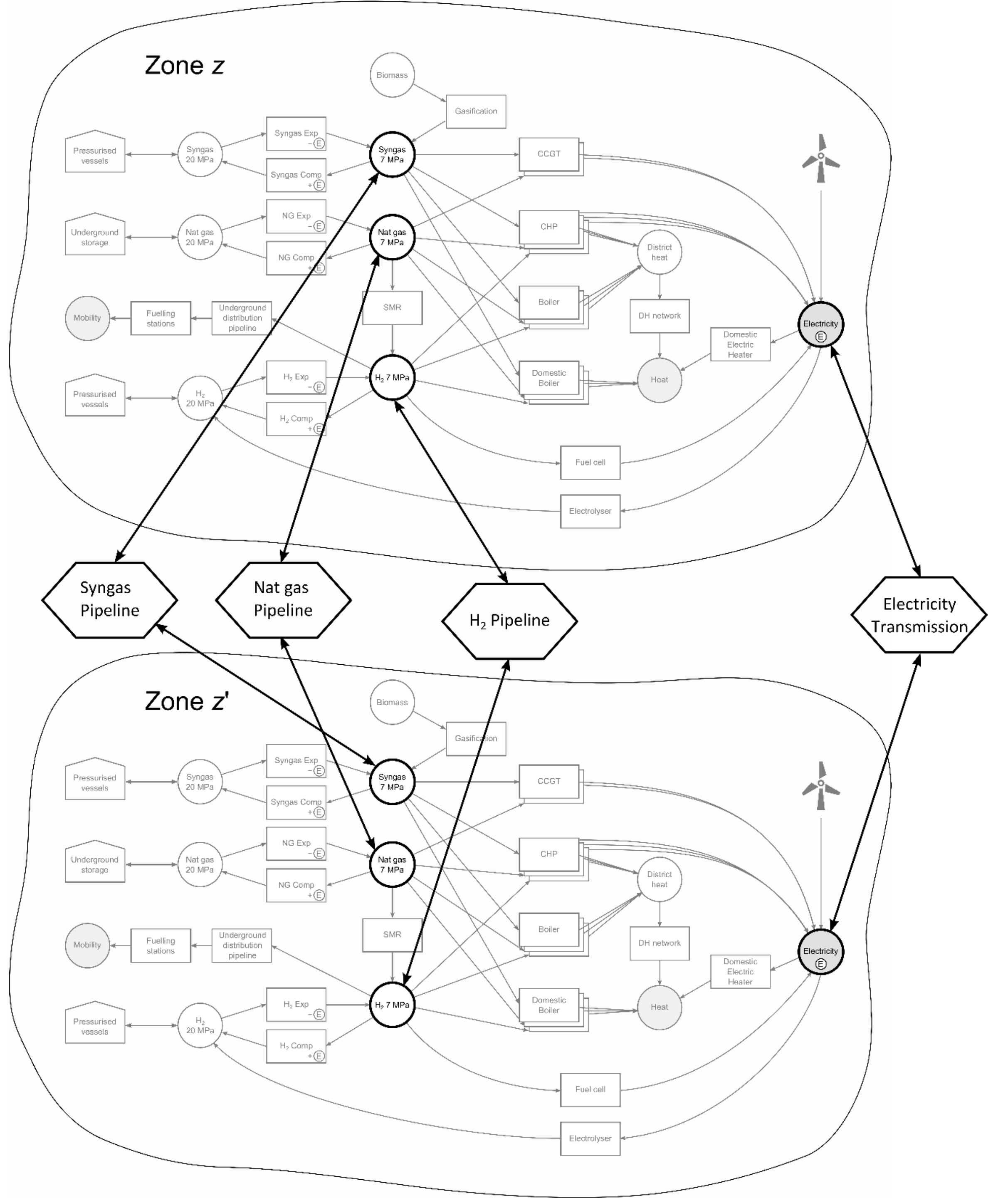
Modelling transport



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)

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

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

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

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

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

Resource balance and availability

Resource balance:

$$U_{rzhdty} + M_{rzhdty} + P_{rzhdty} + S_{rzhdty} + Q_{rzhdty} \geq D_{rzhdty} + X_{rzhdty}$$

$$\forall r \in \mathbb{R},\ z \in \mathbb{Z},\ h \in \mathbb{H},\ d \in \mathbb{D},\ t \in \mathbb{T},\ y \in \mathbb{Y}$$

Resource utilisation: $U_{rzhdty} \leq u^{\text{max}}_{rzhdty} \qquad \forall r \in \mathbb{R},\ z \in \mathbb{Z},\ h \in \mathbb{H},\ d \in \mathbb{D},\ t \in \mathbb{T},\ y \in \mathbb{Y}$

Wind power potential: $u^{\text{max}}_{\text{Elec},zhdt} = 0.5 \times 10^{-6} \eta \rho^{\text{air}} \pi N^{\text{WT}}_{zy} \left(R^{\text{WT}}\right)^2 v^3_{zhdty}$

Biomass potential: $\sum_{hd} U_{\text{Bio},zhdty} n^{\text{hd}}_h n^{\text{dw}}_d n^{\text{wt}}_t \leq A^{\text{Bio}}_{zy} Y^{\text{Bio}}_{zty} \qquad \forall z \in \mathbb{Z},\ t \in \mathbb{T},\ y \in \mathbb{Y}$

Land footprint constraints:

Wind turbines: $\pi \left(5R^{\text{WT}}\right)^2 N^{\text{WT}}_{zy} \leq A^{\text{WT,max}}_{zy} \qquad \forall z \in \mathbb{Z},\ y \in \mathbb{Y}$

Biomass (each zone): $A^{\text{Bio}}_{zy} \leq f_{zy} A^{\text{Bio,max}}_{zy} \qquad \forall z \in \mathbb{Z},\ y \in \mathbb{Y}$

Biomass (GB): $\sum_{z} A^{\text{Bio}}_{zy} \leq f^{\text{GB}}_y \sum_{z} A^{\text{Bio,max}}_{zy} \qquad \forall y \in \mathbb{Y}$

Constraints for conversion technologies

Net production of resource r : $$P_{rzhdty} = \sum_{p} \mathscr{P}_{pzhdty}\alpha_{rpy}$$

Min/max rate of operation $$N^{\mathrm{P}}_{pzy}p^{\mathrm{min}}_{p} \leq \mathscr{P}_{pzhdty} \leq N^{\mathrm{P}}_{pzy}p^{\mathrm{max}}_{p}$$

Technology balance: $$N^{P}_{pzy} = N^{P}_{pz,y-1} + NI^{P}_{pzy} - NR^{P}_{pzy}$$

Retirements: $$NR^{\mathrm{P}}_{pzy} = \sum_{y'} RF^{P}_{py'y}NI^{P}_{pzy'}$$

Max build rate: $$\sum_{z} NI^{\mathrm{P}}_{pzy} \leq BR_{py}$$

- Number of domestic technologies is continuous instead of integers for computational efficiency (i.e. fraction of penetration)

Constraints for transport technologies

Net transport of resource r:

$$Q_{rzhdty} = \sum_{z'|\nu_{z'z}=1} \sum_{l\in\mathbb{L}} \left[\left(\bar{\tau}_{lr,\text{dst},y} + \hat{\tau}_{lr,\text{dst},y} d_{z'z}\right) \mathcal{Q}_{lz'zhdty}\right] + \sum_{z'|\nu_{zz'}=1} \sum_{l\in\mathbb{L}} \left[\left(\bar{\tau}_{lr,\text{src},y} + \hat{\tau}_{lr,\text{src},y} d_{zz'}\right) \mathcal{Q}_{lzz'hdty}\right]$$

Max rate of operation: $\mathcal{Q}_{lzz'hdty} \leq \sum_{b\in\mathbb{B}} q_l^{\max} N^{\text{B}}_{bzz'y} \big|_{LB_{lb}=1 \wedge \nu_{zz'}=1}$

Max infrastructure capacity: $\sum_{l\in\mathbb{L}} \mathcal{Q}_{lzz'hdty} LB_{lb} \leq b_b^{\max} N^{\text{B}}_{bzz'y}$

Infrastructure balance: $N^{\text{B}}_{bzz'y} = N^{B}_{bzz',y-1} + NI^{\text{B}}_{bzz'y}$

Bi-directional links:

$$N^{\text{B}}_{bzz'y} = N^{\text{B}}_{bz'zy} \qquad \forall b \in \mathbb{B} | \beta_b = 1,\ z \neq z' \in \mathbb{Z}$$

Constraints for storage technologies

Max charging and discharging rates:

$$\mathscr{S}^{\text{put}}_{szhdty} \leq N^{\text{S}}_{szy} s^{\text{put,max}}_{s} a_{sz}$$

$$\mathscr{S}^{\text{get}}_{szhdty} \leq N^{\text{S}}_{szy} s^{\text{get,max}}_{s} a_{sz}$$

Net inflow of resource r due to storage operations:

$$S_{rzhdty} = \sum_{s} \left(\mathscr{S}^{\text{put}}_{szhdty} \sigma^{\text{put}}_{sr,\text{src},y} + \mathscr{S}^{\text{hold}}_{szhdty} \sigma^{\text{hold}}_{sr,\text{dst},y} + \mathscr{S}^{\text{get}}_{szhdty} \sigma^{\text{get}}_{sr,\text{dst},y} \right)$$

Inventory levels:

$$I_{szhdty} = n^{\text{hd}}_{h} \sum_{r} \left(\mathscr{S}^{\text{put}}_{szhdty} \sigma^{\text{put}}_{sr,\text{dst},y} + \mathscr{S}^{\text{hold}}_{szhdty} \sigma^{\text{hold}}_{sr,\text{src},y} + \mathscr{S}^{\text{get}}_{szhdty} \sigma^{\text{get}}_{sr,\text{src},y} \right)$$

Changes in inventory:

Daily: $\delta^{\text{d}}_{szdty} = I_{sz,|\mathbb{H}|,dty} - I^{0,\text{sim}}_{szdty}$

Weekly: $\delta^{\text{t}}_{szty} = \sum_{d} \delta^{\text{d}}_{szdty} n^{\text{dw}}_{d}$

Yearly: $\delta^{\text{y}}_{szy} = \sum_{t} \delta^{\text{t}}_{szty} n^{\text{wt}}_{t}$

Cyclic constraint: $\delta^{\text{y}}_{szy} = 0$

Constraints for storage technologies (cont…)

Link inventories between different time levels:

$$I^{0,\mathrm{act}}_{szdty} = I^{0,\mathrm{act}}_{sz,d-1,ty} + n^{\mathrm{dw}}_{d-1}\delta^{\mathrm{d}}_{sz,d-1,ty}$$

$$I^{0,\mathrm{act}}_{sz,1,ty} = I^{0,\mathrm{act}}_{sz,1,t-1,y} + n^{\mathrm{wt}}_{t-1}\delta^{\mathrm{t}}_{sz,t-1,y}$$

$$I^{0,\mathrm{act}}_{sz,1,1,y} = I^{0,\mathrm{act}}_{sz,1,1,y-1} + n^{\mathrm{yy}}_{y-1}\delta^{\mathrm{y}}_{sz,y-1}$$

Shift inventory levels to match average:

$$I^{0,\mathrm{sim}}_{szdty} = I^{0,\mathrm{act}}_{szdty} + \left[\left(n^{\mathrm{dw}}_{d} - 1\right)\delta^{\mathrm{d}}_{szdty} + \left(n^{\mathrm{wt}}_{t} - 1\right)\delta^{\mathrm{t}}_{szty} + \left(n^{\mathrm{yy}}_{y} - 1\right)\delta^{\mathrm{y}}_{szy}\right]/2$$

$$\mathscr{S}^{\mathrm{hold}}_{sz,1,dty} = I^{0,\mathrm{sim}}_{szdty}/n^{\mathrm{hd}}_{1} \qquad \mathscr{S}^{\mathrm{hold}}_{szhdty} = I_{sz,h-1,dty}/n^{\mathrm{hd}}_{h}$$

Storage capacity constraints:

$$s^{\mathrm{hold,min}}_{s} N^{S}_{szy} a_{sz} \le I_{szhdty} \pm \left[\left(n^{\mathrm{dw}}_{d} - 1\right)\delta^{\mathrm{d}}_{szdty} \pm \left(n^{\mathrm{wt}}_{t} - 1\right)\delta^{\mathrm{t}}_{szty} \pm \left(n^{\mathrm{yy}}_{y} - 1\right)\delta^{\mathrm{y}}_{szy}\right]/2 \le s^{\mathrm{hold,max}}_{s} N^{S}_{szy} a_{sz}$$

Objective function

$$\text{Minimise } Z = \sum_{iy} \omega_i \Big(\mathscr{I}^{\mathrm{W}}_{iy} + \mathscr{I}^{\mathrm{P}}_{iy} + \mathscr{I}^{\mathrm{Q}}_{iy} + \mathscr{I}^{\mathrm{S}}_{iy} + \mathscr{I}^{\mathrm{w}}_{iy} + \mathscr{I}^{\mathrm{p}}_{iy} + \mathscr{I}^{\mathrm{q}}_{iy} + \mathscr{I}^{\mathrm{s}}_{iy} + \mathscr{I}^{\mathrm{r}}_{iy} + \mathscr{I}^{\mathrm{m}}_{iy} + \mathscr{I}^{\mathrm{x}}_{iy} - \mathscr{I}^{\mathrm{Rev}}_{iy} \Big)$$

Impacts $\forall i \in \mathbb{I},\, y \in \mathbb{Y}$

	Capital	O&M
Wind turbines	$\mathscr{I}^{\mathrm{W}}_{iy} = \varsigma \sum_{z} D^{\mathrm{C}}_{y} C^{\mathrm{WT}}_{iy} NI^{\mathrm{WT}}_{zy}$	$\mathscr{I}^{\mathrm{w}}_{iy} = \varsigma \sum_{z} D^{\mathrm{OM}}_{y} F^{\mathrm{WT}}_{iy} N^{\mathrm{WT}}_{zy}$
Conversion techs	$\mathscr{I}^{\mathrm{P}}_{iy} = \varsigma \sum_{pz} D^{\mathrm{C}}_{piy} C^{\mathrm{P}}_{piy} NI^{P}_{pzy}$	$\mathscr{I}^{\mathrm{p}}_{iy} = \varsigma \sum_{pz} D^{\mathrm{OM}}_{y} F^{\mathrm{P}}_{piy} N^{P}_{pzy}$
Transport techs	$\mathscr{I}^{\mathrm{Q}}_{iy} = 0.5\varsigma \sum_{bzz'} D^{\mathrm{C}}_{biy} C^{\mathrm{B}}_{biy} NI^{B}_{bzz'y} d_{zz'})$	$\mathscr{I}^{\mathrm{q}}_{iy} = 0.5\varsigma \sum_{bzz'} D^{\mathrm{OM}}_{y} F^{\mathrm{B}}_{biy} N^{B}_{bzz'y} d_{zz'}$
Storage techs	$\mathscr{I}^{\mathrm{S}}_{iy} = \varsigma \sum_{sz} D^{\mathrm{C}}_{siy} C^{\mathrm{S}}_{siy} NI^{S}_{szy}$	$\mathscr{I}^{\mathrm{s}}_{iy} = \varsigma \sum_{sz} D^{\mathrm{OM}}_{y} F^{\mathrm{S}}_{siy} N^{S}_{szy}$

Primary resource production

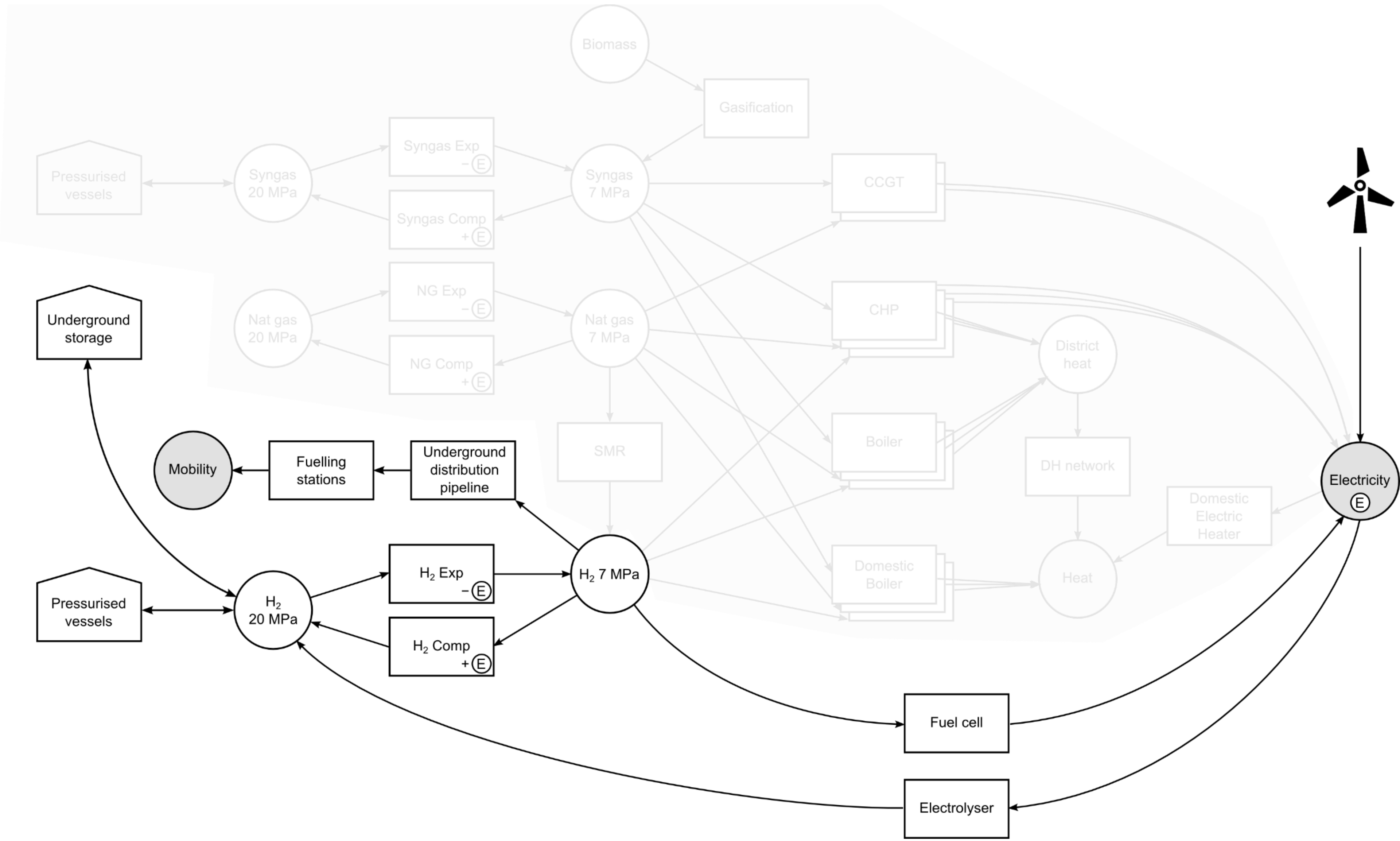
$$\mathscr{I}^{\mathrm{r}}_{iy} = \varsigma \sum_{zhdt} D^{\mathrm{OM}}_{y} \left(RP^{\mathrm{Bio}}_{izty} A^{\mathrm{Bio}}_{zy} Y^{\mathrm{Bio}}_{zty} + \sum_{r \neq \mathrm{Bio}} RP_{rizhdty} U_{rzhdty} n^{\mathrm{hd}}_{h} n^{\mathrm{dw}}_{d} n^{\mathrm{wt}}_{t} n^{\mathrm{yy}}_{y} \right)$$

Export/import

$$\mathscr{I}^{\mathrm{x}}_{iy} = \varsigma \sum_{rzhdt} D^{\mathrm{OM}}_{y} V^{\mathrm{X}}_{riy} X_{rzhdty} n^{\mathrm{hd}}_{h} n^{\mathrm{dw}}_{d} n^{\mathrm{wt}}_{t} \qquad \mathscr{I}^{\mathrm{m}}_{iy} = \varsigma \sum_{rzhdt} D^{\mathrm{OM}}_{y} V^{\mathrm{M}}_{riy} M_{rzhdty} n^{\mathrm{hd}}_{h} n^{\mathrm{dw}}_{d} n^{\mathrm{wt}}_{t}$$

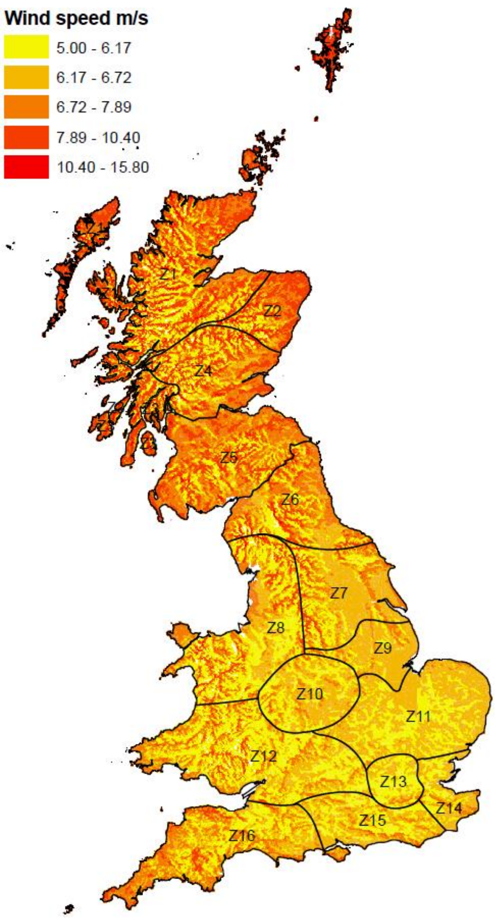
Revenue

$$\mathscr{I}^{\mathrm{Rev}}_{iy} = \varsigma \sum_{rzhdt} D^{\mathrm{OM}}_{y} V^{\mathrm{Rev}}_{riy} D_{rzhdty} n^{\mathrm{hd}}_{h} n^{\mathrm{dw}}_{d} n^{\mathrm{wt}}_{t}$$

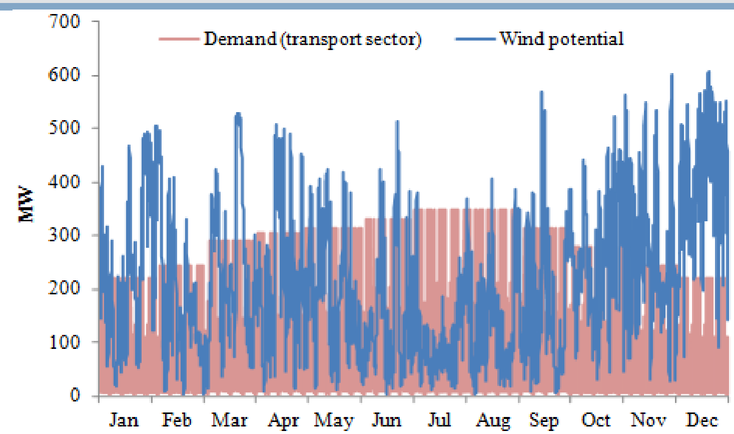


Integrated wind-hydrogen-electricity network to decarbonise the domestic transport sector

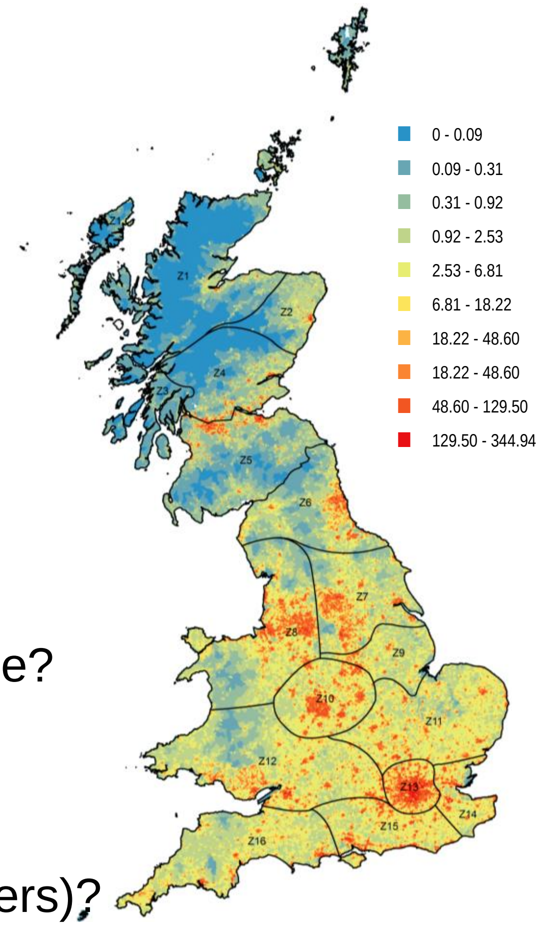
Meeting domestic transport demand using only on-shore wind



Wind availability



How many wind turbines and where?
Electricity or hydrogen?
What will the network look like?
Storage? What and where?
Technologies (fuel cells, electrolysers)?



Demand

S. Samsatli, I. Staffell, N.J. Samsatli (2016). Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain. International Journal of Hydrogen Energy, 41, 447-475.

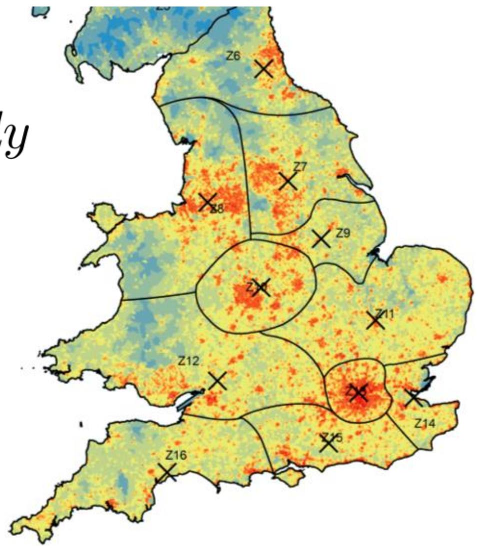
Distribution network

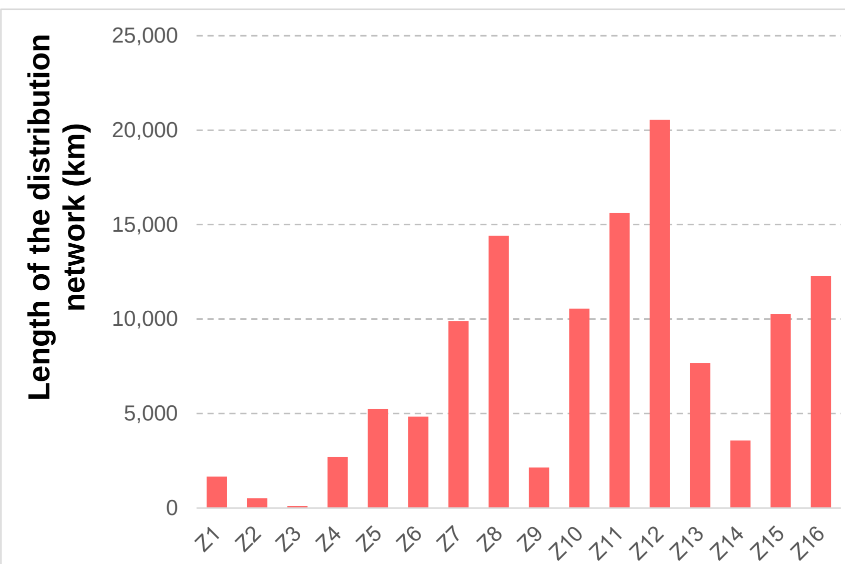
- Length of the distribution pipeline network

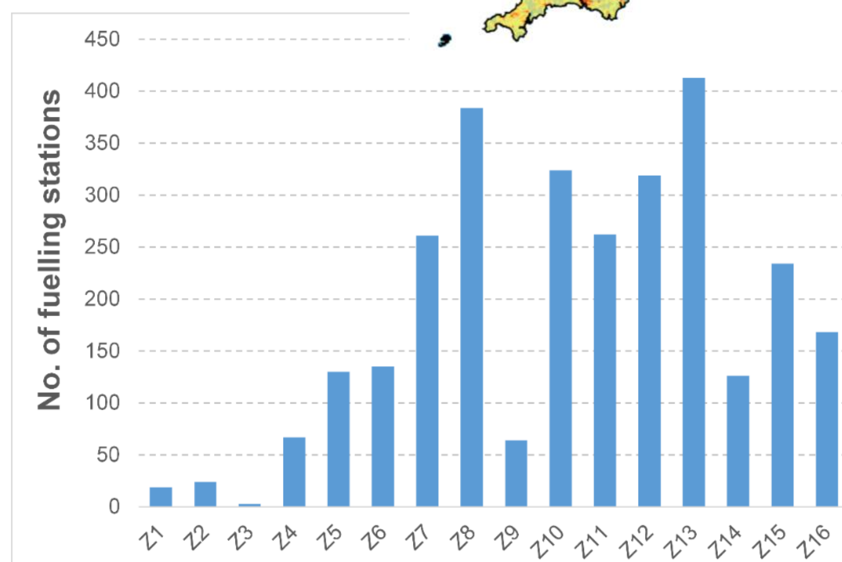
$$L_z^{network} = \iint_{S_z} \frac{D(x,y)}{C} \sqrt{(x-x_z)^2 + (y-y_z)^2} \, dx \, dy$$

- Number of fuelling stations:

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







Imperial College London

Wind turbine siting constraints

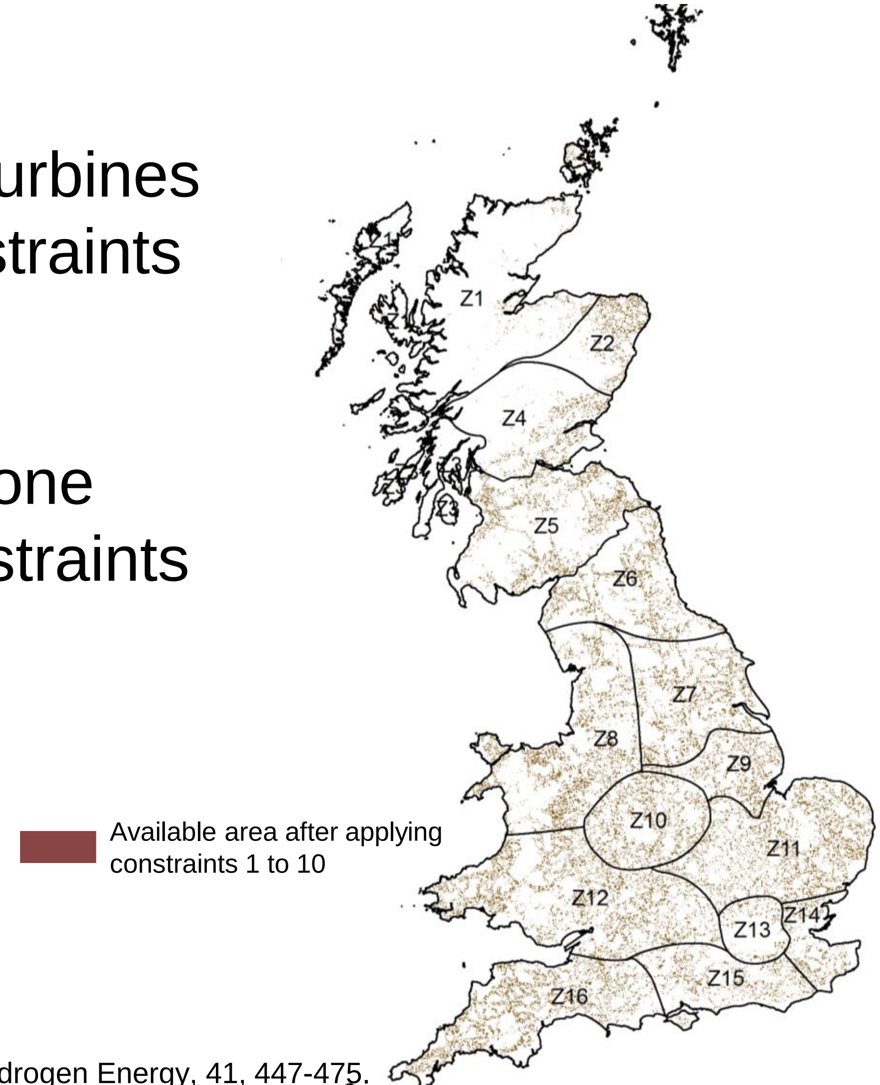
Criteria used to determine the total land area in each zone suitable for siting wind turbines

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



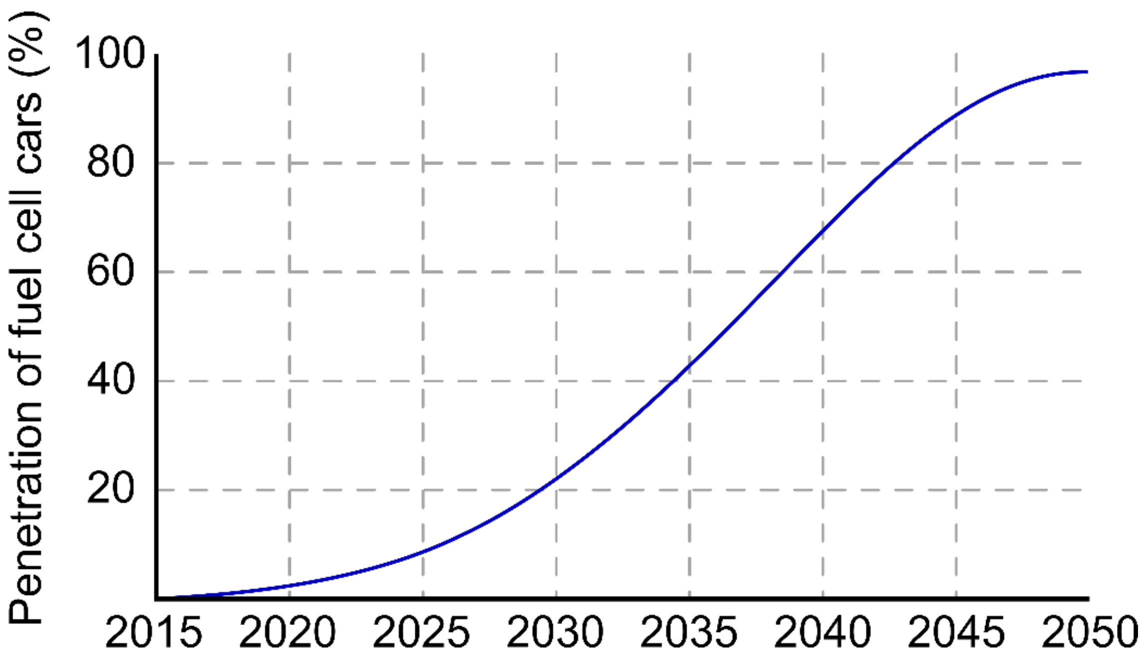
S. Samsatli, I. Staffell, N.J. Samsatli (2016). International Journal of Hydrogen Energy, 41, 447-475.

Imperial College London

Spatio-temporal input data

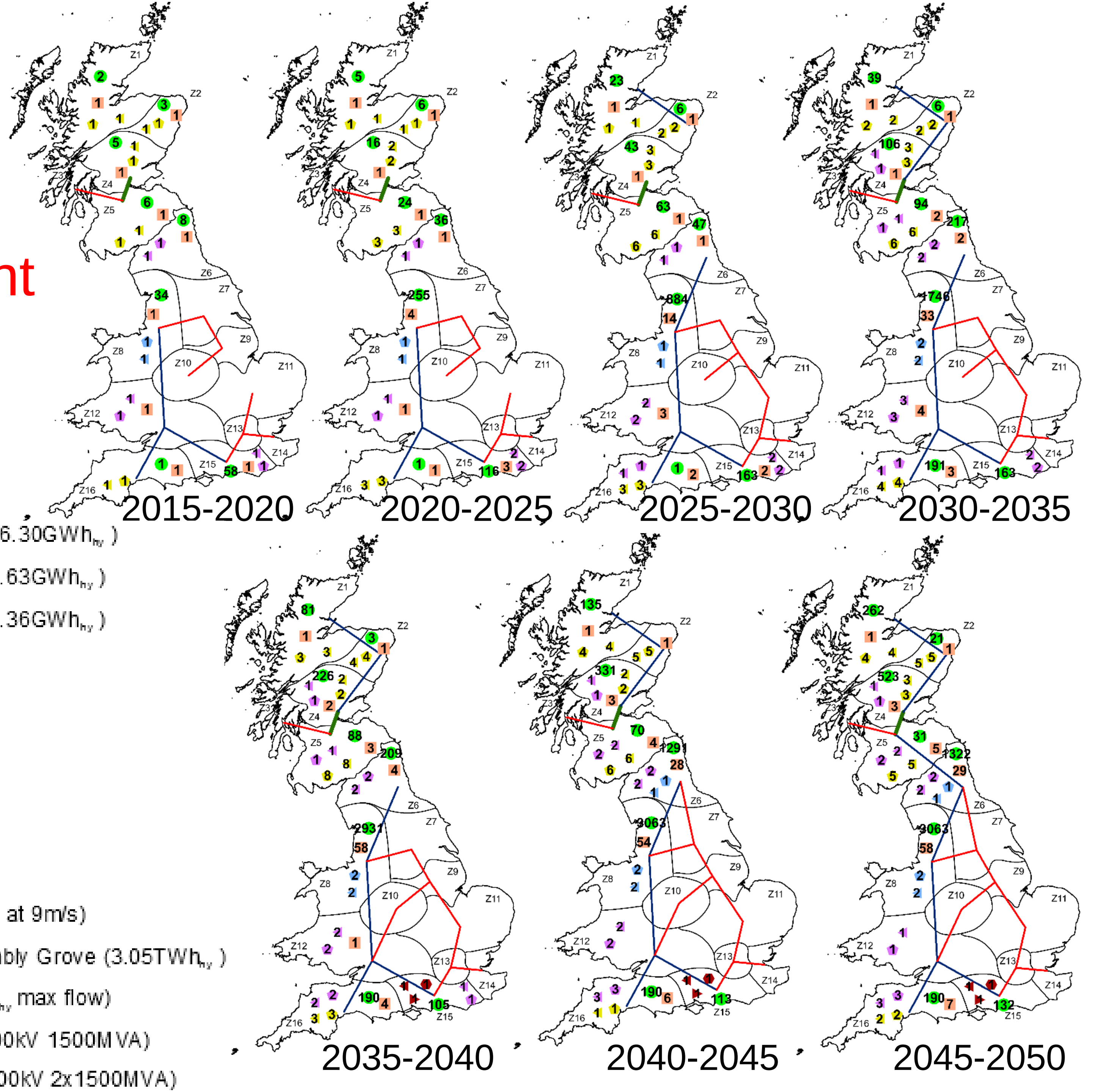
- Hourly time-series wind data obtained from the Virtual Wind Farm Model*
- Future wind speed derived from the UKCP09
- Hourly demand time-series data from DfT data for vehicular usage

- 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.

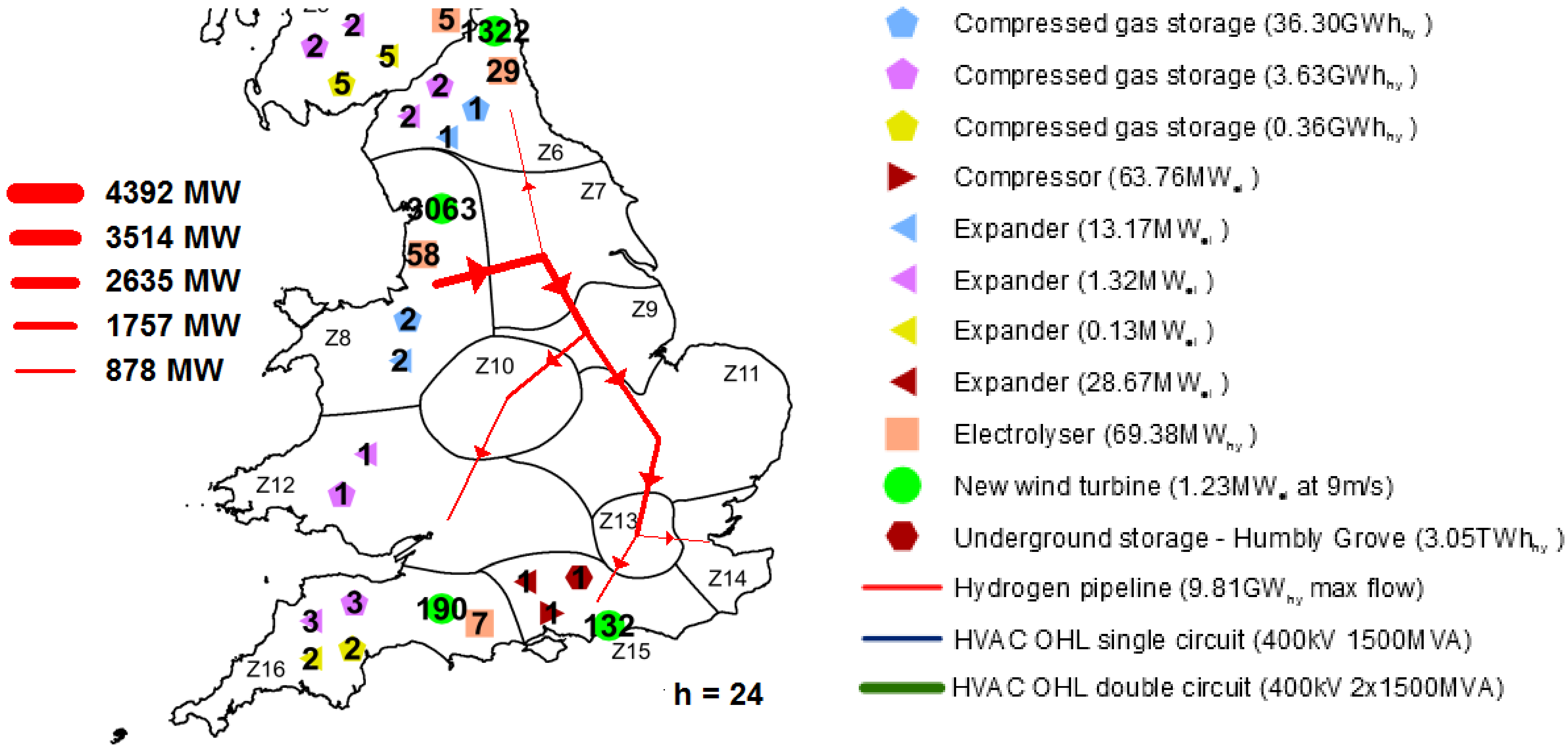
Network configuration for net present cost minimisation



- 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)

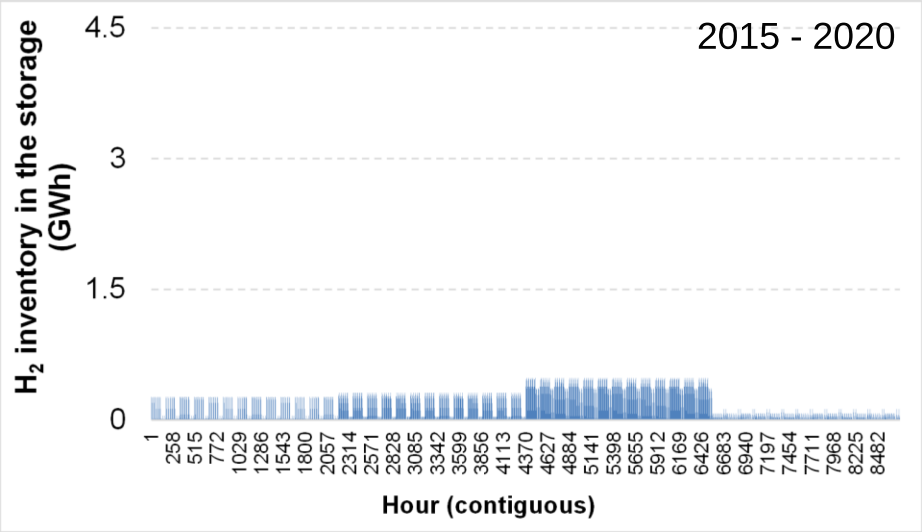
Operation of the hydrogen transmission network

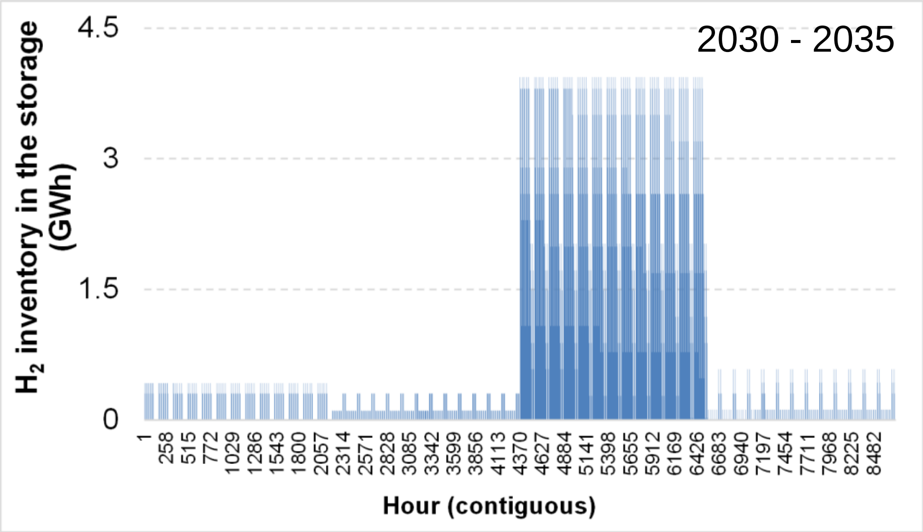
Snapshot during weekdays in summer in 2045-2050



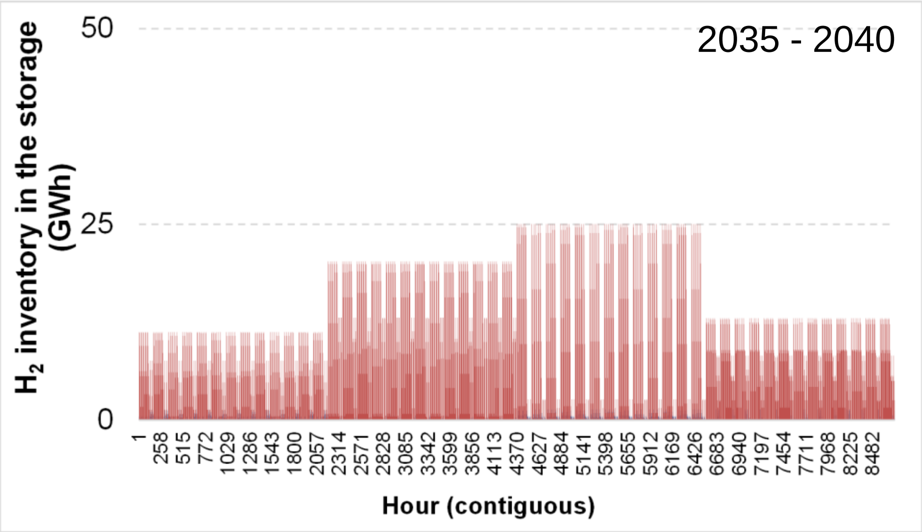
View in slide show mode for the animation

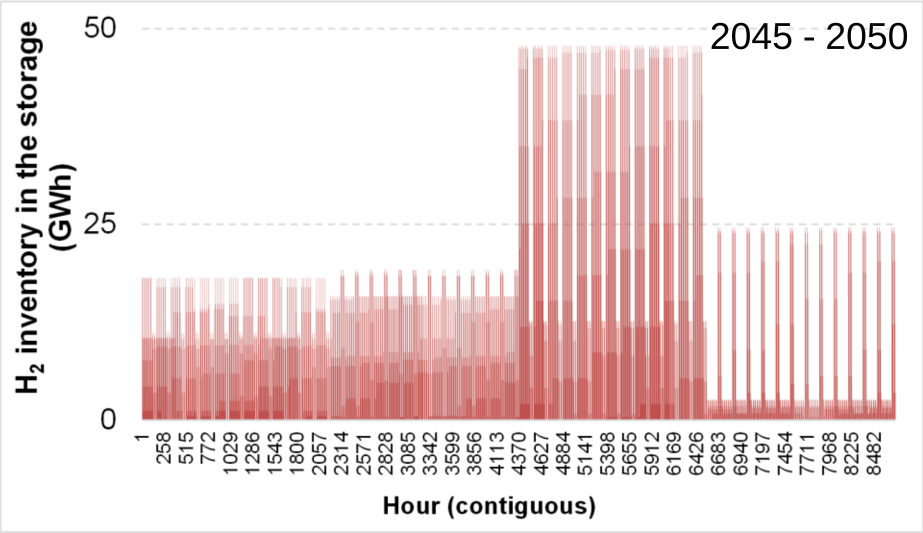
Hourly inventory of hydrogen in zone 15





H_2 gas storage in pressurised vessels from 2015 to 2035





Switching to Humbly Grove underground storage until 2050

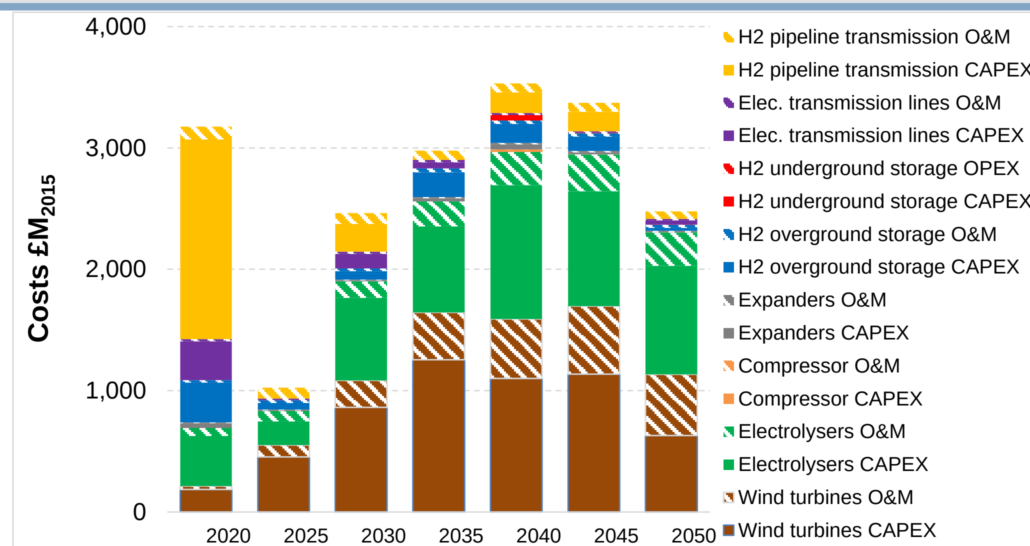
Imperial College London

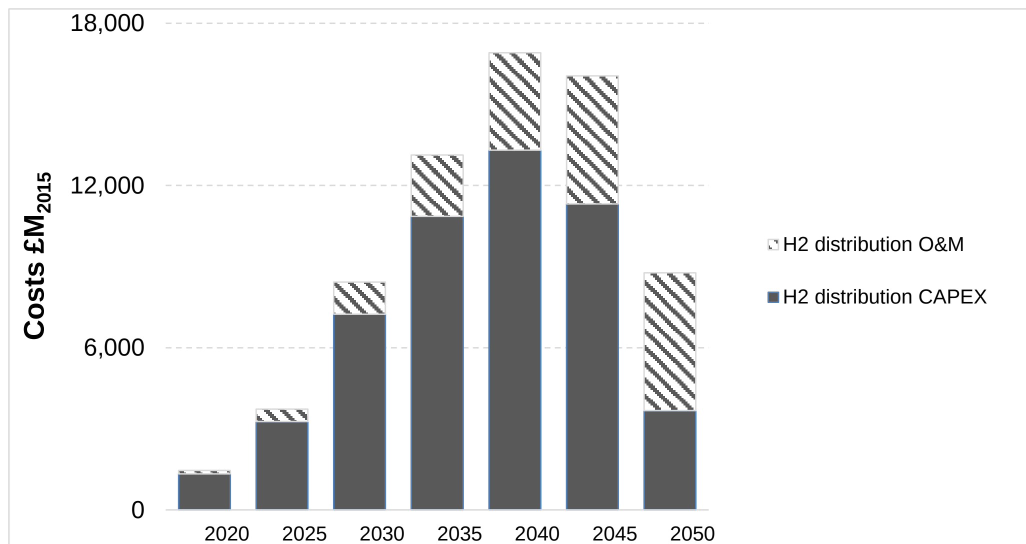
Costs

Net present cost = £87.5 bn

Total avoided CO_2 emissions = 2 bn t

Cost of avoided CO_2: £43.75/t



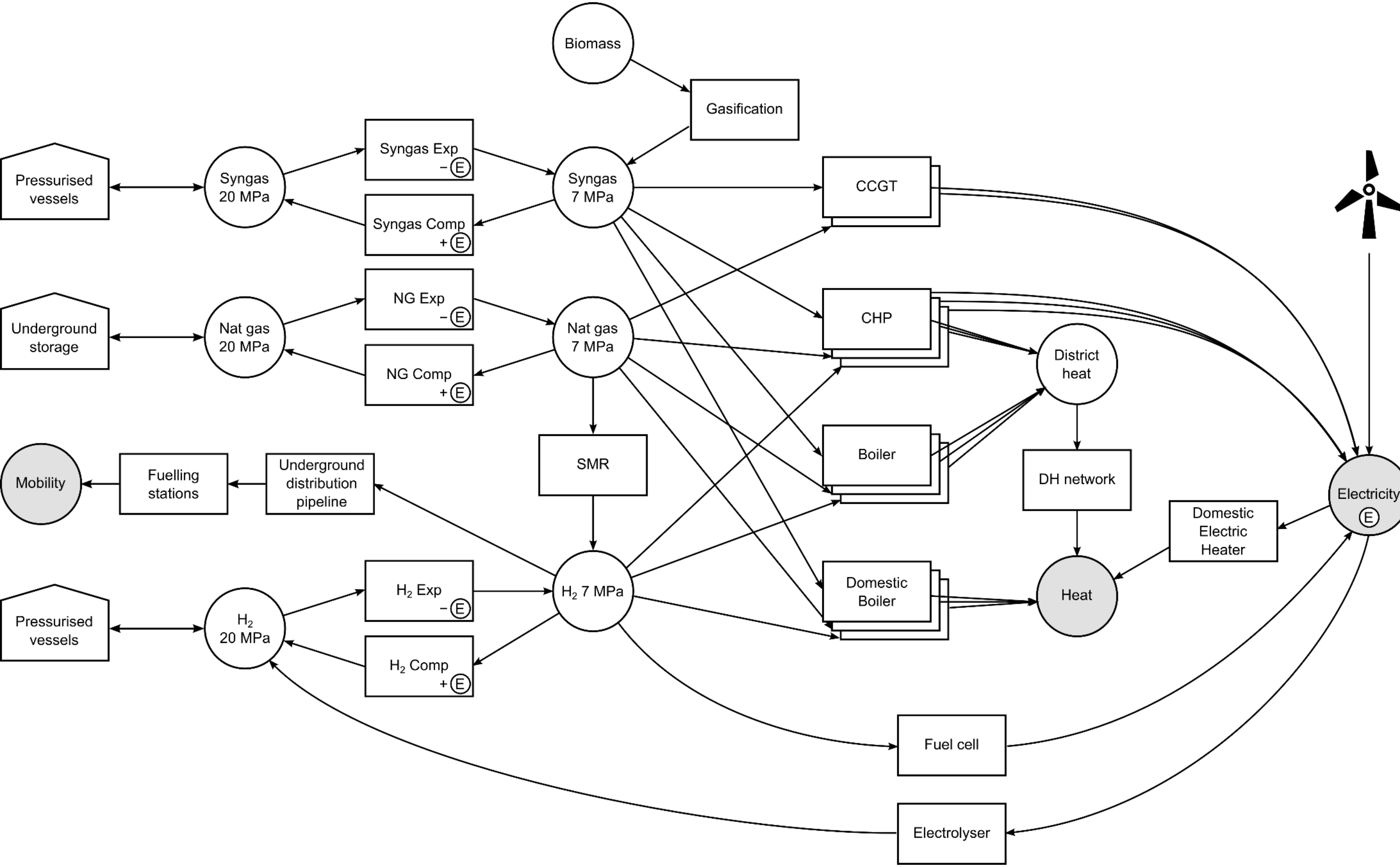


Imperial College London

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

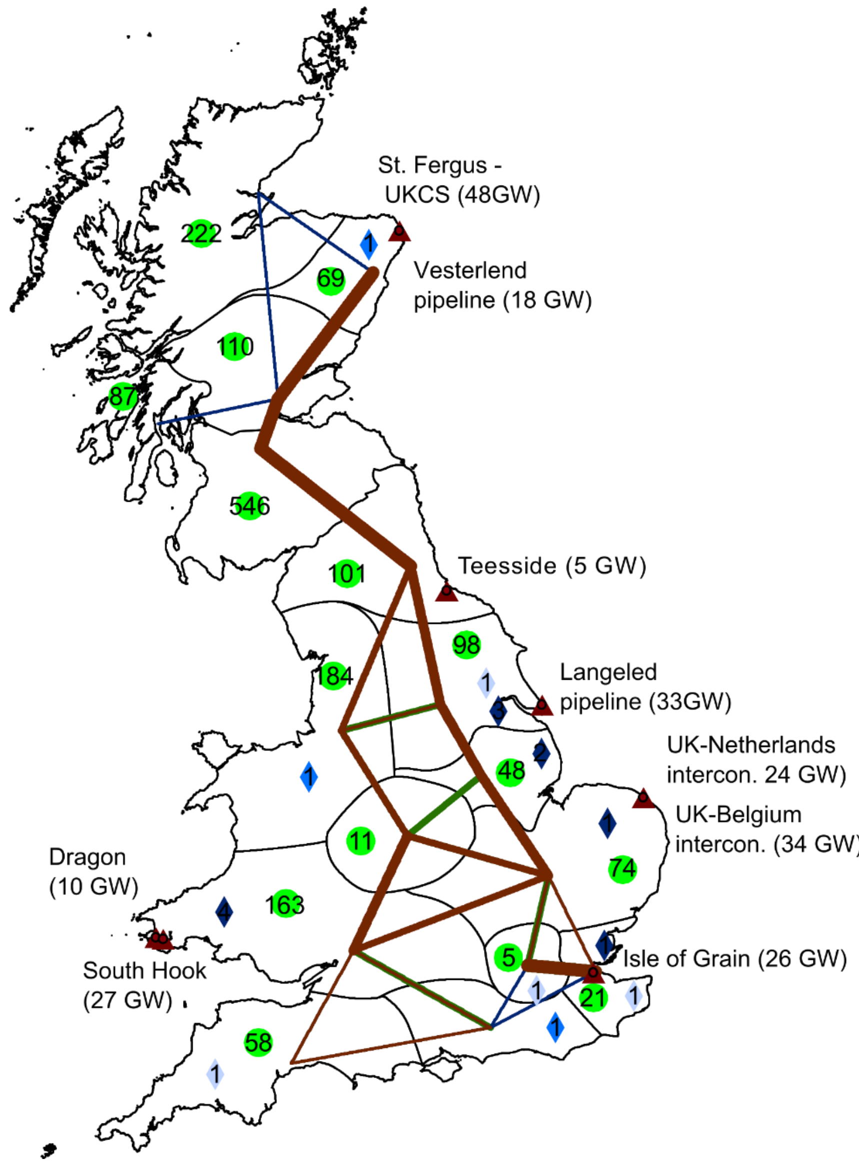
*S. Samsatli and N. Samsatli (2015). A general spatio-temporal model of energy systems with a detailed account of transport and storage. Computers and Chemical Engineering 80, 155-176, 0098-1354.



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

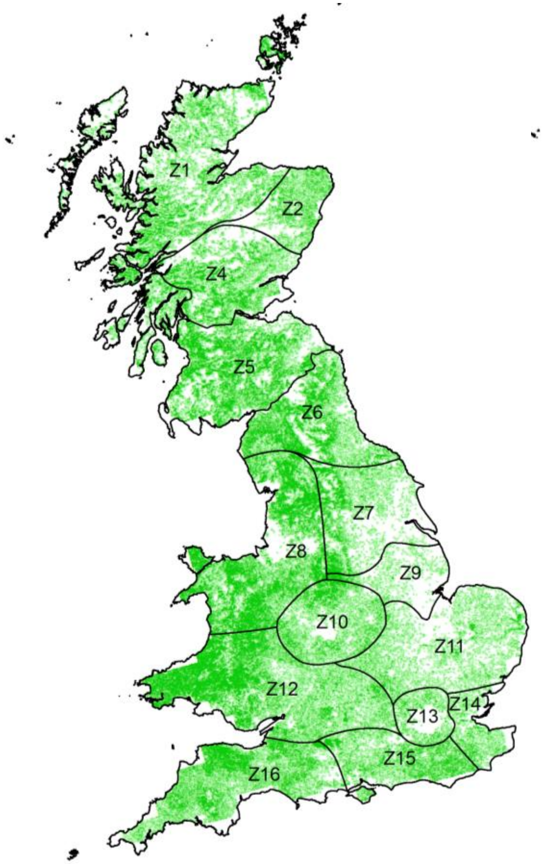


Assumptions:
- Natural gas availability decreases by 2% every year
- Existing wind turbine capacity retires over 15 years (1/3 every 5 years)
- Existing CCGT plants retire 30 years after they were built

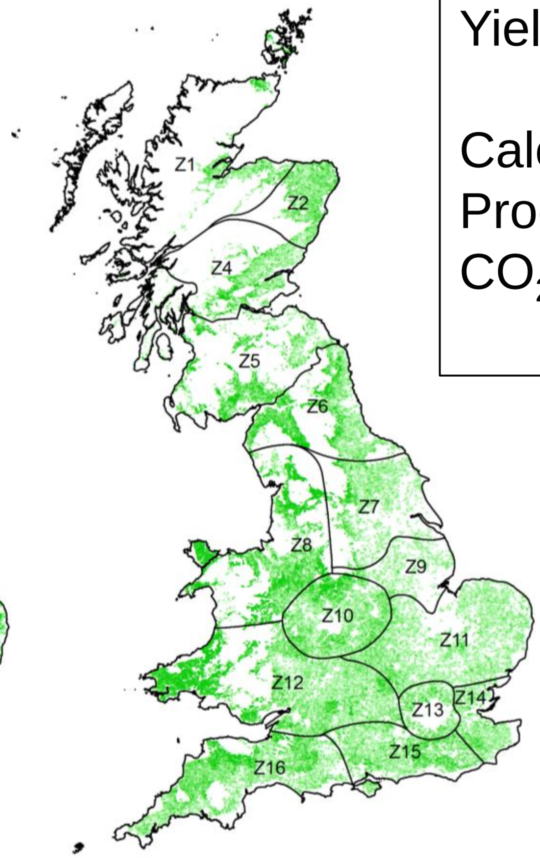
Biomass production

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



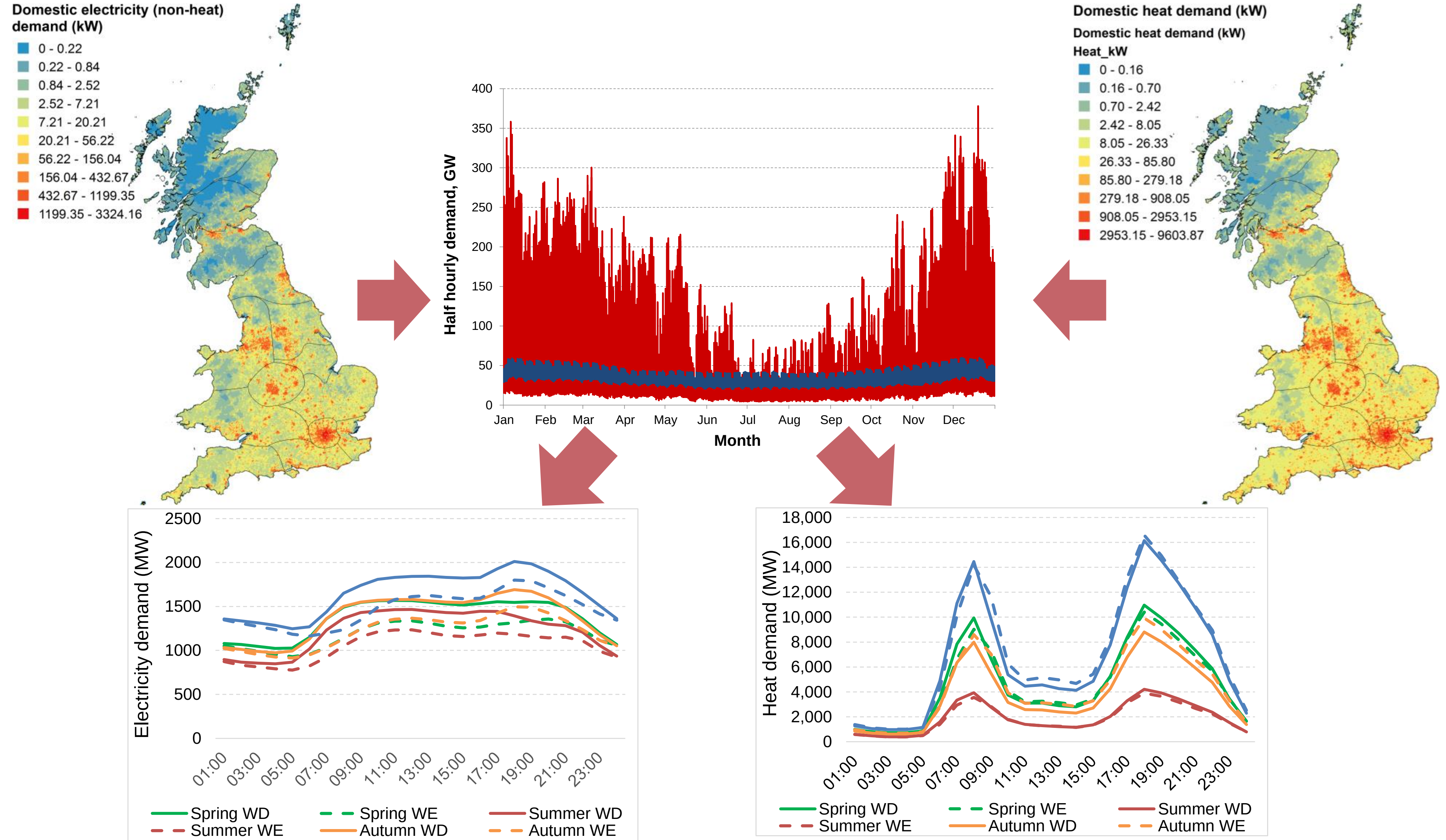
All grassland in GB
32% of GB land area



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 area

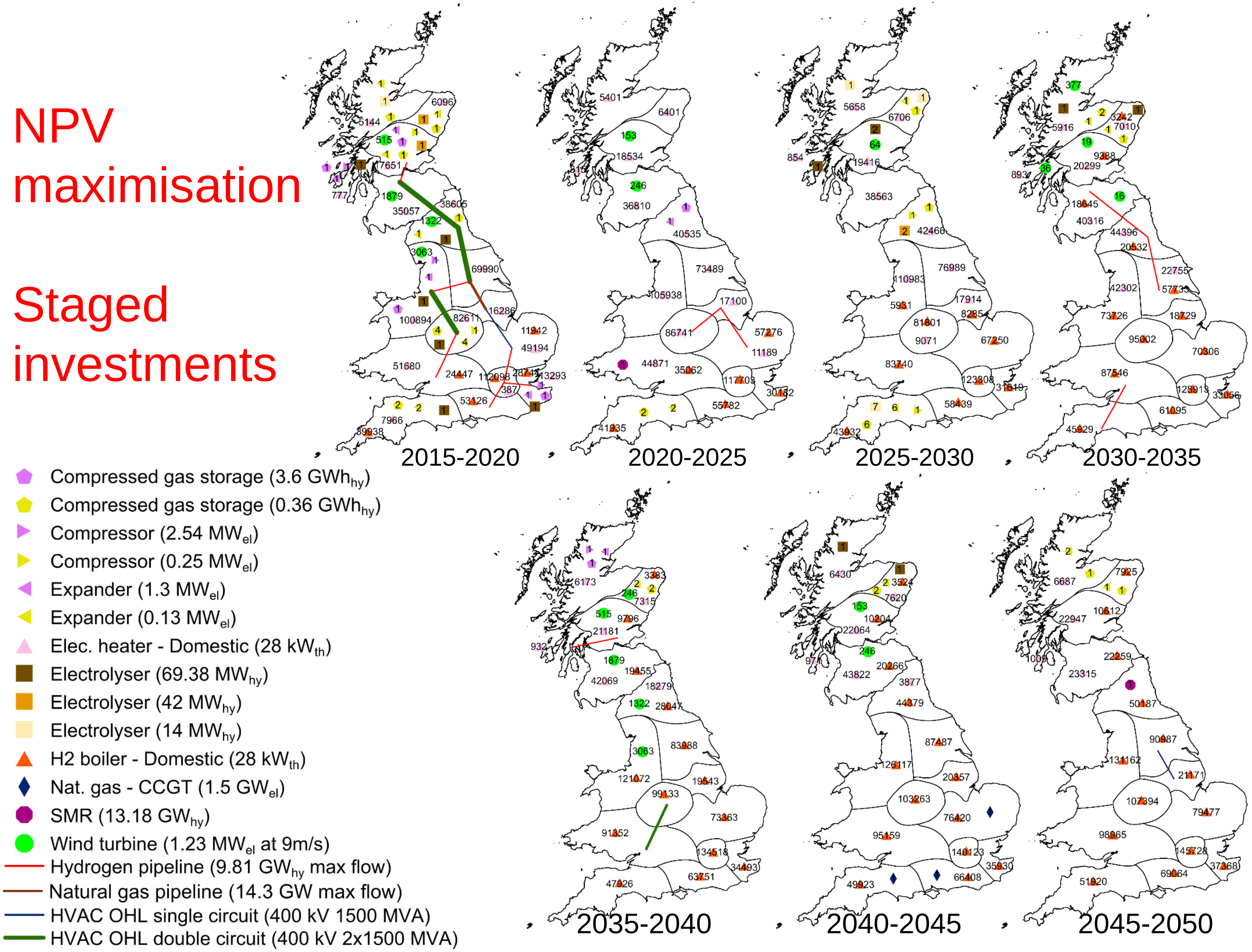
In the case study, further imposed that only 10% of this is available for biomass



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

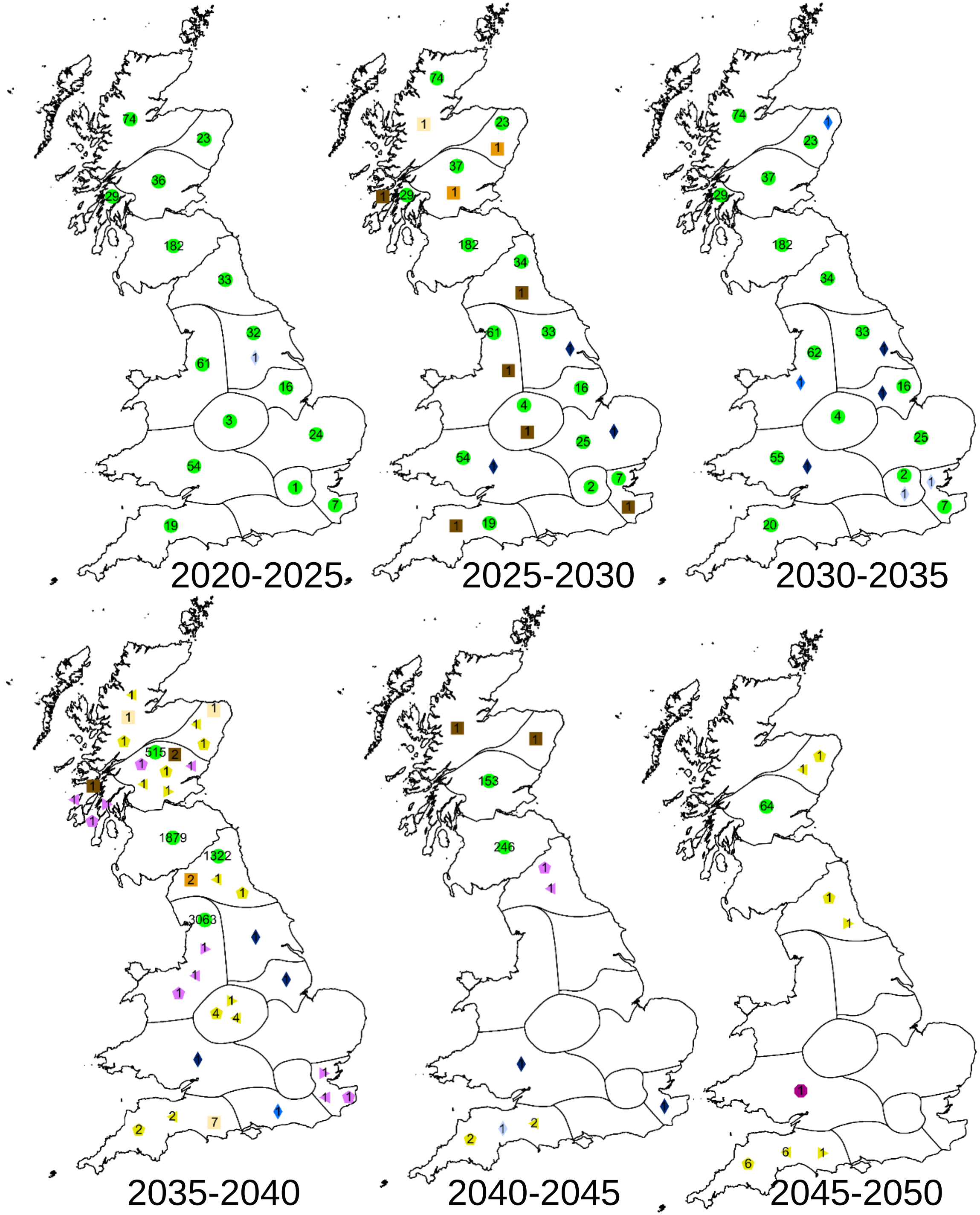
Heat demands in Z13 (similar graphs were derived for the other zones)

- 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)
HVAC OHL double circuit (400 kV 2x1500 MVA)

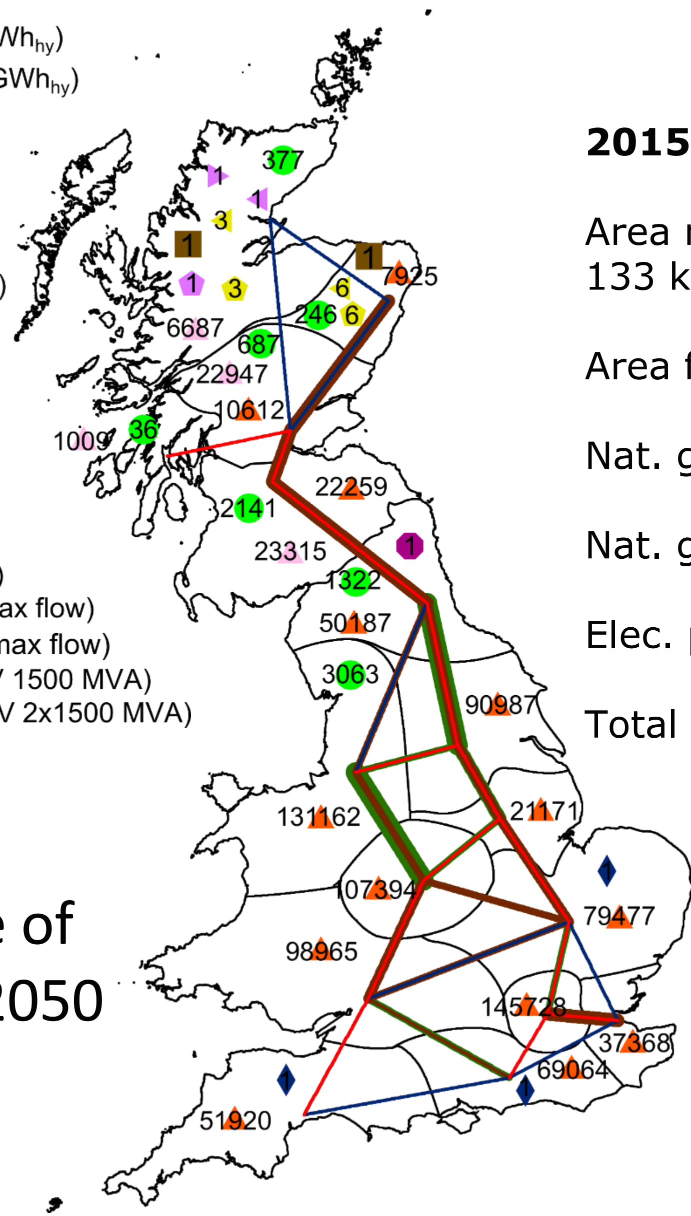
NPV maximisation

Technology retirements



- 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)

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

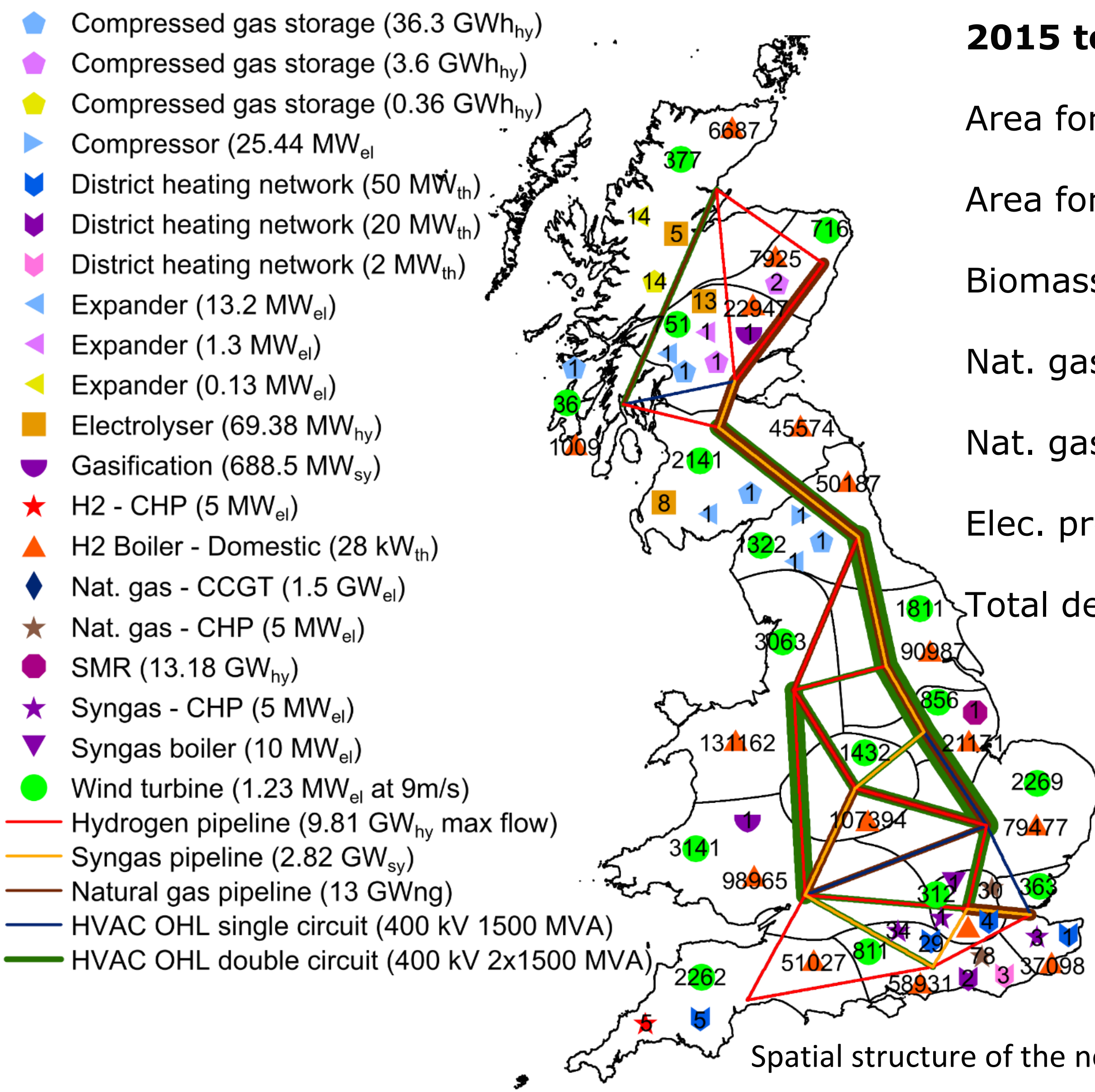
Elec. prod. by wind turbines = 3,536 TWh

Total demands satisfied = 10,083 TWh

NPV = £121 bn

CO_2 Emissions = 2.07 Gt

Minimise CO_2 emissions



Spatial structure of the network in 2050

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

Conclusion

- A spatio-temporal model is needed because primary resource availability and energy service demands are distributed in space and time
- 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

Imperial College London

Work in progress and future work

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