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A general spatio-temporal model of energy systems, STeMES, and its application to integrated wind-hydrogen-electricity networks in Great Britain

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EPSRC
Engineering and Physical Sciences Research Council

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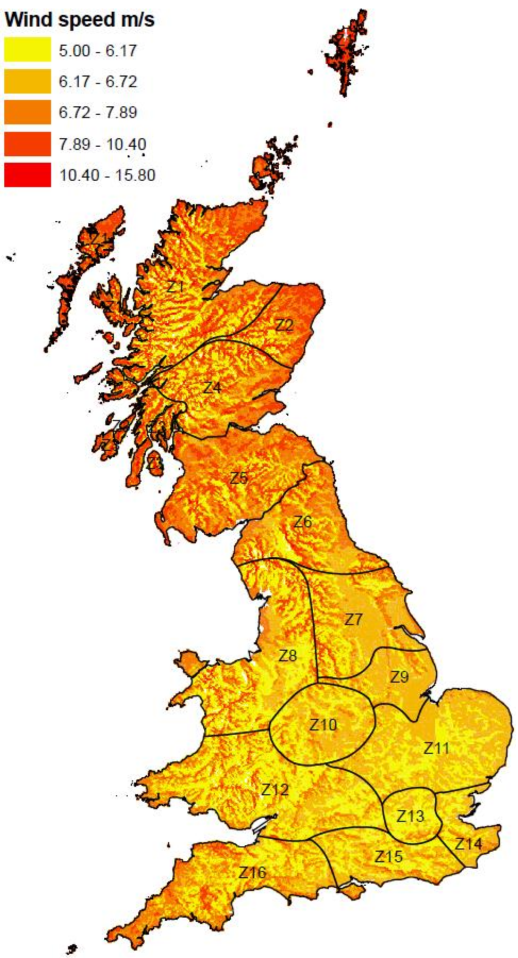
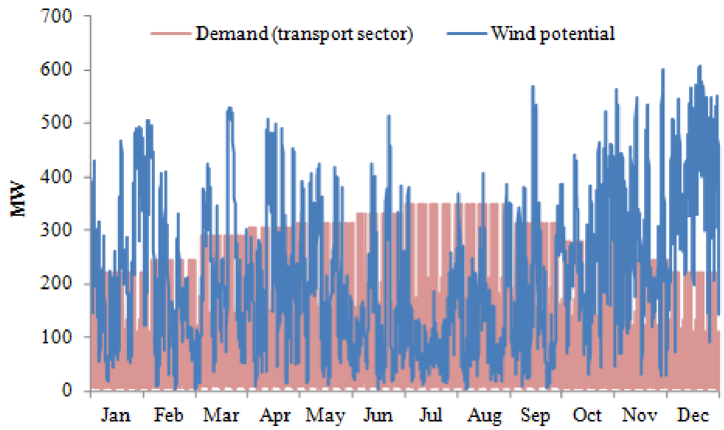
Outline

1. Introduction
2. Integrated wind-electricity-hydrogen networks model
3. Case studies
4. Conclusions

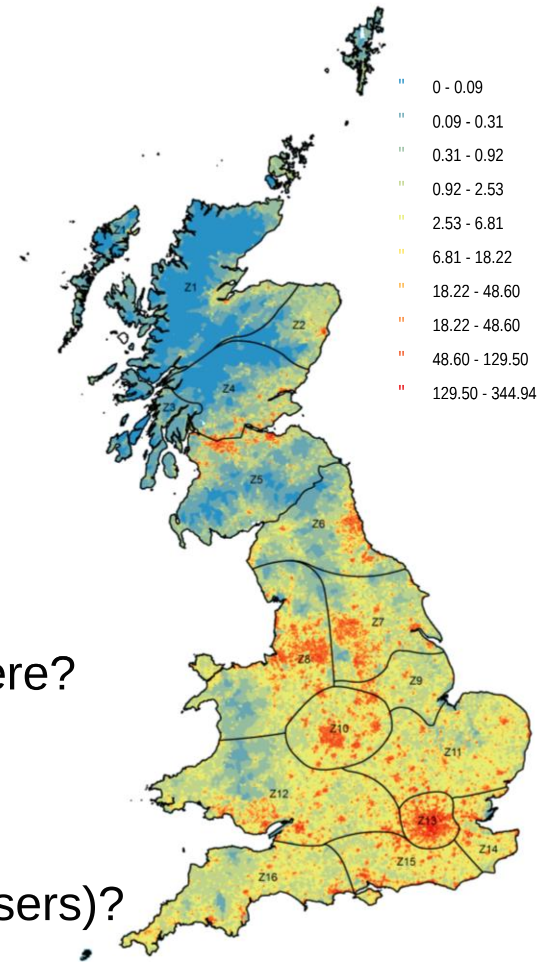
Meeting domestic transport demand using only on-shore wind



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

Integrated wind-hydrogen-electricity networks model

- Modelled in STeMES*, a general model of energy systems
- Mixed Integer Linear Programming (MILP) model
  - Determines the design and operation of the network
- Spatio-temporal model
  - Spatially-distributed (demands, wind availability, location of technologies)
  - Dynamic (demands, wind availability, storage, operation of the network depends on time)
- Network of conversion, storage and transport technologies
- Implemented in AIMMS and solved with CPLEX solver

*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.

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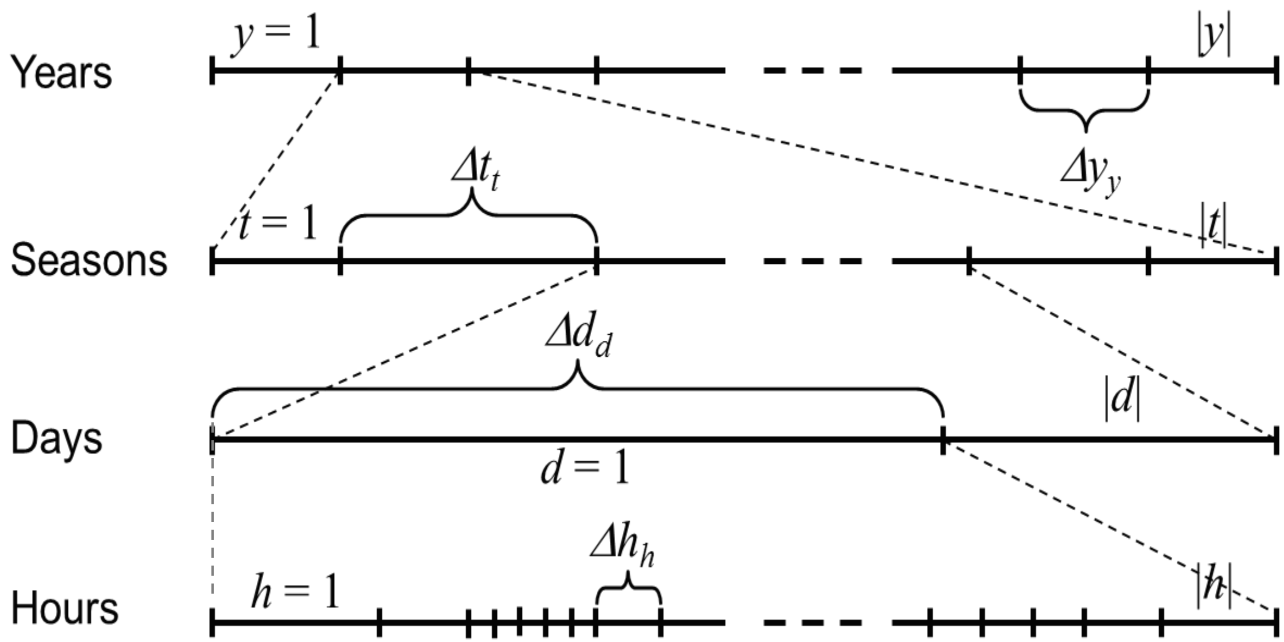
Temporal representation

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

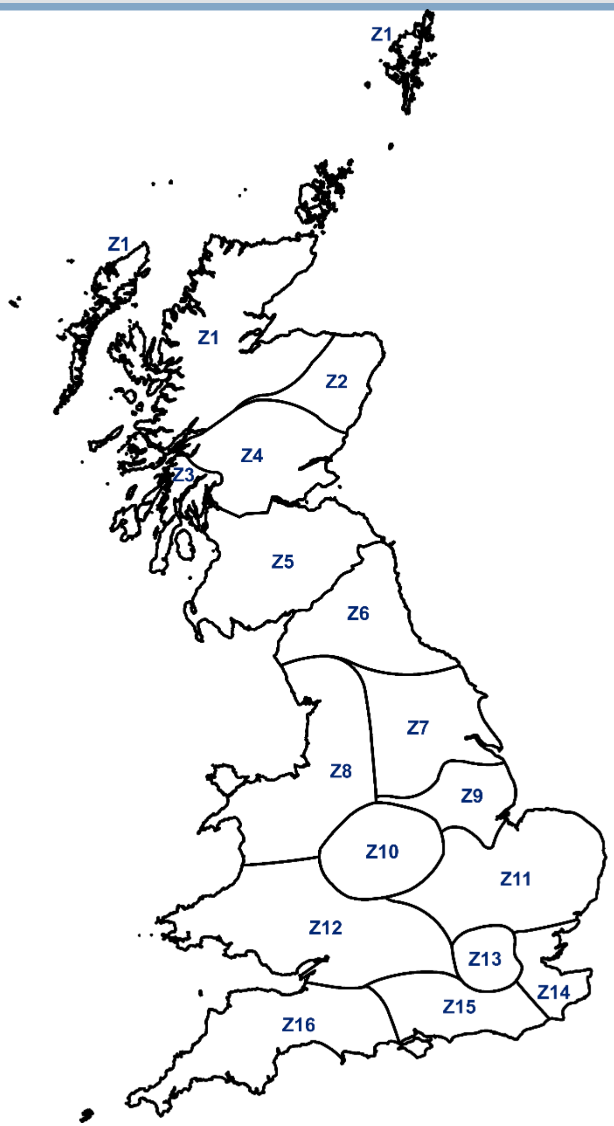


Without storage – very easy!

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

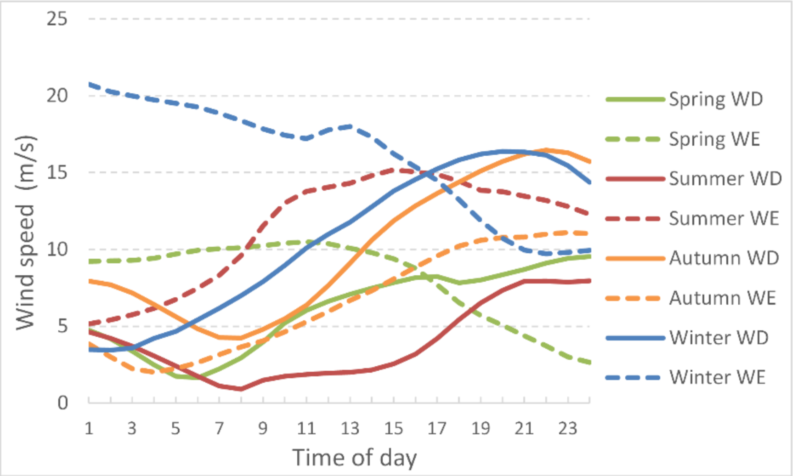
Spatial representation

- GB divided into 16 transmission zones based on the National Grid SYS 17 study zones
- Each zone may contain a number of technologies for generation, conversion, storage and transport
- Transmission lines (e.g. hydrogen pipelines or electricity cables) may connect each zone to its neighbours



Spatio-temporal wind availability

Time-series wind data for each zone were obtained from **Virtual Wind Farm Model** of Iain Staffell



Temporal distribution of wind speed in zone 13 (similar graphs were derived for the other zones)

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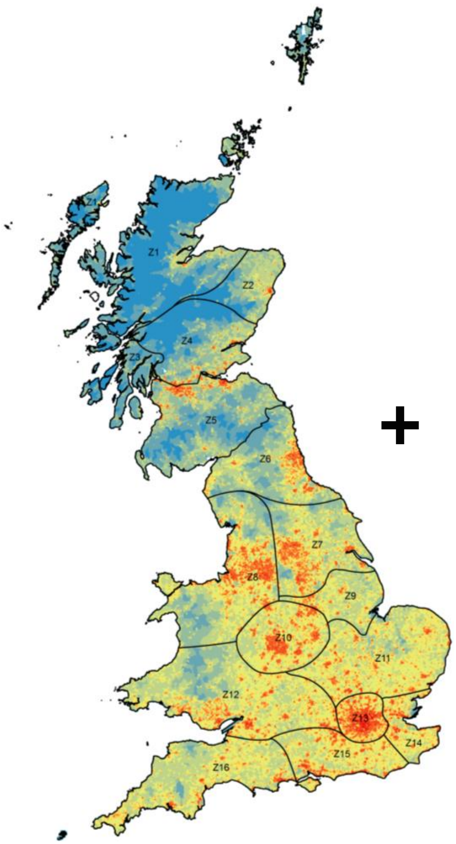
Spatio-temporal demand data

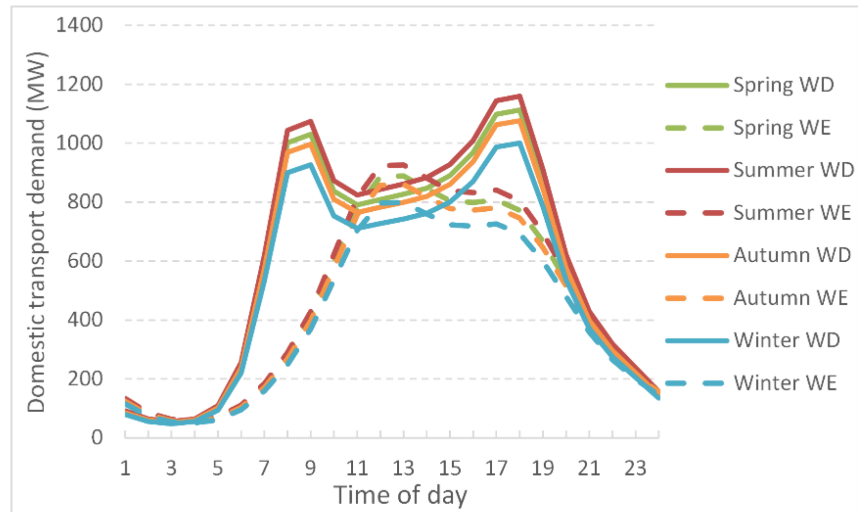


Hydrogen demand at 1km

+

Department of Transport statistics for vehicular usage at different times

=



Temporal distribution of hydrogen demands in Z13 (similar graphs were derived for the other zones)

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Wind turbine siting constraints

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

1. Annual 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

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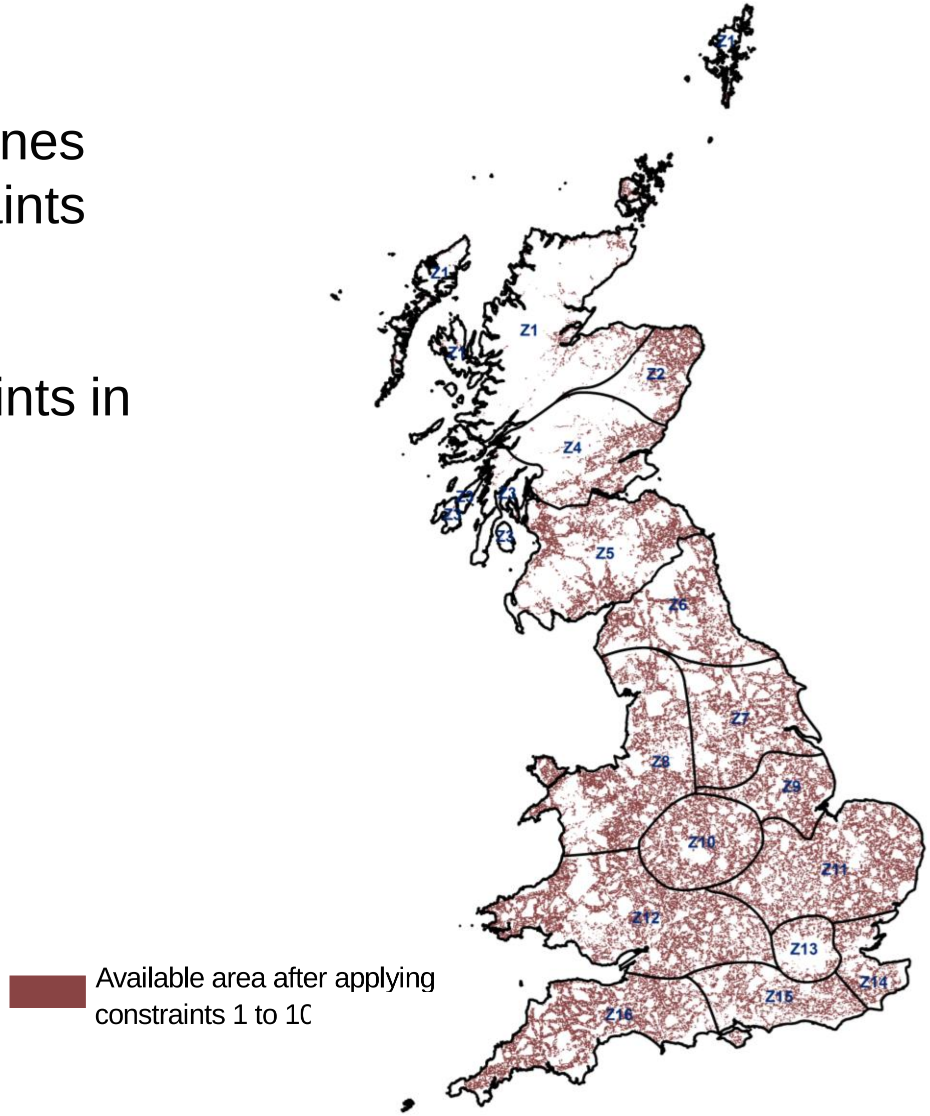
Land footprint constraint

- Total available area for wind turbines
  - Intersection of the 10 constraints

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



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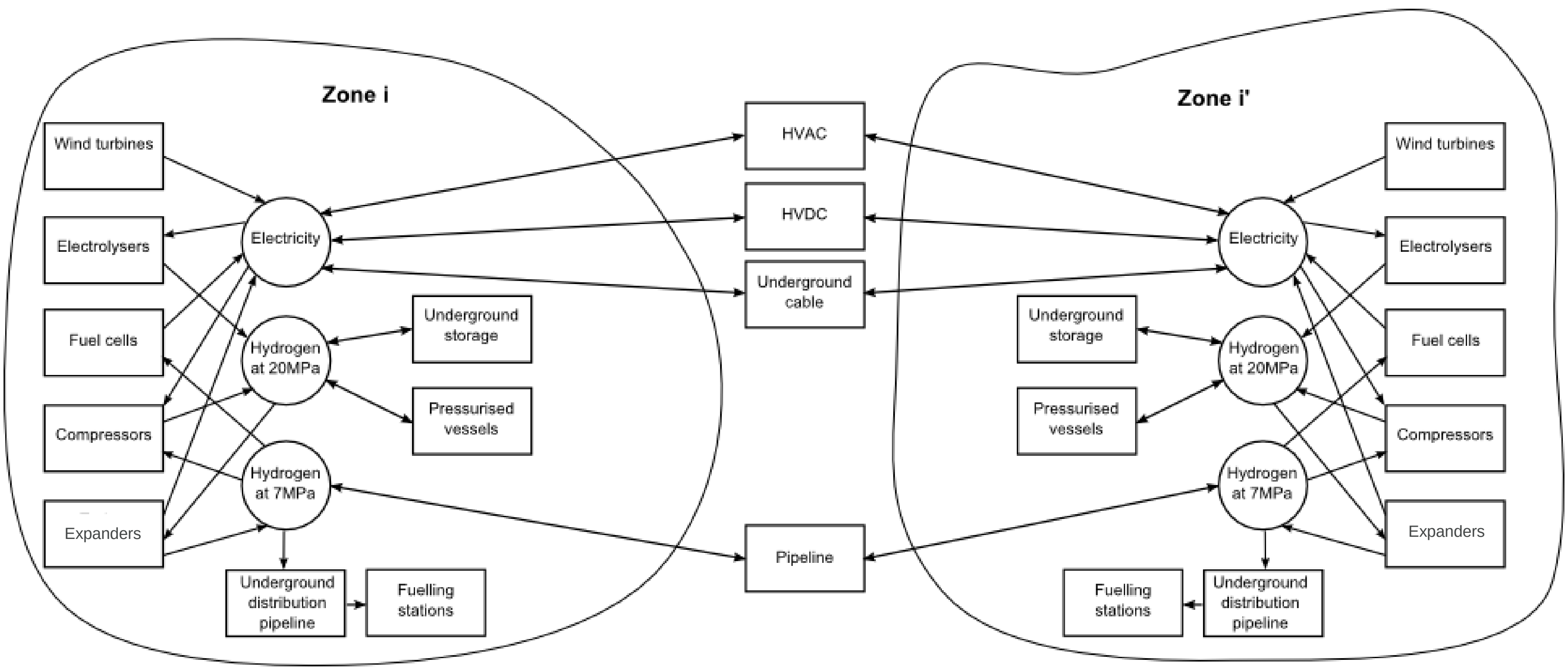
Resource-Technology Network



Network of conversion, storage and transmission technologies connecting 2 zones

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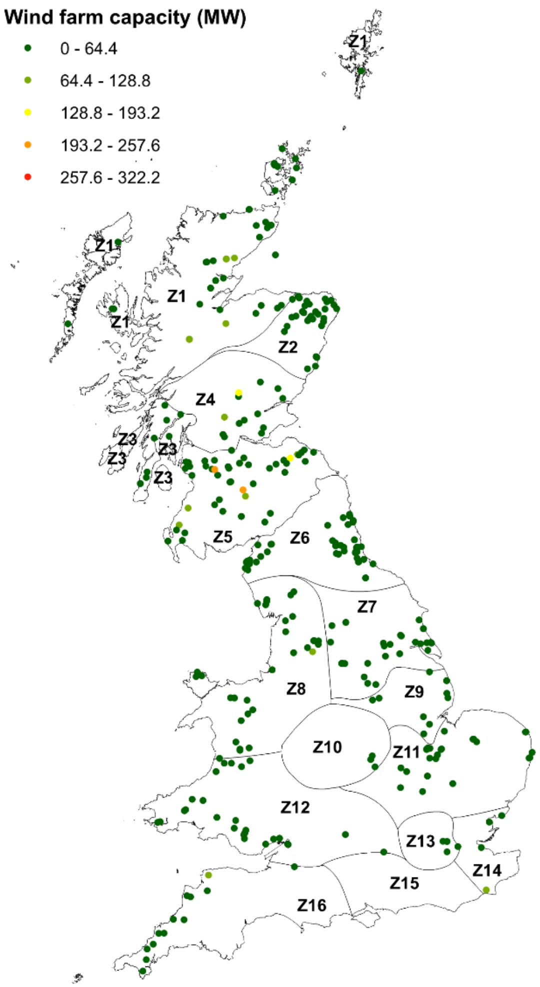
Production technology

Wind turbines

- Considered standard on-shore wind turbines at commercial scale (i.e. rotor diameter of 100m)
- Assumed a minimum spacing of 5 rotor diameters between turbines
- Existing wind turbines can be used if it's cost-effective to do so



Existing wind farm capacity

Conversion technologies

Electrolysers

- Max production rate of 69.38MW
- High pressure electrolysis at 20MPa

Fuel cells

- 41.63MW solid oxide fuel cell

Compressors

- Reciprocating compressors at different sizes

Expanders

- Reciprocating expanders at different sizes

Storage technologies

Characterised by their:

- Maximum available capacity
- Injectability – maximum rate that H_2 gas can be injected into storage
- Deliverability – maximum rate that H_2 gas can be withdrawn from storage

Cushion gas - the volume of gas required to be kept in a facility in order to maintain operating pressure and cannot be recovered until the facility stops operation

Overground storage

- Compressed gas storage tanks at 20MPa
- Considered 3 sizes
  - Small - Max capacity: 0.36GWh; Injectability/deliverability: 15.13MW
  - Medium - Max capacity: 3.63GWh; Injectability/deliverability: 151.25MW
  - Large - Max capacity: 36.3GWh; Injectability/deliverability: 1512.50MW

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Underground storage

- Salt caverns, depleted oil/gas fields and aquifers

- Four underground storage considered in the model:

  Aldborough (Z7)
    - Salt cavern
    - Max capacity: 3.3TWh; Injectability: 9.17GW; Deliverability: 10.82GW

  Humbly Grove (Z15)
    - Depleted oil/gas field
    - Max capacity: 3.05TWh; Injectability: 3.79GW; Deliverability: 3.29GW

  Rough (Z7)
    - Depleted oil/gas field
    - Max capacity: 34TWh; Injectability: 10GW; Deliverability: 18.96GW

  Warmingham (Z8)
    - Salt cavern
    - Max capacity: 1.08TWh; Injectability: 4.88GW; Deliverability: 1.21GW

Transmission technologies

Hydrogen pipeline

- Data obtained from simulation using the pipeline model in gCCS
- Diameter: 100cm, max inlet pressure of 7.1MPa

Electricity cables

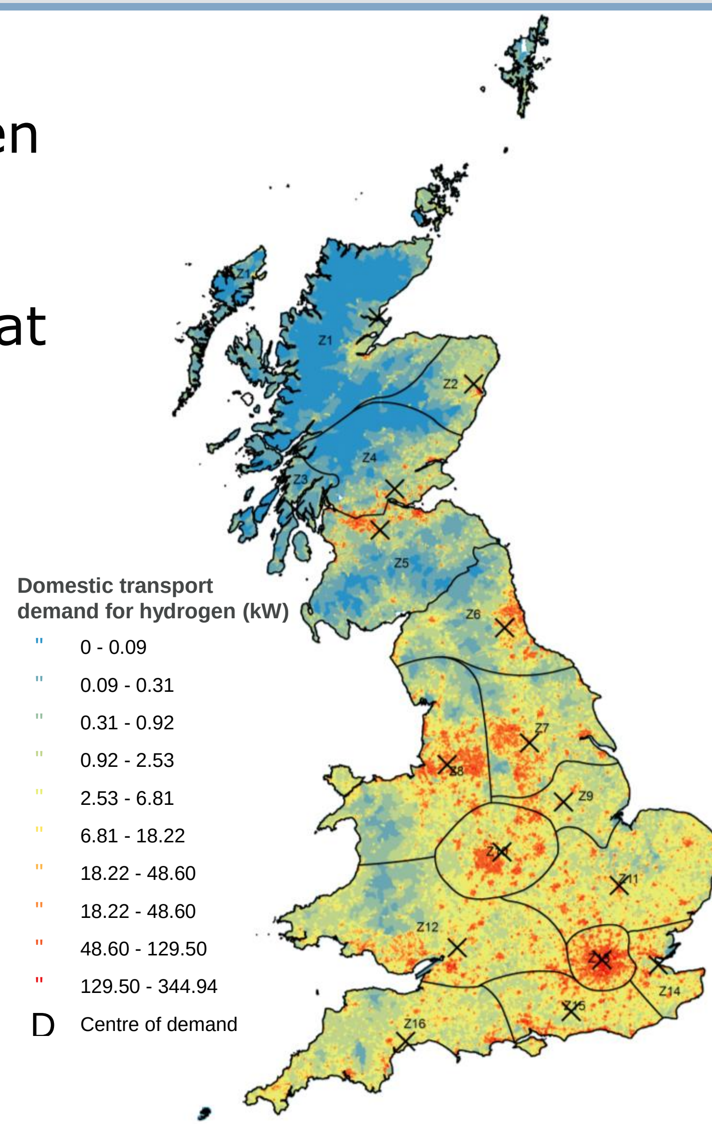
- HVAC OHL, single circuit, 400kV, 1500MVA
- HVAC OHL, double circuit, 400kV, 2x1500MVA
- HVAC underground XLPE cable, single circuit, 400kV, 1000MVA
- HVAC underground XLPE cable, double circuit, 400kV, 2x1000MVA
- HVDC OHL, bipolar, ± 400kV, 1500MW
- HVDC underground cable pair, ± 350kV, 1100MW

Centres of demand

- Transmission assumed to be between the centres of demand of each zone
- Obtained from the demand density at 1km, $D(x,y)$

$$x_z = \frac{\iint_{S_z} xD(x,y)\,dx\,dy}{\iint_{S_z} D(x,y)\,dx\,dy}$$

$$y_z = \frac{\iint_{S_z} yD(x,y)\,dx\,dy}{\iint_{S_z} D(x,y)\,dx\,dy}$$



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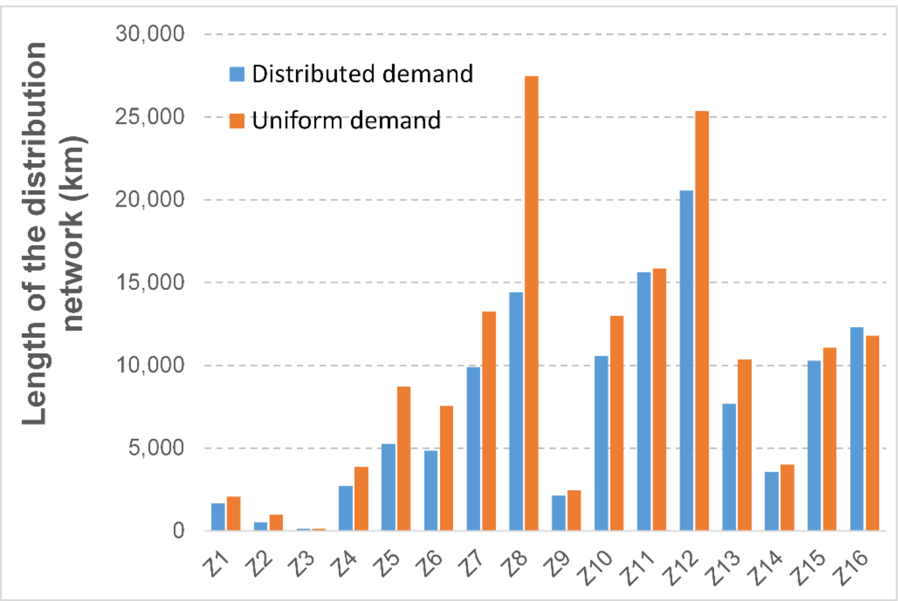
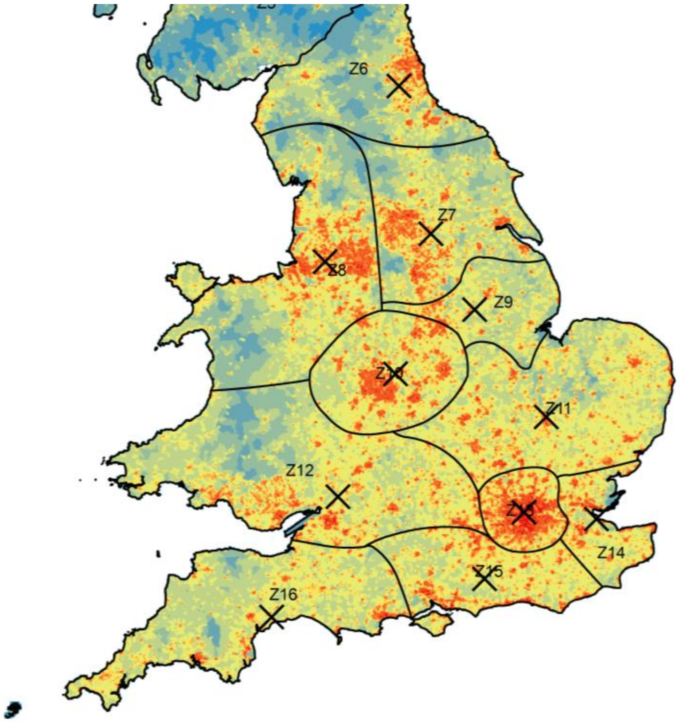
Length of the distribution network

- Previous methods used a grid of square cells and assumed that demands are uniformly distributed.

- A better approximation uses the demand density, $D(x, y)$:

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

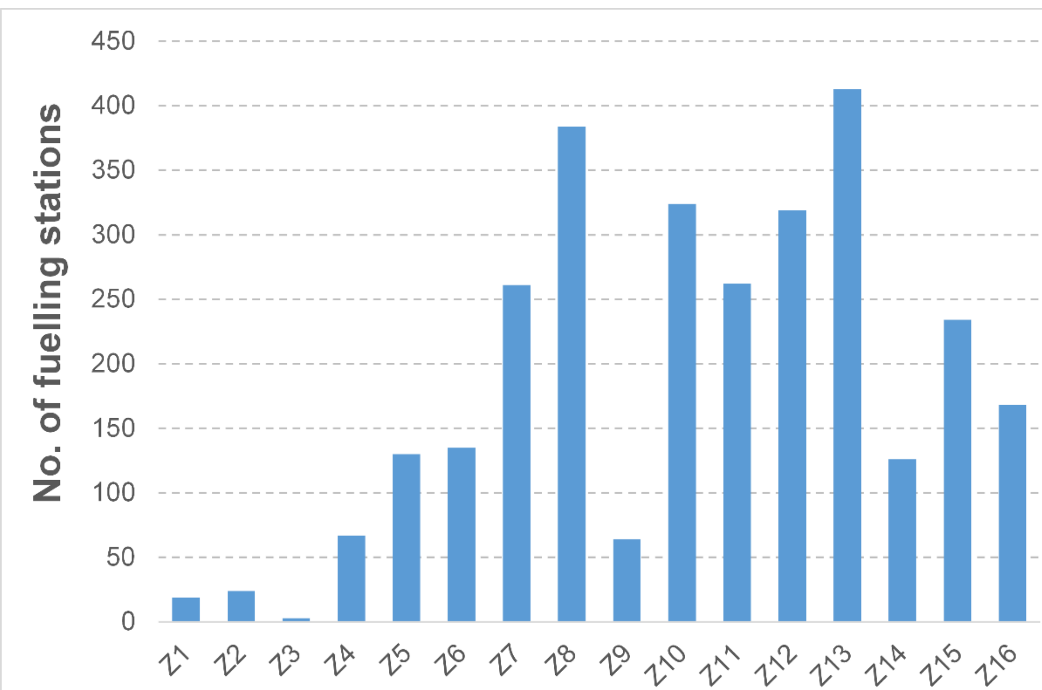




Number of fuelling stations

- Number of fuelling stations:

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



Total distribution cost ≈ £bn17/yr
Assuming:

- Fuelling station capacity of 1,500kg/day
- Distribution pipeline diameter of 20cm
- Capital charge factor of 3

Production/conversion-storage-transmission network problem

Given:

- The hydrogen demand and availability of wind power
- Characteristics of each technology (e.g. unit costs: CAPEX, O&M; efficiency)

Determine:

- The optimal number, size and location of wind turbines, electrolysers, fuel cells, compressors, expanders and hydrogen storage
- Whether to transmit the energy as electricity or hydrogen or both
- The structure of the transmission network
- The hourly operation of each network component

Subject to:

- Max available land area for the technologies (only land footprints of wind turbines are considered in this study)
- Satisfying all of the demands

Objective:

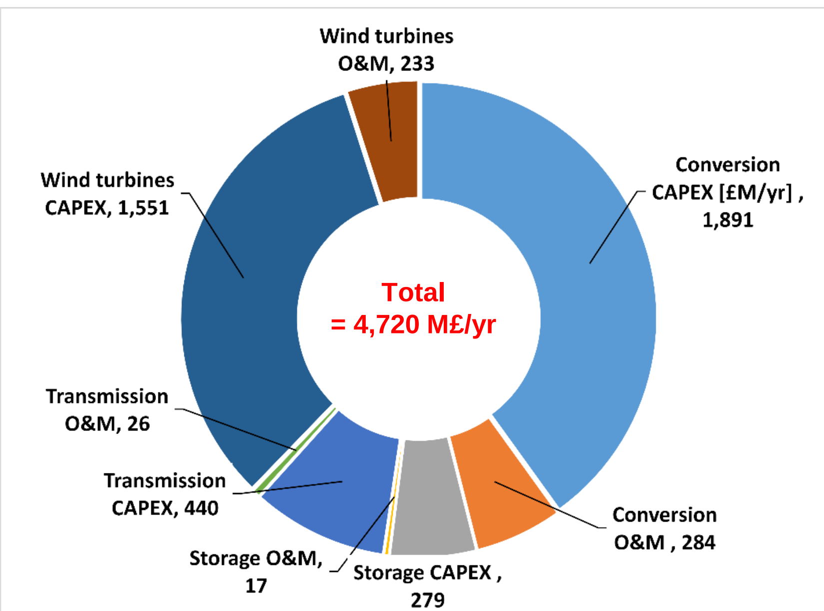
- Minimise total system cost

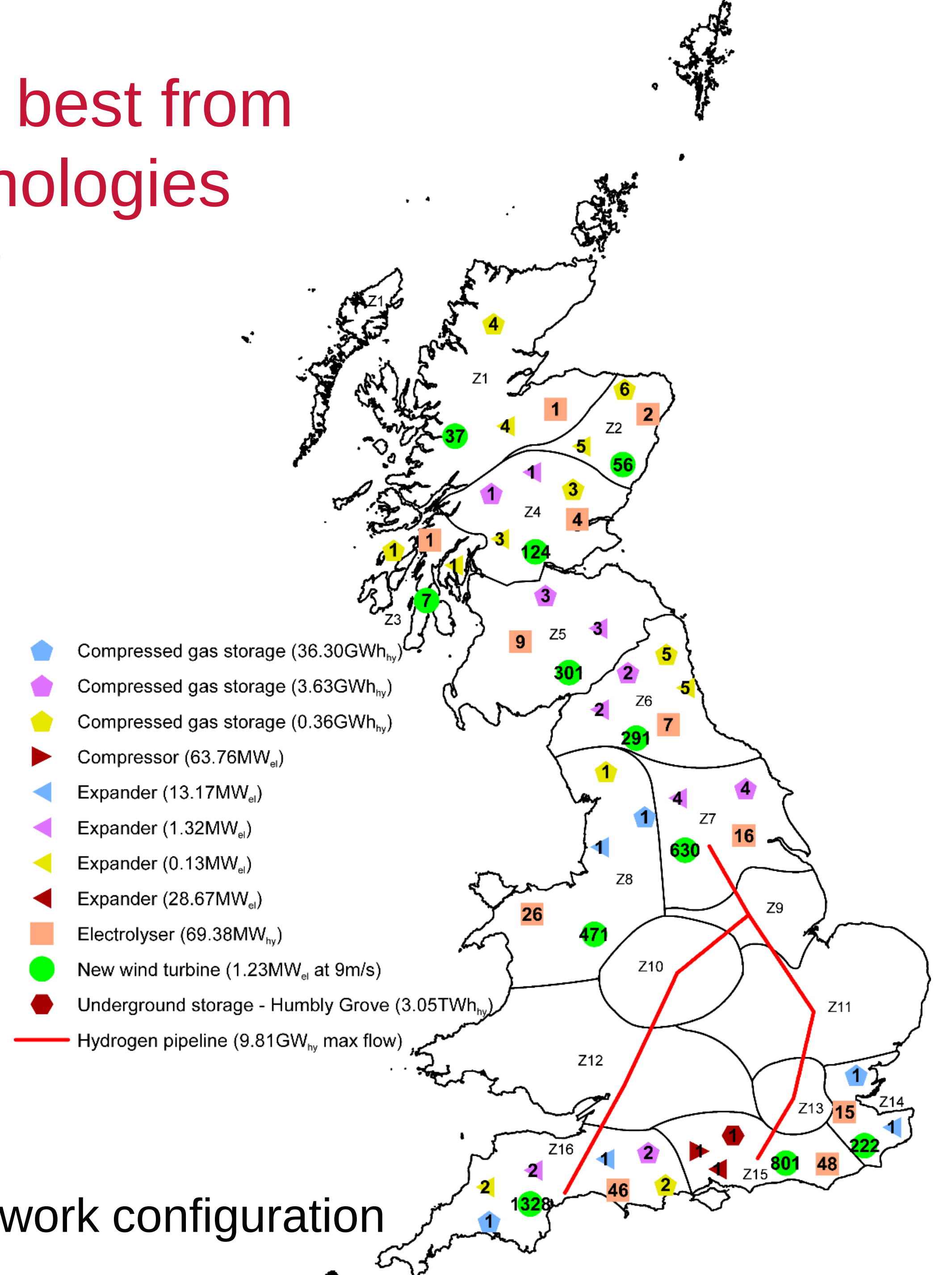
Base case: choose the best from all of the possible technologies

(existing wind turbines not included)

Breakdown of costs [£M/yr]

(excluding distribution costs)

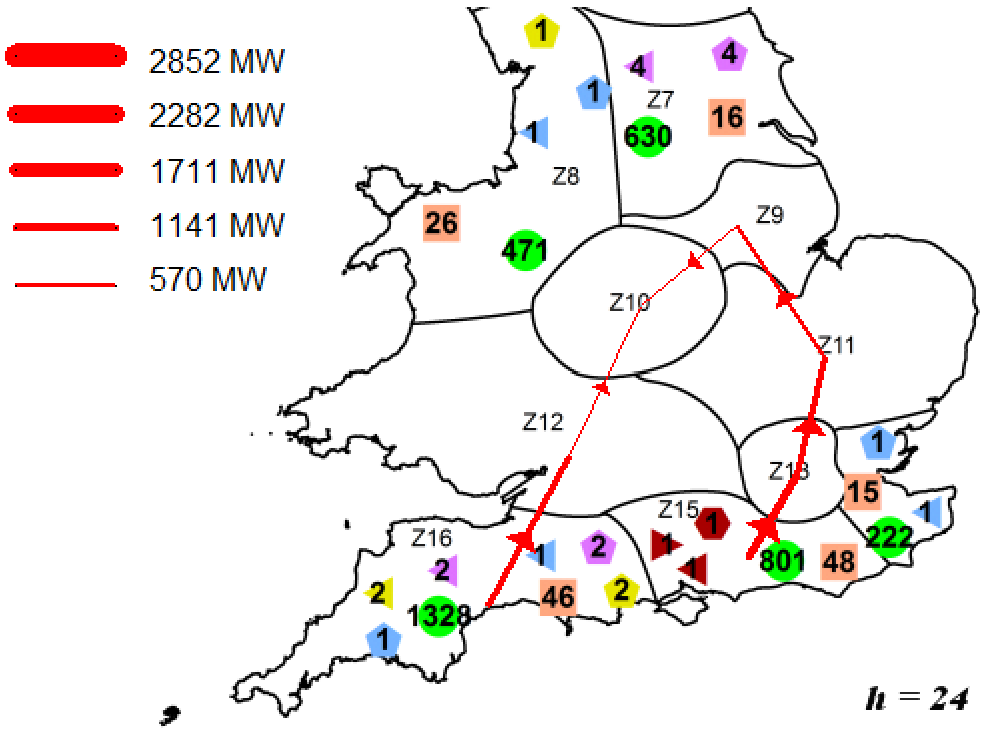




Least-cost network configuration

Base case (cont…)

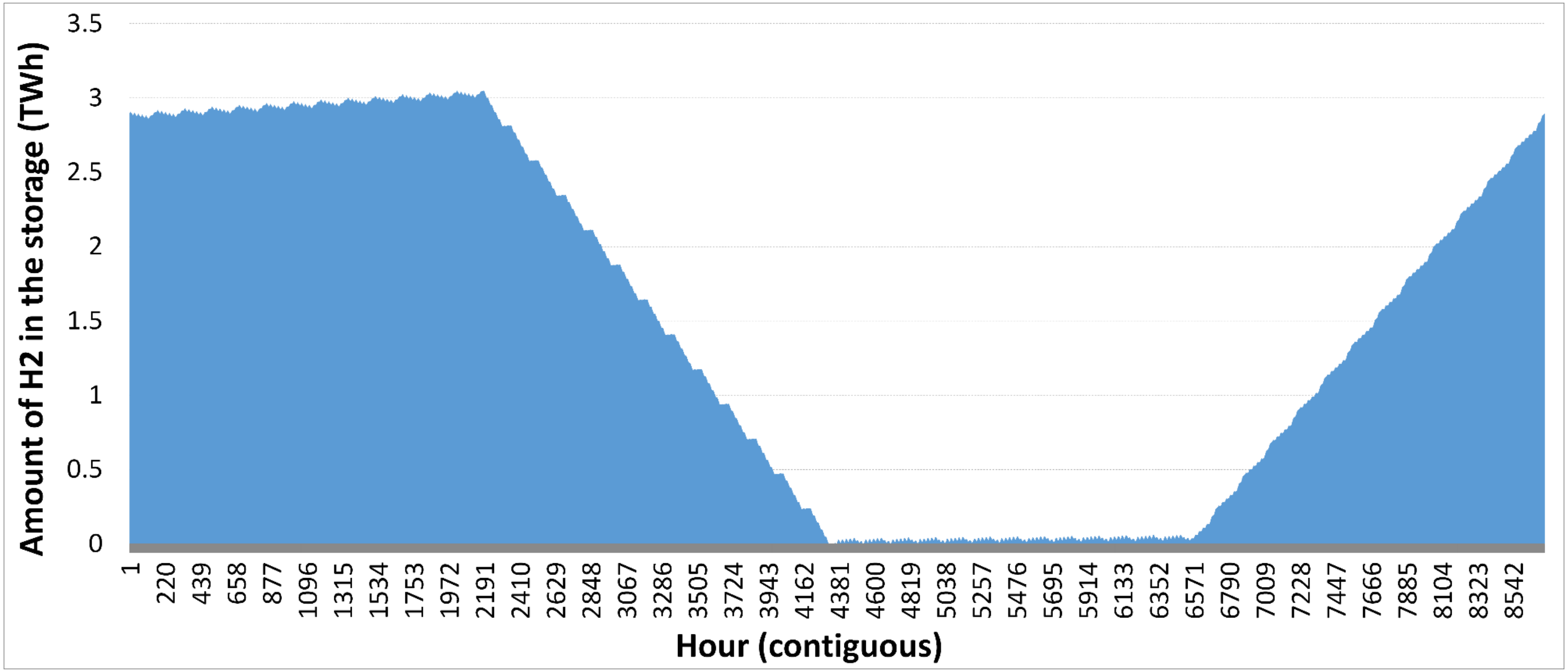
Snapshot of the operation of the transmission network (pipeline) during weekdays in summer



View in slide show mode for the animation

Base case (cont…)

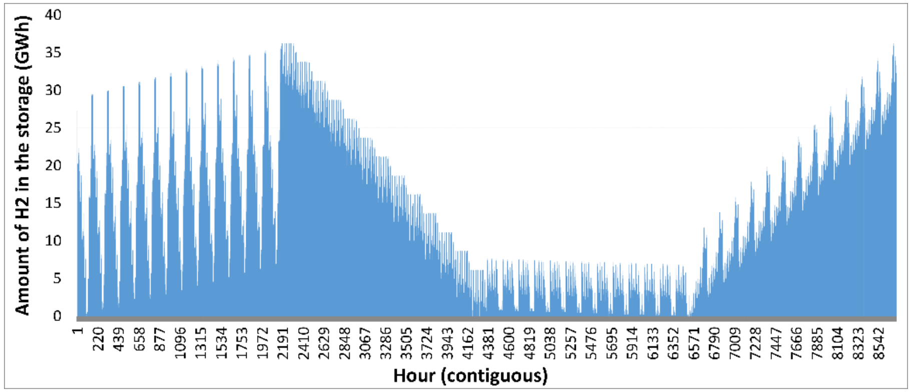
Inventory of hydrogen in the Humbly Grove underground storage (Z15)



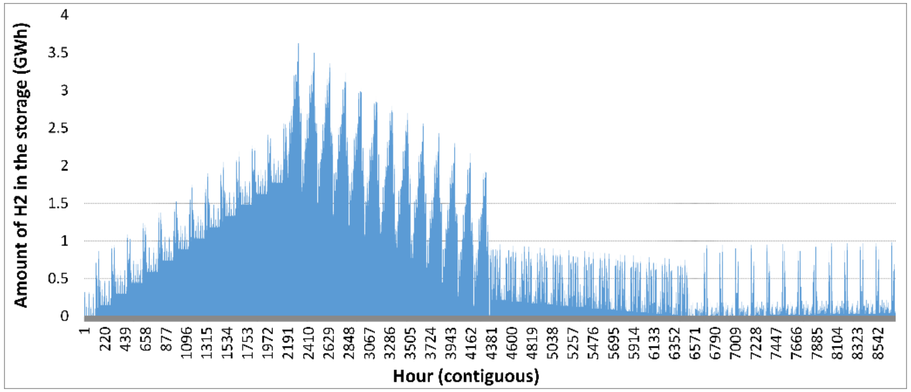
The underground storage is being used effectively as a seasonal storage.

Base case (cont…)

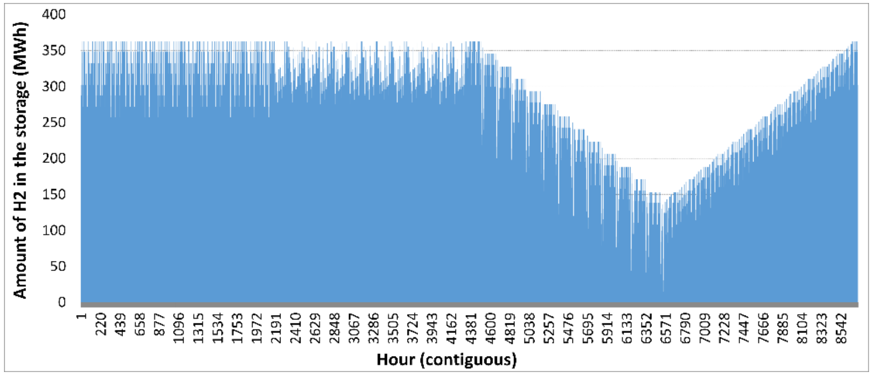
Inventory of hydrogen in overground storage (tanks) at different zones



36.3GWh storage in zone 16



3.63GWh storage in zone 4

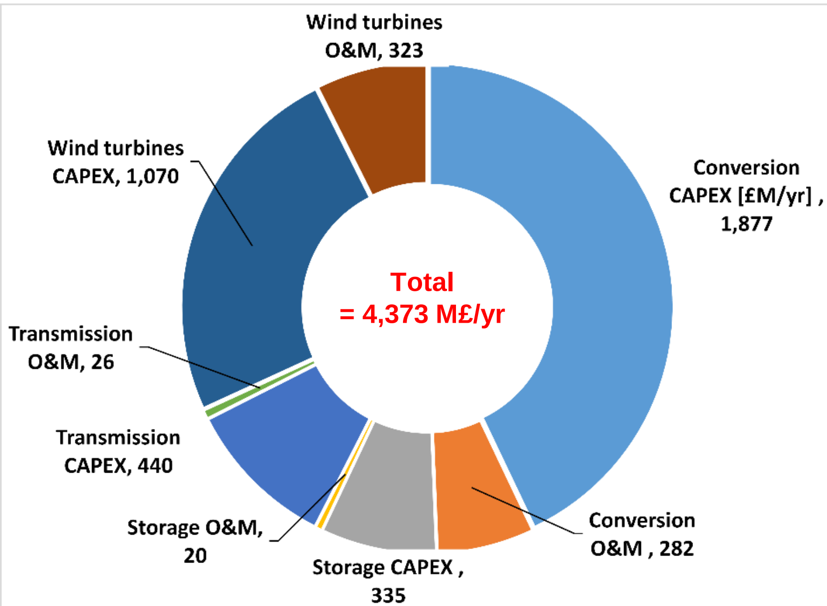


363MWh storage in zone 8

The tank storage are being used as seasonal storage as well as for hourly balancing

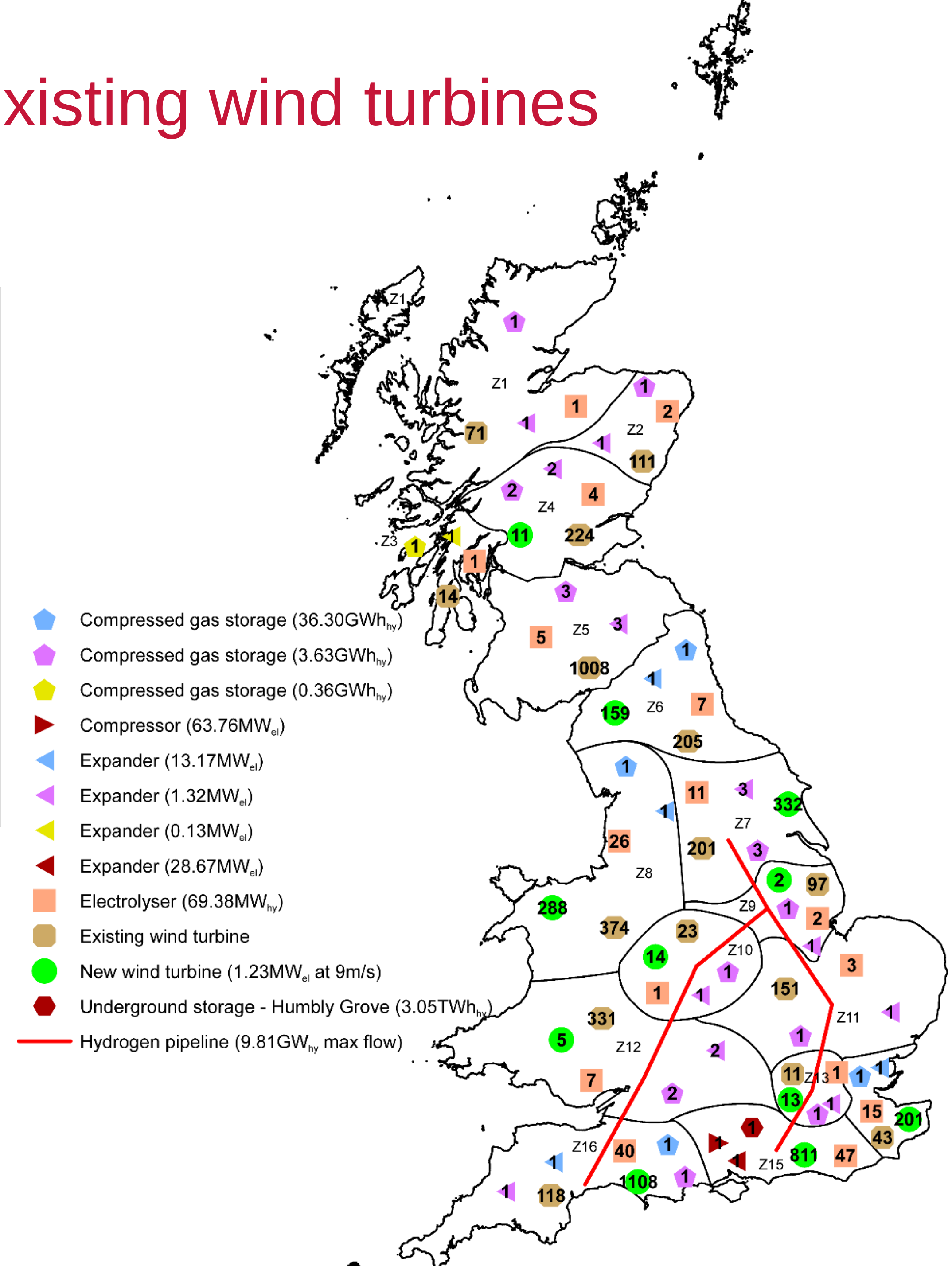
Case 2: The value of existing wind turbines

Breakdown of costs [£M/yr]
(excluding distribution costs)



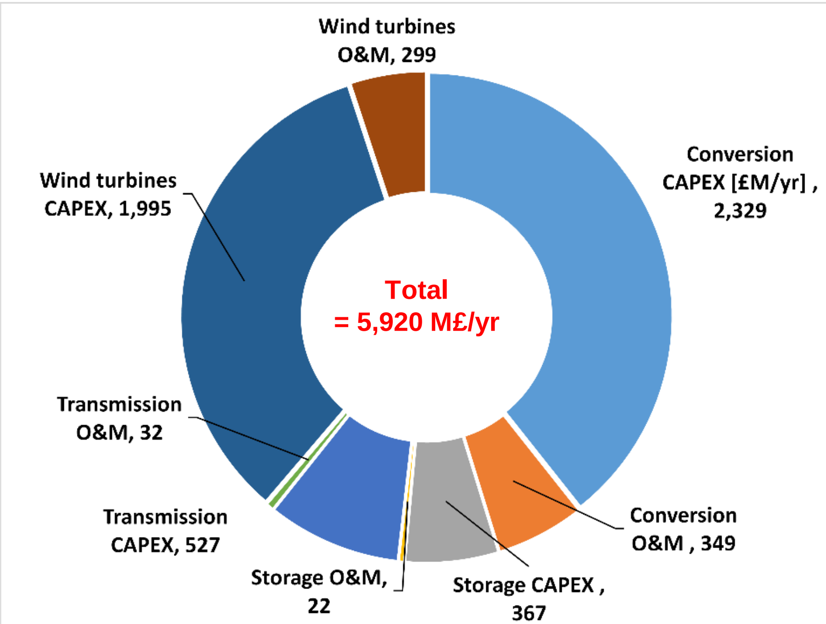
Comparison with base case

	% difference
Wind turbines	-22%
Conversion	-1%
Storage	20%
Transmission	0%
Overall network	**-7%**



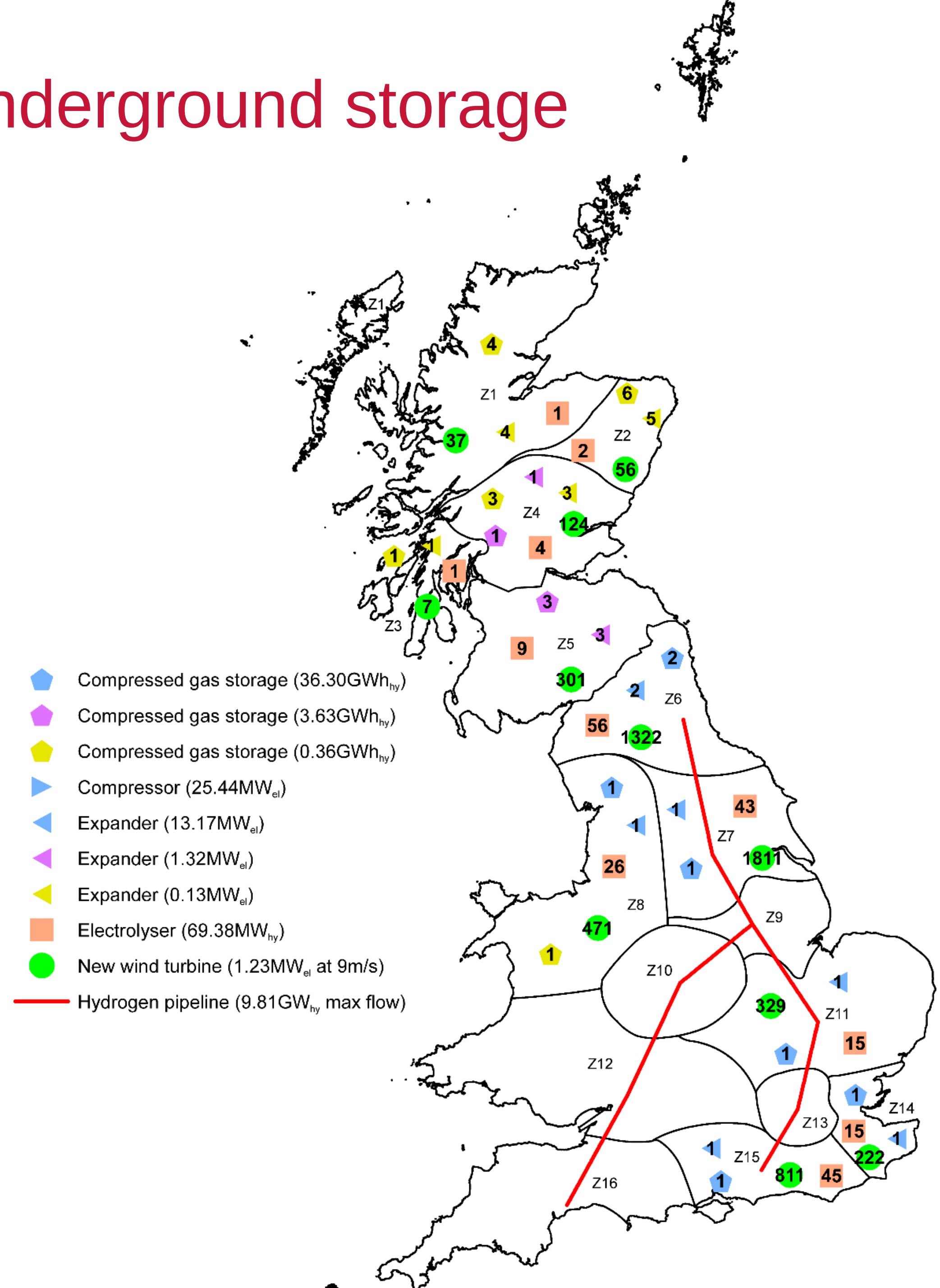
Case 3: The value of underground storage

Breakdown of costs [£M/yr]
(excluding distribution costs)



Comparison with base case

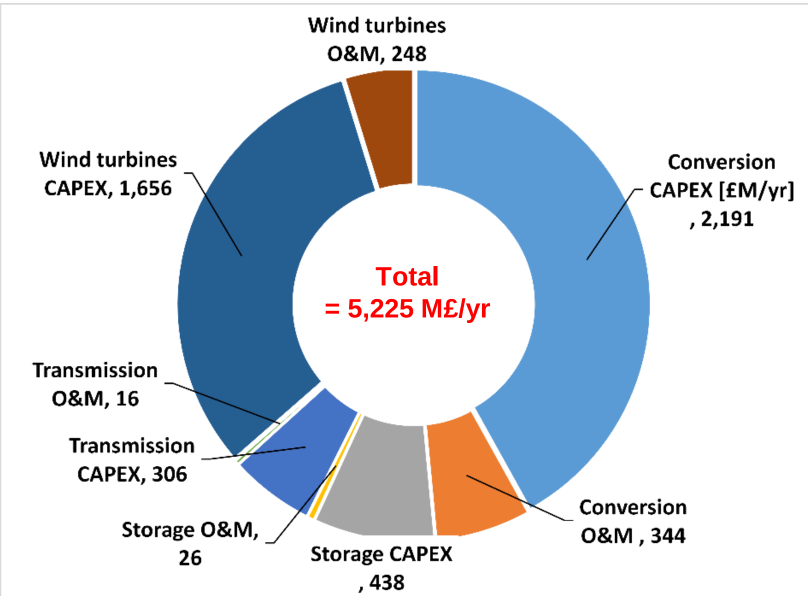
	% difference
Wind turbines	29%
Conversion	23%
Storage	32%
Transmission	20%
Overall network	**25%**



Case 4: The value of pipeline transmission

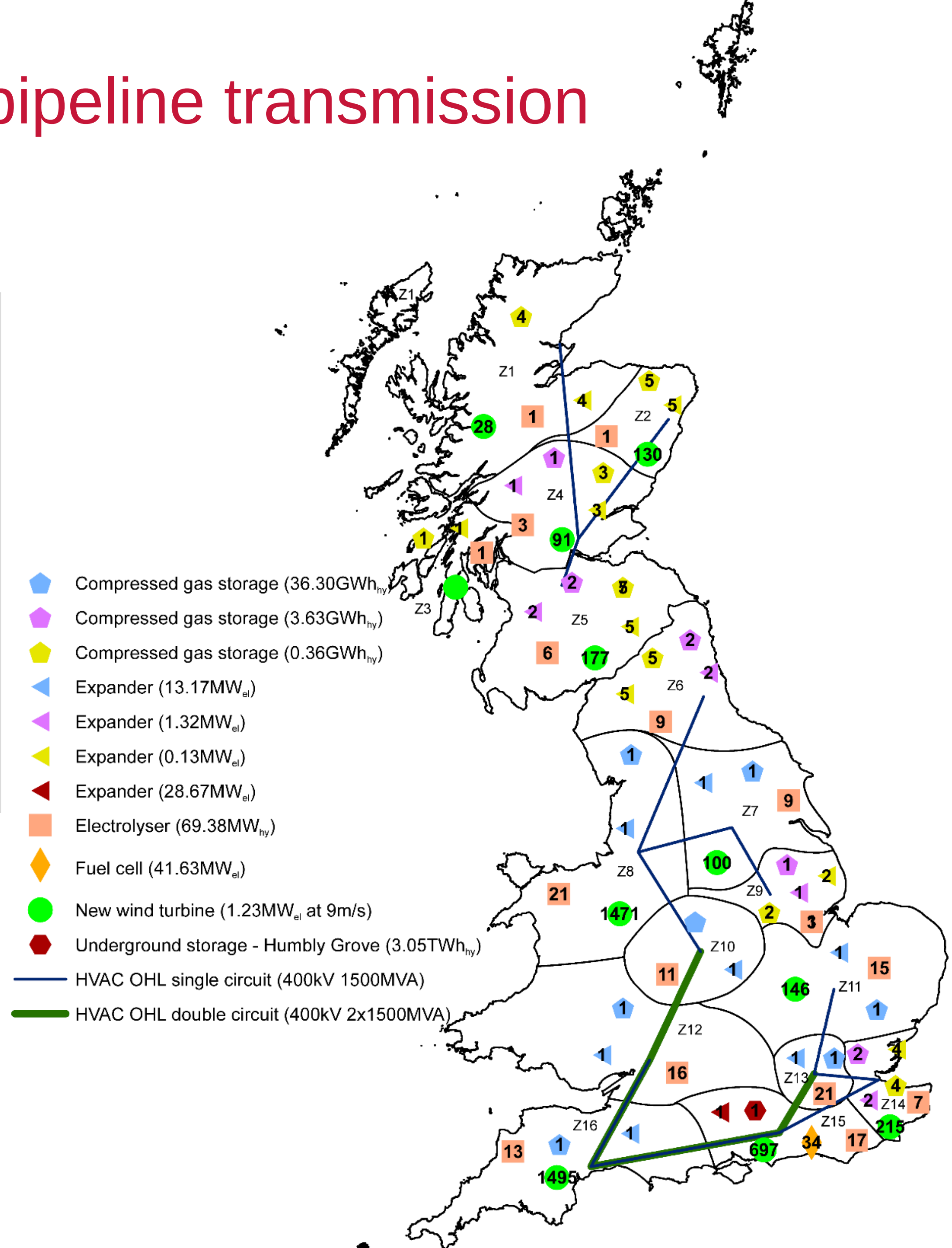
Breakdown of costs [£M/yr]

(excluding distribution costs)



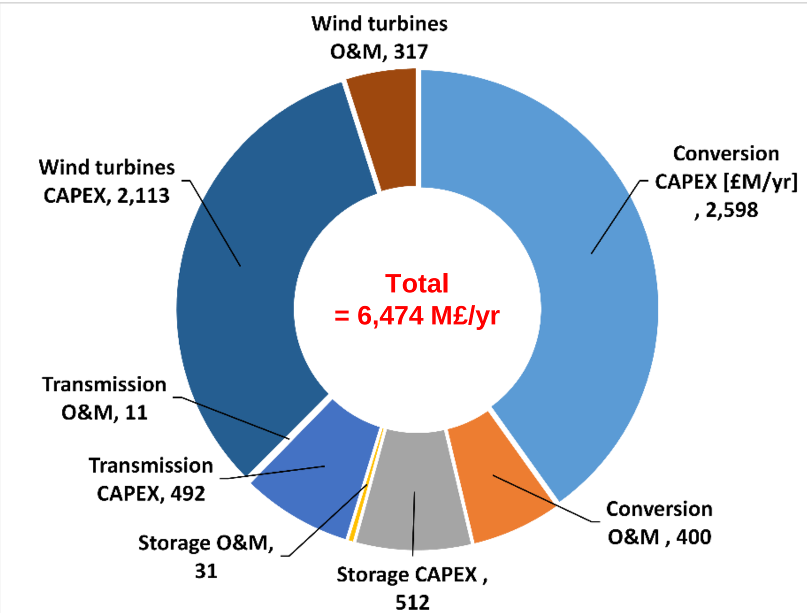
Comparison with base case

	% difference
Wind turbines	7%
Conversion	17%
Storage	57%
Transmission	-31%
Overall network	**11%**



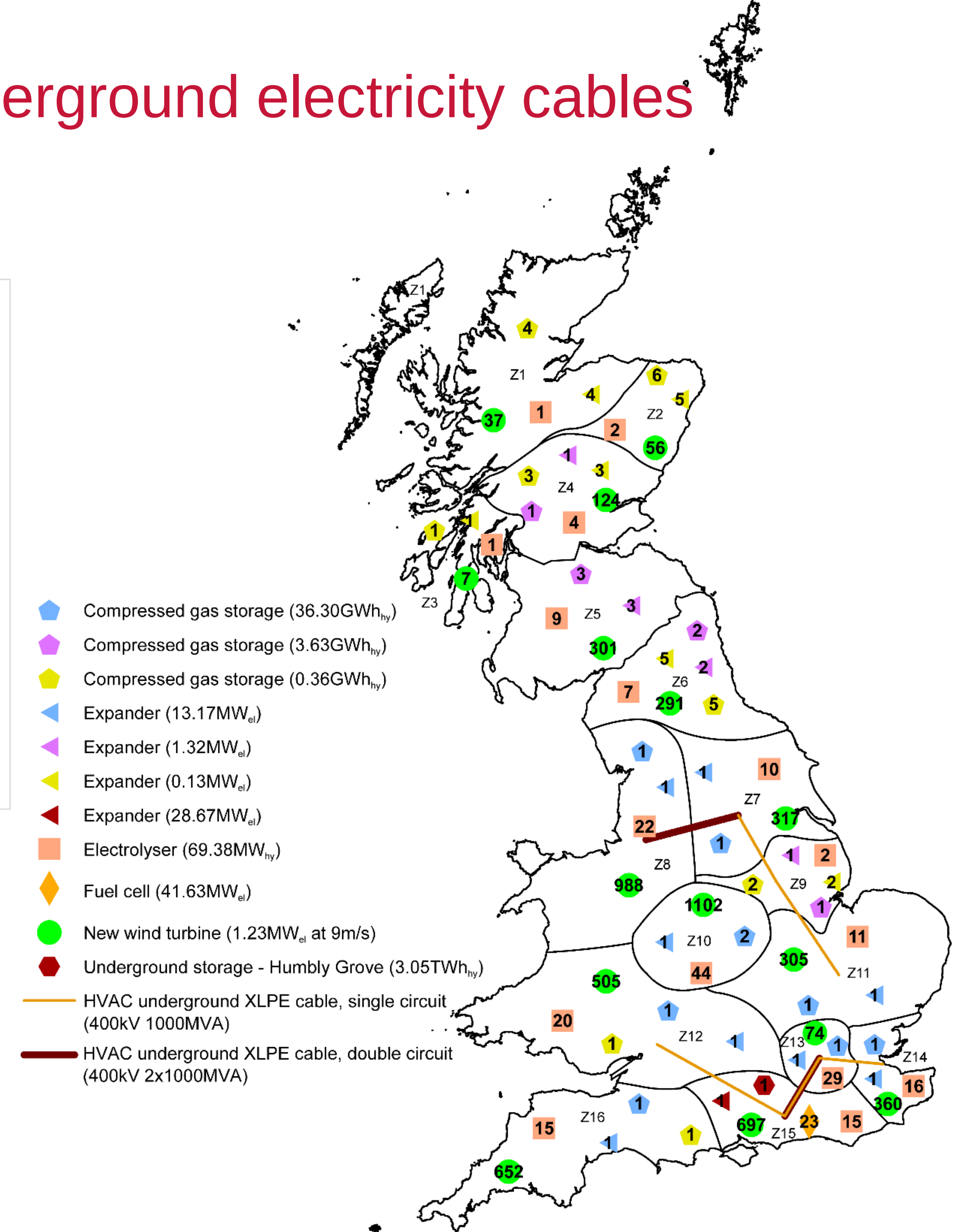
Case 5: The cost of underground electricity cables

Breakdown of costs [£M/yr]
(excluding distribution costs)



Comparison with base case

	% difference
Wind turbines	36%
Conversion	38%
Storage	83%
Transmission	8%
Overall network	**37%**



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Conclusions

- All of the domestic transport demand can be met by wind
- Optimal solution (without using existing turbines)
  - Build a hydrogen pipeline network in the south of England and South Wales
  - Use the Humbly Grove underground storage
  - No wind turbines or technologies in the Midlands and Greater London
  - Northern Wales, England and Scotland self sufficient
  - Humbly Grove is used for seasonal storage
  - Storage tanks elsewhere used for hourly balancing as well as seasonal storage
- Results may change with the inclusion of more technologies, e.g. batteries, electric vehicles

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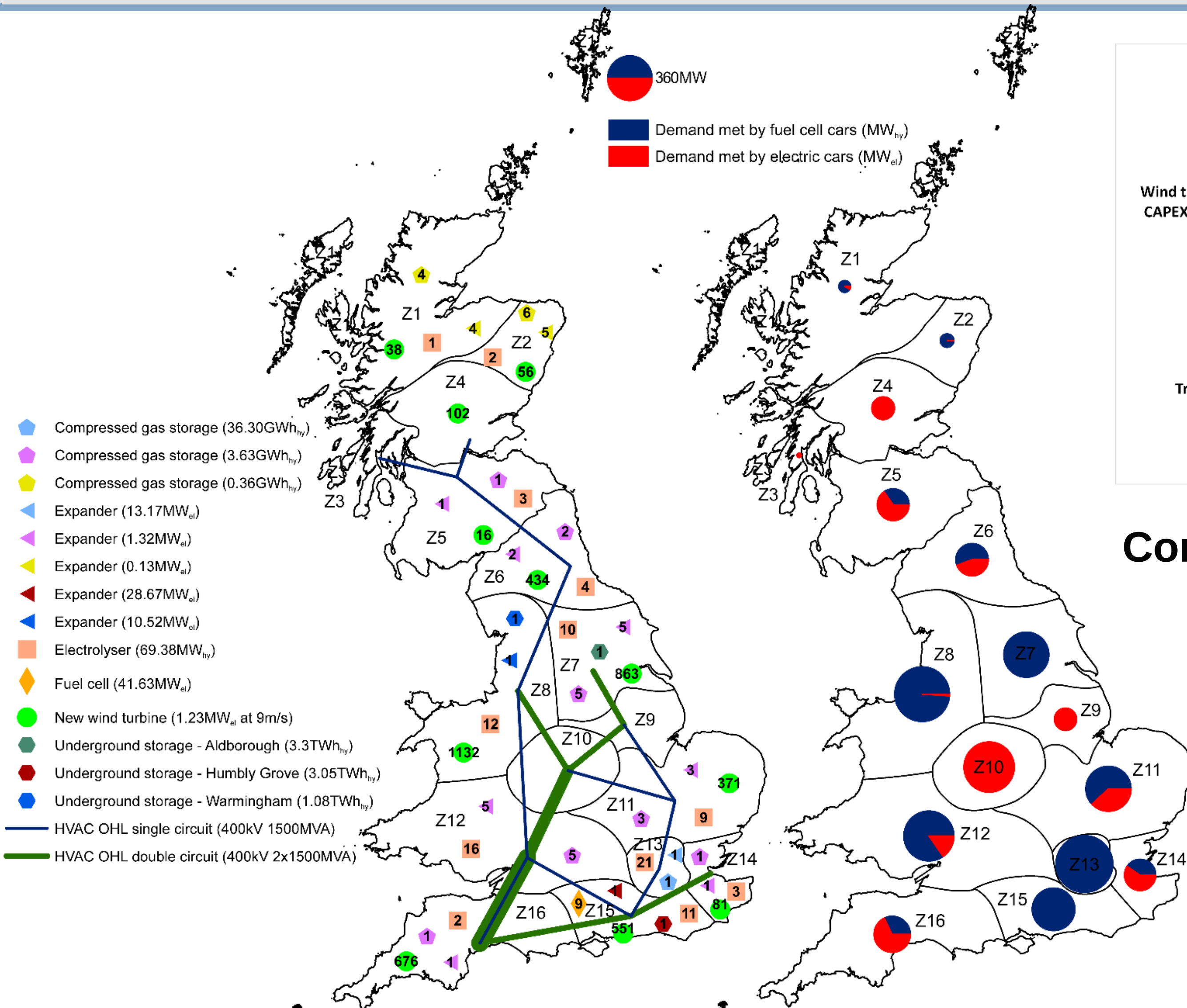
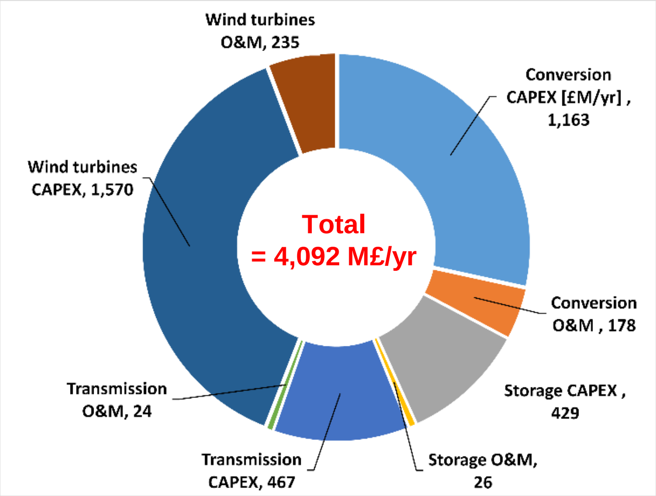
Future work

- Electric vehicles
  - Determine optimal penetration of electric and FC vehicles
  - Allow electricity storage in some electric vehicles
- Pipeline storage
- Integrate natural gas networks
  - H_2 injection into gas pipelines
- Include demands from other sectors
- Uncertainty

The value of electric cars





Comparison with base case

	% diff
Wind turbines	1%
Conversion	-38%
Storage	54%
Transmission	5%
Overall network	**-13%**

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Acknowledgements

- Iain Staffell for the wind data
- EPSRC funding through the wholeSEM consortium (EP/K039326/1)