Modelling long-term energy pathways with high shares of variable renewable energy sources with highRES and UKTM

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Background

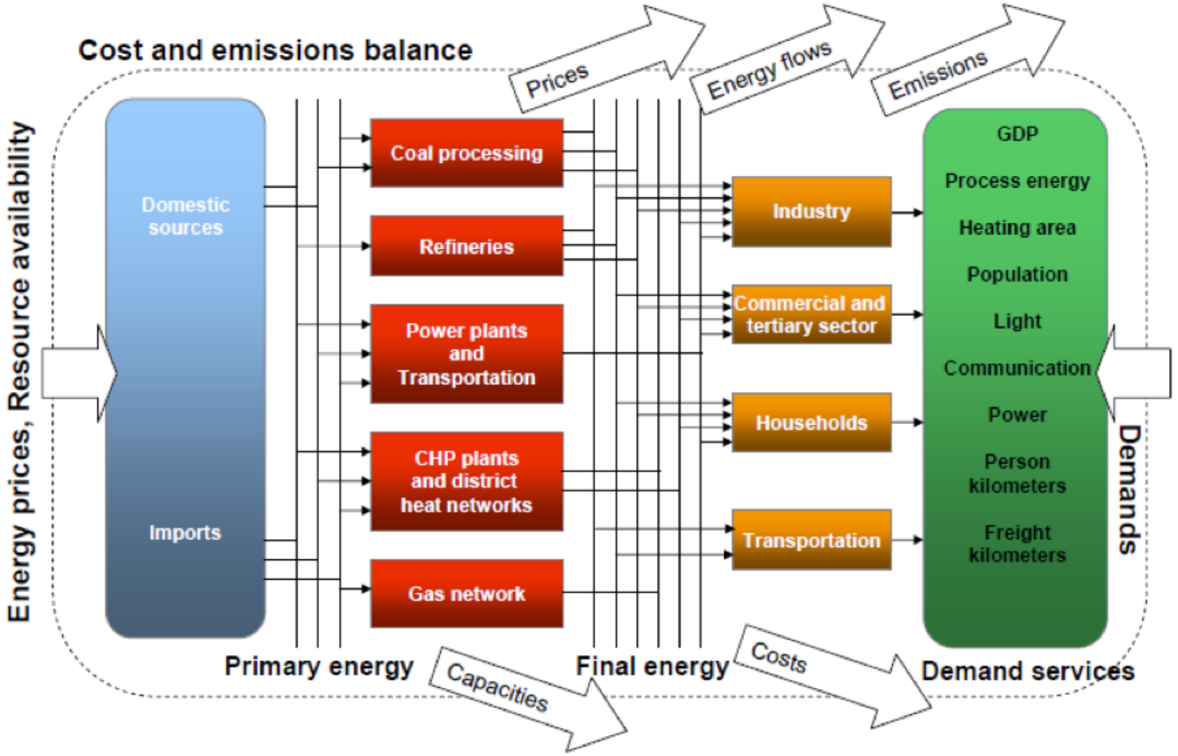
- Climate Change Act commits us to a 80% reduction in GHG emissions by 2050.

- To assist policy makers in achieving this goal WholeSEM team at UCL have been working with DECC and other stake holders to develop a UK TIMES model (UKTM) over the last 4 years.

- DECC (now BEIS) using UKTM to address key policy questions around long term decarbonisation pathways for the UK and it was one of the principal tools used in setting the 5th carbon budget.

Background

- UKTM:
  - Cost optimising, long time horizon model of the whole UK energy system.
  - Runs from 2010 to 2050 in 5 year steps with each year represented as 16 time slices (4 seasons, 4 intraday).
  - UK spatially modelled as one region.
  - Matches demand with supply across all sectors simultaneously subject to whatever constraints are placed on it (e.g. emissions) at least cost.



Motivation

- Power system widely regarded as one of the “lowest hanging fruits” to achieve 2050 emissions reduction goal.
- While long term evolution of power system is uncertain (e.g. CCS competition axed, ongoing uncertainty around new nuclear, the role of fracked gas, etc), renewables are likely to feature prominently.
- Variable renewable sources (VRE; i.e. wind and solar) and demand vary in space and time.
- Require a new model with high spatial and temporal resolution which complements UKTM’s long time horizon approach to study the integration of high shares of VRE.

highRES

- ***hi**gh* spatial and temporal ***r**esolution* ***e**lectricity* ***s**ystem* model (highRES) – developed as part of WholeSEM, cost optimising, runs for one “snapshot” year.

- Always makes dispatch decisions, either the model decides on capacity investment into generation and integration options or these can be fixed (taken from UKTM or elsewhere).

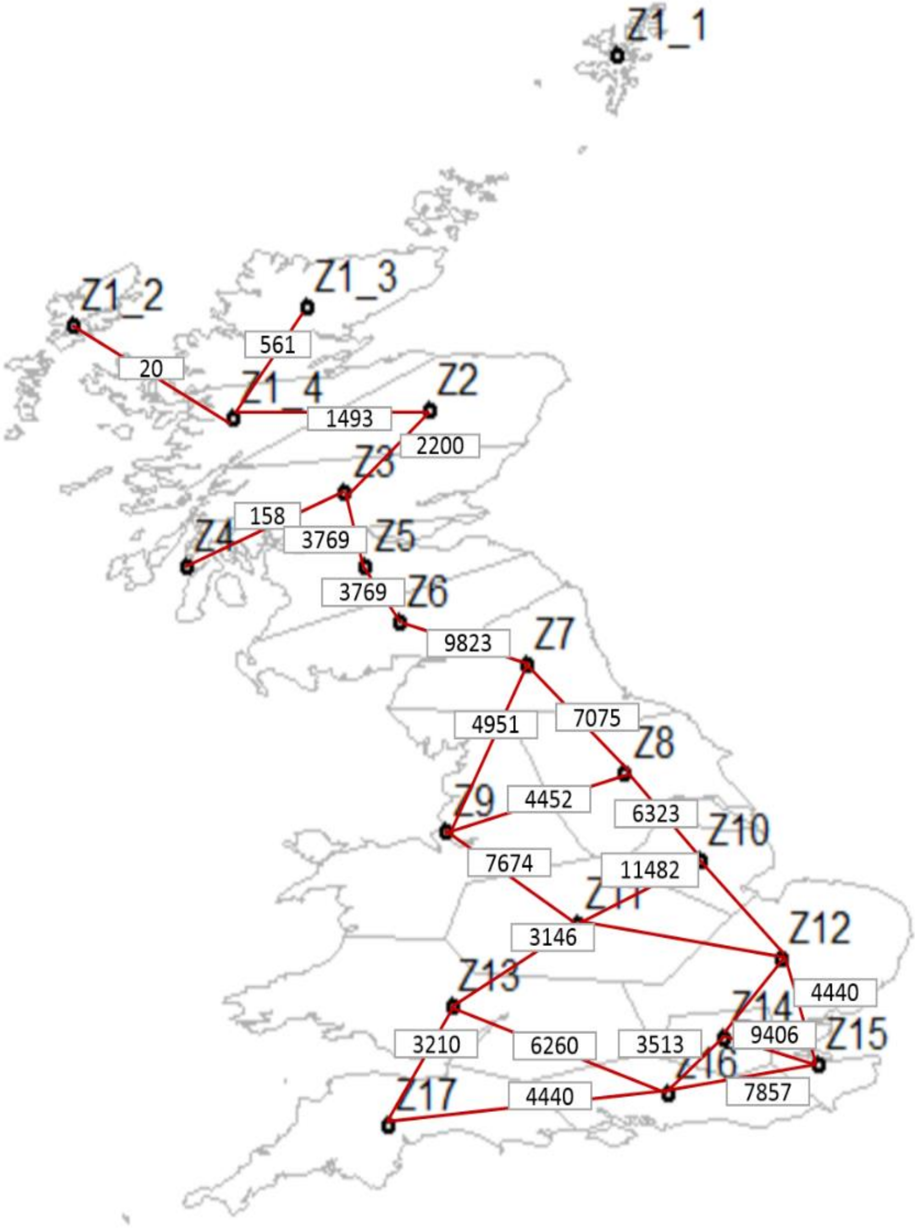
- Objective to minimise annual power system costs to meet hourly demand subject to:
  - →Technical constraints: ramping, minimum & maximum generation
  - →Storage constraints
  - →Transmission constraints
  - →Emission constraints, e.g. grid CO_2 intensity

- Output: Location of generation and VRE integration options, total system costs, electricity price, power plants usage rates, emissions, renewable curtailment, etc

Demand-Supply Balancing

Demand Supply Matching at Zonal Level

- Zones and demand shares per zone based on National Grid data
- Simplified high voltage transmission grid connecting the zones enables demand-supply balancing between zones
- Default network is based on 2015 capacities



highRES – Flexibility options

- One of the primary aims of the model is to understand how to use flexibility (or synonymously integration options) to address VRE intermittency.

- highRES currently includes the following options:
  - Spatial diversification – if the wind isn't blow in Cornwall, it may be in Scotland. The model has sufficient spatial resolution to represent this key option facilitated by grid reinforcement (and/or expansion) to smooth output variability.
  - Technological diversification – combine solar, wind and any other relevant renewables -> again can lead to less output variability.
  - Flexible generation – fast ramping technologies like OCGT used to fill "gaps" in VRE supply.
  - Storage – used to time shift VRE generation to match demand. Currently modelled in highRES as a generic grid scale battery.

- To be included:
  - Interconnection to nearby countries – Currently simple, static interconnection in place but ongoing work to make this more dynamic.
  - Demand side response – Currently no DSR in the model but in time we are keen to include it.

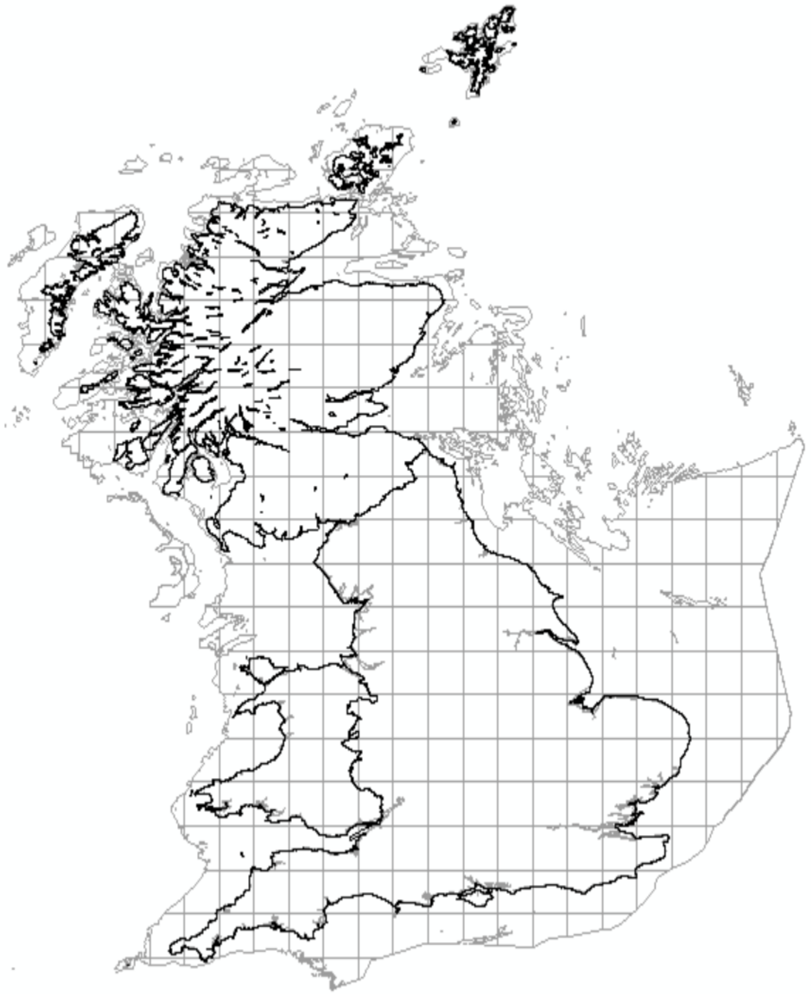
Weather data

- Core focus of highRES is a good representation of renewables -> this means input weather data with sufficient:
  - Temporal coverage (number of years), one single year is not enough.
  - Temporal resolution, as high as possible subject to computational constraints and data availability.
  - Spatial coverage, at least enough to capture whole of GB power system (on and offshore). Ideally uniform.
  - Spatial resolution, fine enough to represent simplified implementation of high voltage transmission system.
- Combined this allows us to begin to capture temporal and spatial variability of VRE generation.

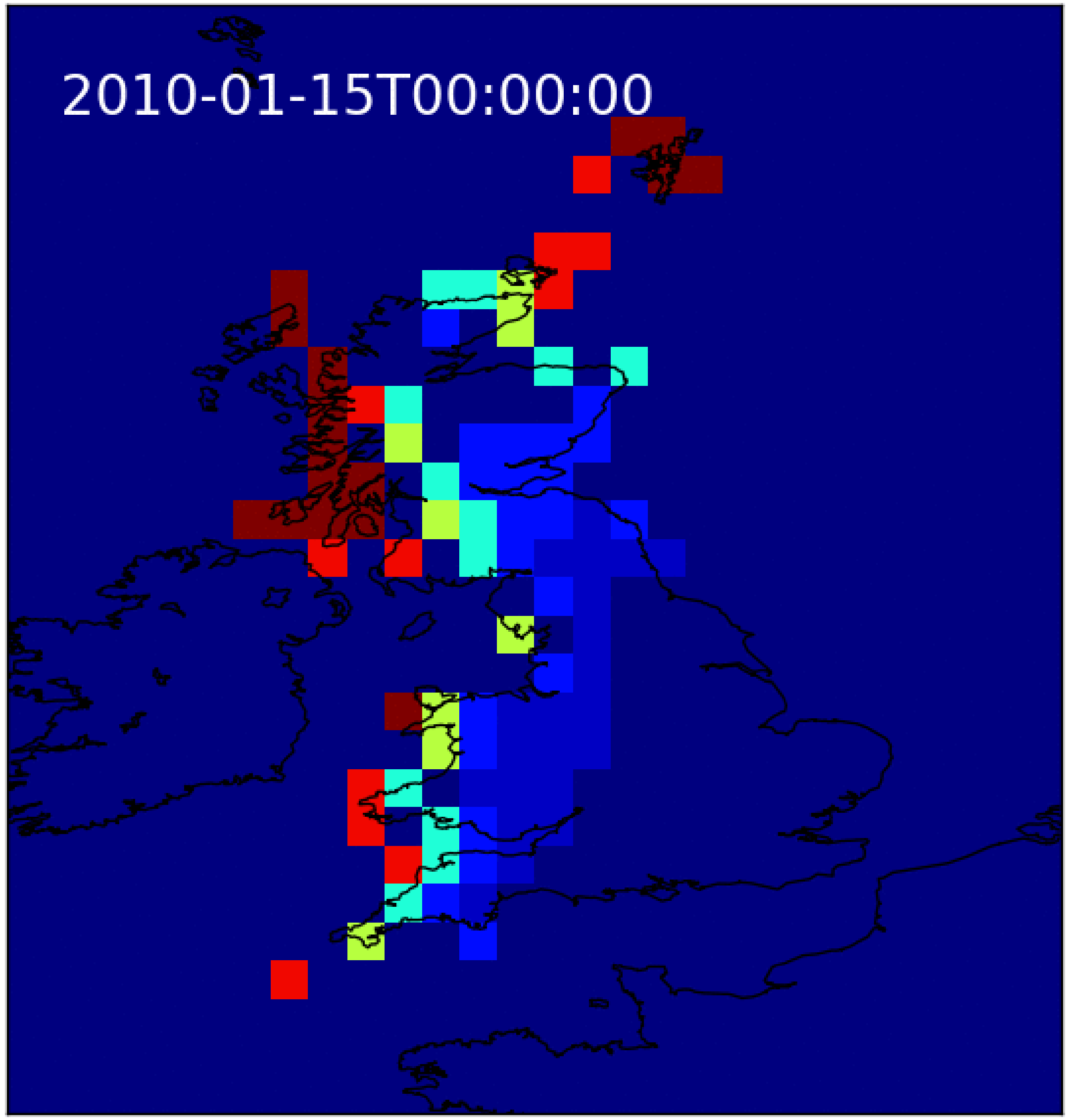
Weather data – On and offshore wind

- For wind use NCEP Climate Forecast System Reanalysis (CFSR
  - Ingests (assimilates) historical observations (satellites, radiosondes, surface stations, etc) every 6 hours from 1979-2010.
  - Produces a consistent representation of the state of the globa atmosphere and ocean on a 3D grid.

- CFSR gives us:
  - 2m and 10m instantaneous wind speeds every hour.
  - Data available both on and offshore on a uniform grid at 0.5°x0.5° (35km x 50km) resolution.
  - Adopt this as our reference grid for the model.
  - Extrapolate wind to hub height, use archetype farm power curves to get CF per hour.



Weather data – On shore wind



Weather data – Solar PV

- For solar PV (roof and ground mounted) use data from Satellite Application Facility on Climate Monitoring (CMSAF).
  - Based on observations from Meteosat First and Second Generation – geostationary satellites covering Europe and Africa – between 1983-2013.
  - Satellite sees cloud cover which is converted to global horizontal irradiance (GHI) and direct normal irradiance (DNI) by CMSAF*.

- Use physical model (in python) to:
  - Convert GHI and DNI -> on panel irradiance given desired angle of tilt and orientation of module.
  - Power output obtained from simple model that accounts for impact of module temperature on relative efficiency given module type (here crystalline Silicon).

* For details see Meteosat Solar Surface Irradiance and effective Cloud Albedo CDR manual on www.cmsaf.eu

Weather data – Wind and Solar

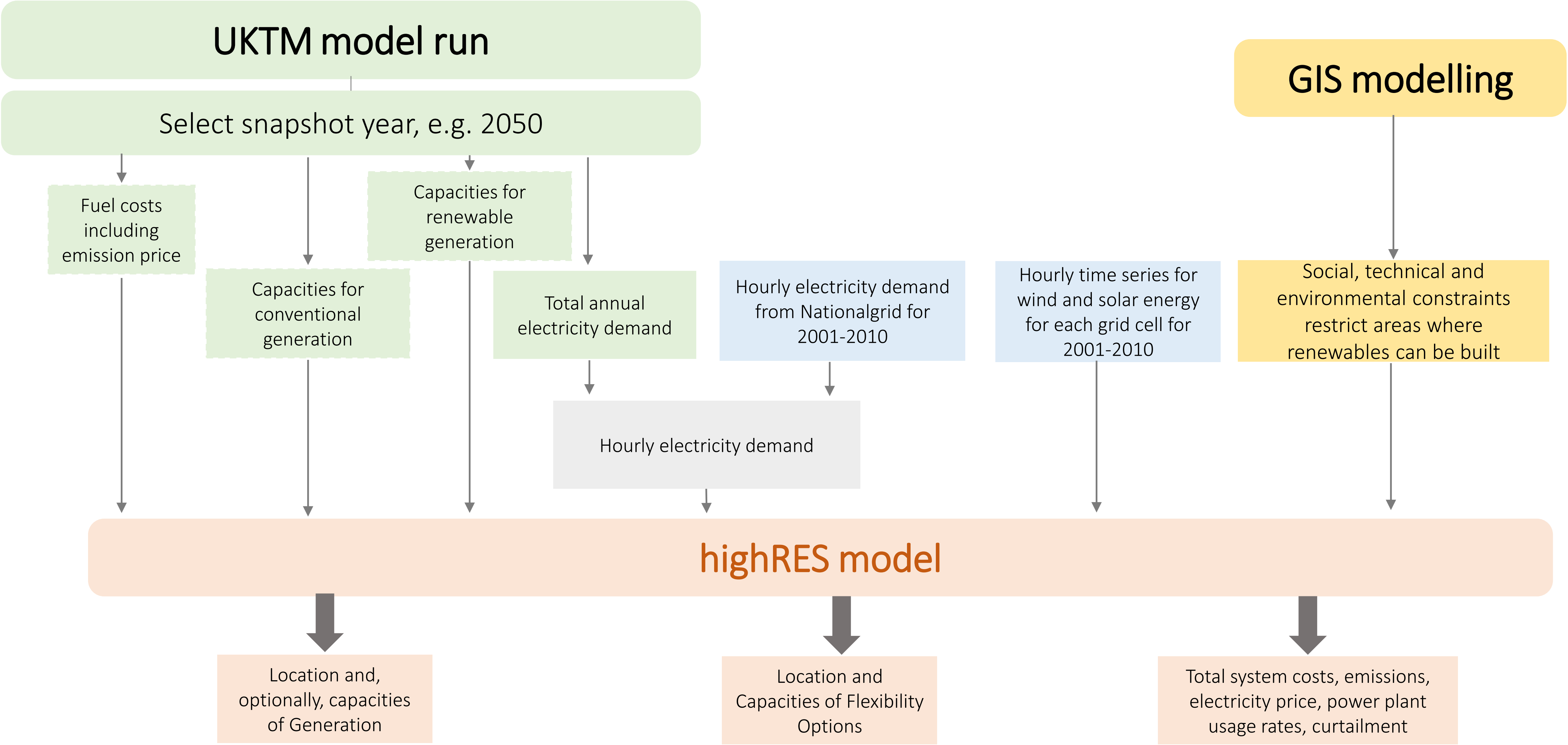
- Currently have 2001-2010 data processed and ready to use in highRES for both wind (on and offshore) and solar (version 1).

- Fed into the model as hourly capacity factors, i.e. the model decides how much capacity is built in a grid cell and that capacity is multiplied by CF to get generation.

- VRE component of model can run in two modes, either at full grid cell resolution or with the cells aggregated to zones *prior* to execution, i.e. each zone has an average wind and solar CF per hour.

- VRE capacity assessment (how many MW per grid cell, which can then be aggregated to the zones) based on a GIS analysis of technical, social and environmental constraints drawn from literature.

Methodology: Model linkage



highRES studies

- Various on going studies using highRES, two examples:

1. The impact of the variability of weather on the GB power system with high shares of VRE:
   - Most high resolution models use only one weather year and so do not capture inter-annual variability.
   - We use 10 weather years, one at a time, to begin to examine the impact of this variability on the integration of VRE.

2. A spatial analysis of opportunities and challenges facing GB VRE deployment:
   - Long term evolution of VRE planning restrictions uncertain.
   - Attempt to capture and explore this by varying social, technical and environmental constraints used to exclude areas of GB available for VRE deployment.
   - Aim to analyse a large set of scenarios.

Variability of the weather

UKTM NO CCS scenario which meets 2050 80% GHG reduction target

Capacities/demand for 2050:

Solar 43 GW
Wind offshore 38 GW
Wind onshore 31 GW
Nuclear 33
Biomass 7 GW
Geothermal 0.5 GW
Hydro 1.6 GW

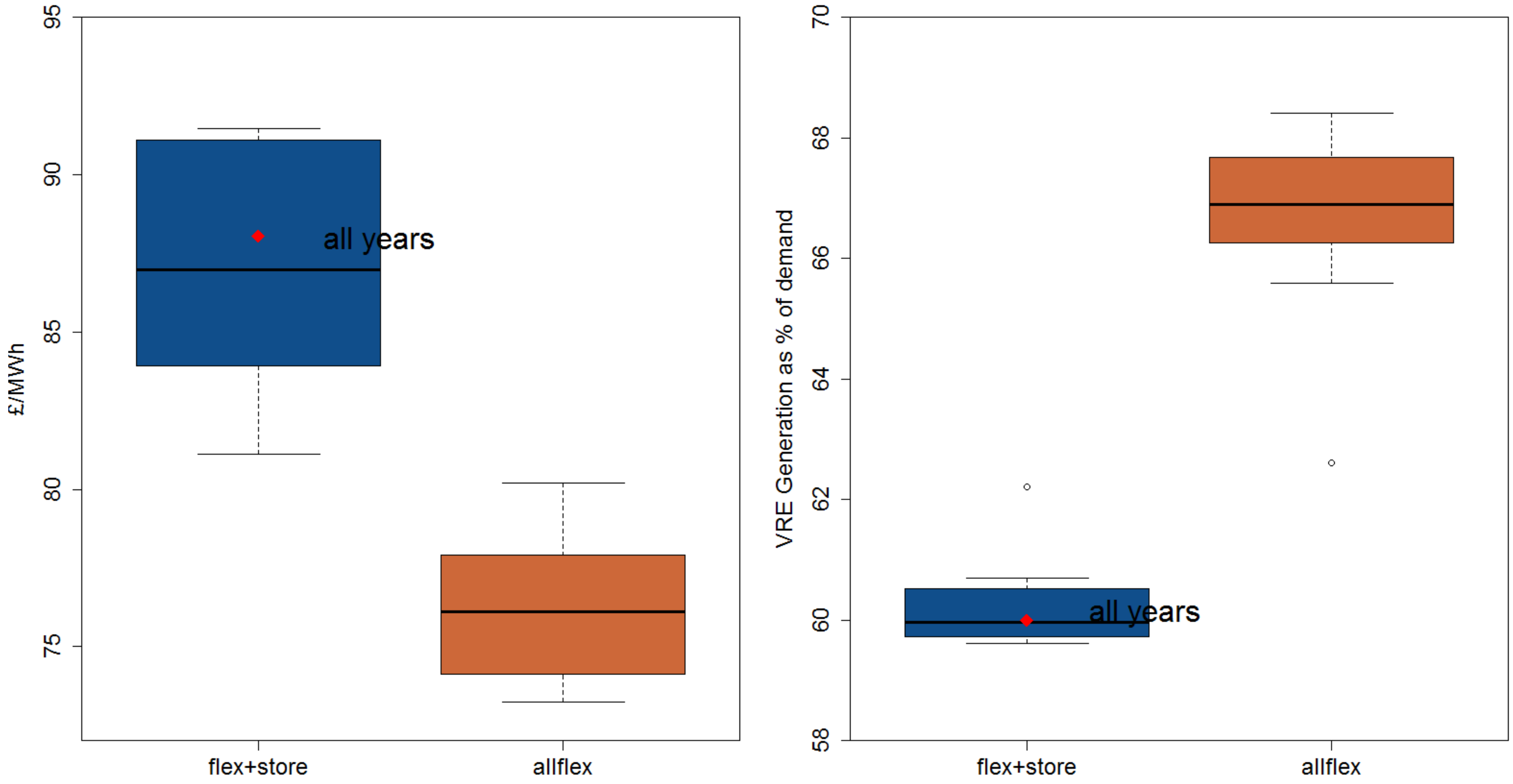
Electricity demand: 503TWh

20 highRES runs:

1. Flexible generation and storage free
2. All flexible options free

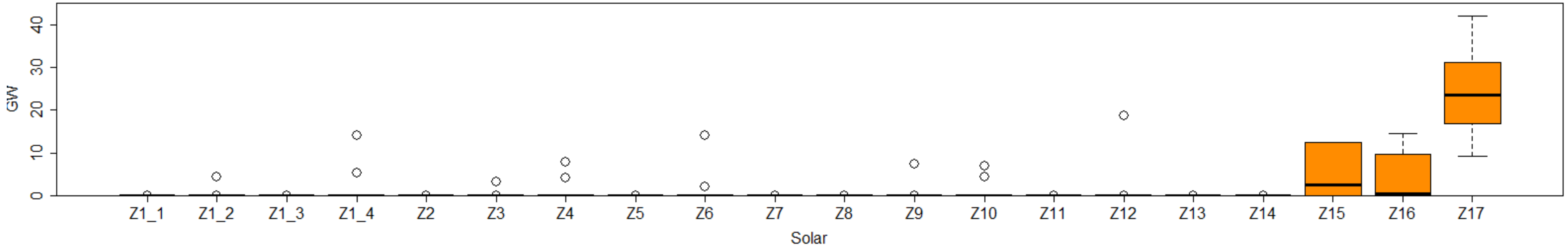
for 2001-2010, **one year** at a time
(all 10 years at once currently in progress)

Results: LCOE

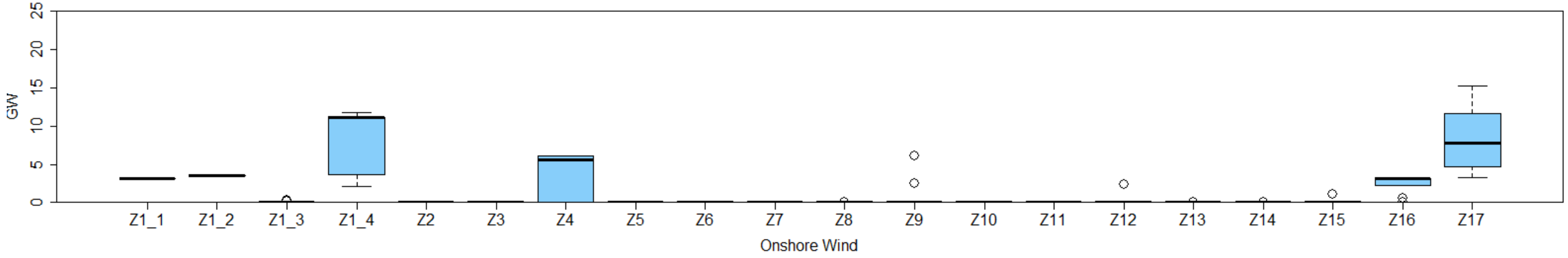


Results: Where are VRE located in the all flex scenario?

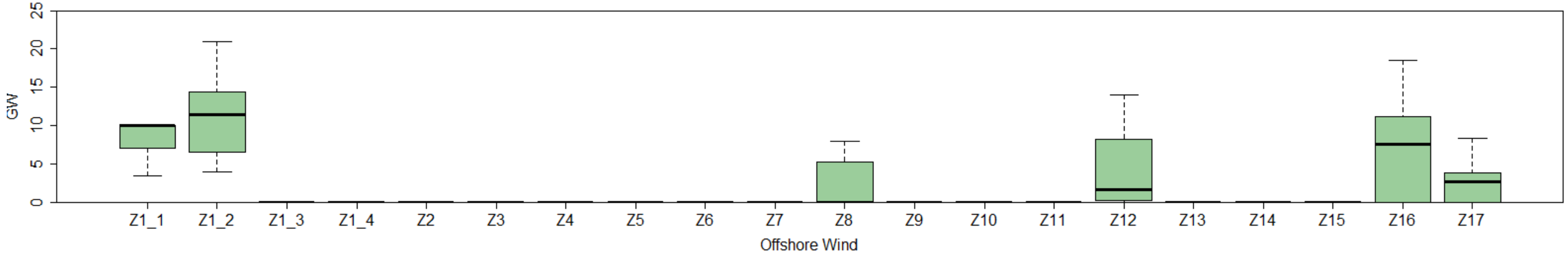
Solar



Onshore wind

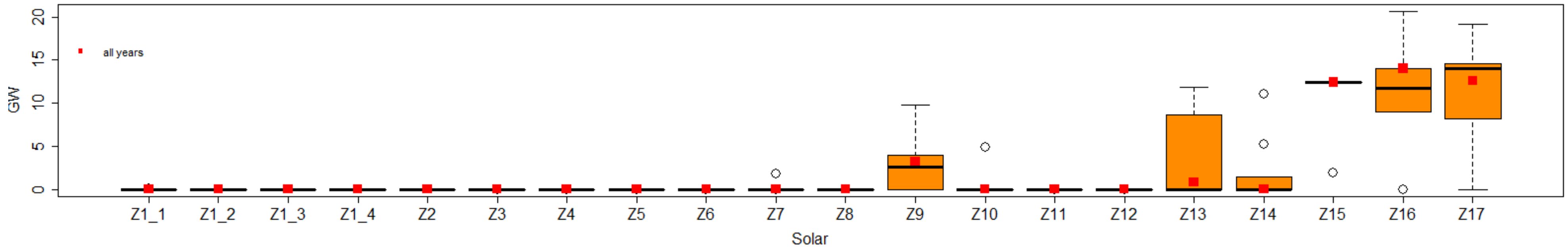


Offshore wind

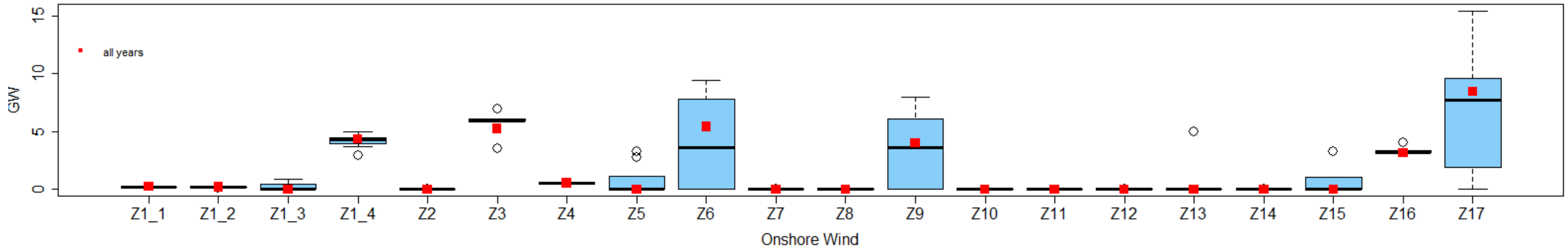


Results: Where are VRE located in the storage+flex generation scenario?

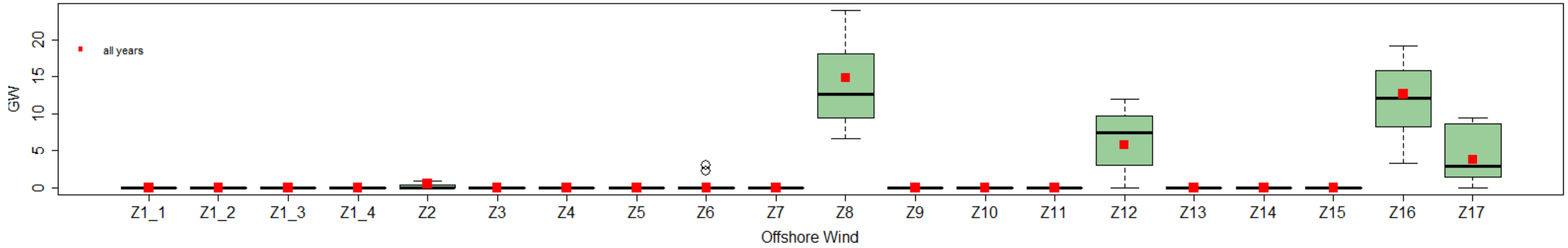
Solar



Onshore wind

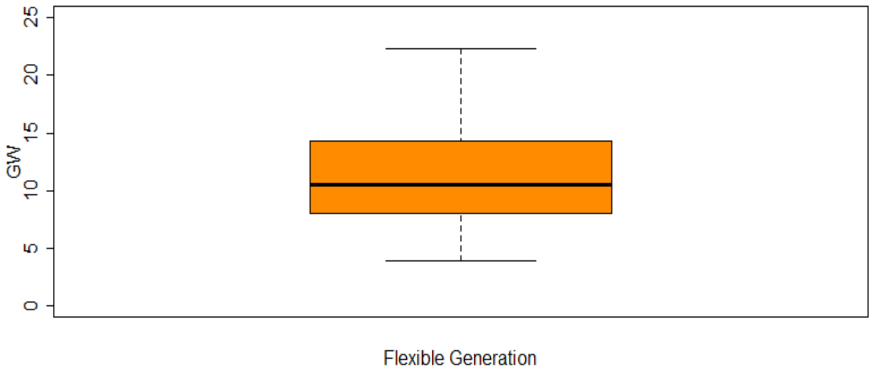


Offshore wind

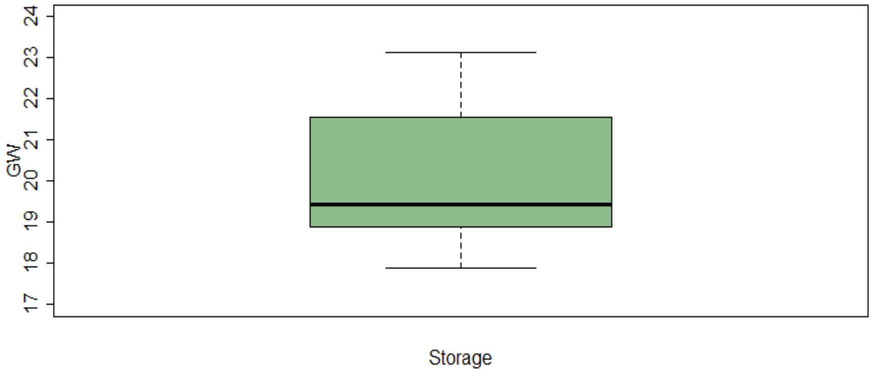


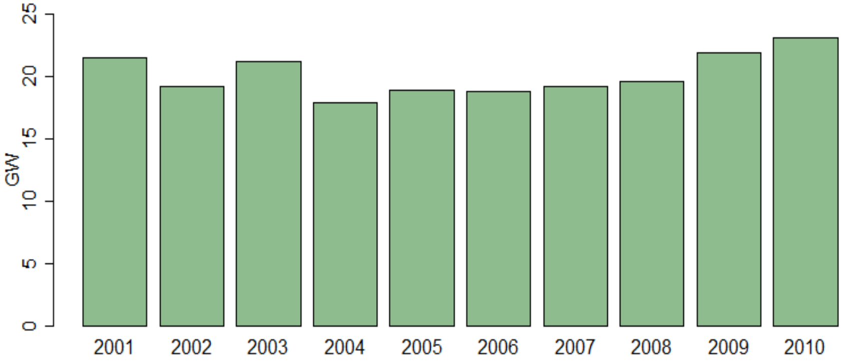
Results: What are the installed capacities of flexibility options (all flex scenario)?

Flex gen

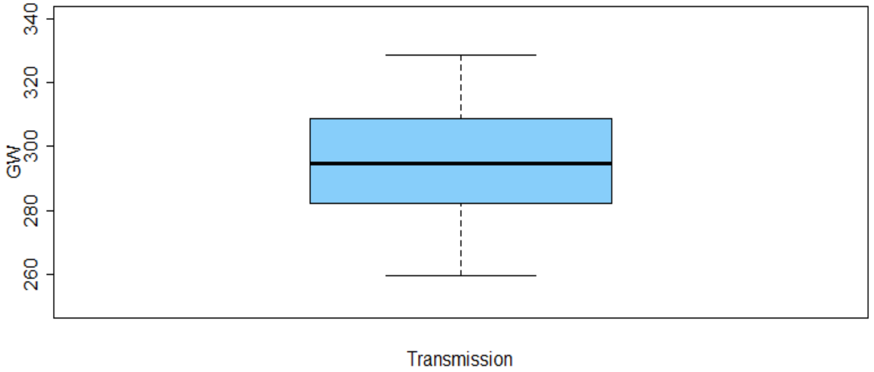


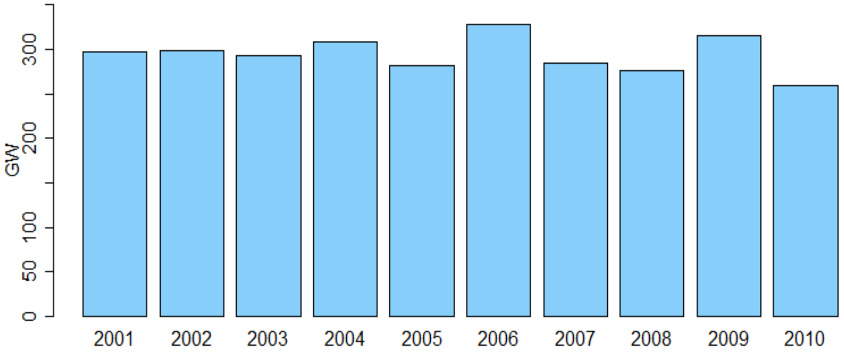
Storage



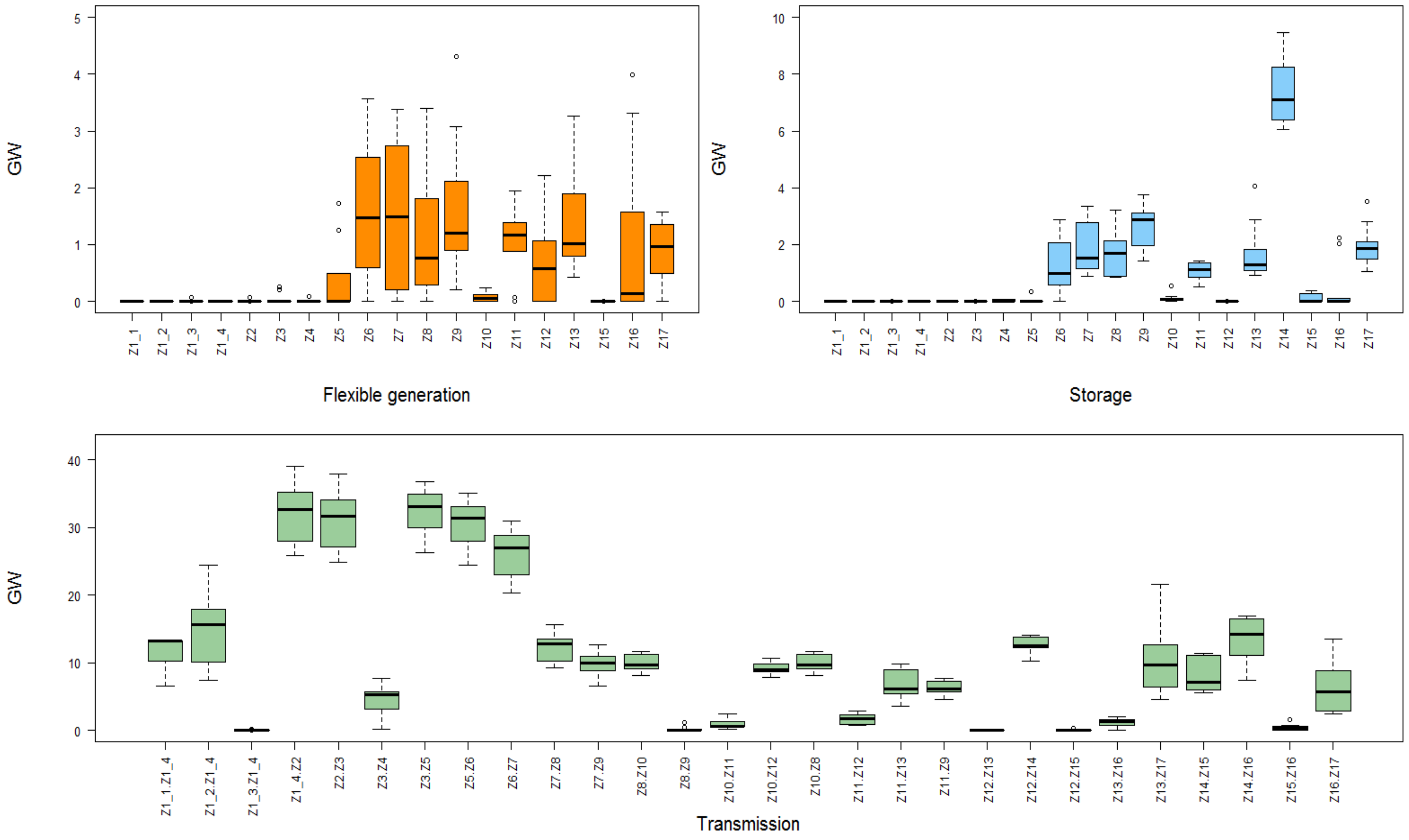


Transmission

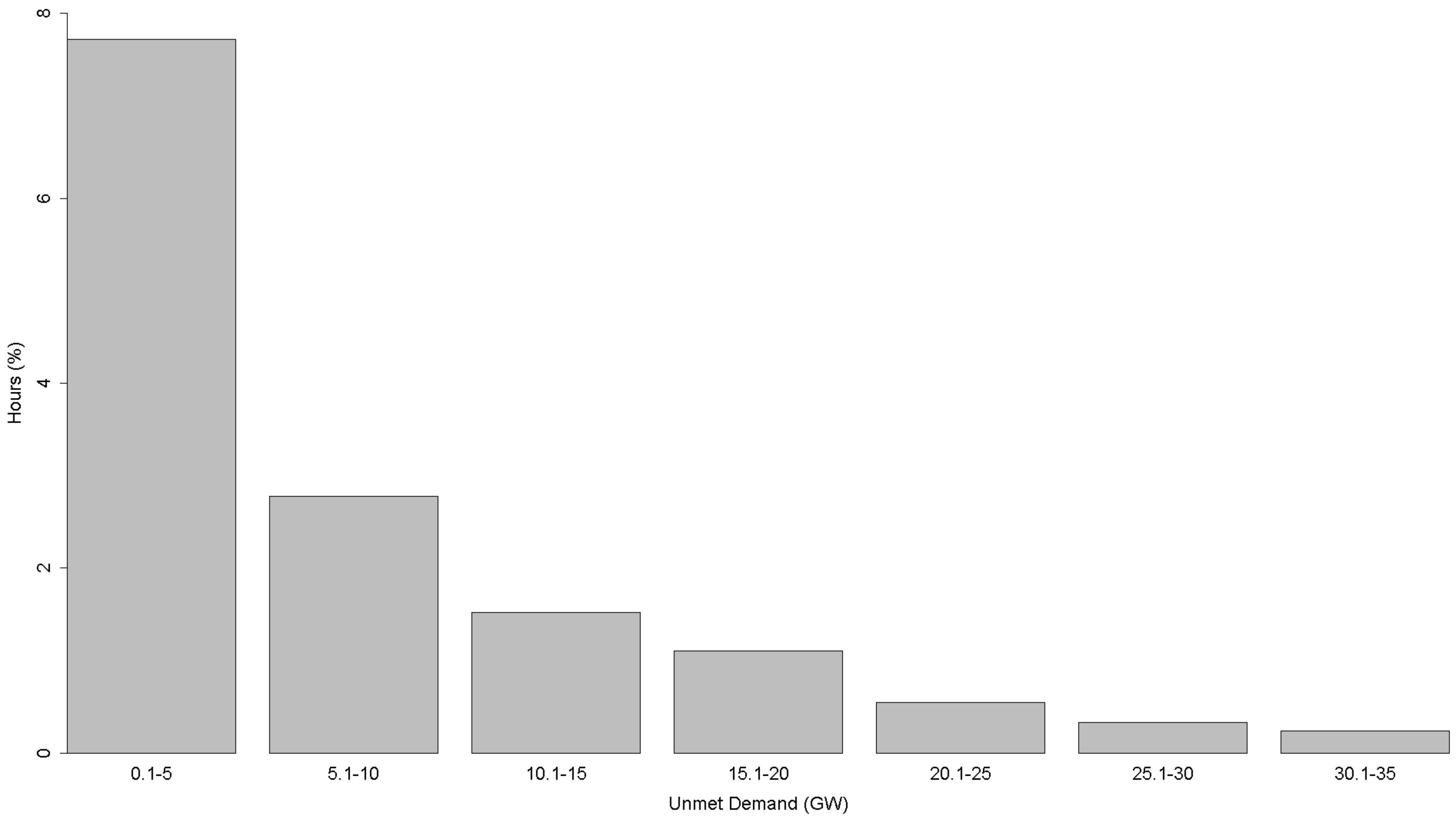




Results: Where are the flexibility options located (all flex scenario)?



Results: System design for 2001 applied to the other 9 weather years – unmet demand



Conclusions

- Using different weather year results in different optimal system designs.

- Flexibility options:
  - Capacities of storage and transmission generally consistent (at most +/-20%), flexible generation varies substantially -> likely due to meteorological specifics of each year, e.g. 2010 was a very poor wind year.
  - Flexible generation and storage located near demand centres but location sensitive to weather year.
  - Transmission line reinforcement consistently used to move VRE output from north to south and east from Cornwall/Devon.

- VRE:
  - Solar predominately in the south and central zones (transmission capacities fixed). Outliers of note in some years.
  - Onshore wind is deployed in Scotland and the southern England and again in central zones when transmission line capacity fixed.
  - Offshore wind favours maximum spatial diversity (Scotland, North Sea and southern England) when transmission reinforcement allowed.
  - For all three, while consistent patterns emerge, installed capacities per zone varies substantially between years.

- LCOE consistently lower when transmission reinforcement permitted.

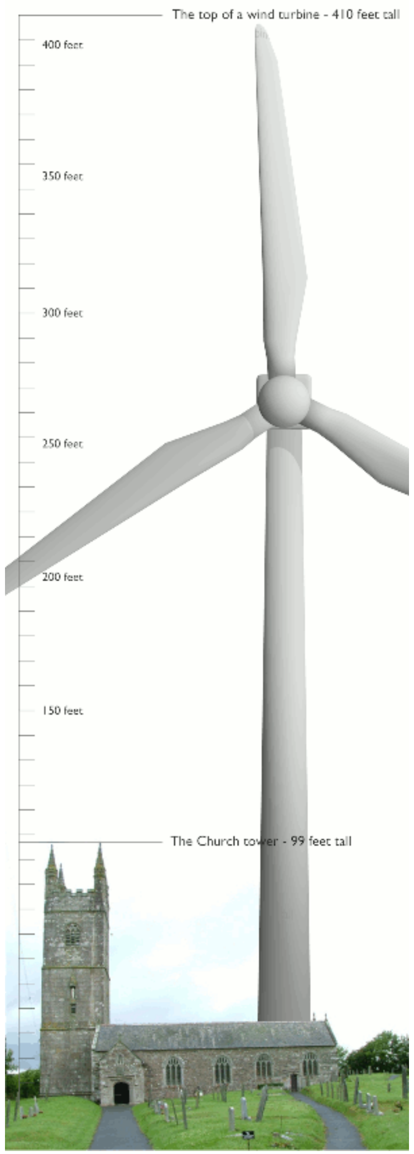
Spatial analysis of VRE deployment

- The location of VRE determines
  - total output and timing of production
  - technical feasibility
  - the impact on the environment and the communities they are sited

- Nationally support for renewables consistently high during the Energy and Climate Change Public Attitudes tracker (DECC) at around 75-80%

- However, local level opposition can be substantial with some particularly vocal groups, e.g. communities against rural exploitation (CARE) who oppose The Big Field project in Cornwall (see graphic).

- In recent years government seen as hostile to onshore wind having given more power to local communities to block development (c.f. fracking).



Spatial analysis of VRE deployment

- Lack of studies that assess multi-aspect restrictions for multiple VRE technologies
- And then quantify in terms of costs and system design the impact of these restrictions

- Methodology:

1. GIS analysis to develop a framework of scenarios that combine different levels of technical, social and environmental criteria of exclusion areas in order to scope out the feasible potential and location of VRE deployment.

2. Scenarios are used as input to highRES for 2050 snapshot year.

3. Costs, capacities of flexibility options and their locations and the deployment locations of VRE compared across scenarios.

GIS analysis: Onshore wind

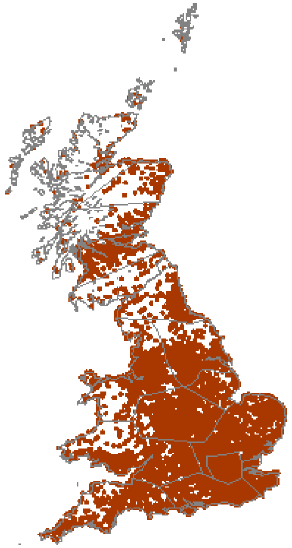
Env low

Soc low

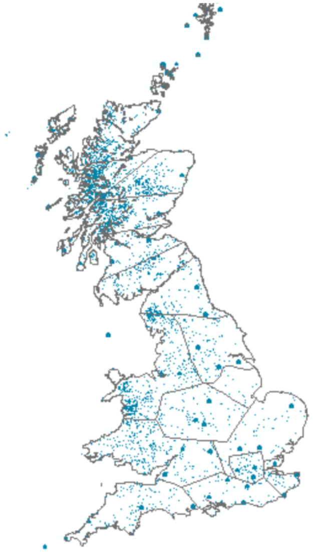
Tech low

Env high

Soc high

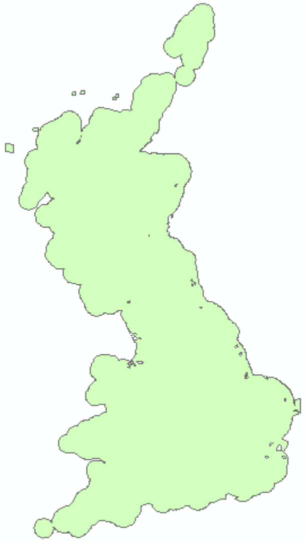


Tech high



GIS analysis: Offshore wind

Env
low

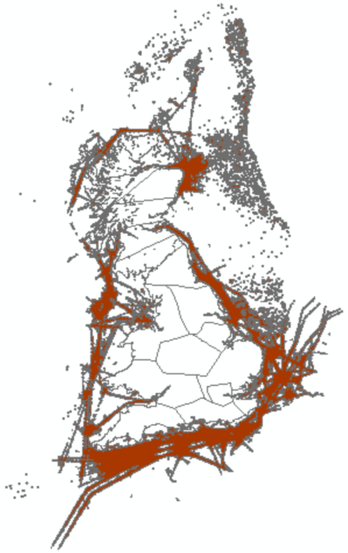


Soc
low

Tech
low

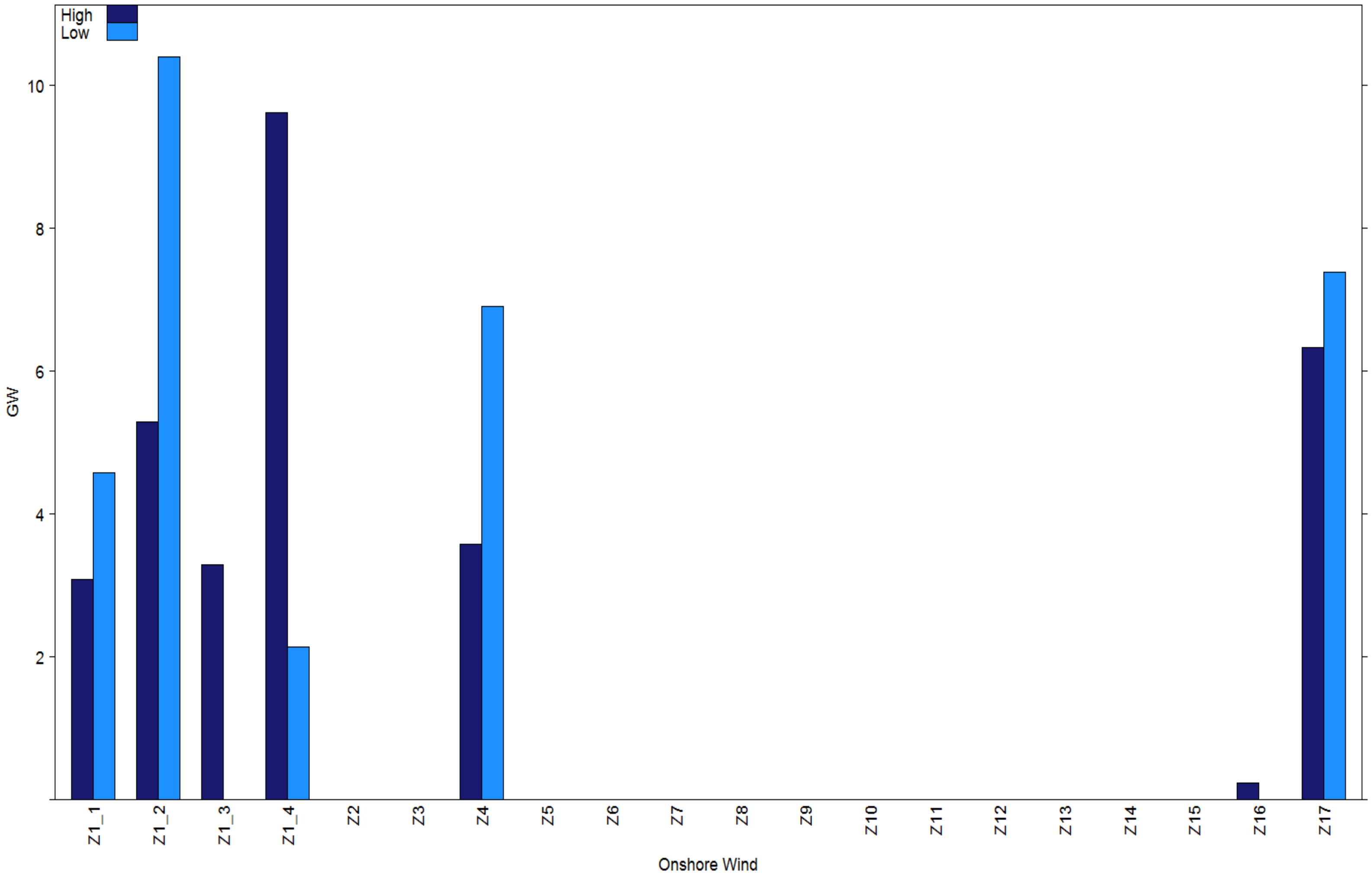
Env
high

Soc
high



Tech
high

Early results (still iterating on precise level of some restrictions)



- Variable costs in high restriction case at 14% greater than low restrictions.
- High case installs more storage (3.5 GW more), less gas backup (0.5 GW) and less transmission reinforcement (8% less).
- Some spatial differences, see left.

Ongoing work

- Modelling of neighbouring countries to include interconnection as additional flexibility option.
- Take demand profile shape changes due to, e.g. electrification of heating or transport, into account.
- Parameterise and include demand side response.
- Integrate the model world with the real world:
  - Community/stakeholder engagement to understand barriers to VRE deployment
  - Possible policies/regulation to overcome them
  - Broadly combine technical modelling with a social science perspective