# …ated electricity-gas system modelling and analysis and development of future fuels

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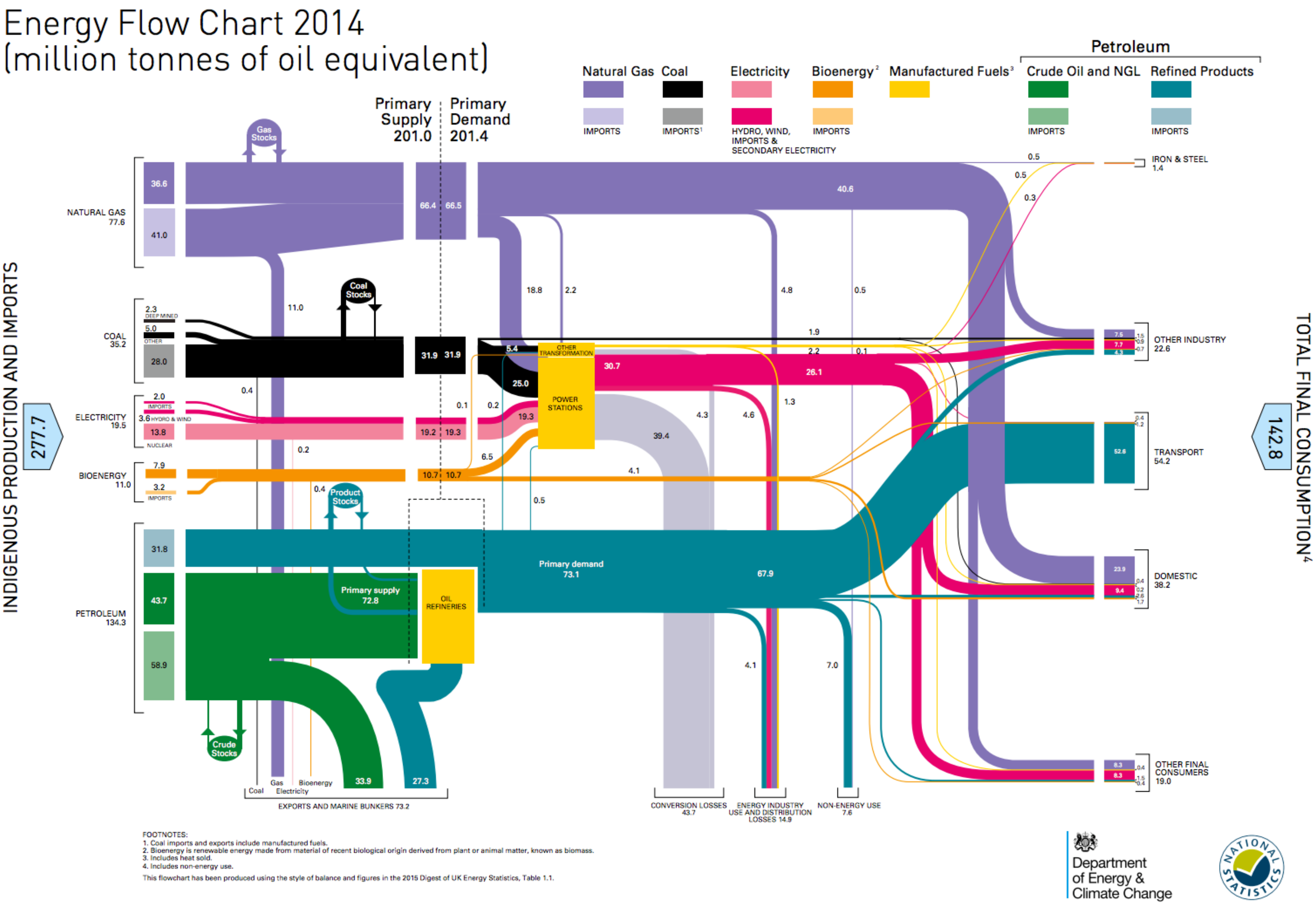
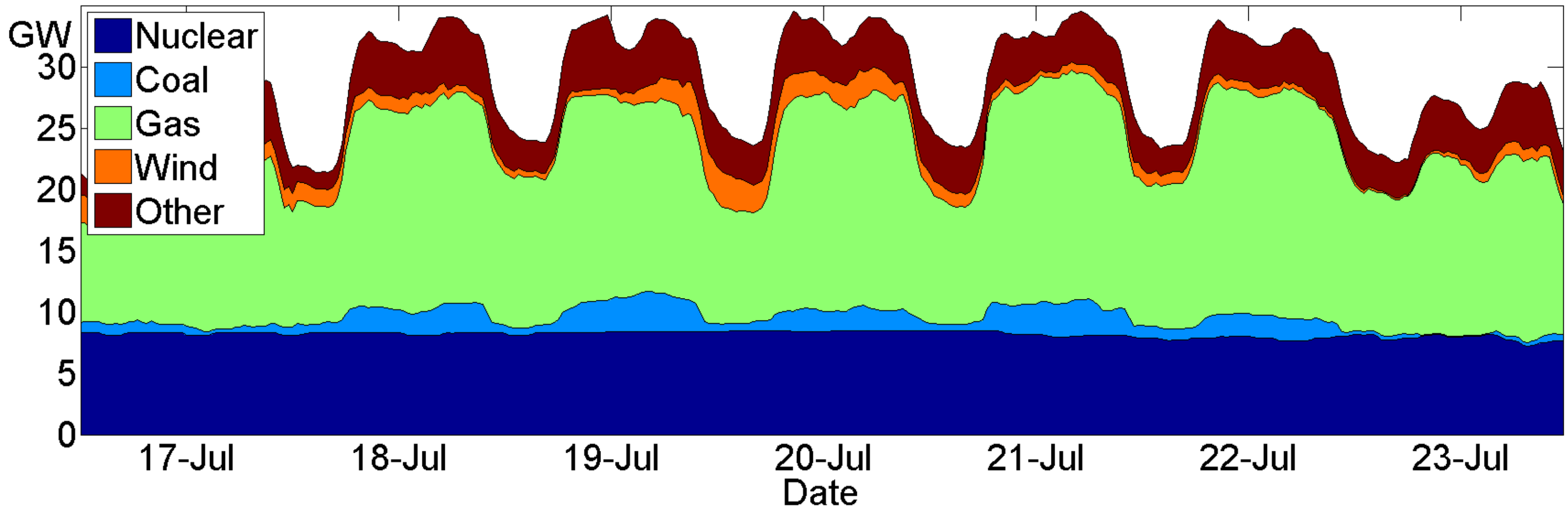
MEM Congress

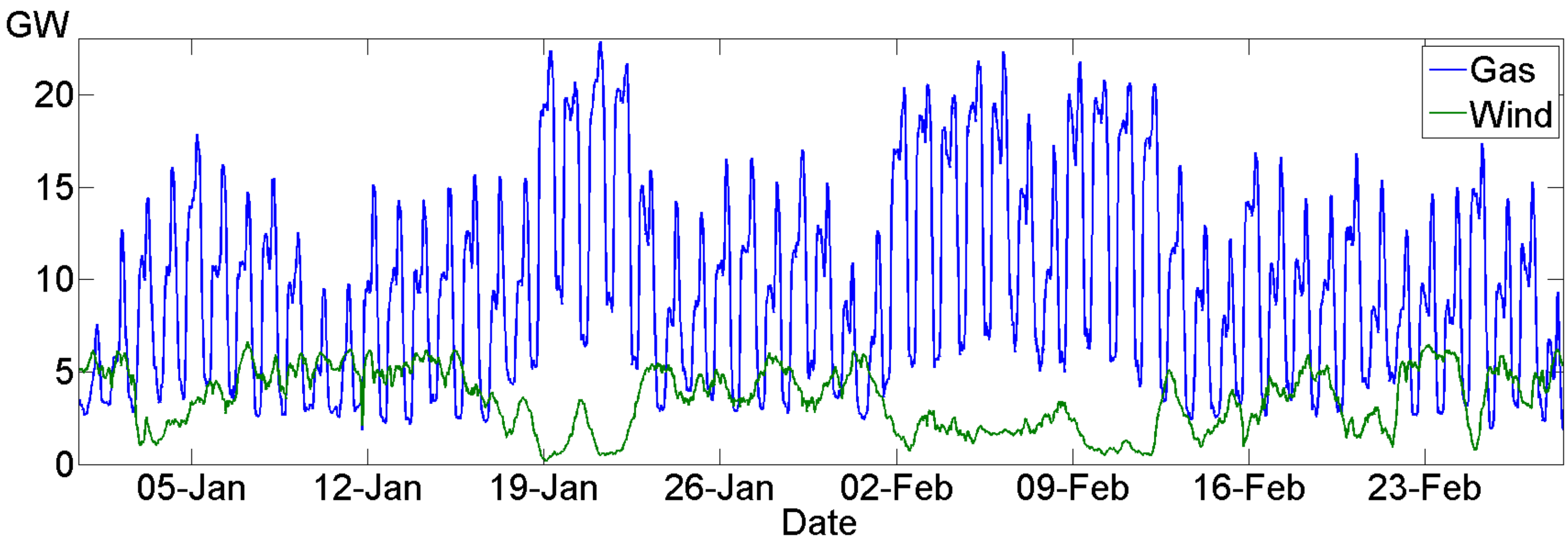
Cartagena, 1st November 2019

# Background

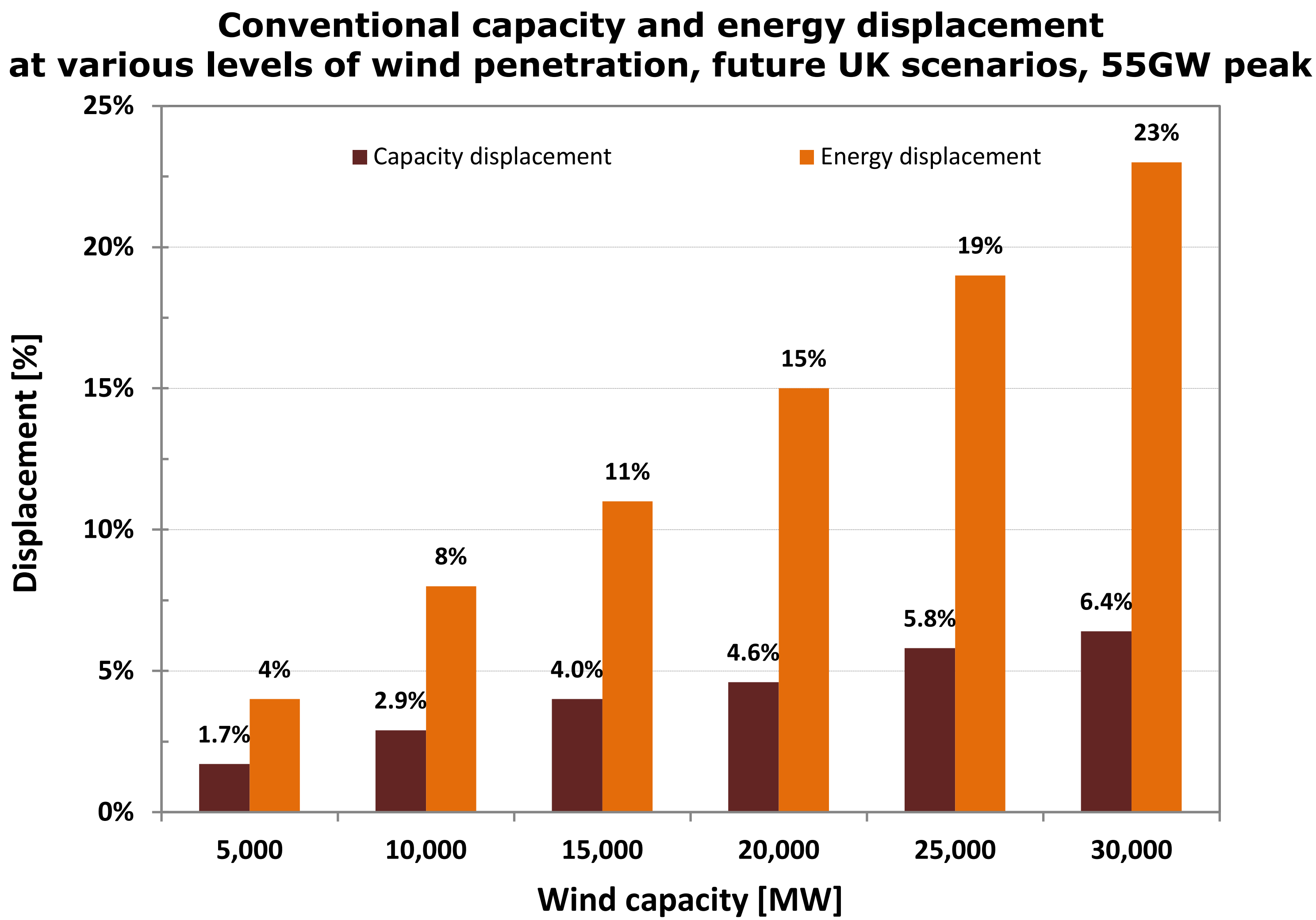

Energy Flow Chart 2014
(million tonnes of oil equivalent)
Primary Supply 201.0
Primary Demand 201.4
Petroleum
Natural Gas
Coal
Electricity
Bioenergy²
Manufactured Fuels³
Crude Oil and NGL
Refined Products
IMPORTS
IMPORTS¹
HYDRO, WIND, IMPORTS & SECONDARY ELECTRICITY
INDIGENOUS PRODUCTION AND IMPORTS
277.7
TOTAL FINAL CONSUMPTION⁴
142.8
NATURAL GAS 77.6
COAL 35.2
ELECTRICITY 19.5
BIOENERGY 11.0
PETROLEUM 134.3
Gas Stocks
Coal Stocks
Product Stocks
Crude Stocks
OTHER TRANSFORMATION
POWER STATIONS
OIL REFINERIES
Primary supply 72.8
Primary demand 73.1
IRON & STEEL 1.4
OTHER INDUSTRY 22.6
TRANSPORT 54.2
DOMESTIC 38.2
OTHER FINAL CONSUMERS 19.0
EXPORTS AND MARINE BUNKERS 73.2
CONVERSION LOSSES 43.7
ENERGY INDUSTRY USE AND DISTRIBUTION LOSSES 14.9
NON-ENERGY USE 7.6
FOOTNOTES:
1. Coal imports and exports include manufactured fuels.
2. Bioenergy is renewable energy made from material of recent biological origin derived from plant or animal matter, known as biomass.
3. Includes heat sold.
4. Includes non-energy use.
This flowchart has been produced using the style of balance and figures in the 2015 Digest of UK Energy Statistics, Table 1.1.
Department of Energy & Climate Change

# The impact of renewable generation



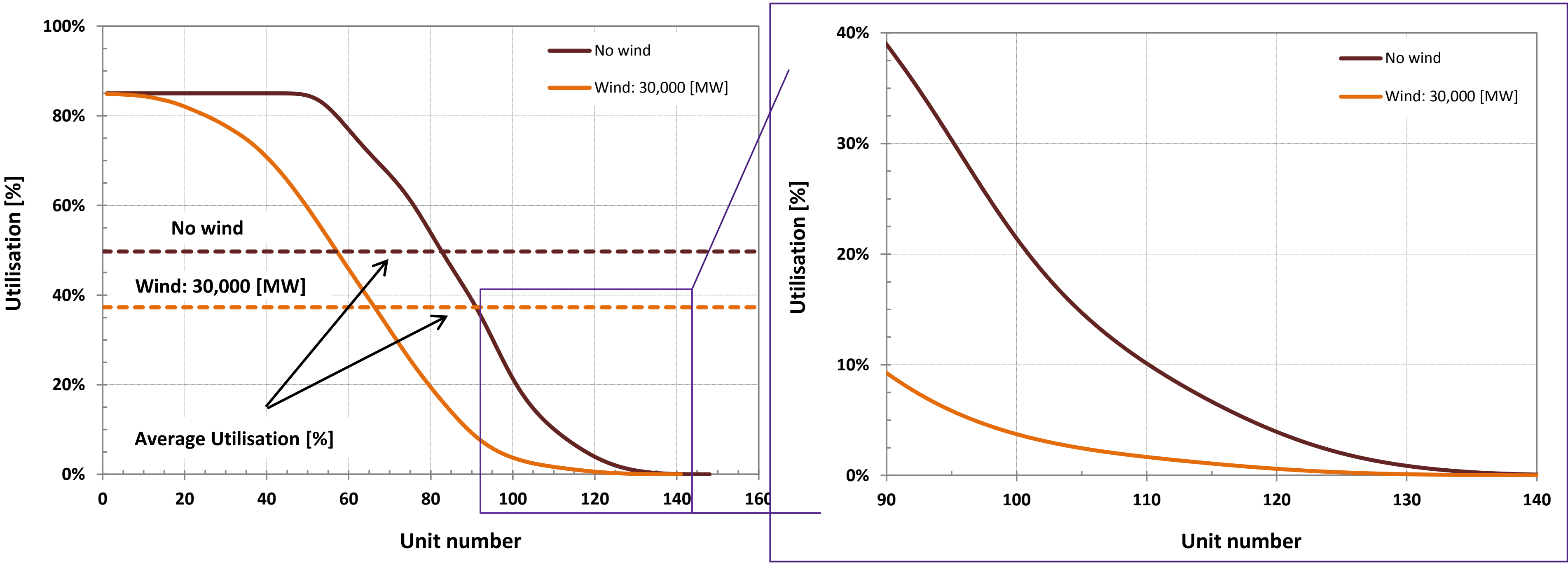
# Variability, energy and secure capacity




Source: P. Mancarella et al, Business case for flexible demand, Final report for the DD-FD project

# Cost impact of intermittency on conventional generators

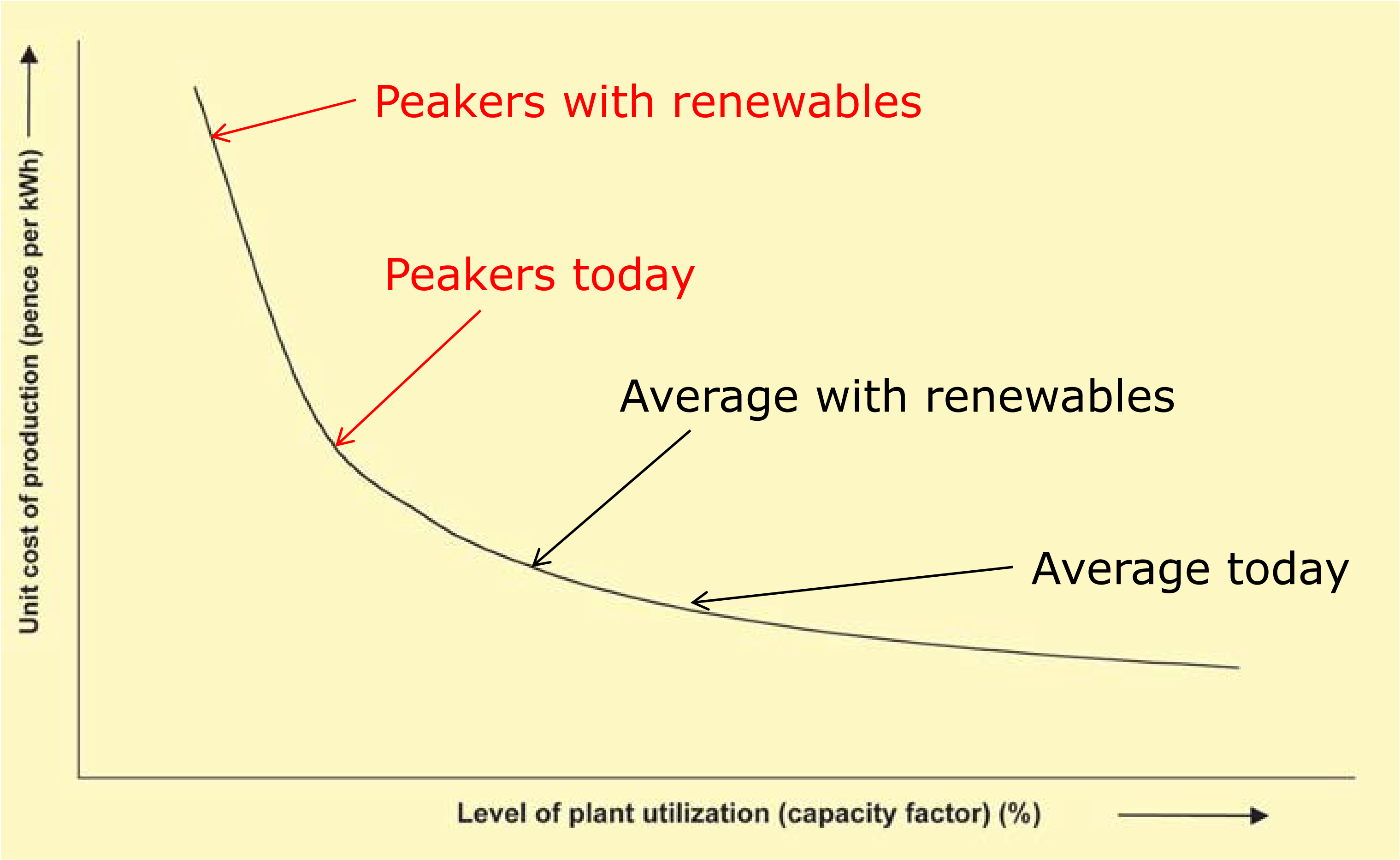
## Conventional plant utilisation (thermal only and wind-thermal system)




Source: P.Mancarella et al, Business case for flexible demand, Final report for the DD-FD project

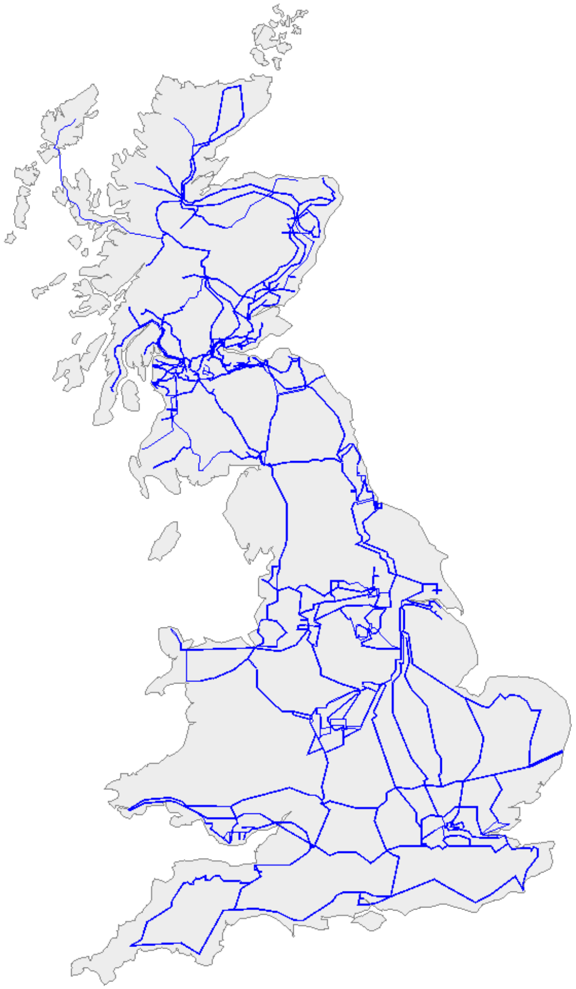
# What happens to conventional power plants?

**Effect of plant utilization on the unit cost of electricity production**




Source of underlying picture: The Cost of Generating Electricity, PB Power for the Royal Academy of Engineering

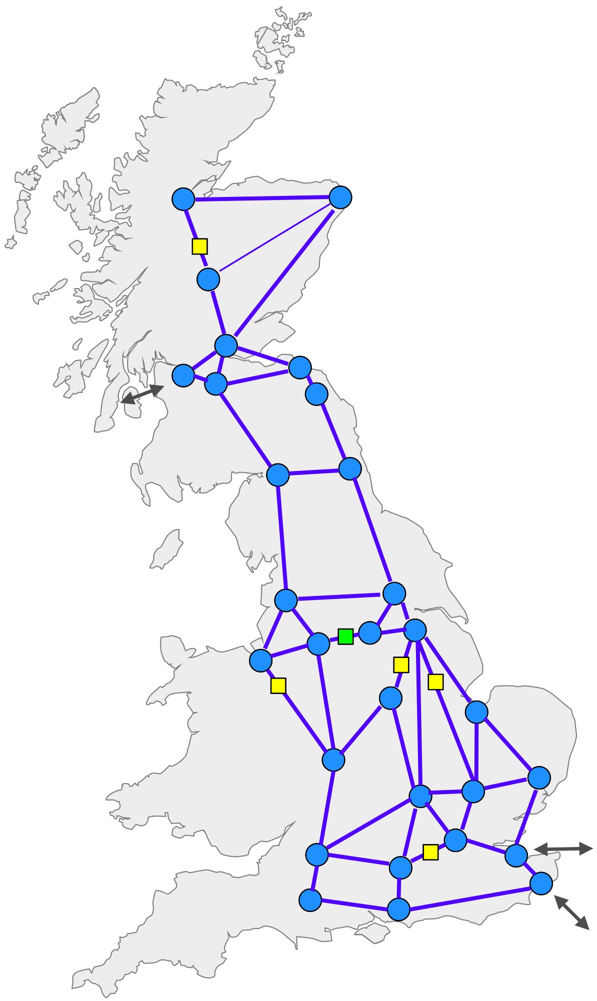
# Network studies



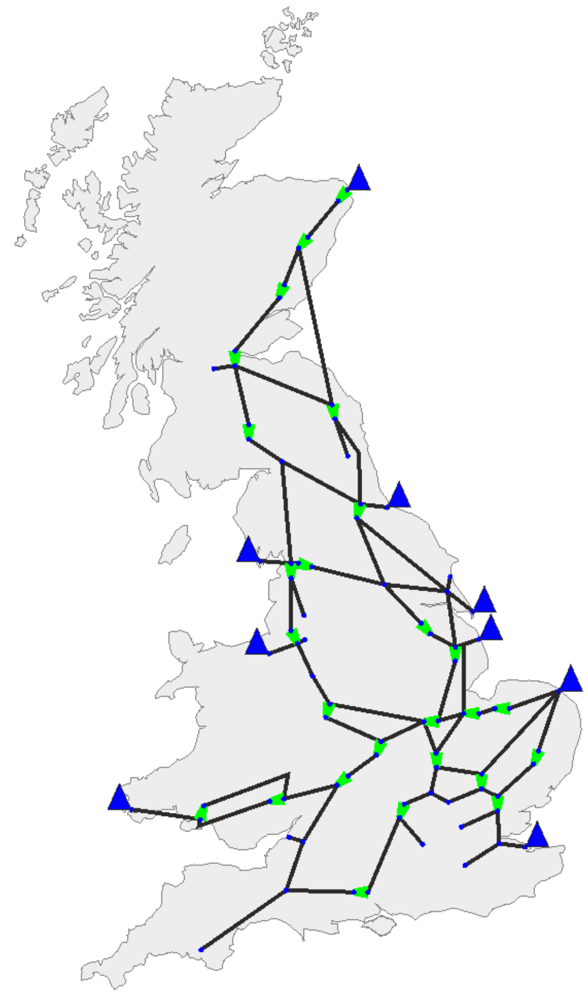
Electrical transmission network

Gas transmission network

# Network studies



Simplified electrical transmission network



Simplified gas transmission network

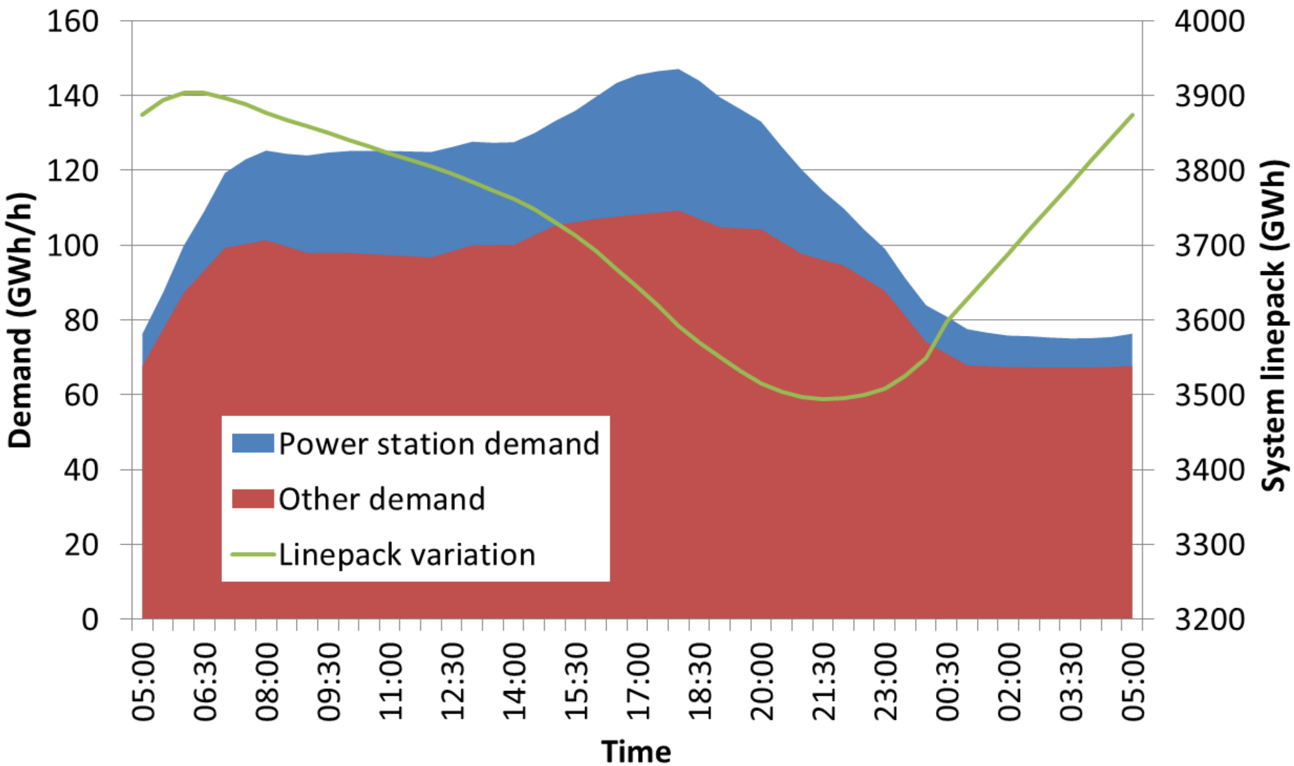
# How about system dynamics?
# Role of linepack

- Defined by quantity of gas in network's pipes at given time

- Used for:
  - Maintaining system pressures
  - Balance instantaneous changes in supply/demand
  - An indicator to network operators to system state
  - Means of gas network energy storage

S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718−731, 2015,

# Intraday linepack swing

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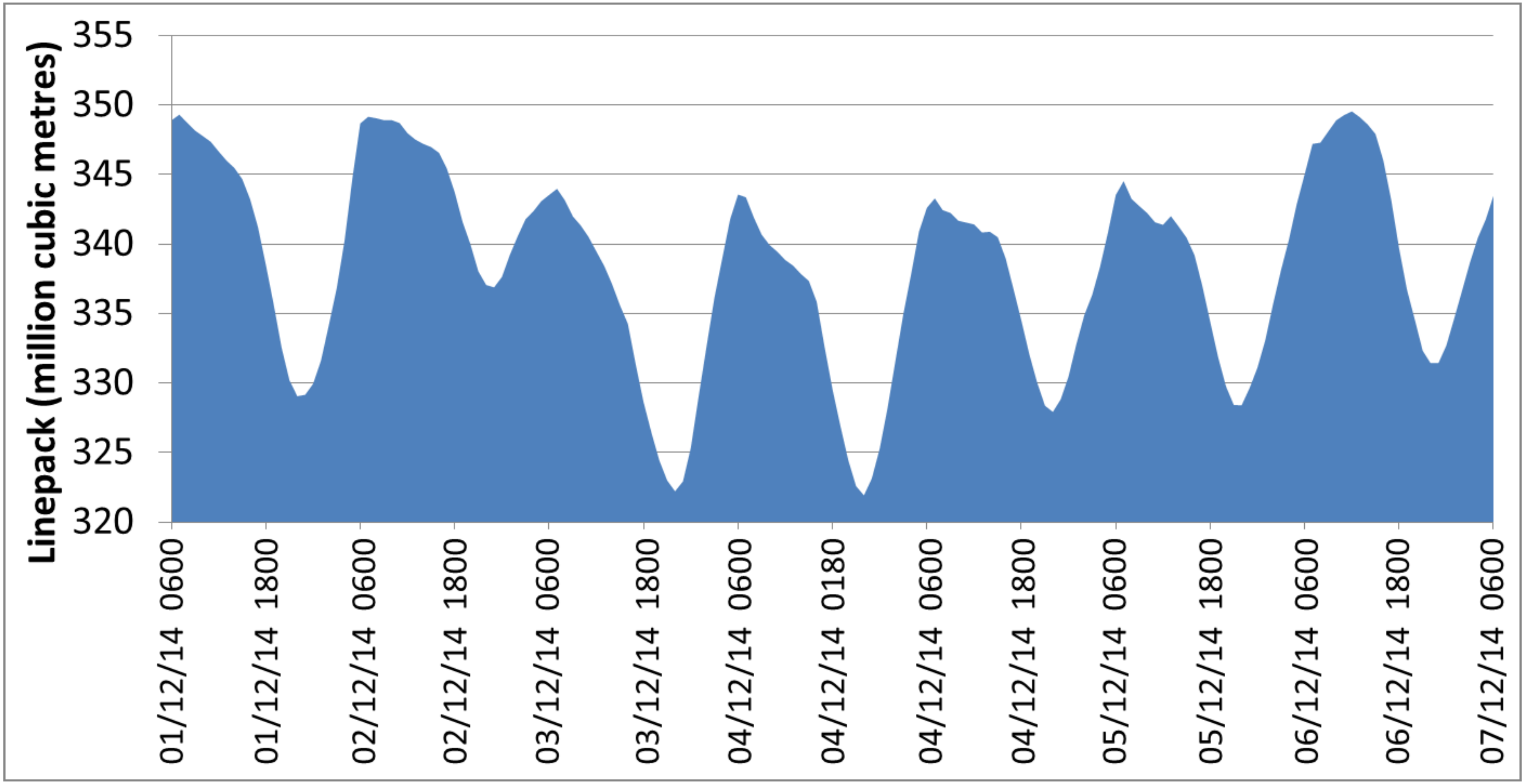
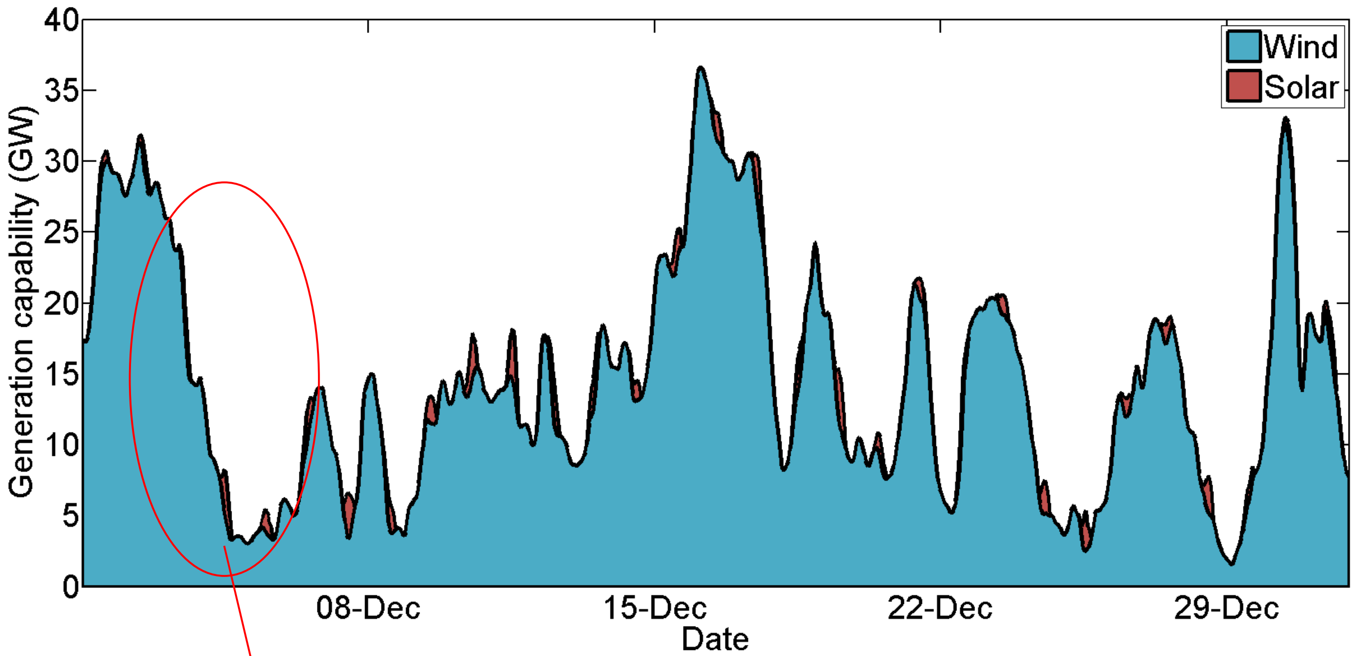
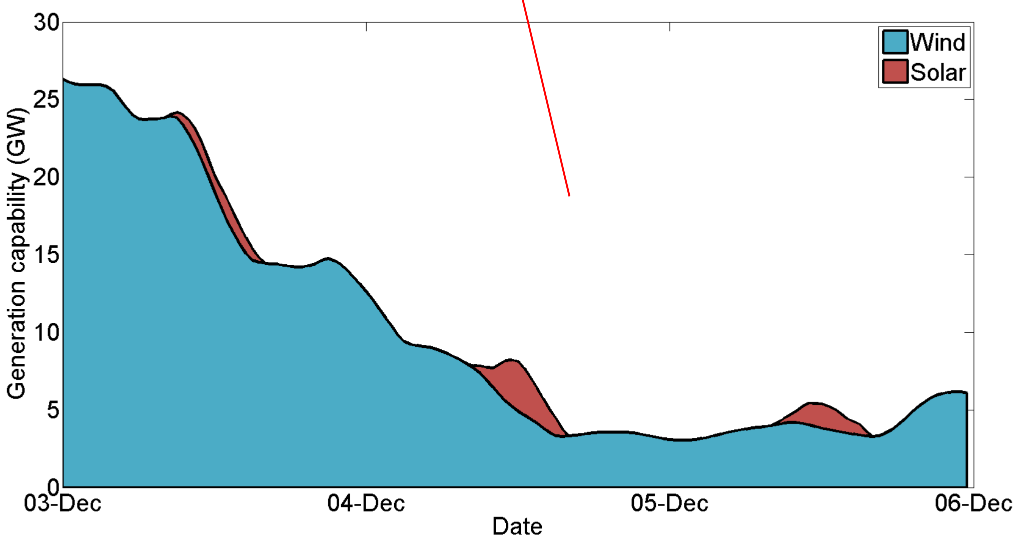
# Intraday linepack swing – Historical example



# RES variability and gas resilience

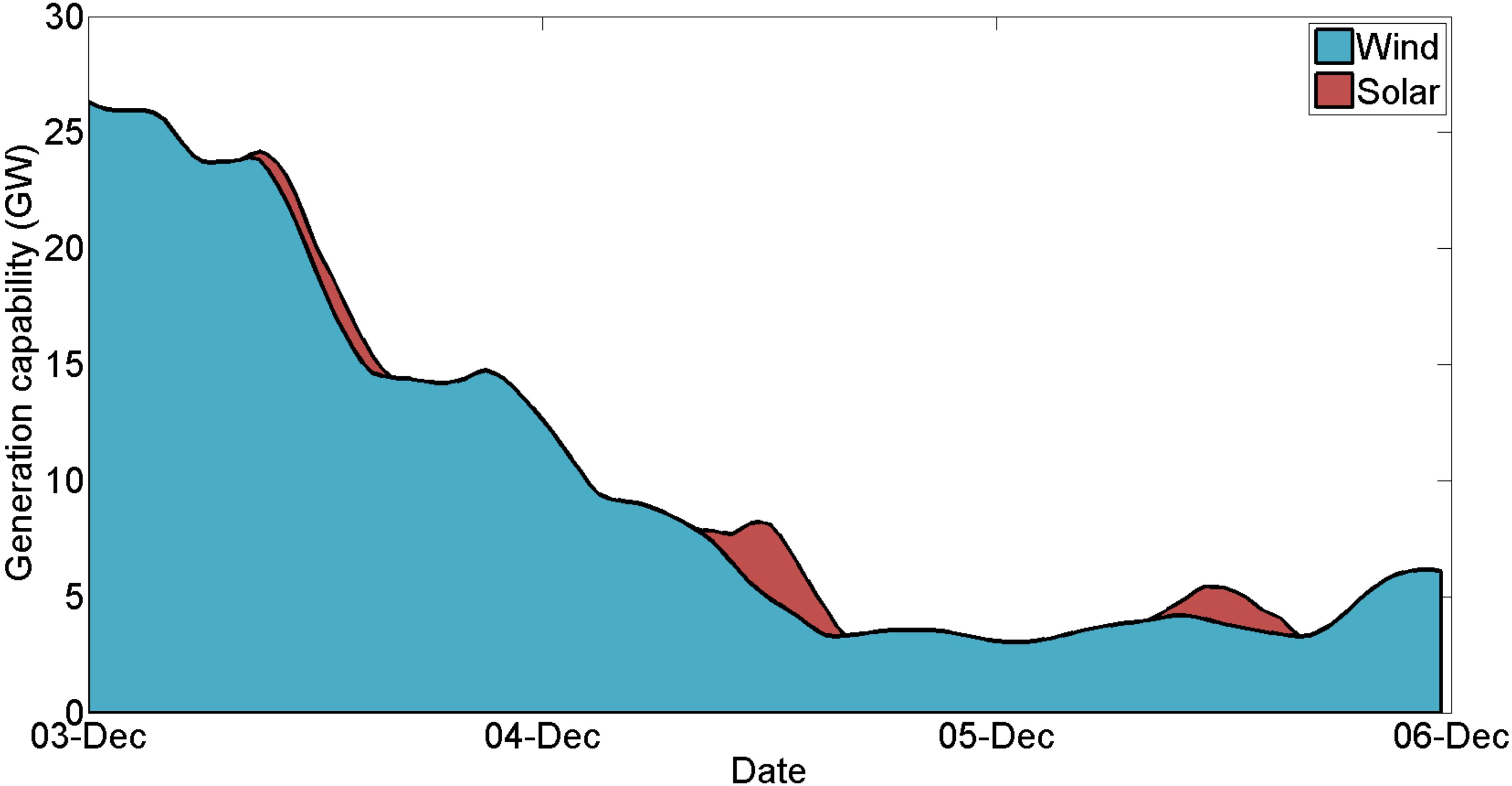



National Grid's 2030 Gone Green Scenario:

- Wind 47.5 GW
- PV 15.6 GW

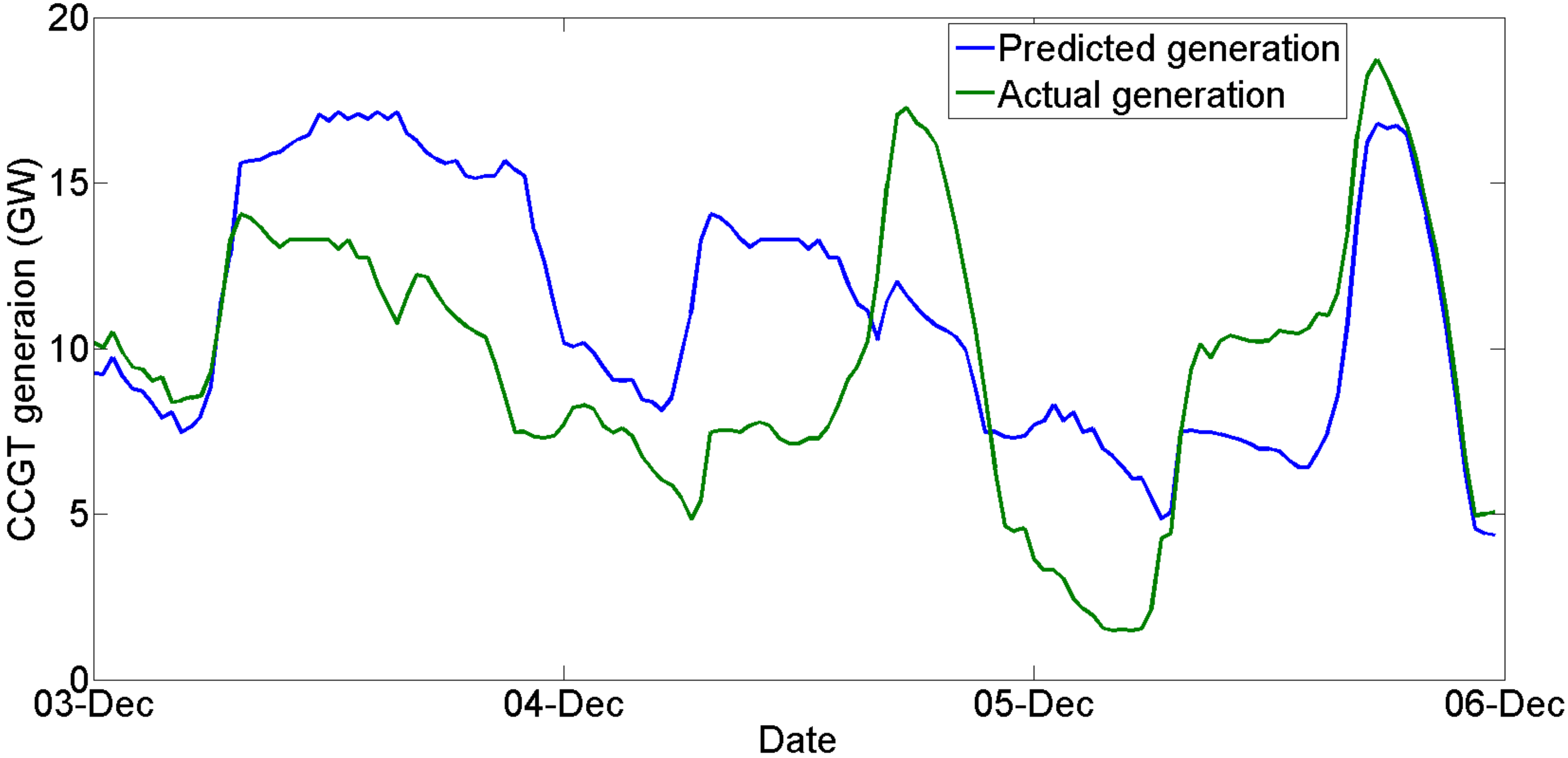
# Variability…
# and unpredictability…



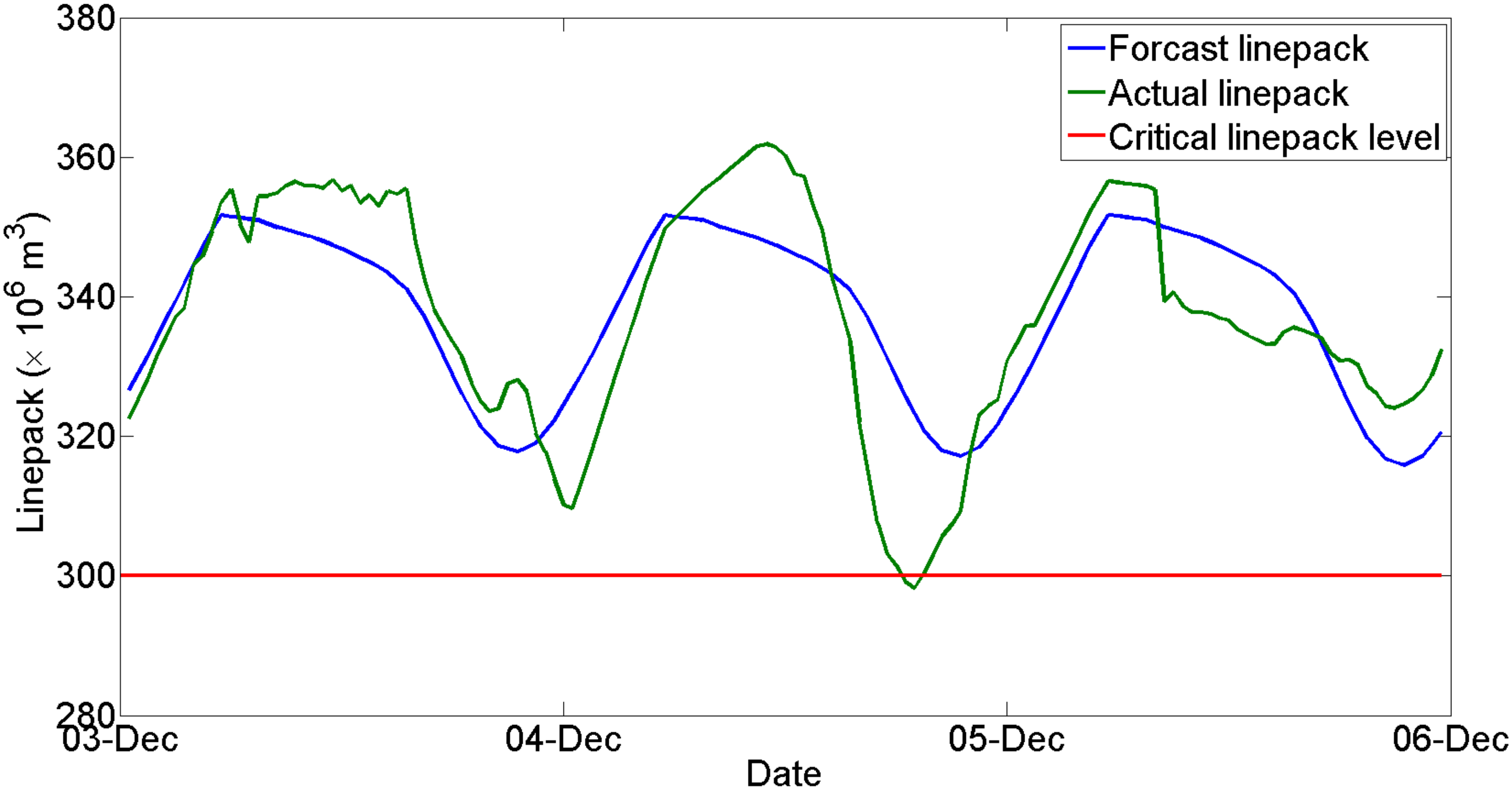
# Management by gas system operator

- Day ahead:
  - Sell transportation rights
  - Plan day's operation
- Within-day
  - Manage operation and network flows
  - Deal with real time changes to flows
  - Tendency to take retrospective action
  - On off-peak days, gas network operators extremely flexible allowing CCGTs to change their output at short notice
- After day
  - Act as residual balancer

# Impact of Renewable Energy Sources (RES) on gas network: Effect on CCGT generation

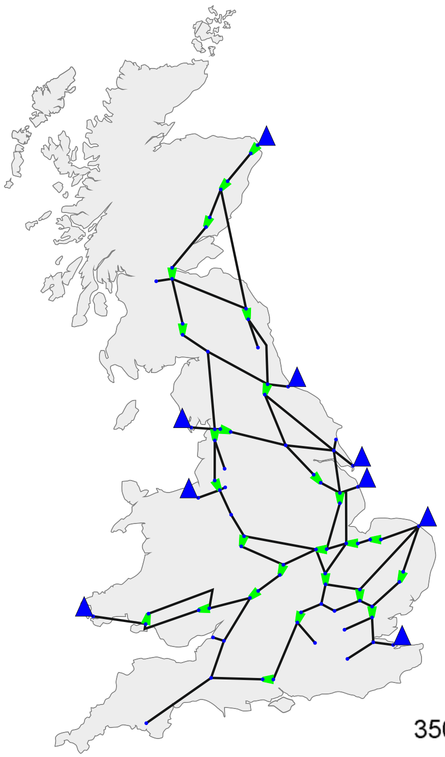


# Effect on linepack on gas network



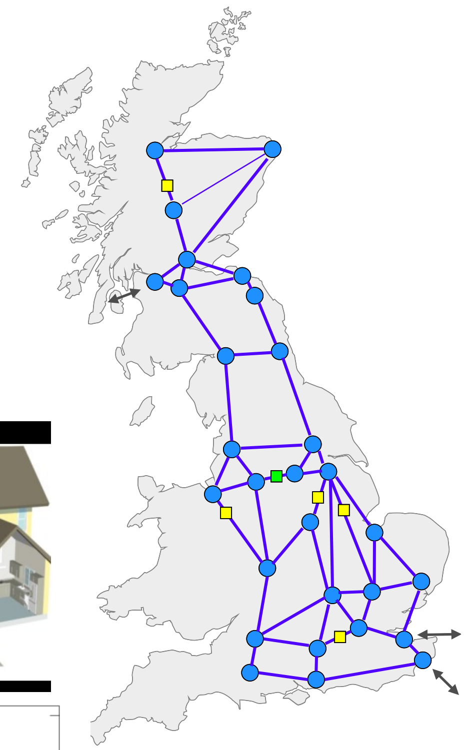
# Whole-energy system modelling: Integrated electricity-heat-gas systems

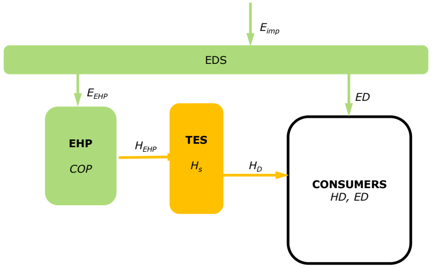
Gas network model

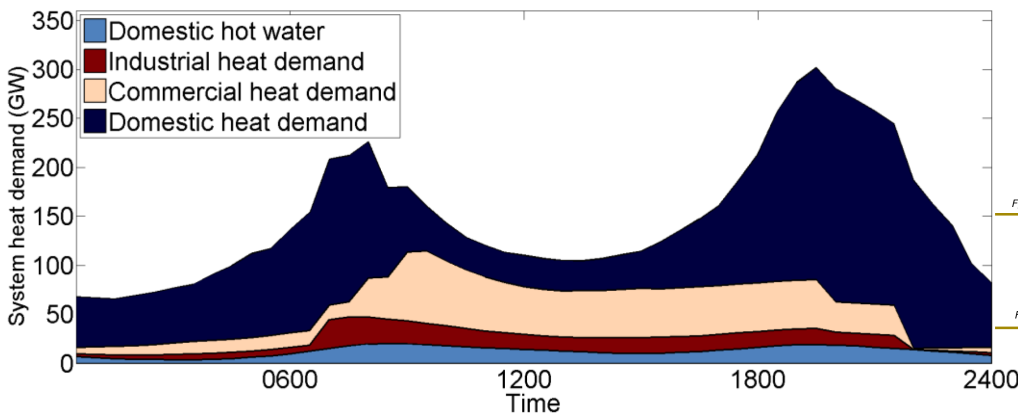


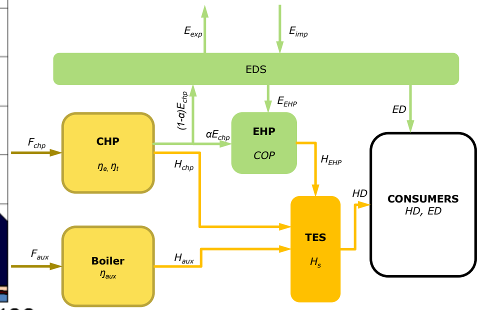
Heat regional model

Electrical network model





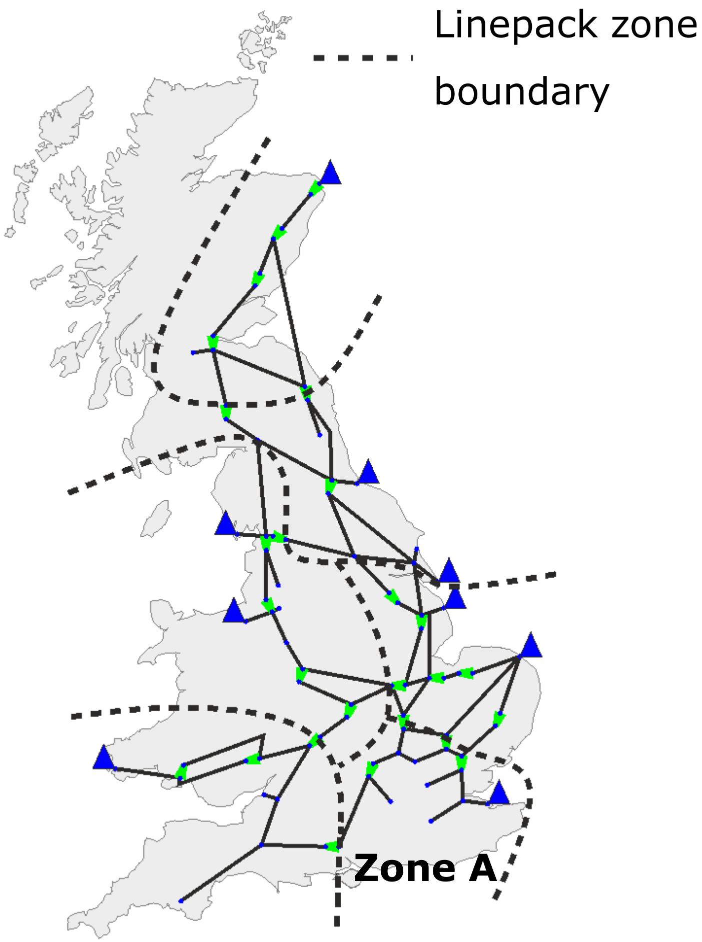



# Linepack flexibility for integrated system analysis

- For each linepack zone define:
  - Maximum/minimum linepack for transport
  - Upper/lower linepack limits
  - Linepack flexibility

- Each assessed through iteratively running steady-state gas flows for predefined maximum/minimum pressures or linepack




S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718–731, 2015,

# Integrated gas and electrical network flexibility

- Integrated metric considers
  - The upward generation capability of CCGTs from that scheduled over a given timeframe
  - Includes requirements for power system reserve
  - Linepack available to meet this flexibility
- Metric defined as the limit to increase in generation output considering bounds imposed by linepack limitations

S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718–731, 2015,

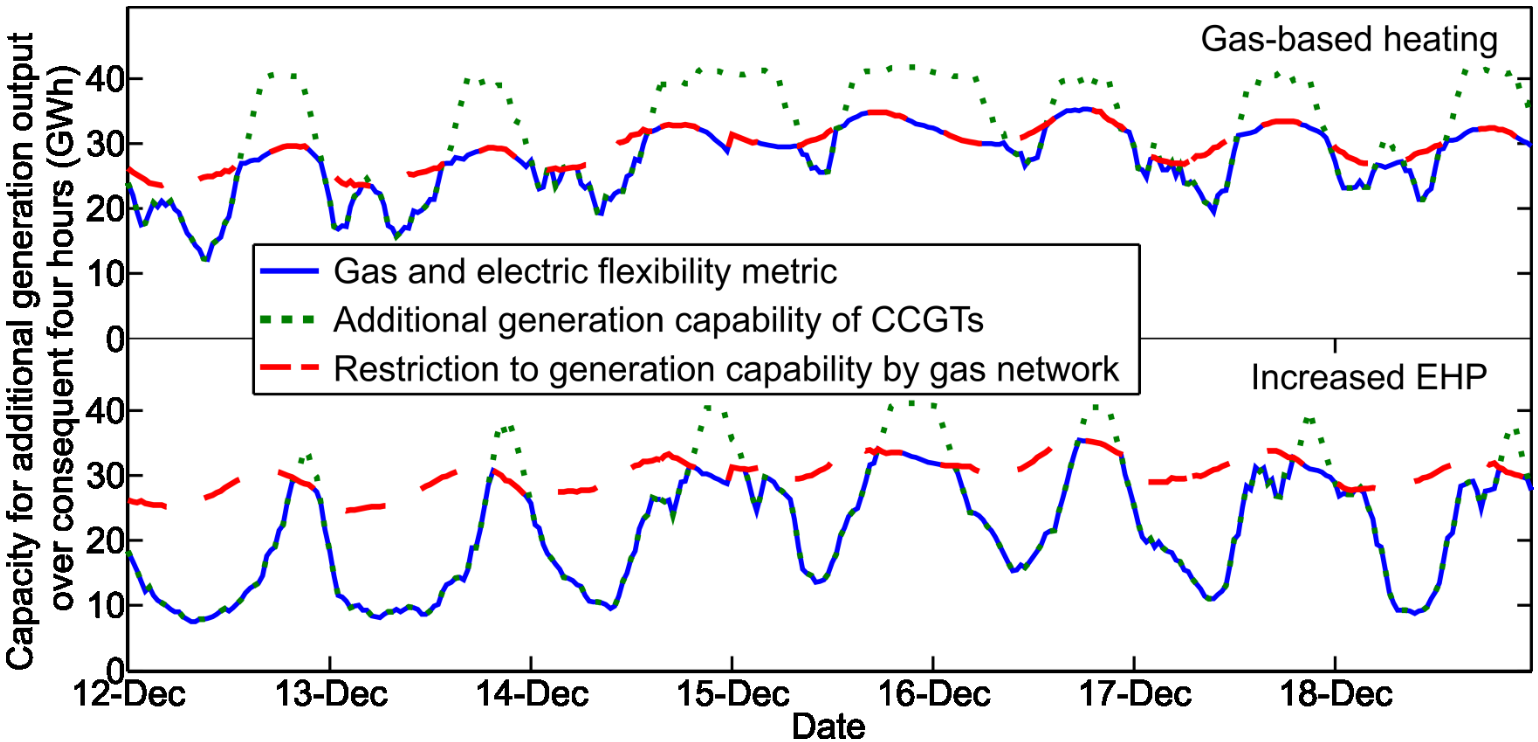
# Flexibility case study: operational impacts

- Gas network operation assessed at 0600
- Wind forecast for the day are assessed at 0600 at which point the CCGT unit-commitment for the day is scheduled
- Upon change to CCGT dispatch, then that scheduled linepack flexibility is utilized
- Gas is replenished by an increase in terminal/storage flow 2 hours after change in CCGT output
- Consider a flexibility utilisation period of 4 hours

S. Clegg, P. Mancarella, “Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems”, IEEE Transactions on Sustainable Energy, 7 (2), pp.718−731, 2015,

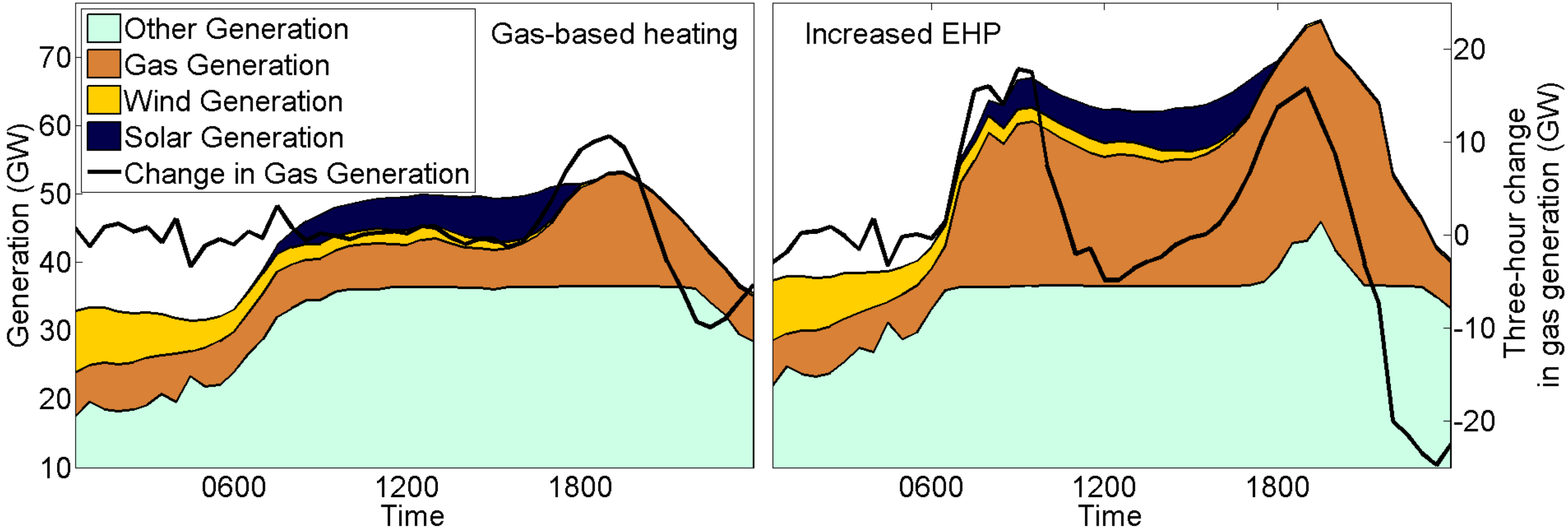
# Flexibility case study: operational impacts

Compared gas-based with electrified heating scenarios




S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718−731, 2015, (Special Issue on "Reserve and flexibility for handling variability and uncertainty of renewable generation").

# Impact of heating electrification on gas generation ramps

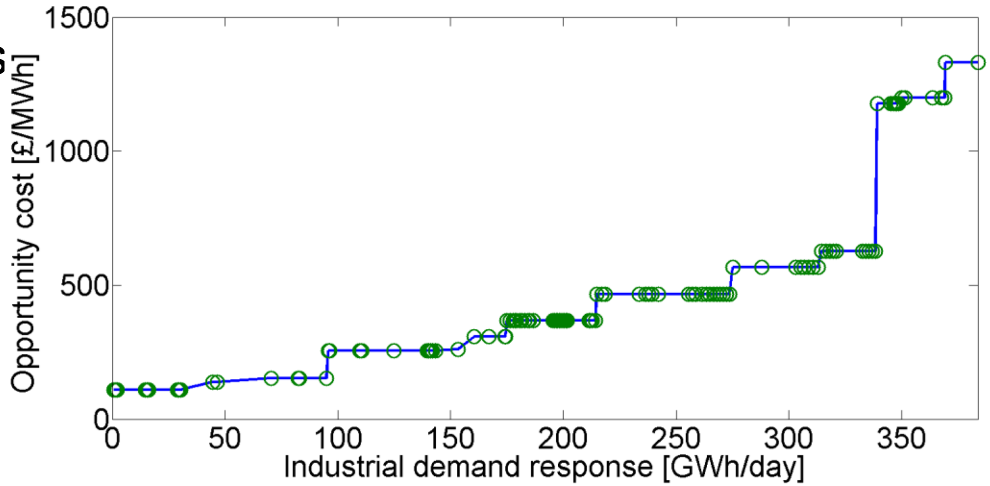



S. Clegg, P. Mancarella, “Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems”, IEEE Transactions on Sustainable Energy, 7 (2), pp.718−731, 2015,

# Benefits of demand response in gas sector

Demand response opportunities:

- Many industrial gas customers can offer price-driven demand response
- Hybrid heating technologies (e.g., hybrid CHP and boiler) can reduce gas demand

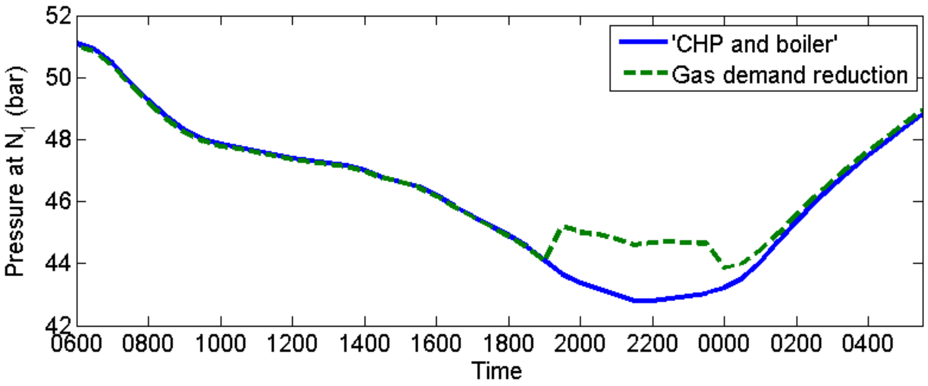



Demand response benefits:

- Avoid gas network expansion for meeting days of extreme cold conditions
- Alleviate supply limitations and gas transportation limitations

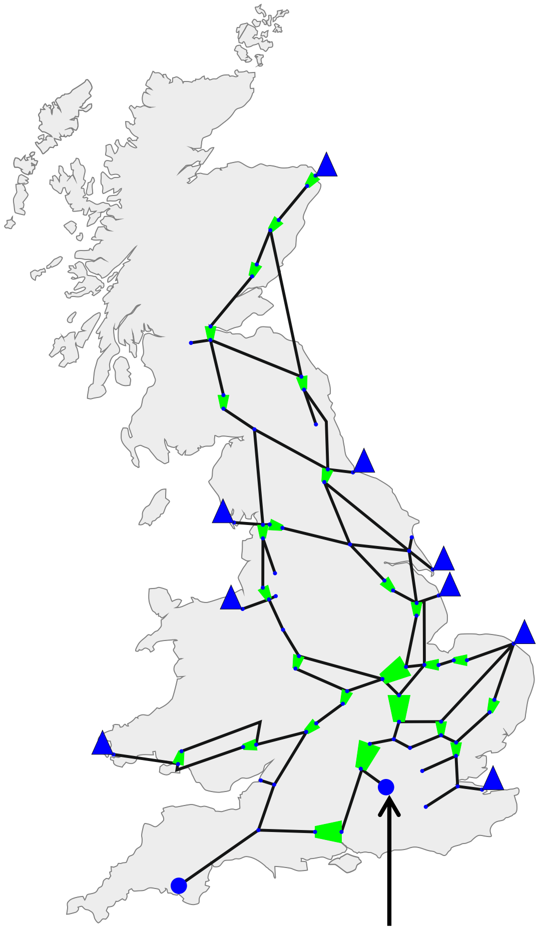
# Hybrid CHP and boiler as a means of demand response in gas network

- Gas network extremities are prone to low pressure violations
- Gas demand response can raise pressures at critical hours in day



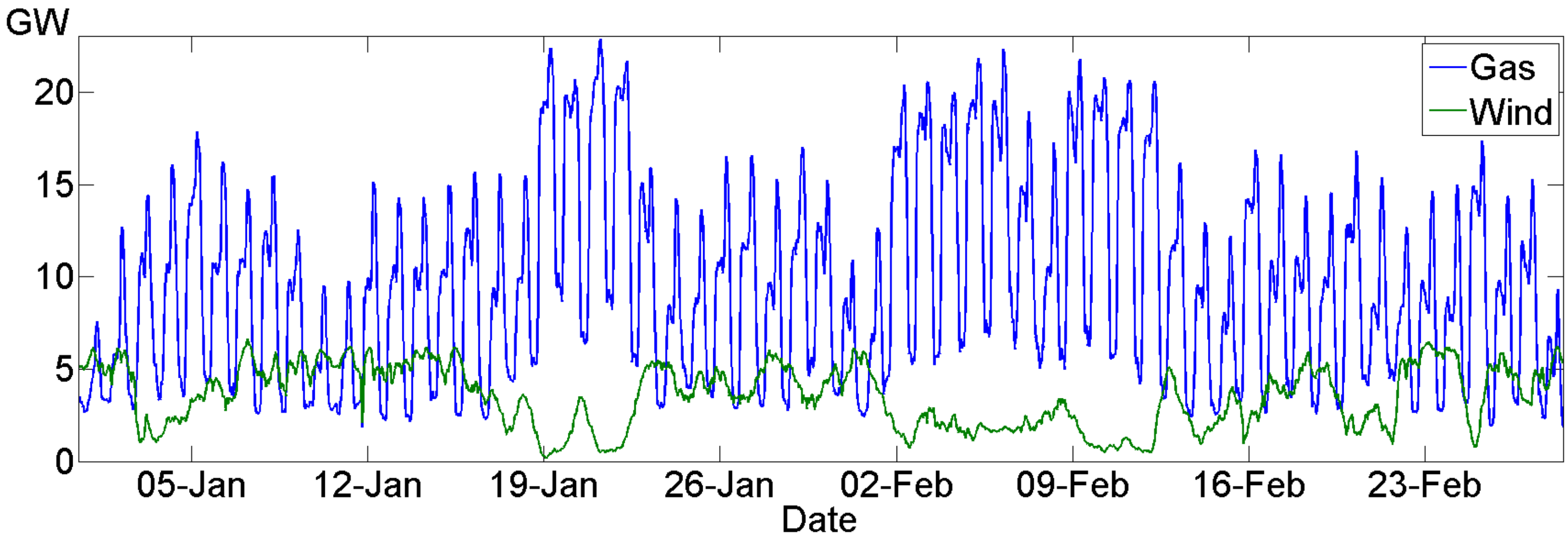

S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part II: Transmission Network Analysis and Low Carbon Technology and Resilience Case Studies", *Energy*, February 2018

S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part I: High-Resolution Spatial and Temporal Heat Demand Modelling", *Energy*, February 2018



Node of low pressure and high gas demand ($N_1$)

# What is the future of the gas network?

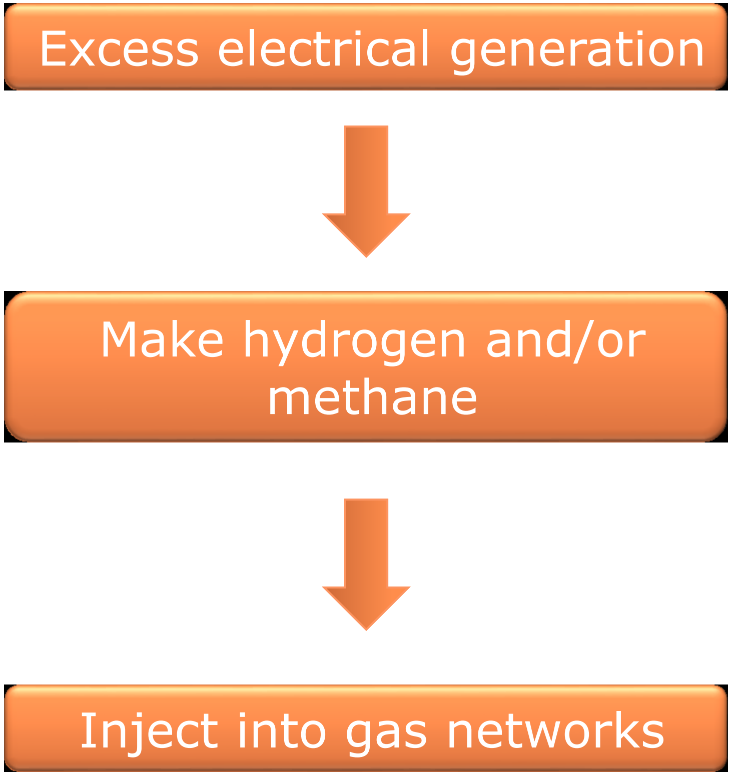



Excess wind energy → Power-to-gas → Hydrogen via electrolysis

S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

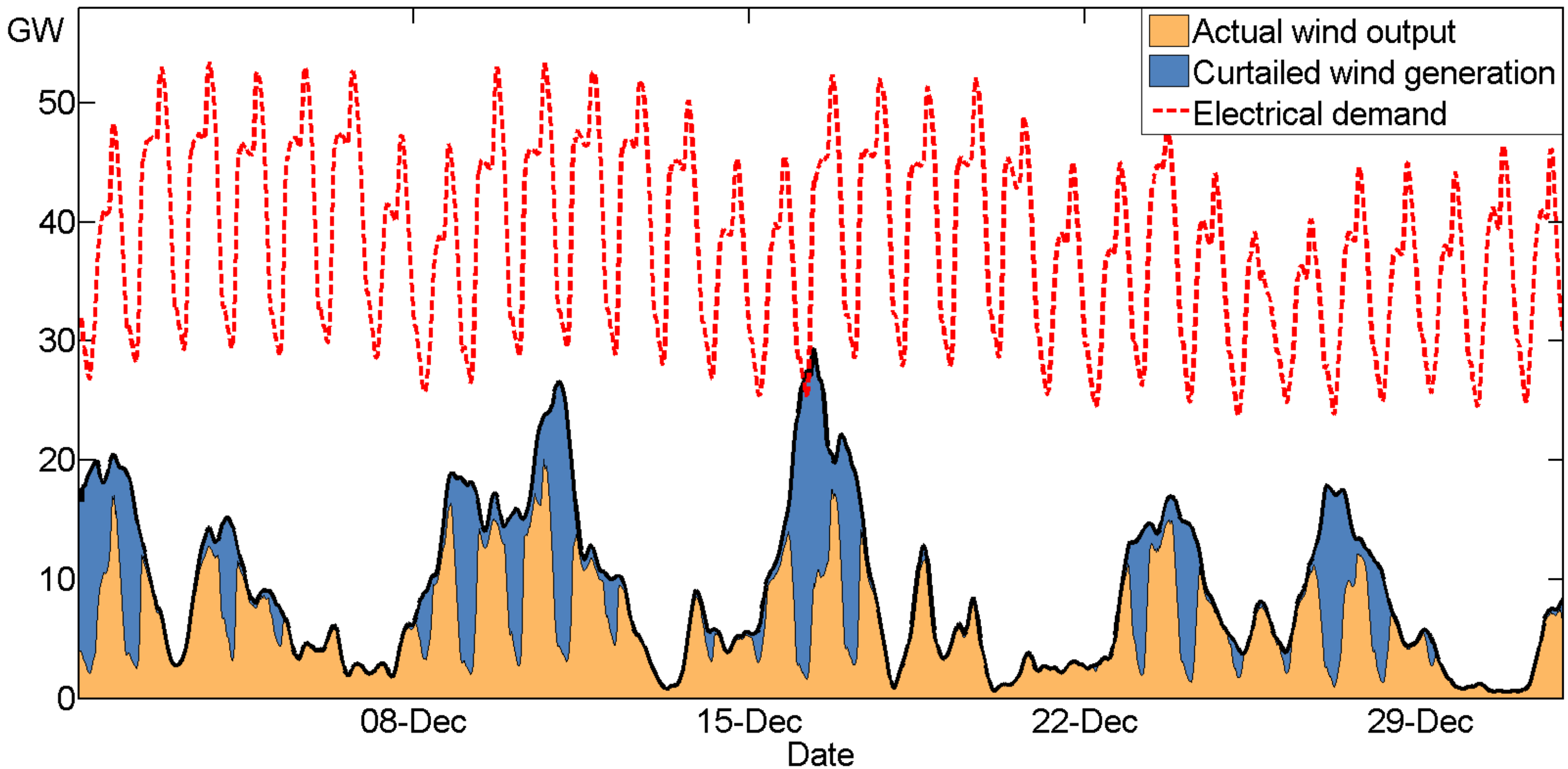
# Power-to-gas

- Utilising cheap, otherwise wasted energy
- Increases proportion of generation from renewables
- Use of hydrogen as a substitute to natural gas leads to reduction in $CO_2$ emissions
- Can be used as a means of storing the wasted energy




S. Clegg, P. Mancarella, “Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks”, IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

# Wind curtailment




S. Clegg, P. Mancarella, “Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks”, IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

# The hydrogenation and methanation process

- Hydrogen production
  - Produced via electrolysis at electrolyser
  - Proton exchange membrane (PEM) have efficiency 77%
  - The electrolysers are able to ramp up and down quickly to follow sudden changes in the wind output

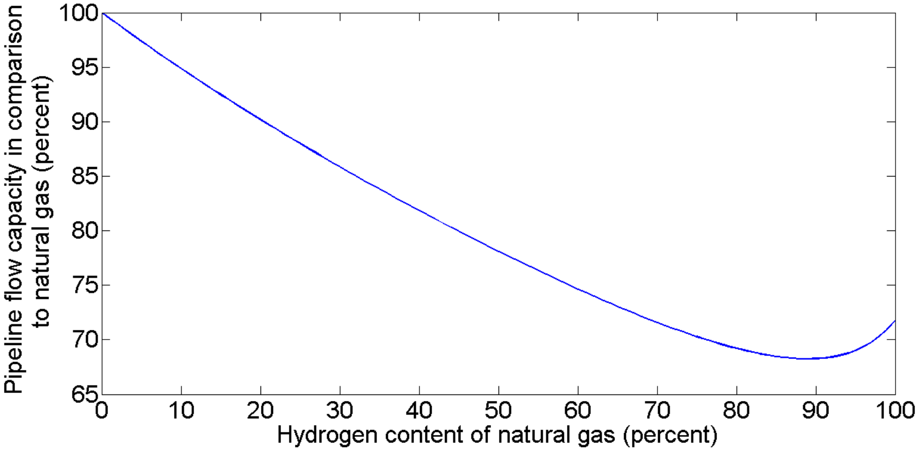
- Methanation process
  - Converting of hydrogen into synthetic natural gas
  - Process can be biological or chemical
  - Efficiency 75-85%
  - Efficiency of combined process 43-62%

S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

# The introduction of hydrogen into gas network

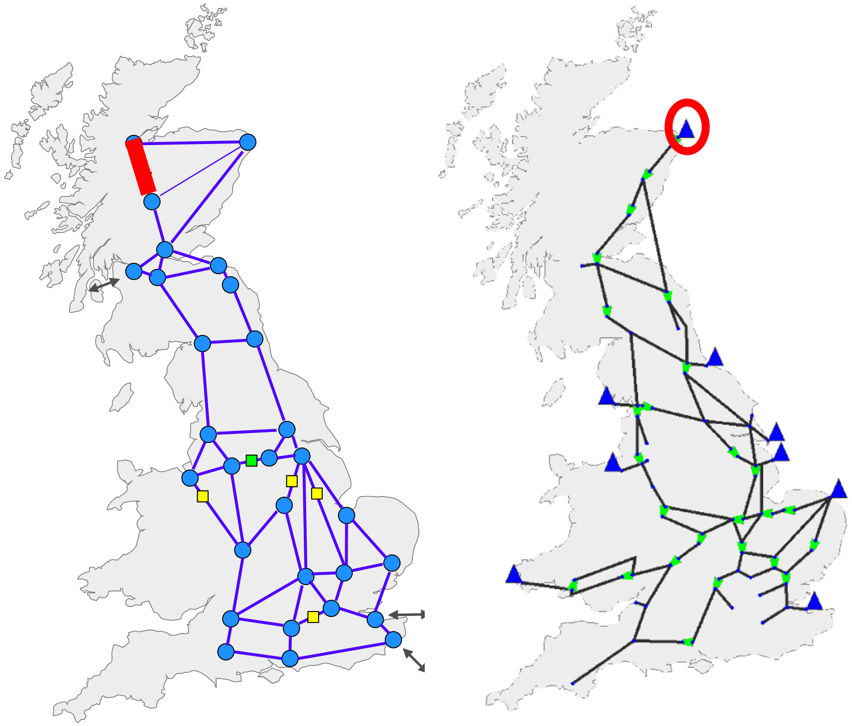
- Limits on the level of hydrogen in the gas network
  - Regulatory restrictions
  - Technical restrictions
  - Blending would be helped by blending upstream with help of throughput to distribute hydrogen

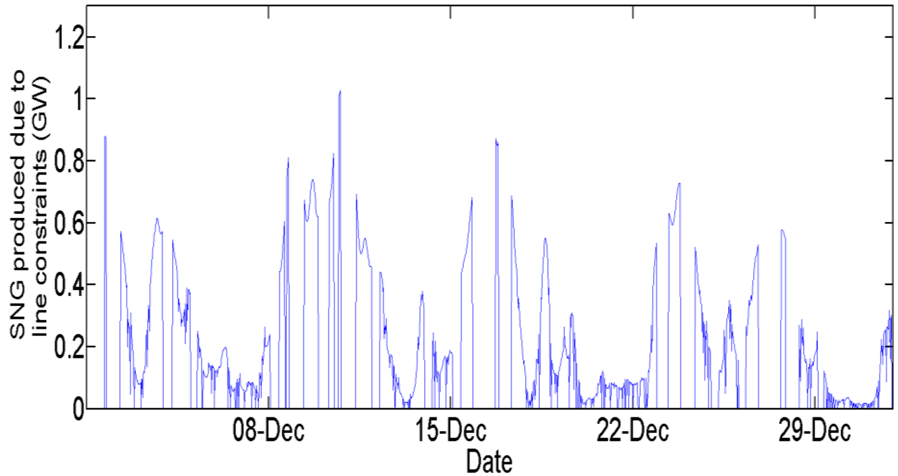
- For modelling:
  - Supposed limits on the level of hydrogen in the gas network
  - Regulatory restrictions

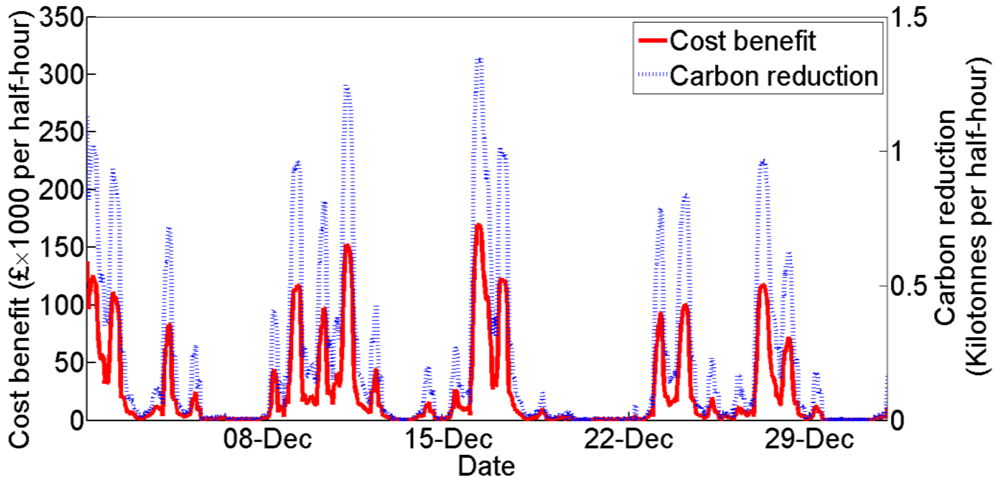



S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

# Integrated system operation: P2G to bypass electricity constraints





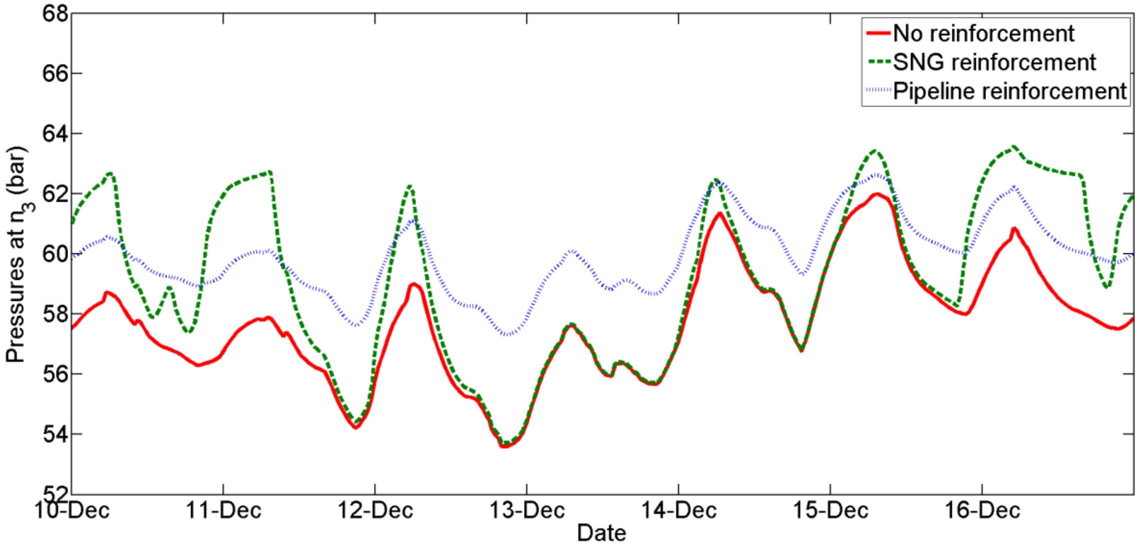



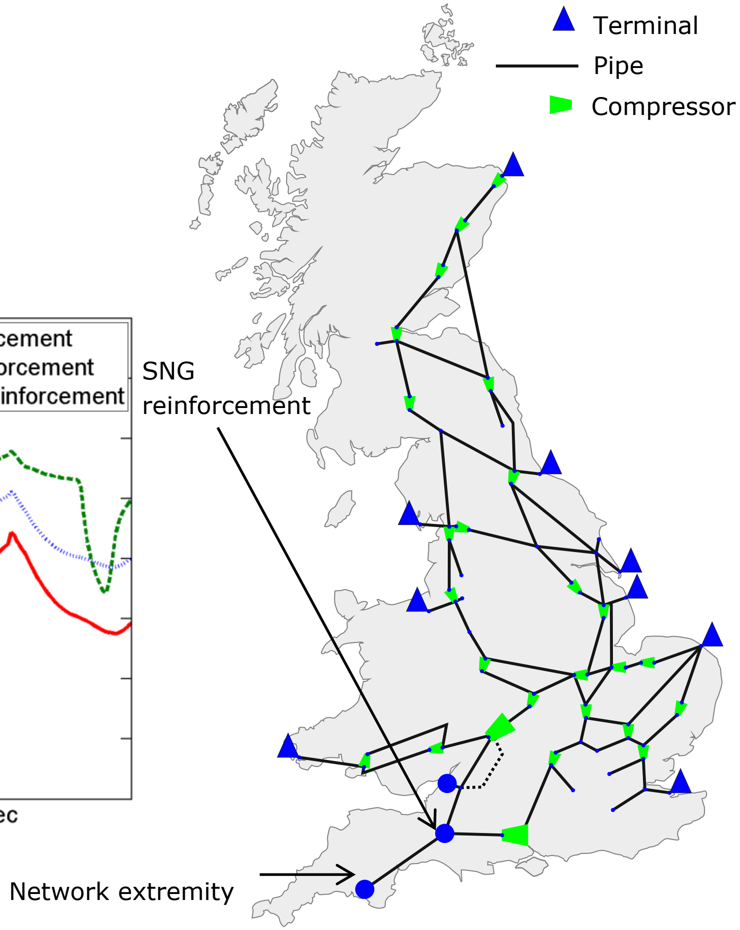

Modelling the impact of H2 injection on gas flows

S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", IEEE Transactions on Sustainable Energy 6 (4), pp.1234–1244, 2015

# Gas network congestion relief – GB study

Impact of power-to-gas on pressures of gas network extremities

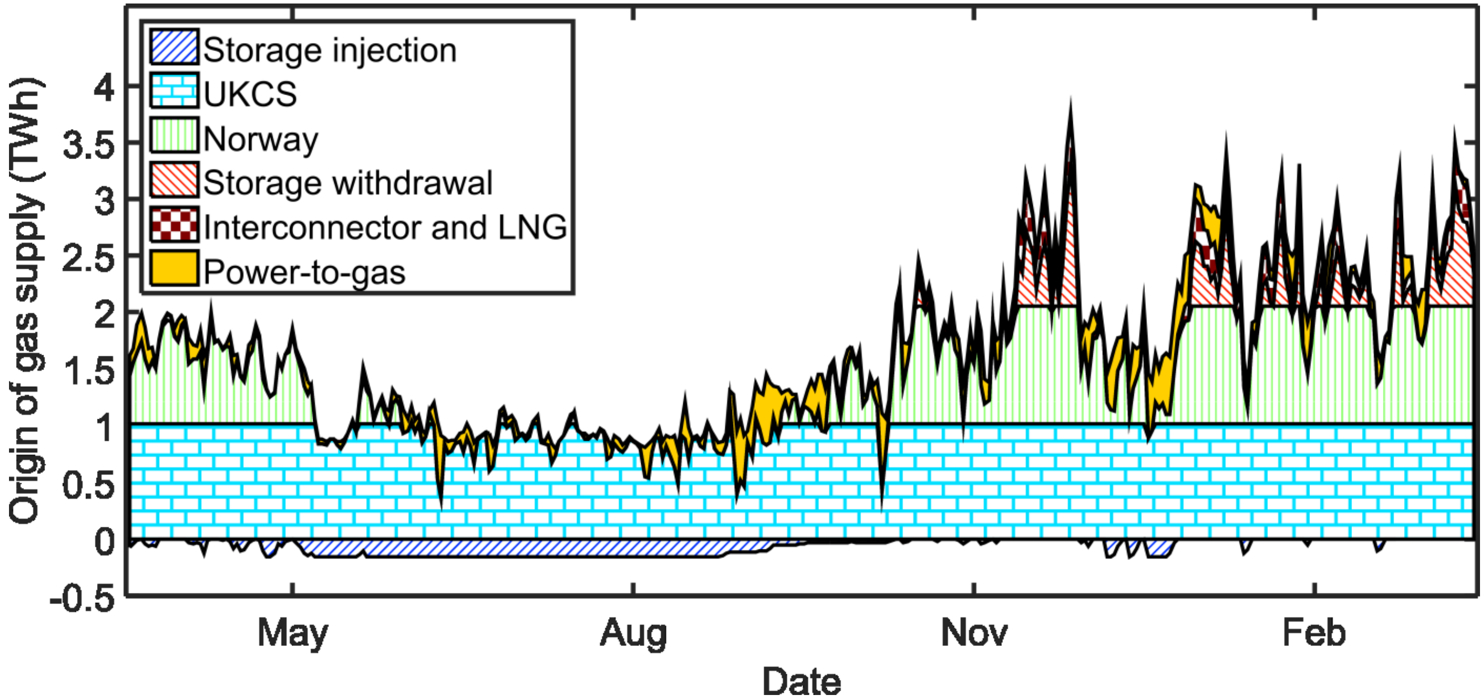



S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", IEEE Transactions on Sustainable Energy 6 (4), pp.1234−1244, 2015

# Integrated system operation: P2G for seasonal storage

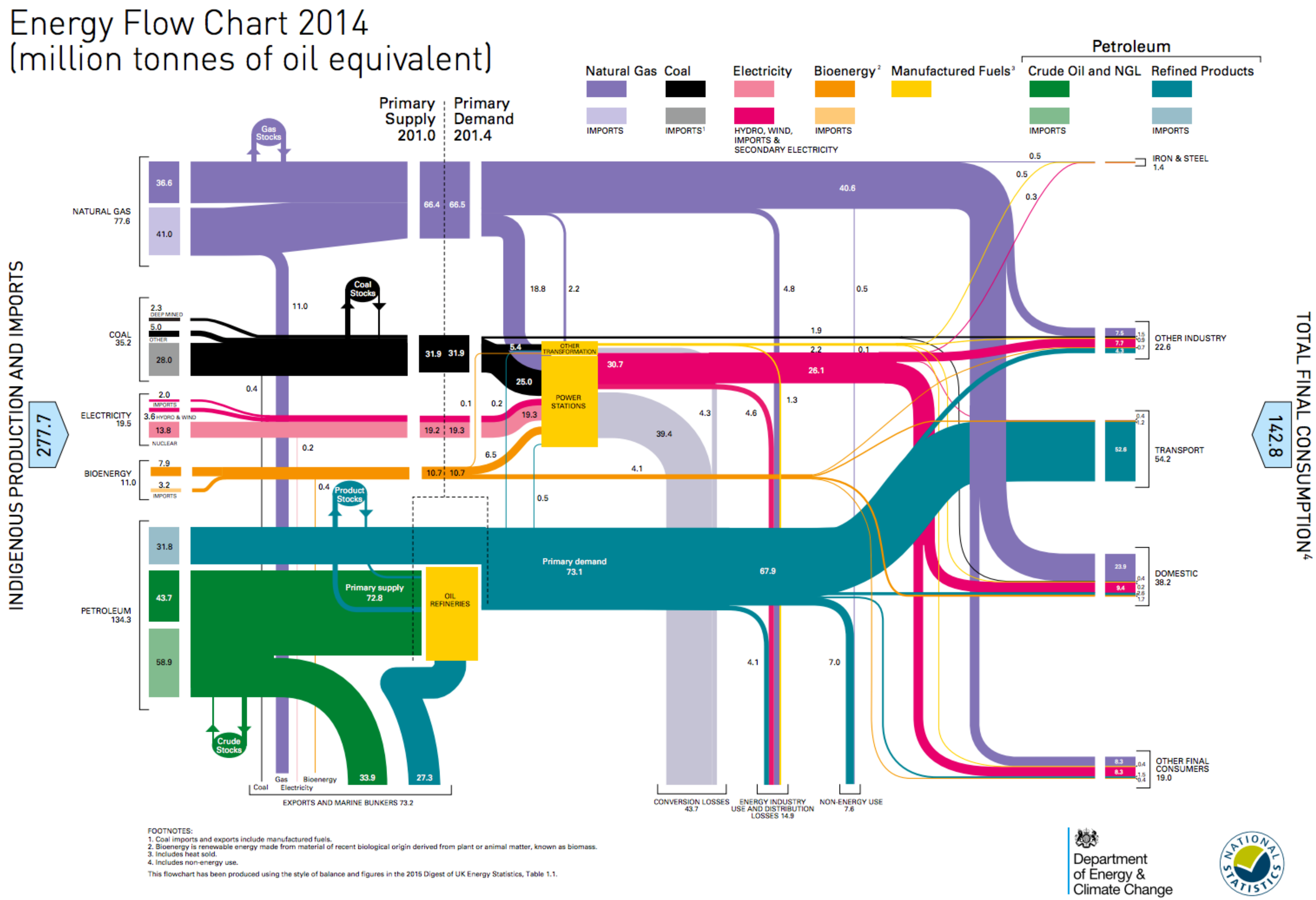
| Installed generation capacities | | Peak demand [GW] |
|---|---|---|
| Wind [GW] | Solar [GW] | |
| 92 | 40 | 87 |




- Use of gas network for RES storage - Impact on gas prices over seasons

S. Clegg, P. Mancarella, "Storing renewables in the gas network: modelling of power-to-gas seasonal storage flexibility in low-carbon power systems", IET Generation, Transmission & Distribution, 10 (3), pp.566−575, 2015

# How about transport?

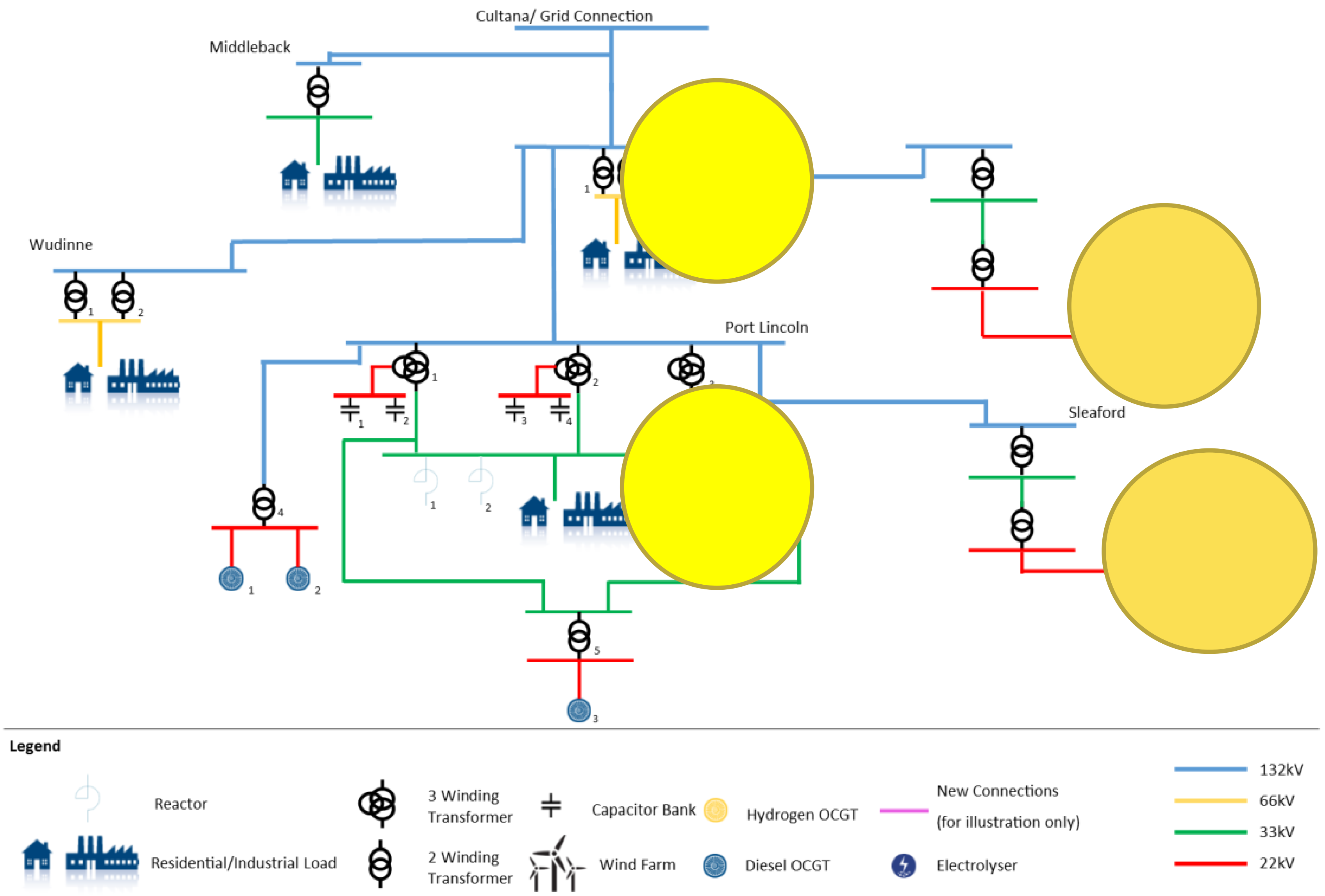


# Power-to-hydrogen-to-X

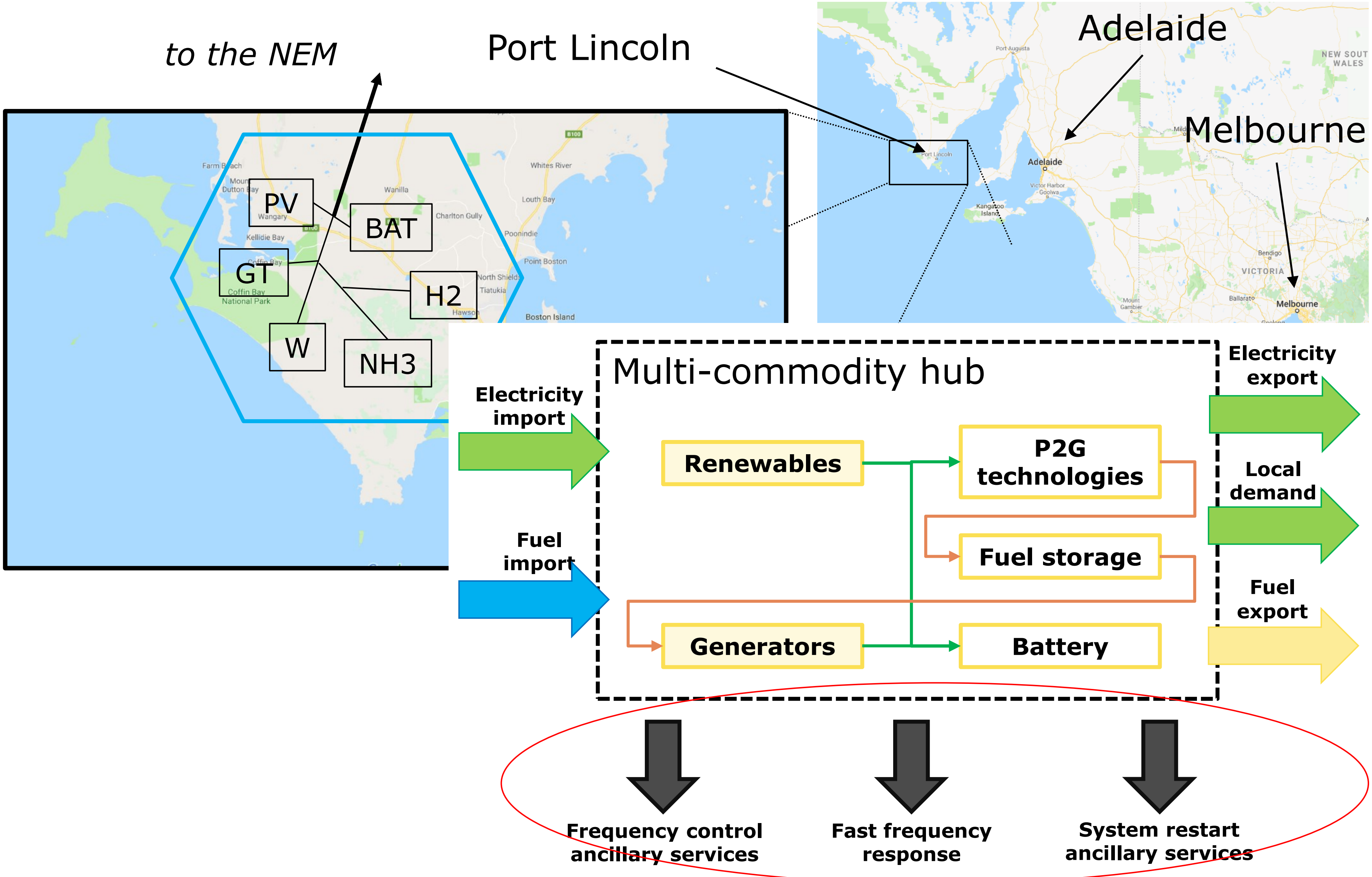
Moves to decarbonise transportation sector via hydrogen fuel cell electric vehicles

Excess wind energy → **Power-to-gas** → Hydrogen via electrolysis


# A look down under!

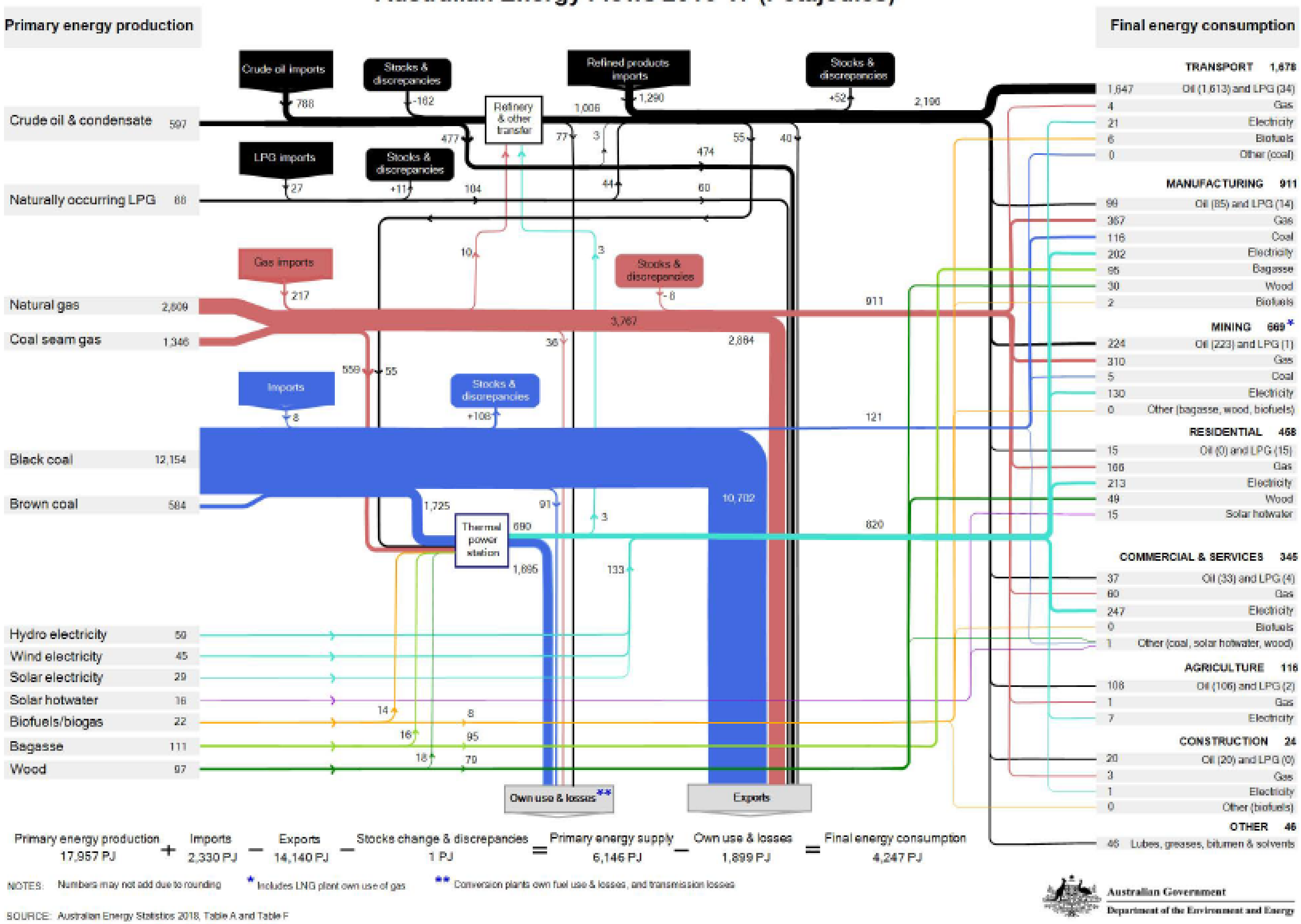


# Port Lincoln multi-commodity hub



# The bigger picture:
# It's not (at all) only about electricity…

### Australian Energy Flows 2016-17 (Petajoules)



# Key ongoing projects

- **Future Fuel CRC**
  - System-level and regional integrated electricity-gas-hydrogen modelling
  - City-level integrated energy system studies
- **UK National Grid**
  - Review of planning methodologies

- Looking forward to collaborations!

# Concluding remarks

- Renewables introduce power system flexibility challenges
- Gas generators are greatly affected
- Increasing need for electricity-gas system operation and market coordination
- This will be enhanced in the future with electrification and new energy vectors (hydrogen)
- Need for coordinated expansion that takes into account multiple forms of uncertainty in planning

# Key references


- S. Clegg and P. Mancarella, “Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part II: Transmission Network Analysis and Low Carbon Technology and Resilience Case Studies”, *Energy*, February 2018
- S. Clegg and P. Mancarella, “Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part I: High-Resolution Spatial and Temporal Heat Demand Modelling”, *Energy*, February 2018
- S. Clegg and P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems,“ *IEEE Transactions on Sustainable Energy,* vol. 7, no. 2, pp. 718-731, April 2016.
- S. Clegg and P. Mancarella, “Storing renewables in the gas network: modelling of power-to-gas (P2G) seasonal storage flexibility in low carbon power systems”, *IET Generation, Transmission and Distribution*, vol. 10, Issue 3, 18 February 2016, p. 566 – 575
- S. Clegg and P. Mancarella, “Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks”, *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1234 - 1244, October 2015

# Thank you!

# Any Questions?

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# ated electricity-gas system modelling and analysis and development of future fuels

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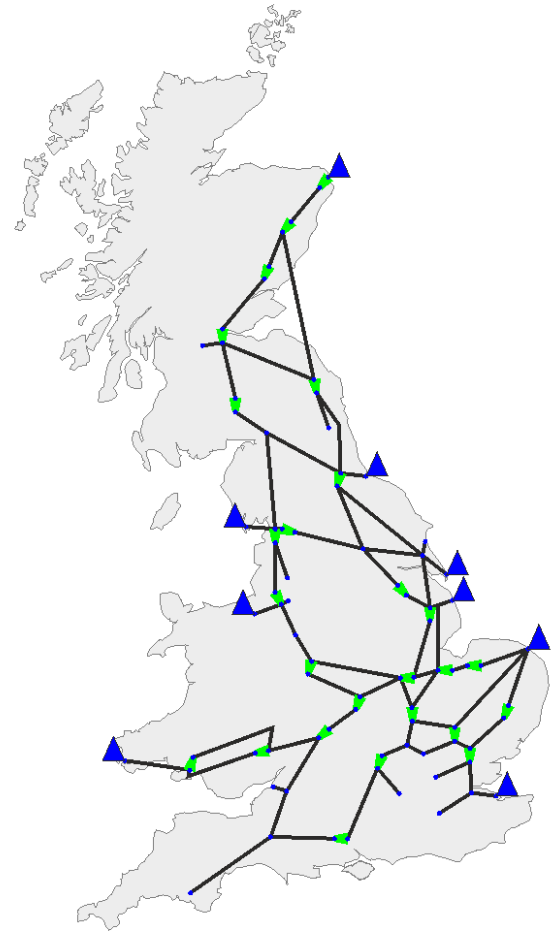
MEM Congress

Cartagena, 1st November 2019

# Terminals

- Beach terminals/wells
  - Little flexibility
  - Flat delivery throughout the day
- LNG
  - Can respond to network requirements within an hour
- Interconnectors
  - British-Irish interconnector exports over the day, British-Dutch interconnector faster turn-around



# Storage

- Long-term/seasonal storage
  - Depleted gas fields
  - Meets seasonal variations in demand and price
- Medium-term storage
  - Salt caverns
  - Responds to both daily and intraday price signals
- Short-term/peak-shaving LNG
  - Meets peak day demand
  - Can be a substitute for gas network reinforcement

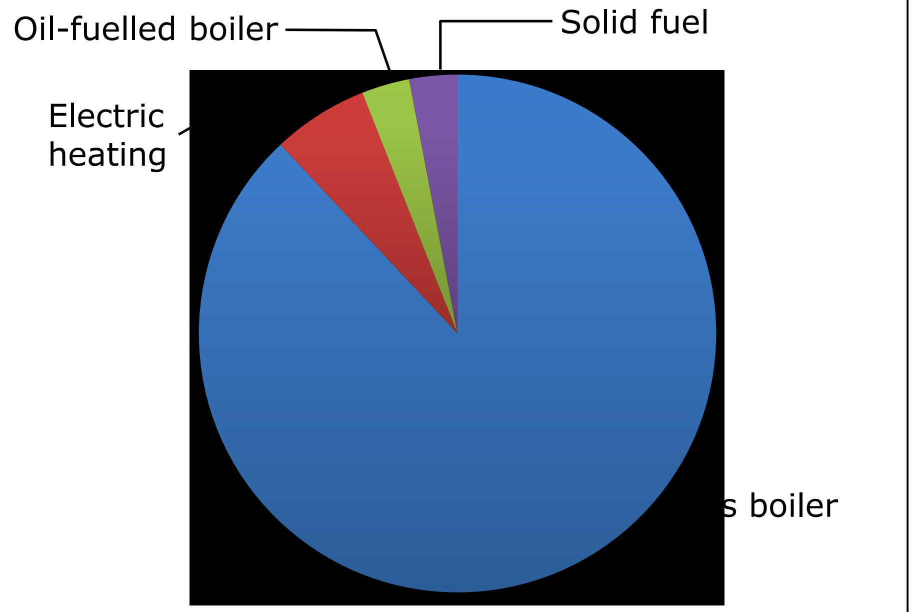
# Application of alternative modelling

- Steady-state analysis
  - Examples of application:
    - day ahead network operation planning
    - network expansion planning
    - when the variations in flows are small
    - pipeline capacity evaluations
  - Assumption of supply-demand balance

- Transient analysis
  - Examples of application:
    - Real time modelling
    - Evaluation of pipeline gas storage, linepack variations
    - System pressures throughout the day

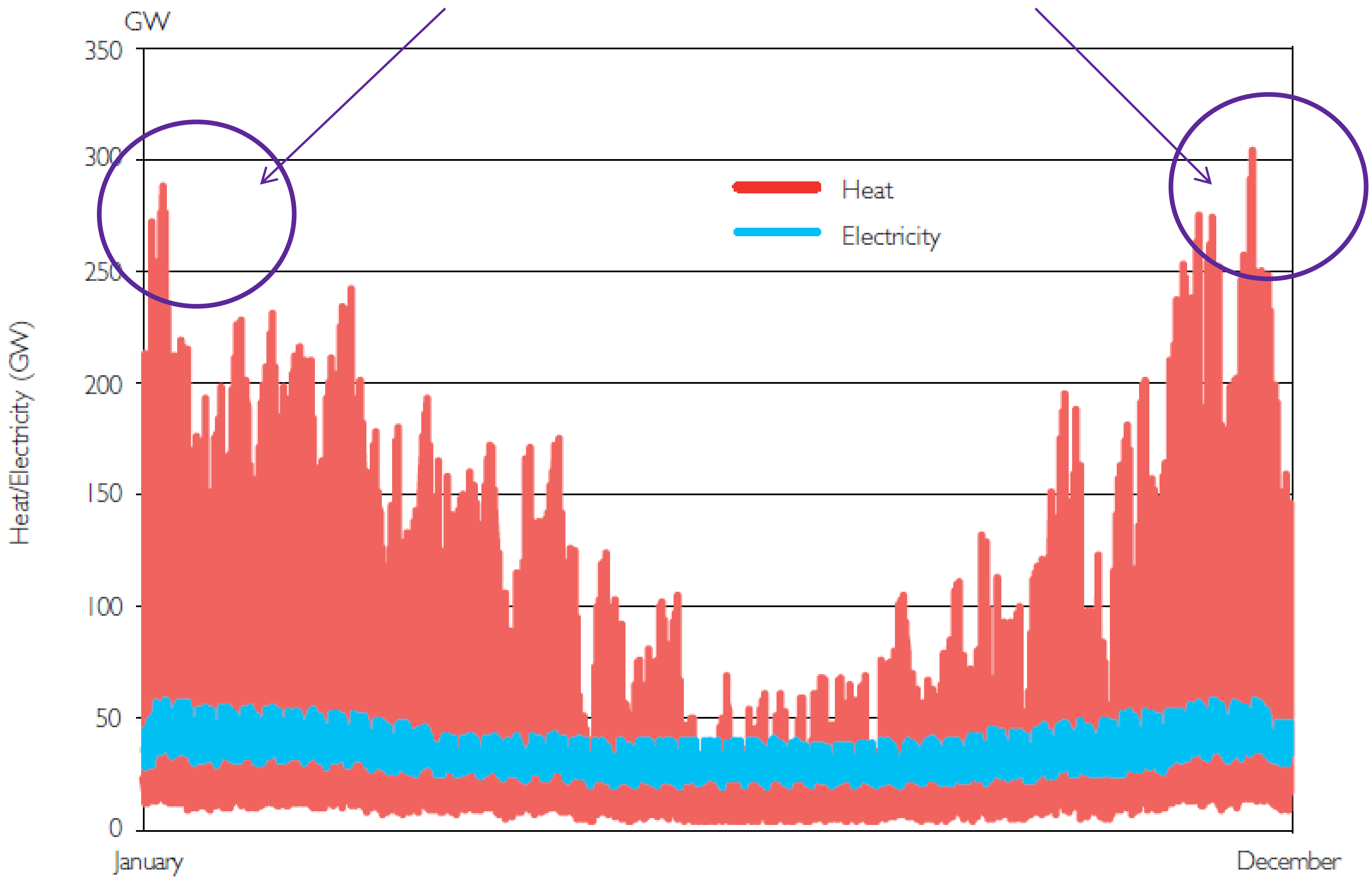
# Motivation – The current UK heating sector

- 37% of UK $CO_2$ emissions arise from the heating sector
- Any attempt to meet targets in the reduction of greenhouse gas emissions needs to include a change in the heat generating technologies
- The primary fuel used for heating in the UK is natural gas




Breakdown of domestic space heating generation technologies

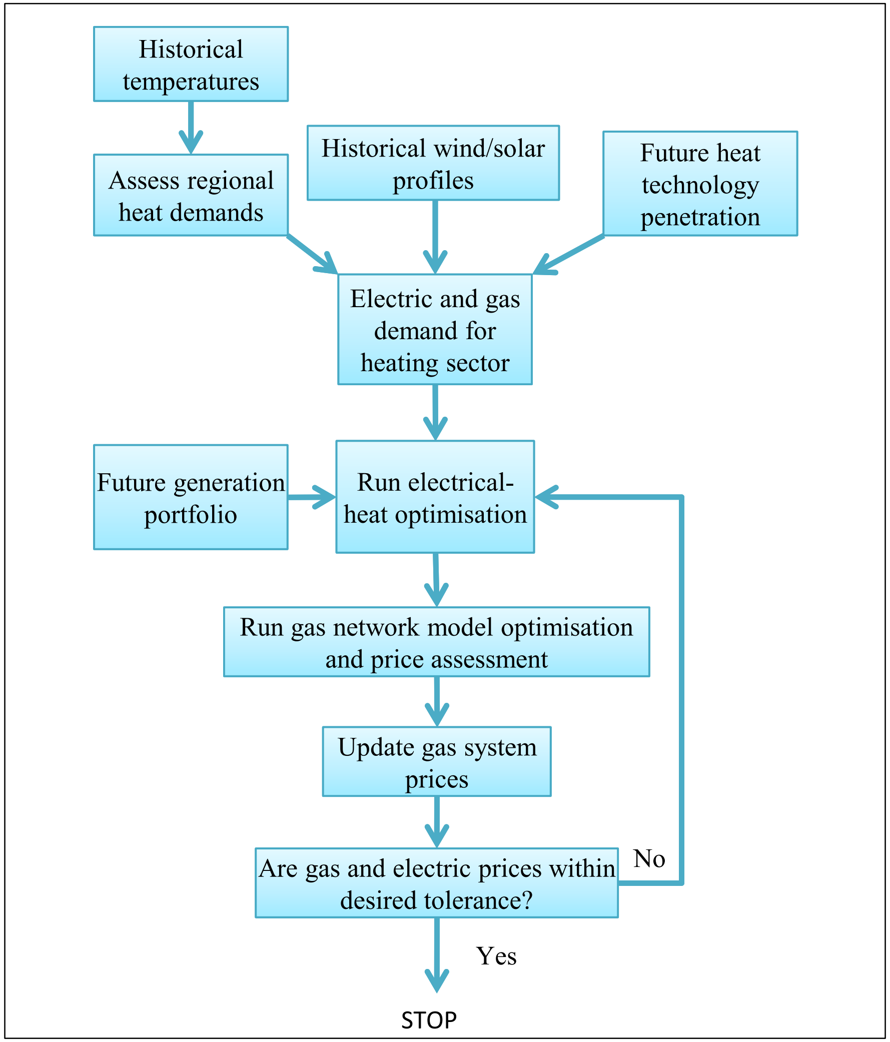
# Electrification: the magnitude of the problem…




Source: Courtesy of Imperial College. For illustrative purposes only and based on actual half-hourly electricity demand from National Grid and an estimate of half hourly heat demand.

# Integrated system modelling

- System modelling accounts for
  - Meeting electricity and heat demands by cheapest means
  - Electrical line constraints (assessed using DC OPF)
  - Gas transmission line constraints (assessed using steady-state analysis)
  - Regional wind/solar generation
  - Regional gas prices



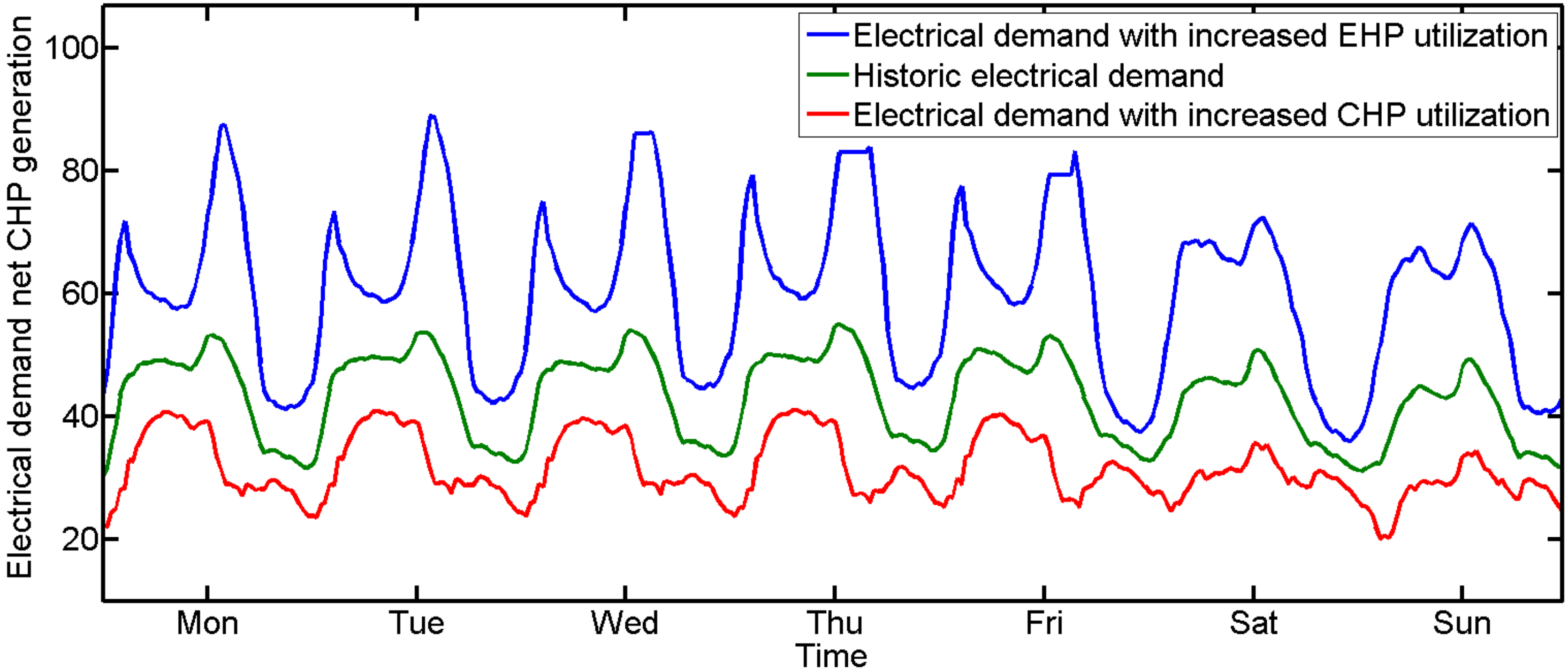


S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part II: Transmission Network Analysis and Low Carbon Technology and Resilience Case Studies", *Energy*, February 2018

S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part I: High-Resolution Spatial and Temporal Heat Demand Modelling", *Energy*, February 2018

# Impacts of heating sector changes to power sector

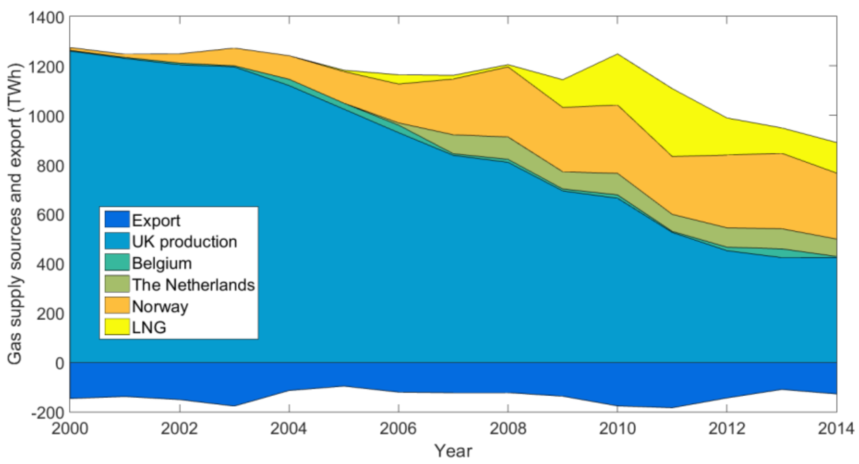
- Electrification of heating leads to increases in electricity demand
- Morning increase in heat demand precedes increase in electrical demand leading to lower electrical demand net CHP generation



# Resilience study – Background and precedents in Britain

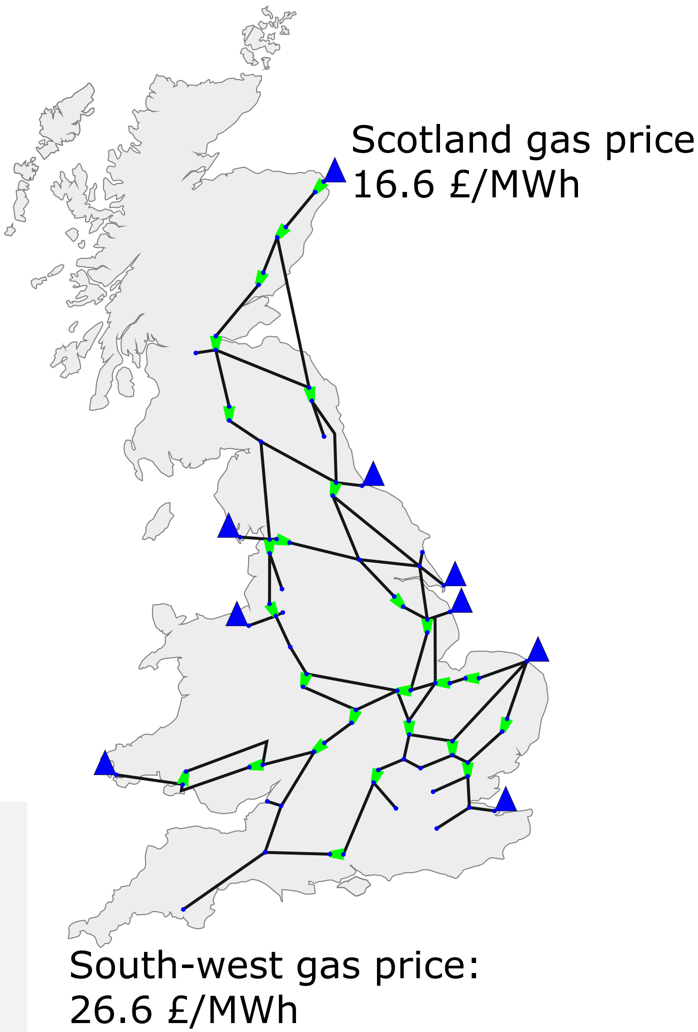
- Decommissioning of ageing gas storage infrastructure
  - Rough storage facility, accounting for 70% of Britain's gas storage capacity, set for closure

- Change in Britain gas supplies
  - Since 2014, Britain has been a net importer of gas
  - In long-term forecasts, Britain expects LNG to be the principal source of gas
  - International factors influence gas availability in Britain



# Implications of gas network transportation on peak day requirements

- Scenario considers:
  - Storage decommission/outages reduces supply by $136\times10^6$ $m^3$ of gas
  - Demand is 97% of supply capability
- British network capable of meeting peak day requirements
- Peak day compressor fuel requirements and transportation limitations leads to large variations in gas price
- South-west gas price 60% greater than minimum price

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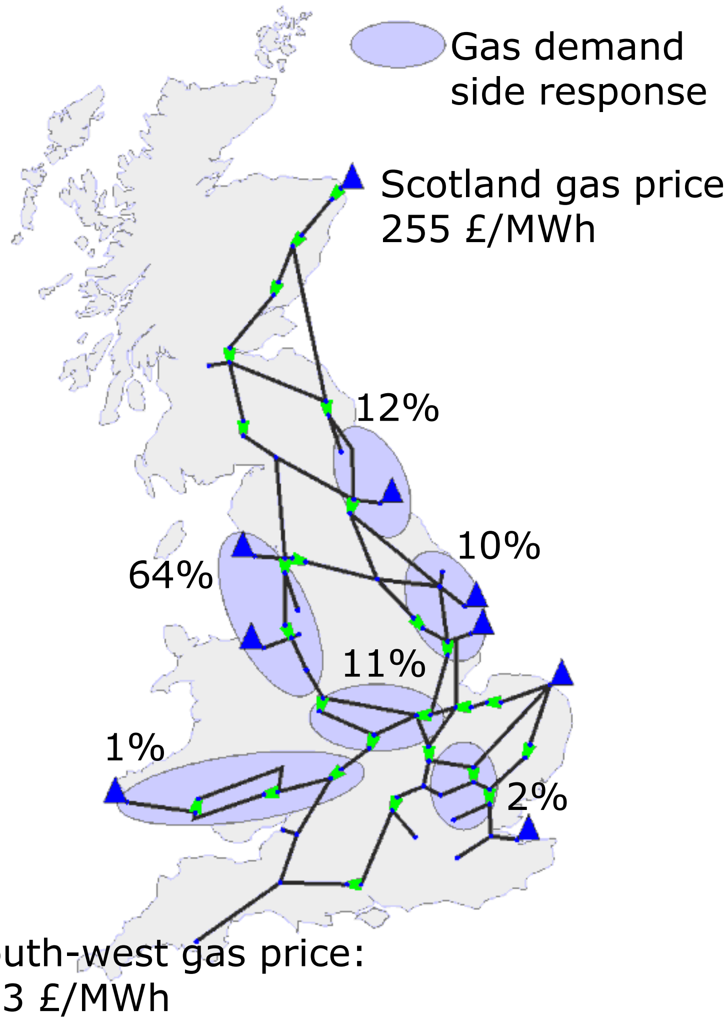
# Opportunities for gas demand response

- Scenario considers:
  - Storage decommission/outages reduces supply by $136\times10^6$ $m^3$ of gas
  - Limited LNG availability due to tanker delivery schedule
  - Demand exceeds supply by 116 GWh/day
- Gas demand response predominantly from industry in Northern England allows for maintaining firm gas demand

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# Fuel cell electric vehicles

## Fuel cell vehicles

- On-board fuel cell used to convert hydrogen into electric power to drive motor
- Refuelling occurs at hydrogen refuelling stations
- Refuelling process takes a couple of minutes
- A hydrogen fuel cell car can have range of over 500km

## Refuelling stations

- Can create hydrogen using on-site electrolyser
- On-site storage allows for decoupling of electrolyser power demand from vehicle demand
- Electrolysers have extremely flexible characteristics and are able to react to power system changes and offer ancillary services

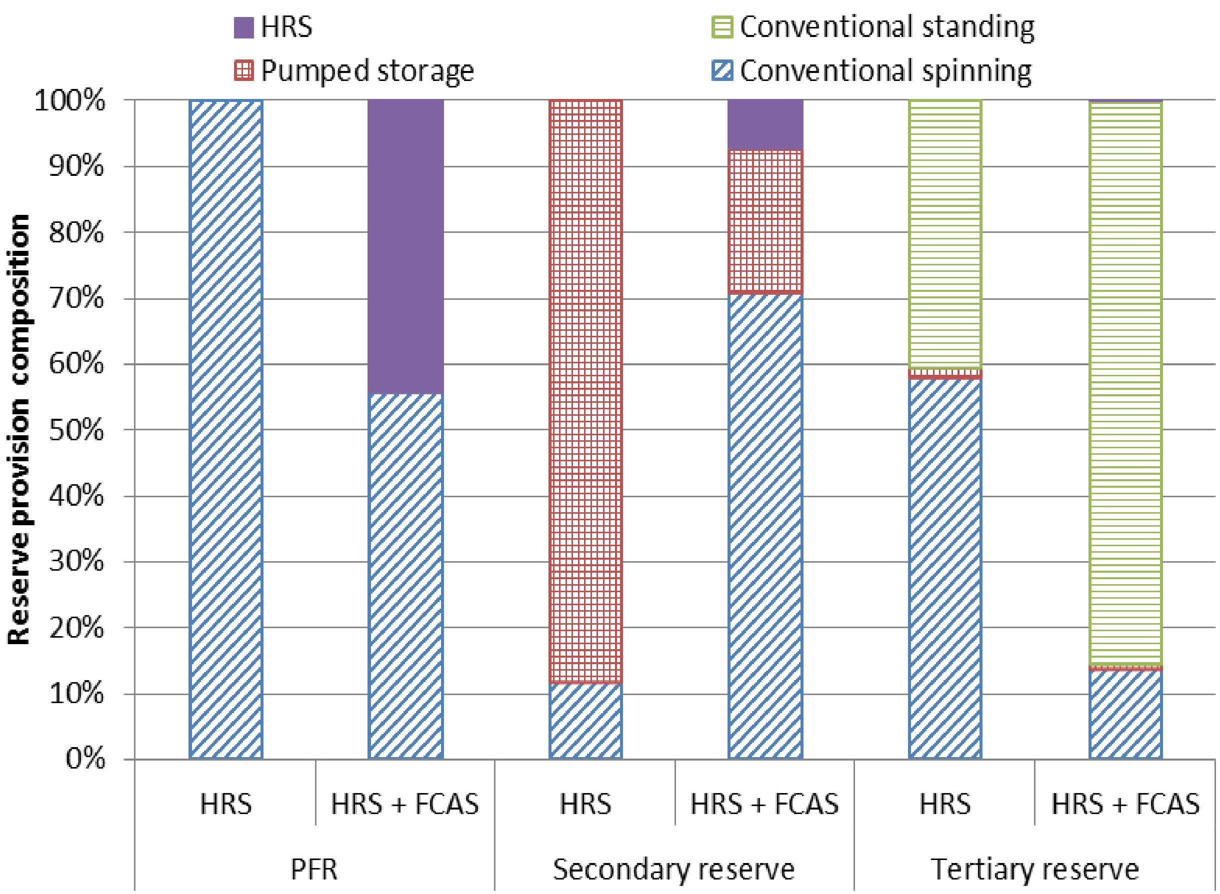
# Looking at the system value: FCAS from electrolizers

- Modelling considers roll-out of hydrogen electric vehicles which leads to 3% increase in power system demand

| | No contribution to FCAS | With contribution to FCAS | Reduction |
|---|---|---|---|
| Carbon emissions (Mtonnes $CO_2$e / year) | 31.1 | 12.3 | 61% |
| Operating costs (£×$10^9$/ year) | 5.84 | 4.74 | 19% |

L. Zhang, S. Clegg, P. Mancarella, "Modelling of electrolyzers in hydrogen vehicle refuelling stations for provision of ancillary services ", IREP 2017, Espinho, Portugal, August 2017

# Electrolyser contribution to power system ancillary services




L. Zhang, S. Clegg, P. Mancarella, "Modeling of electrolyzers in hydrogen vehicle refueling stations for provision of ancillary services" IREP Symposium, X Bulk Power Systems Dynamics and Control Symposium, Espinho, 2017.