wholeSEM

topDIP-
topDown Integration Project

Marko Aunedi, Dennis Konadu, Pei-Hao Li,
Kavin Narasimhan, Dimitrios Papadaskalopoulos,
James Price, Zenaida Sobral Mourão,
Marianne Zeyringer

UNIVERSITY OF SURREY
Imperial College London
UNIVERSITY OF CAMBRIDGE
UCL

Introduction

Background on topDIP

- Energy system transitions are complex
- As part of wholeSEM each team developed models covering different aspects of the transition
  - UCL: Energy system
  - Surrey: Social practices
  - Imperial: Power system
  - Cambridge: Energy, land and water
- A core goal of wholeSEM was to undertake hybrid (or whole systems) modelling
- In topDIP we selected one overarching question that needs a combination of models to study its different aspects

Background on the overarching research question

- The decarbonisation of the electricity sector is a low hanging fruit→ key to achieve national and international emissions reduction goals (Climate Change Act 2008 and Paris Agreement)

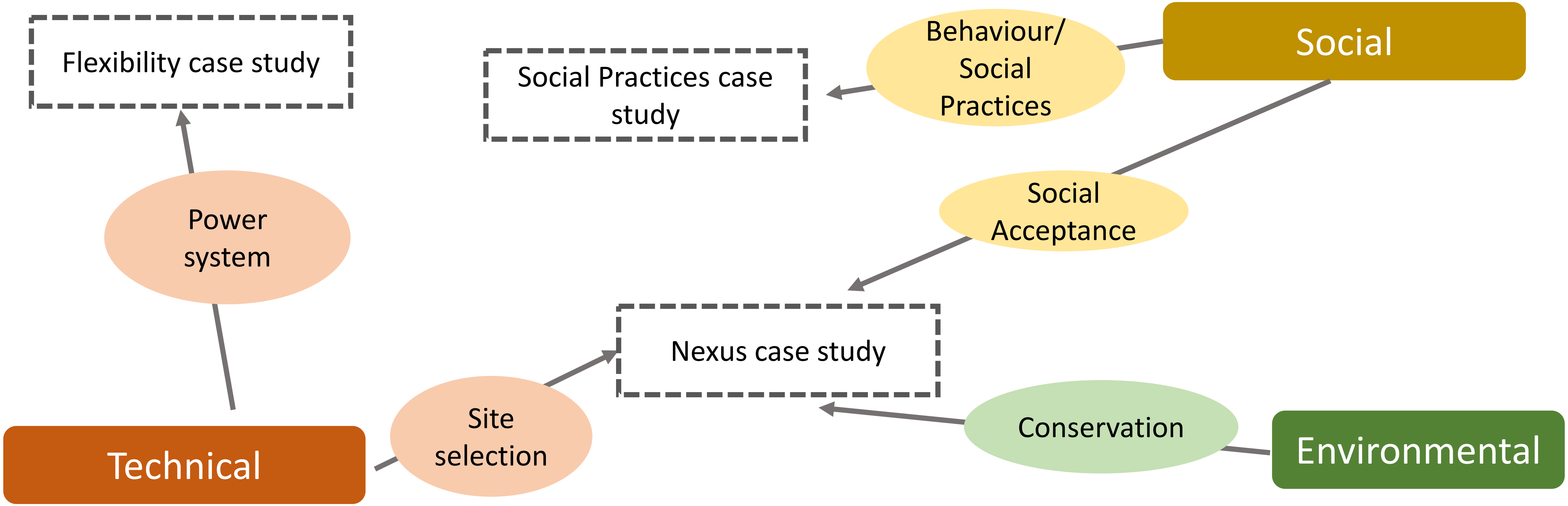
- Research shows that options to reach goals are available but the question is whether these models accurately reflect technical, social (and environmental), political challenges and realities[1,2]

→ Given the importance and urgency to decarbonise the electricity sector we need to include more social, environmental and technical realism to our models

Research question: How to model the decarbonisation of the electricity sector when considering social, environmental and technical issues?

Study Overview

How to model the decarbonisation of the electricity sector when considering social, environmental and technical issues?



Presentation overview

- Flexibility Case study: *Accounting for Impact of Flexibility on System Integration of Variable Renewables in Low-Resolution Models*
  Marko Aunedi

- Social Practices Case study: *Integrating social practice and economic rationality principles in household energy demand modelling*
  Kavin Narasimhan

- Nexus Case study: *Planning low carbon electricity systems for Great Britain in 2050: a land-energy-water perspective*
  James Price

- *Conclusions*
  Marianne Zeyringer

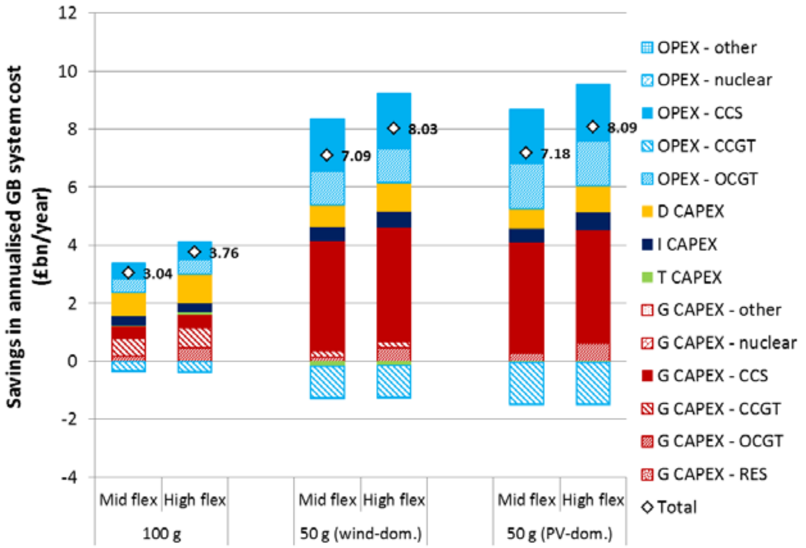
Accounting for Impact of Flexibility on System Integration of Variable Renewables in Low-Resolution Models

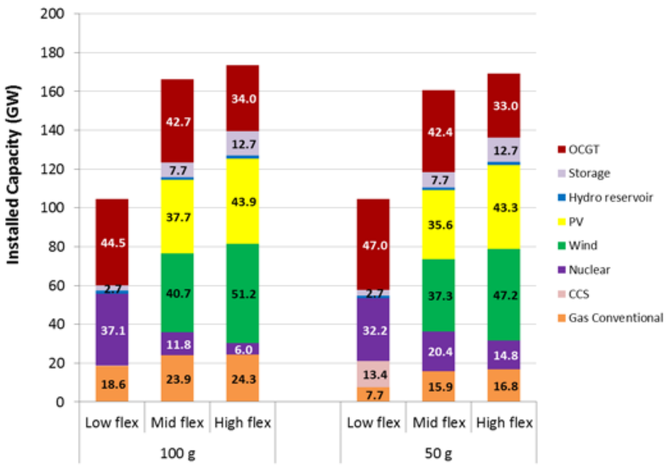
Marko Aunedi (Imperial College London)

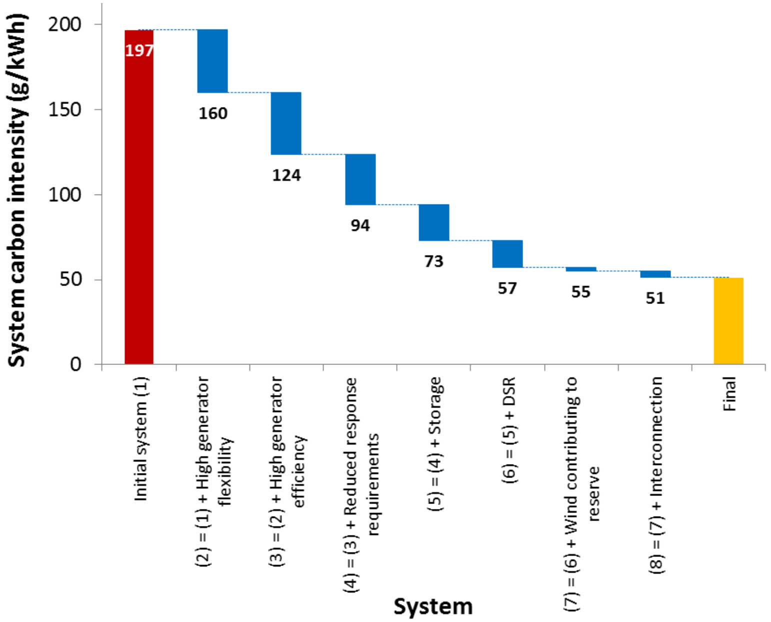
Peihao Li (UCL)

Why flexibility matters?

- Previous studies (CCC, BEIS, Carbon Trust, NIC…) have shown that **flexibility is critical** for cost-effective integration of low-carbon technologies, in particular variable renewables (VRE)
  - Flexibility includes DSR, energy storage, network solutions and flexible generation
- **High-resolution** modelling is necessary to capture full implications of flexibility for VRE integration
- Multi-vector long-term energy system models typically work with lower resolutions
- Hence, an approach to **link high and low-resolution models** is proposed to consider the impact of flexibility on system integration of VRE in long-term energy system planning



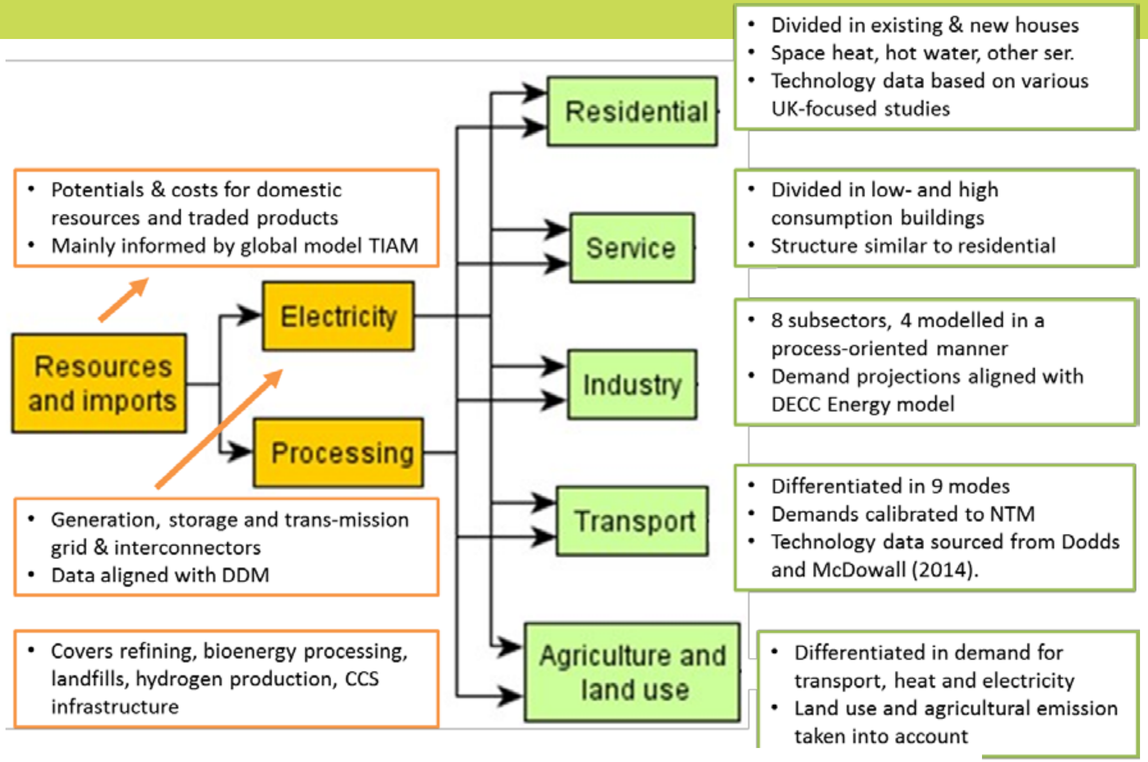




- ***How does the variability of RES generation affect its economic attractiveness?***
- ***What is the role of flexible technologies?***

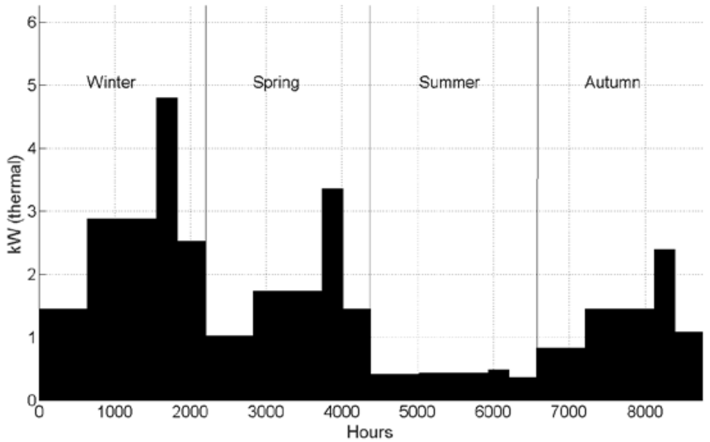
UKTM – The UK TIMES Model

- Developed by UCL Energy Institute
- Whole UK energy system
- Technology-rich
- Least-cost model
- Coarse spatial and temporal resolutions
  - National scale, 16 time-slices (4 slots in 4 representative days)
- Adopted by BEIS for policy making
  - 5th Carbon Budget
  - Emissions reduction plan



Key input data
- System configuration
- Resource supply curves
- Energy service demands
- Technology characterisation
- Constraints

Key outputs
- Total and annual energy system costs
- Primary & final energy - by sector / fuel
- GHG emissions; marginal emissions prices
- Im-/Exports & domestic production of fuels
- Electricity generation– by fuel / technology
- End-use technologies and fuel use
- Use of conservation, efficiency



Whole-electricity System Model (WeSIM)

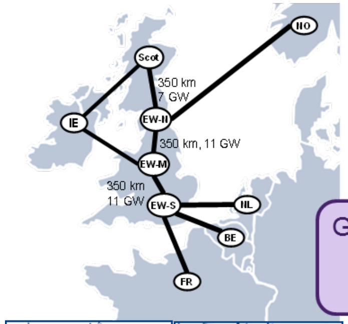
wholeSEM

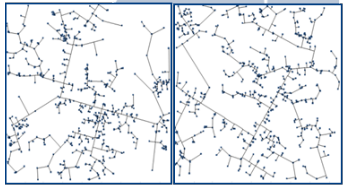
Imperial College London

UCL

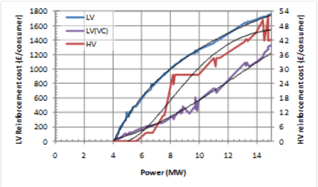
- Makes optimal investment and operational decisions that minimise total system cost:
  - Generation CAPEX
  - Transmission CAPEX
  - Distribution CAPEX (Representative Networks)
  - OPEX
- High temporal and spatial resolution
- Highly suitable for evaluating flexible options – time and location effects
- Endogenous security and CO_2 constraints
- Advanced treatment of system inertia and frequency regulation requirements
- Used in a number of previous studies (CCC, BEIS, Carbon Trust, NIC etc.)

Interconnected GB system





~10 representative DNs



Future development scenarios (GB & EU):
- Generation mix evolution (RES etc.)
- Demand (electrification etc.)

GB + EU Grid Model: Transmission + Distribution

WeSIM: Generation, Transmission and Distribution Investment and Operation Model

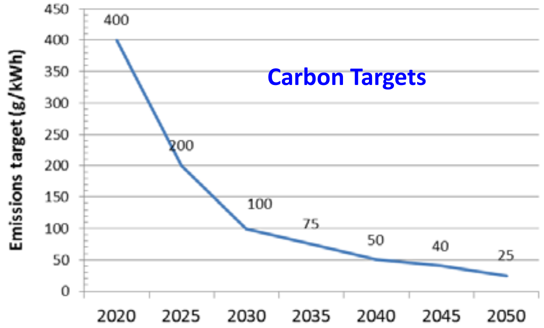
CO_2 constraints

- Investment in G/T/D & storage infrastructure
- Generation & storage output, RES curtailment & CO2 emissions
- Overall investment and operation cost

Key results

Outturn carbon intensity

System value of flexibility



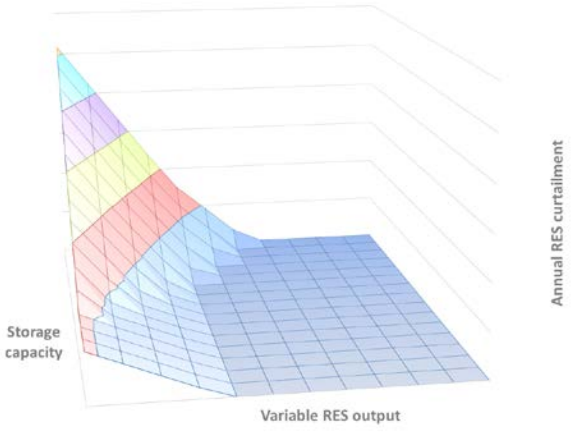
Model integration approach

- Two key models:
  - **UKTM** – low-resolution, all-energy system, technology-rich model
  - **WeSIM** – high temporal and spatial resolution model of electricity system
- Key parameter adopted to quantify the ability of electricity system to integrate VRE: output **curtailment**
  - Function of flexibility
  - Requires high-res modelling (WeSIM)
- **Proposed linking** of UKTM and WeSIM: use multiple WeSIM runs to represent VRE curtailment as function of two variables:
  - VRE penetration (or installed capacity)
  - Level of flexibility in the system
- Represent curtailment levels as constraints on annual output of VRE in UKTM

WeSIM

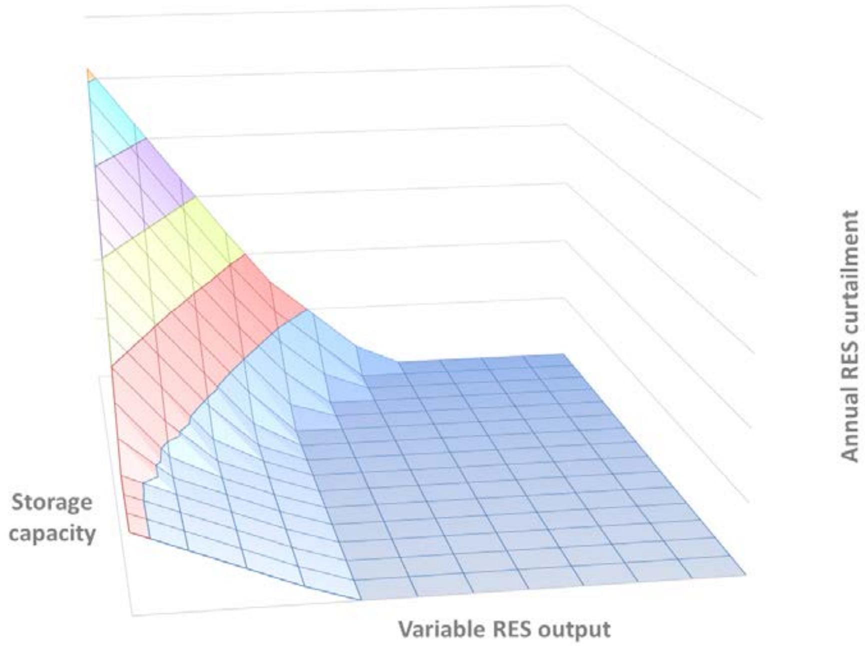
Curtailment of VRE
= f(installed VRE, Flex)

UKTM



Implementation

1. Run a number of WeSIM simulations to quantify VRE curtailment (*z*) as function of:
   - Varying VRE (wind + PV) penetration (*x*)
   - Varying installed storage capacity (*y*, proxy for system flexibility)
2. Use these data points (*x*,*y*,*z*) to construct planes through triplets of adjacent points: $z_i = A_i x + B_i y + C_i$
   - Results in a piecewise linear 3D curtailment surface
3. Constrain annually available output of VRE in WeSIM: $E_{VRE} \leq E_{VRE}^{avail} - z_i \; \forall i$

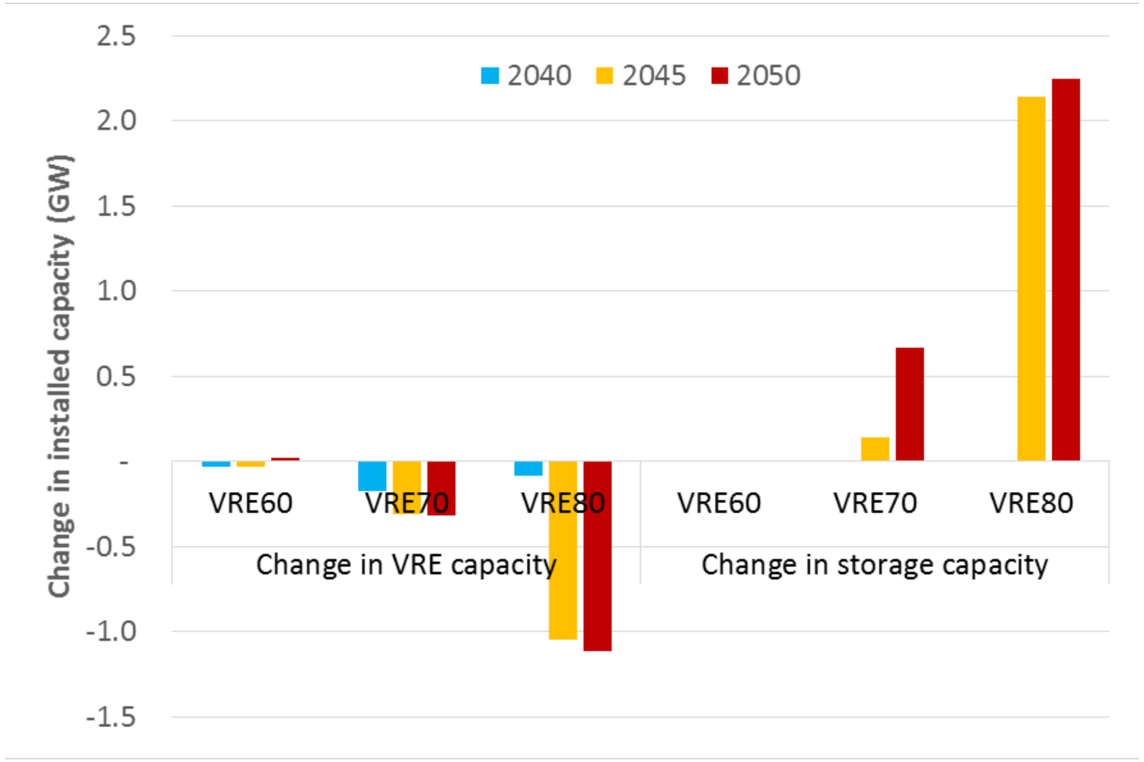


- Curtailment of VRE may trigger investing in energy storage to ensure a more efficient VRE integration.
- This will provide a proxy for the System Integration Cost (SIC), enabling a fair comparison to other low-carbon technologies (e.g. nuclear).

Preliminary results

- We analysed three high-level scenarios in terms of VRE share in 2050 electricity supply:
  - VRE penetration = 60% (VRE60)
  - VRE penetration = 70% (VRE70)
  - VRE penetration = 80% (VRE80)
- UKTM was run for these scenarios with and without the modification to account for VRE curtailment
- As expected, the modification of UKTM resulted in ***lower installed VRE capacity*** and ***higher storage capacity***
- Impact of proposed approach more pronounced at high VRE levels

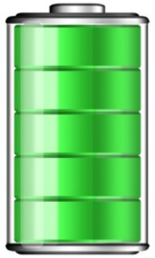
(Note that UKTM can shift demand from/to electricity sector given its multi-vector dimension. This is why the same VRE penetration could be maintained with lower capacity.)



Future refinements

- Additional testing and validation
- Include other influencing variables:
  - Demand
  - Nuclear capacity
  - Other forms of flexibility
- Increase number of data points used to construct 3D curtailment surface
- Separate curtailment for wind and PV
- Refine cost assumptions on VRE, nuclear and energy storage to identify tipping points
  - When does VRE become more competitive than nuclear?





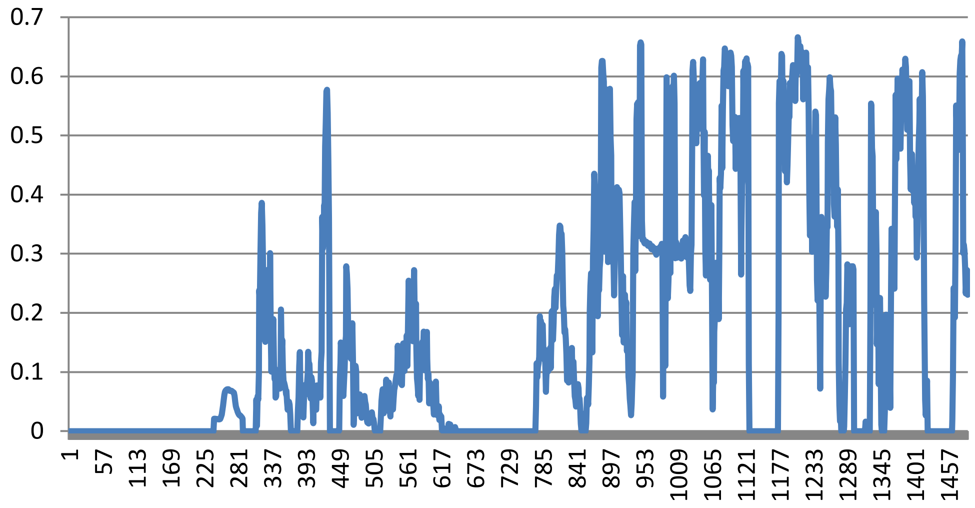
vs.

Integrating social practice and economic rationality principles in household energy demand modelling

Kavin Narasimhan (Surrey University)

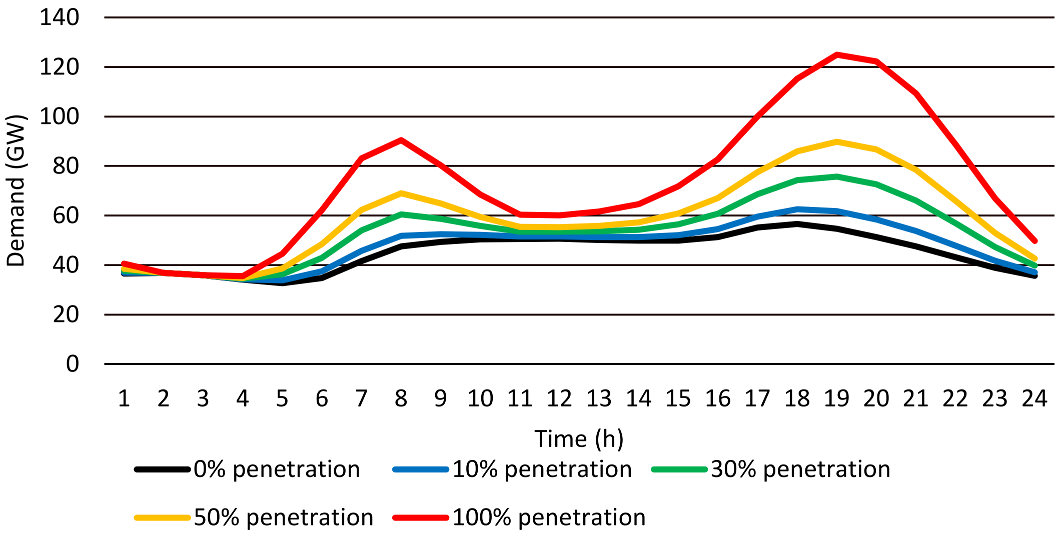
Dimitrios Papadaskalopoulos (Imperial College London)

Emerging Challenges for Power Systems and Role of Demand



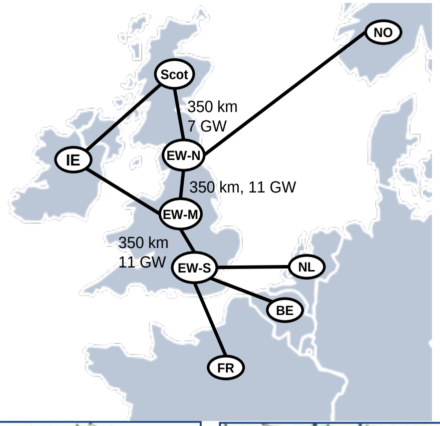
Underutilized generation and network capacity needs to be built in order to cover new demand peaks

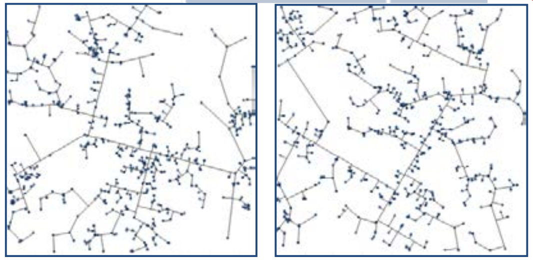
Underutilized conventional generation needs to remain in the system as a "back-up" energy source and flexibility provider



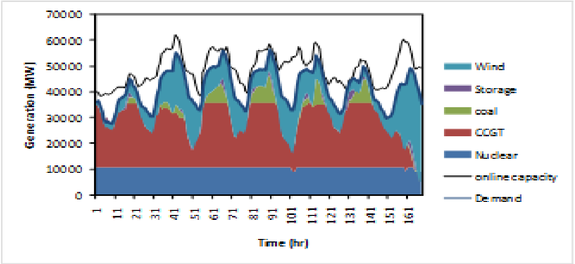
Power system modelling (WeSIM)

Interconnected GB system





Representative distribution networks



Future development scenarios

EU Electricity Demand, Generation and Network data

WeSIM:
Minimise overall investment and operation costs of power system

Renewable generation targets and system security constraints

- Investment in network assets
- Investment in generation assets
- Operation scheduling of generation, storage and flexible demand

REPRESENTATION OF DEMAND?

Economic rationality / utility maximisation framework

- The consumers determine the schedule of their appliances by maximizing their perceived utility
  - based on microeconomics foundations
  - the most common approach in power systems / energy economics literature

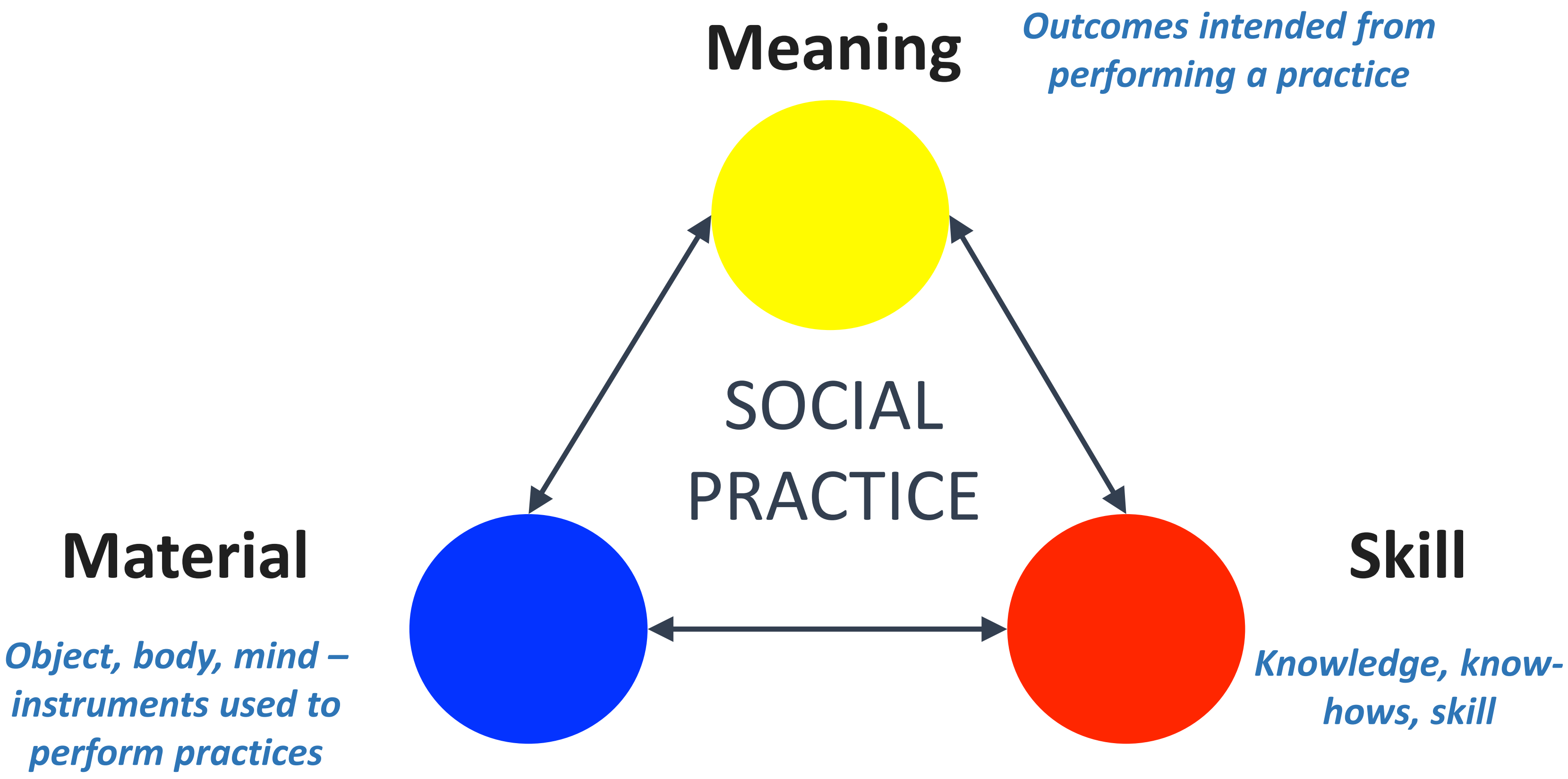
- Maximize $U = B(P) - \lambda * P$ subject to operational constraints
  - U : perceived utility (expressed in monetary terms e.g. £)
  - B : perceived benefit or satisfaction from the use of the appliances, expressing consumers' preferences and requirements (£)
  - λ : electricity price at each time period (£/kWh)
  - P : electrical power consumed at each time period (kW)
  - $\lambda * P$: electricity payment (£)

Limitations of the framework and the move to a sociological approach

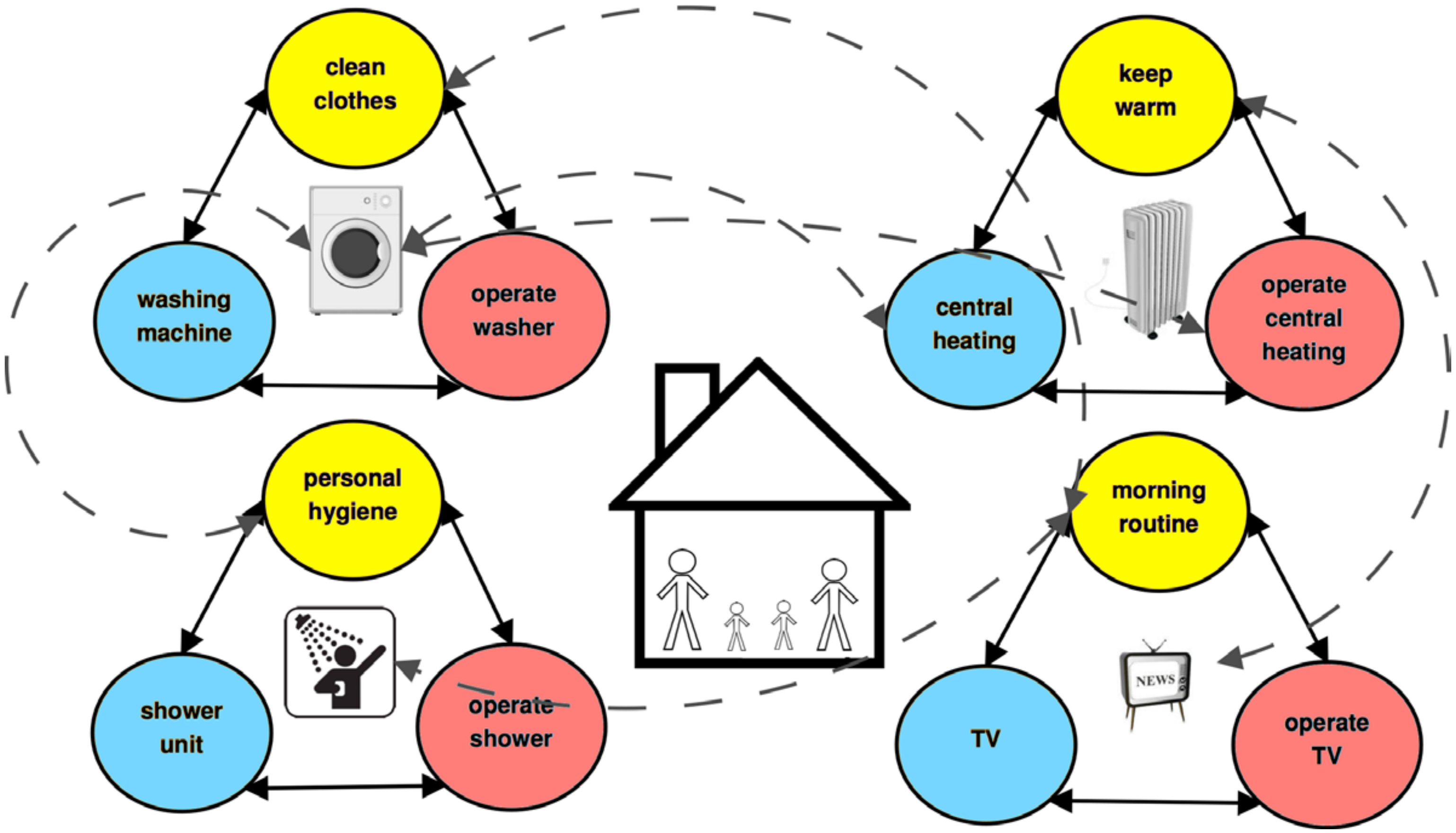
Insights from a sociological approach to understand the dynamics of household energy demand:

- Satisfaction is not a function of electrical power (kW); the satisfaction that consumers perceive will depend on the service quality and will be appliance-specific
- Satisfaction cannot be accurately expressed in monetary terms, even by consumers themselves
- Consumers do not generally behave economically rationally, e.g. they do not always act according to future prices
- Interdependencies between different household practices are neglected
- Various contextual factors, habits and routines drive consumers' behavior

Social practice theories: Concept 1

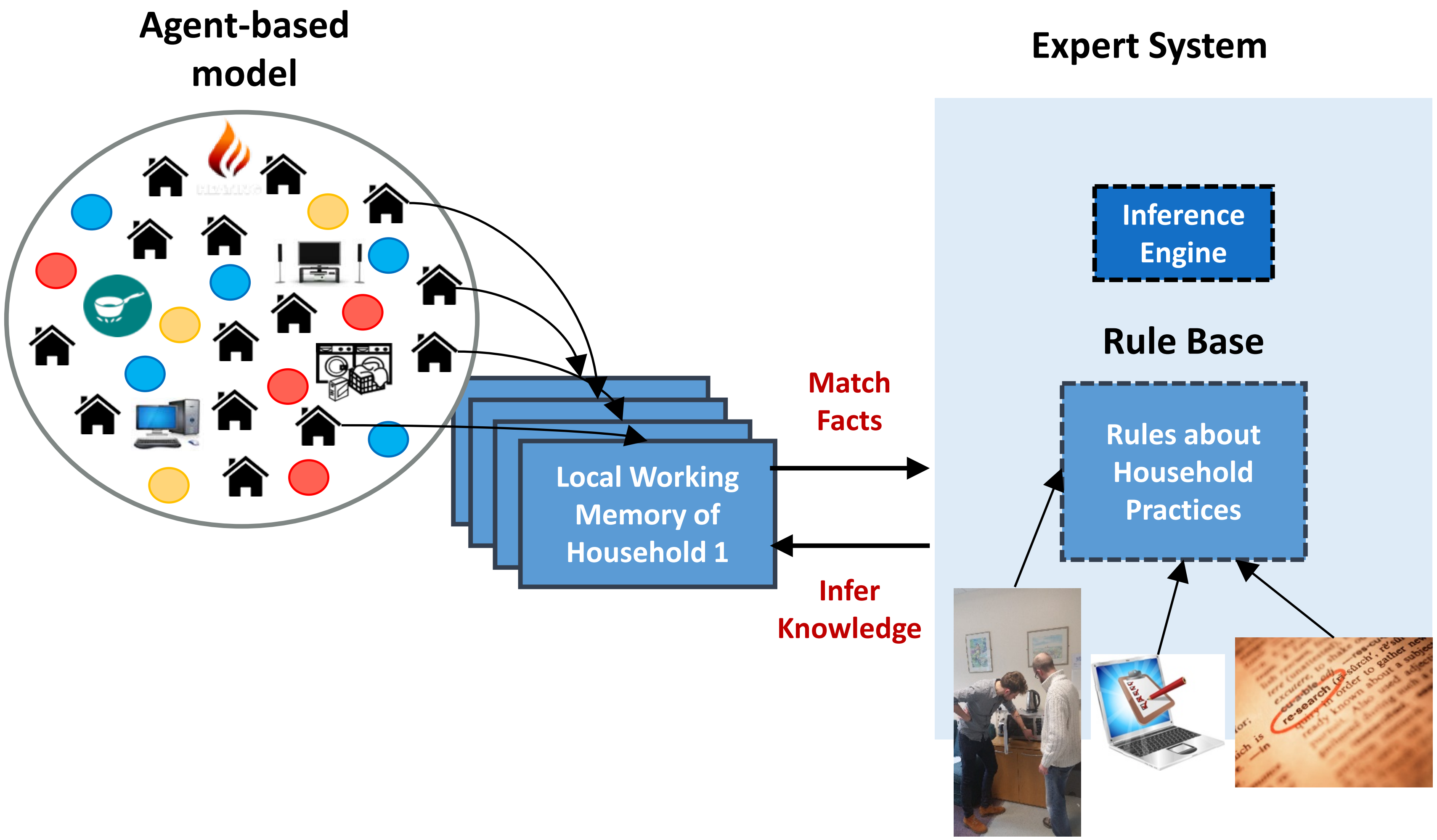


Social practice theories: Concept 2

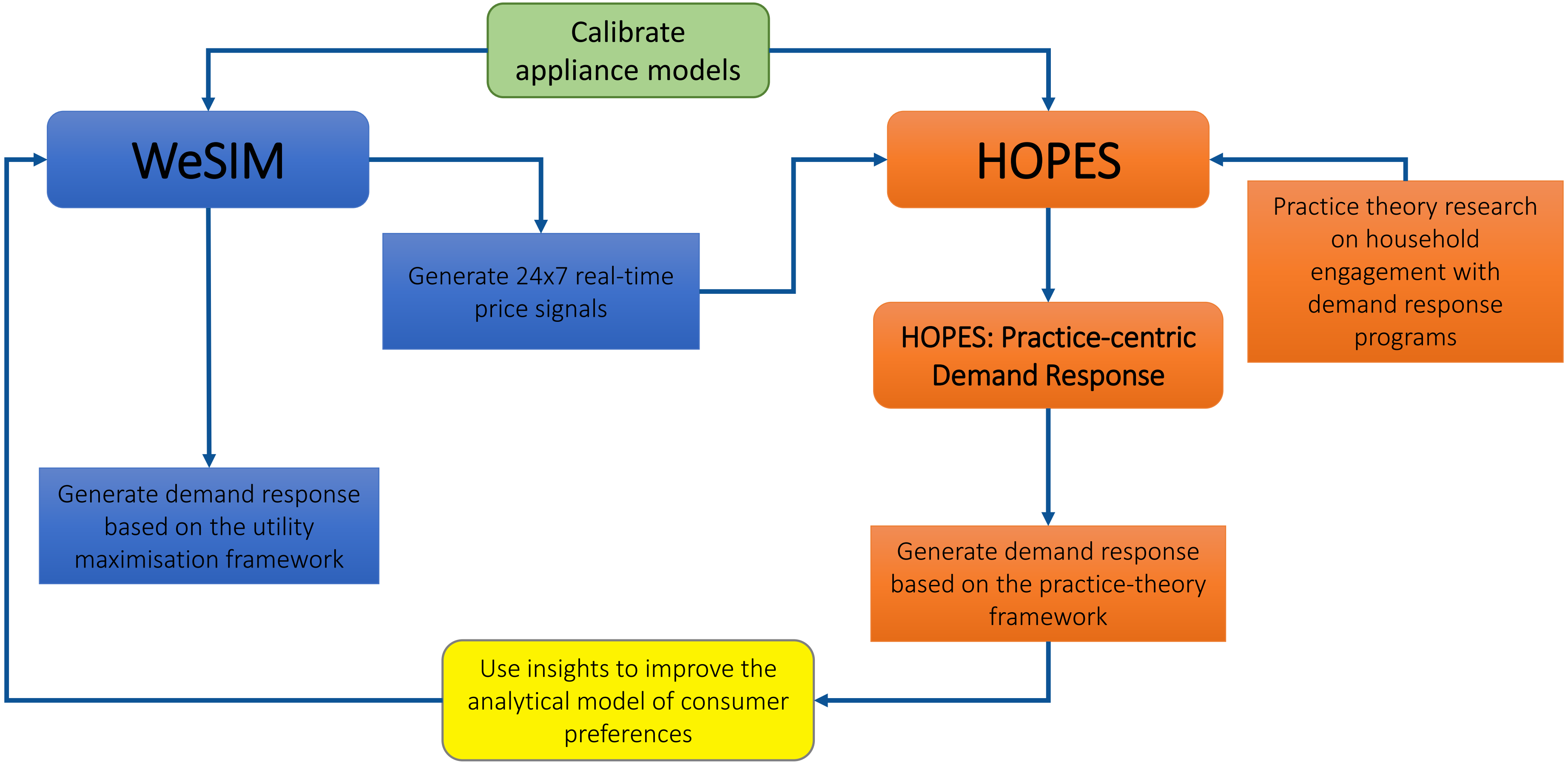


Key
- Meaning
- Material
- Skill

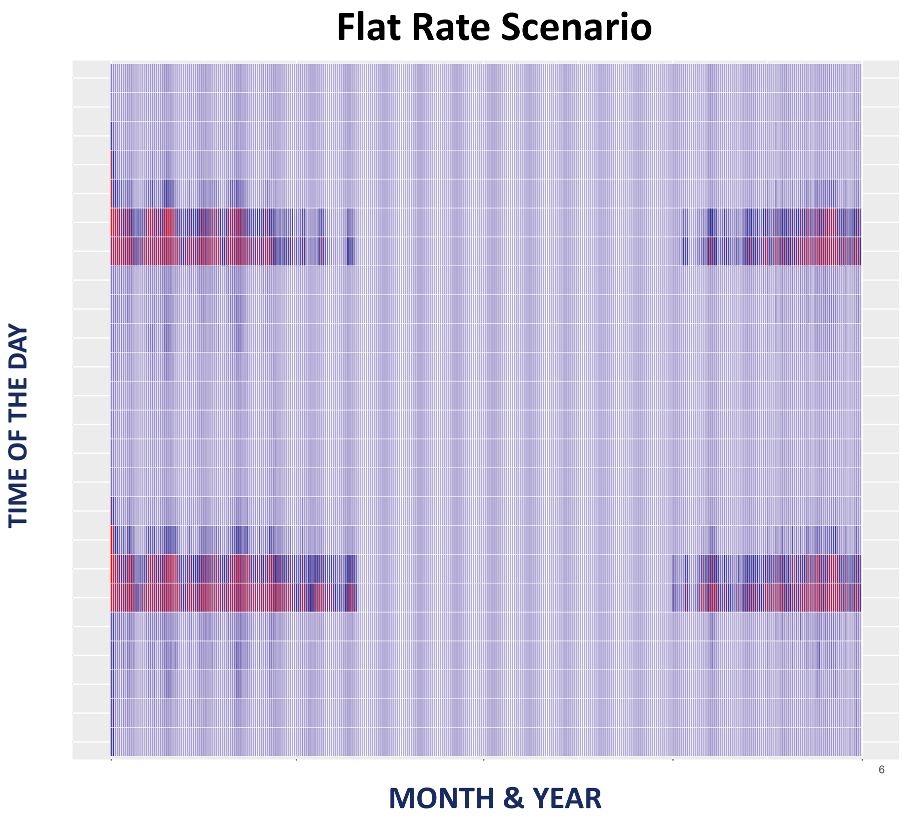
The HOPES model

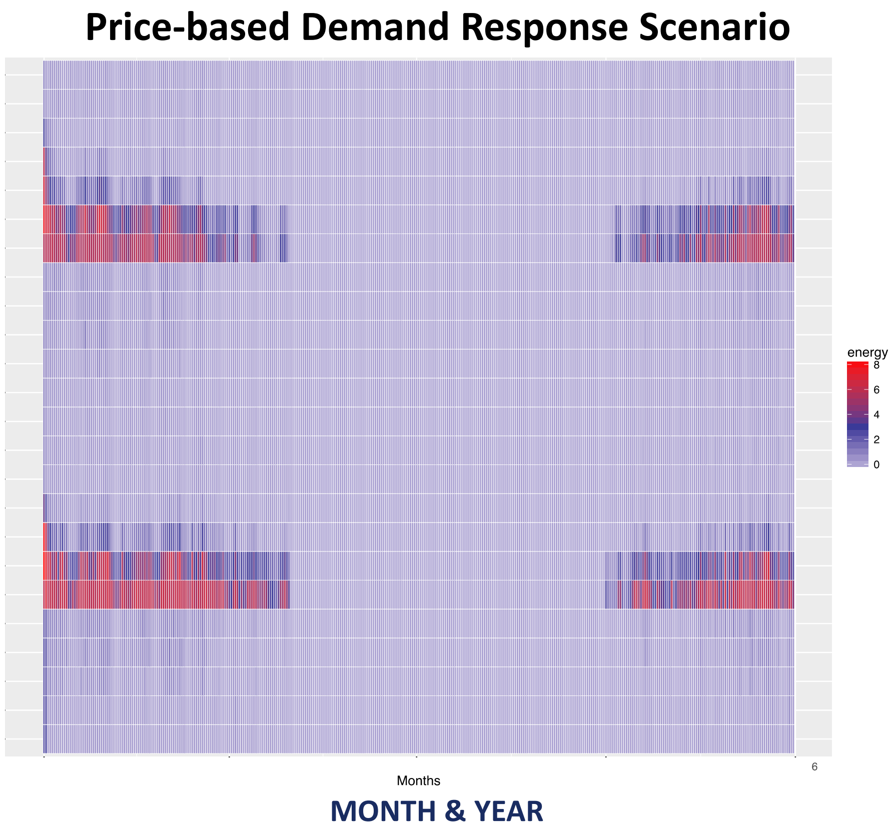


Overview of the Integration of WeSIM and HOPES



Heating Profiles of Households

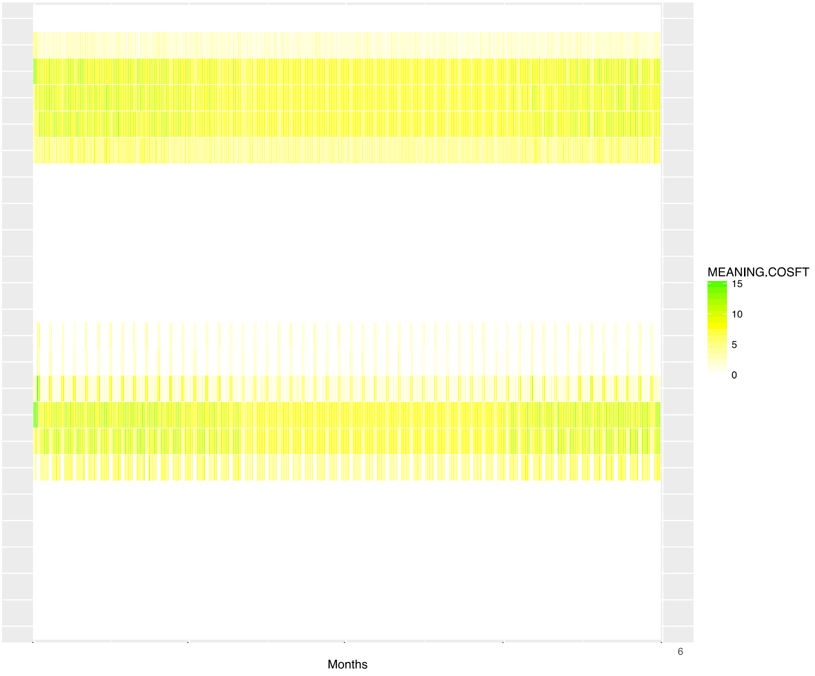




Although both scenarios produce roughly similar profiles of annual heating demand, the price-based demand response scenario results in an overall increase of demand, which happens because consumers are (in a sense) passively encouraged to use heating when the tariffs are low

Deriving a practice-centric understanding of the demand profile

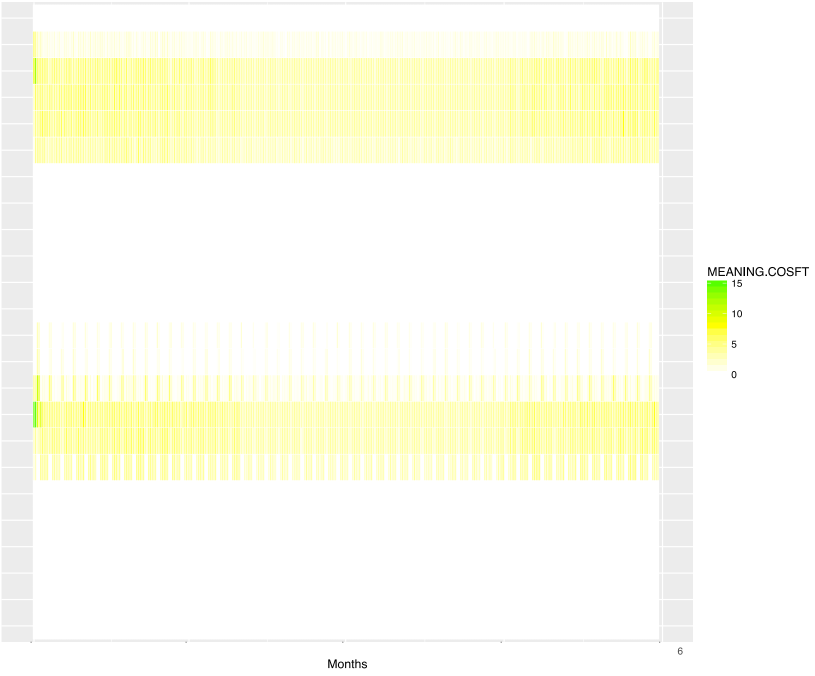
Flat Rate Scenario



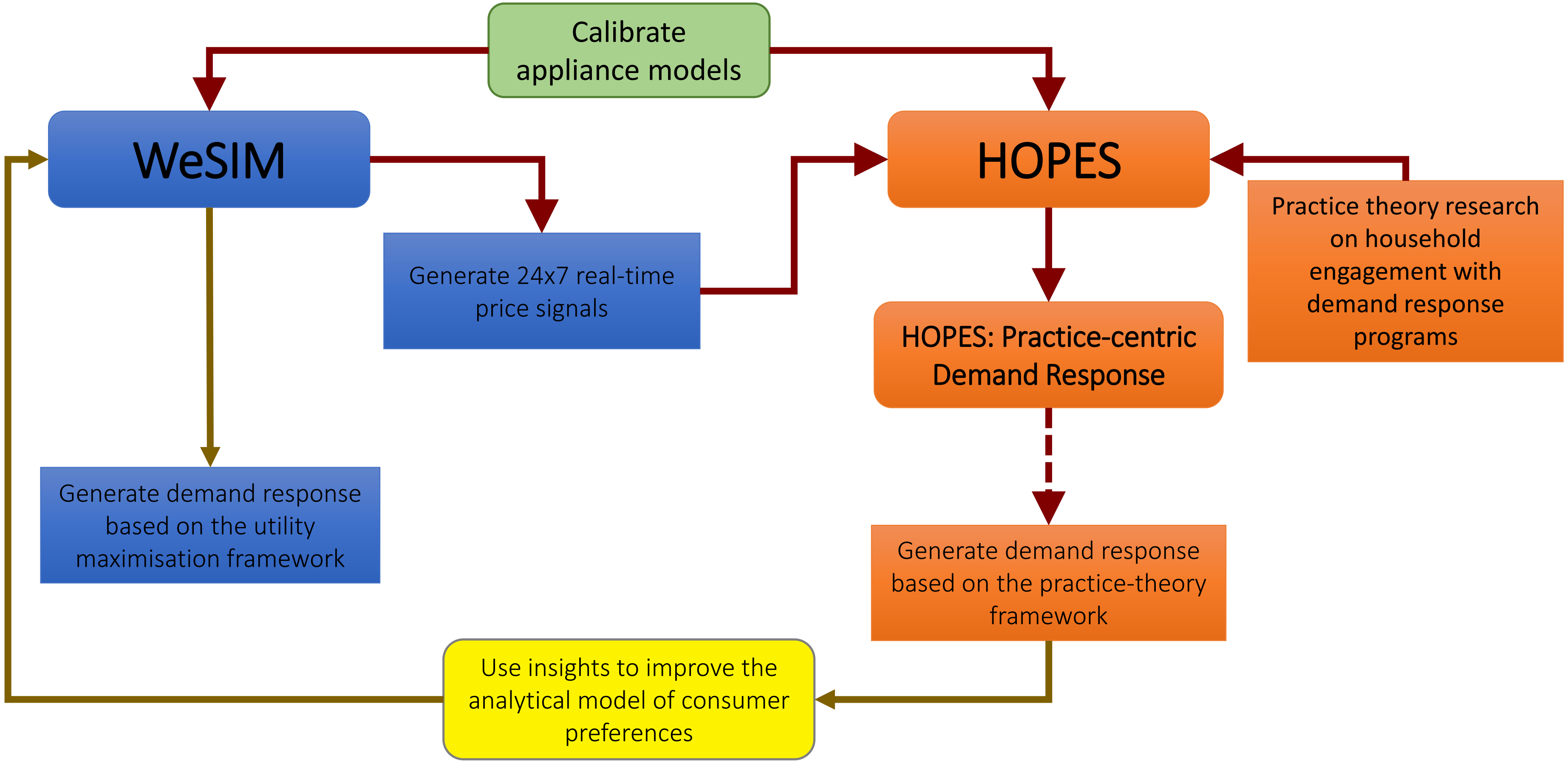
Responding to Peak Prices makes consumers view Heating as a Necessity rather than as a Comfort at other times of the Day

Meaning = Cosiness

Price-based Demand Response Scenario



Revisiting the Integration Plan



Contributions and Expected Outcomes

- Use the HOPES model to determine the main factors that drive consumers' behavior, and consequently, their demand profiles

- However, combining the HOPES ABM expert system model with a whole electricity system model is practically infeasible with the available tools and resources

- Therefore our approach involves deriving an approximate analytical model of consumers' preferences based on the outputs of HOPES and use this approximate model to investigate how a more accurate representation of the demand side can affect power system operation and investment policies

Planning low carbon electricity systems for Great Britain in 2050: a land-energy-water perspective

James Price (UCL)

Dennis Konadu (Cambridge University)

Andy Moore (UCL)

Zenaida Sobral Mourão (Cambridge University)

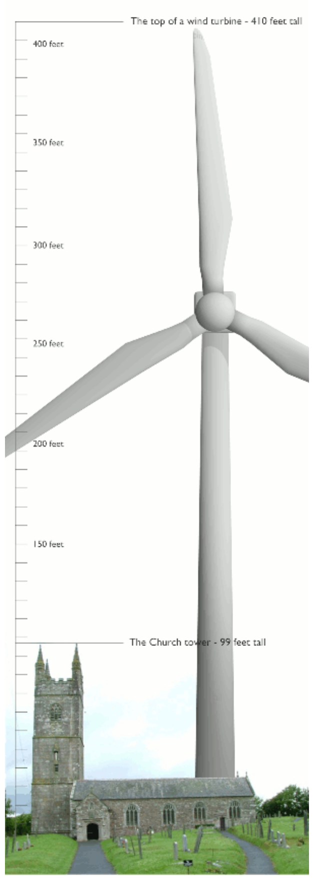
Marianne Zeyringer (UCL)

Background

Aim: to represent more of the key factors that shape future low carbon power system design.

Variable renewables (wind + solar):

- How much and where driven by land availability -> social, environmental and technical factors.
- Determines total output and timing of production
- “Good”/”Bad” sites -> lower/higher project levelised cost of electricity (LCOE).



Nuclear:

- Very strict siting requirements
- Significant social acceptability issues
- Typically limited to legacy sites

Non-nuclear thermal generation:

- Siting and cooling technology determined by future water availability
- Some social acceptability issues

To achieve this complex task we bring together three models: UK TIMES, Foreseer and highRES

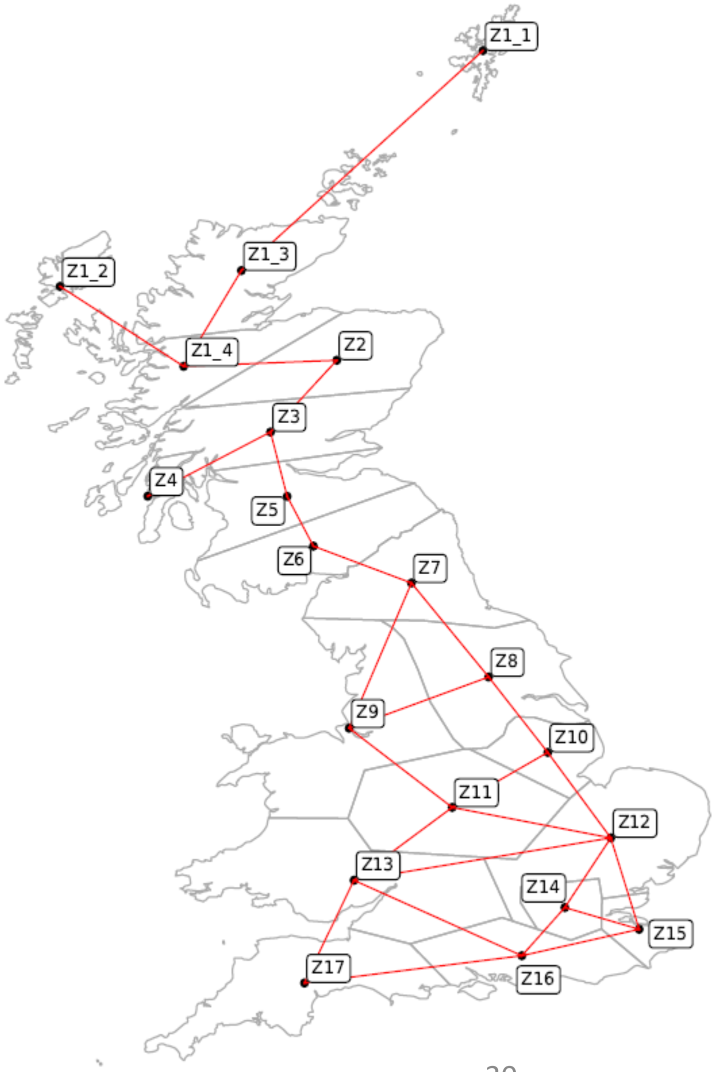
The models

- **high** spatial and temporal **r**esolution **e**lectricity **s**ystem model (**highRES**) – developed at UCL as part of WholeSEM – runs for one "snapshot" year (8760 hours).

- Makes capacity investment (annualised costs) and operational (dispatch) decisions so supply >= demand in every hour of the year, at least cost, subject to:
  - Technical constraints: ramping, storage, transmission and grid CO2 intensity.
  - Land constraints: social, environmental and technical factors that shape VRE deployment (***NEW!***)
  - Water constraints: abstraction and consumption limits for thermal generation (***NEW!***)

- Soft linked to UK TIMES (**UKTM**; also developed at UCL as part of WholeSEM):
  - Cost optimising, long time horizon model of the whole UK energy system.
  - highRES complements **UKTM**'s long term, holistic view.

- Here integrated with **Foreseer**:
  - Developed University of Cambridge, designed to investigate land-energy-water nexus.
  - Estimates land & water availability based on future demand by different sectors at high spatial resolution.

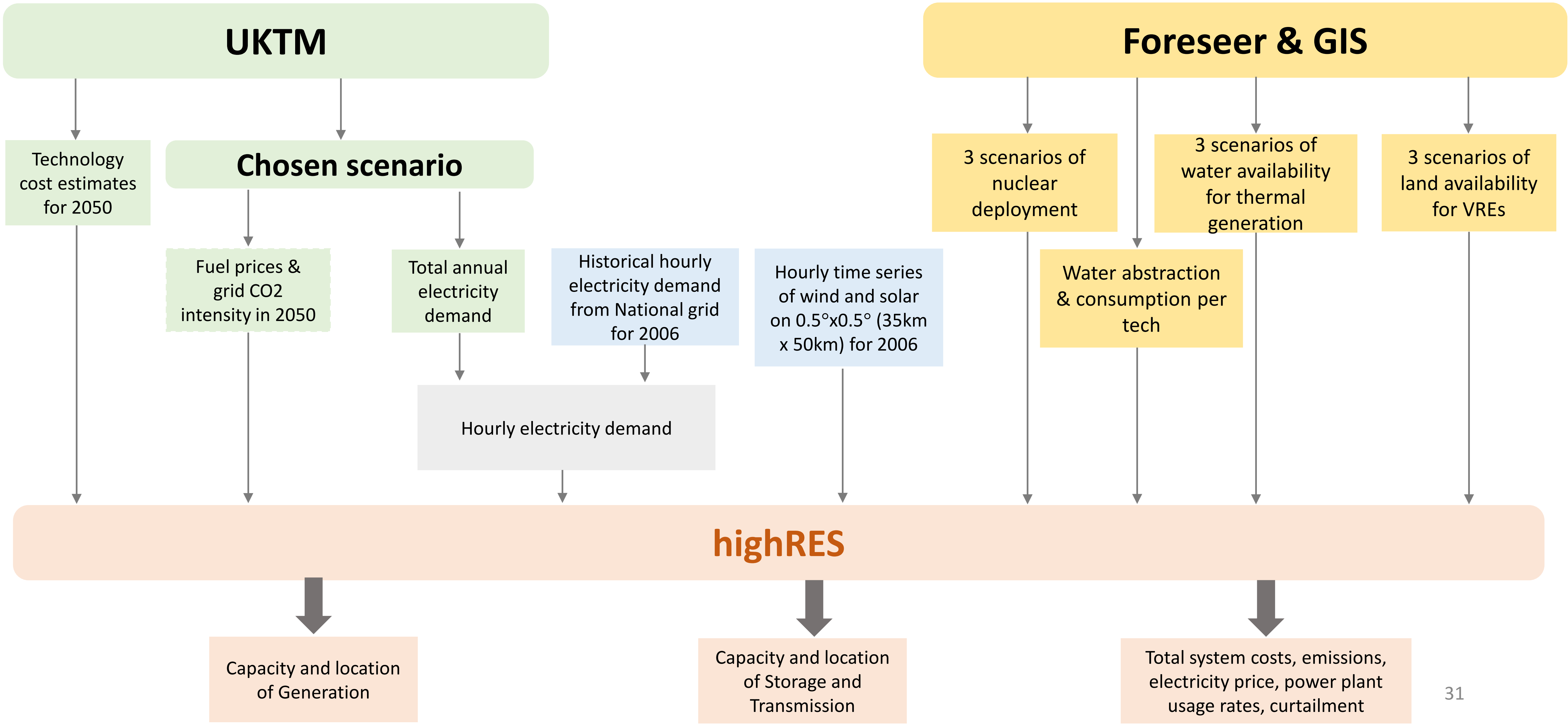


wholeSEM

Linkage

UNIVERSITY OF CAMBRIDGE

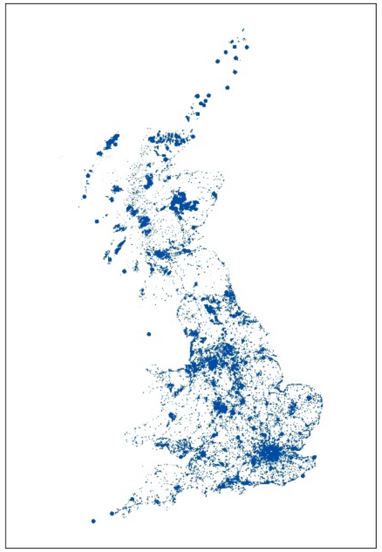
UCL



Land availability for VRE

PV low

Onshore wind low



Offshore wind low

PV high

Onshore wind high

Offshore wind high

Study setup

UKTM Inputs	
UKTM Scenario	NO CCS, achieves 80% GHG cut by 2050
Electricity demand (2050)	503TWh
Grid intensity (2050)	4.4 gCO_2/kWh

highRES	
Generators:	Solar PV, Wind on/offshore, Biomass (Open, closed and hybrid cooling), Nuclear
VRE integration options:	NG OCGT, Battery storage, Transmission reinforcement

+

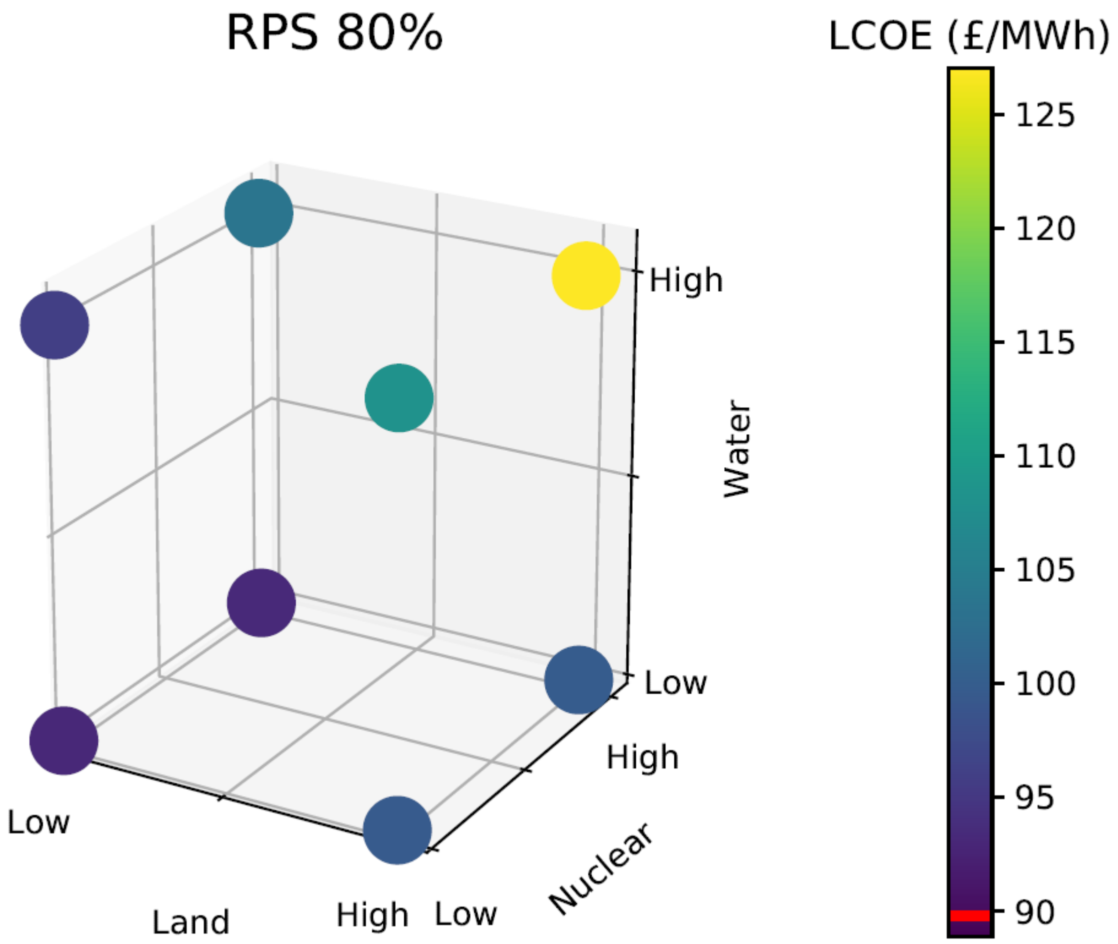
Scenarios	
Land for VRE:	Low, med, high
Water:	Low, med, high
Nuclear:	Low, med, high
Renewable share:	30%, 50% and 80%

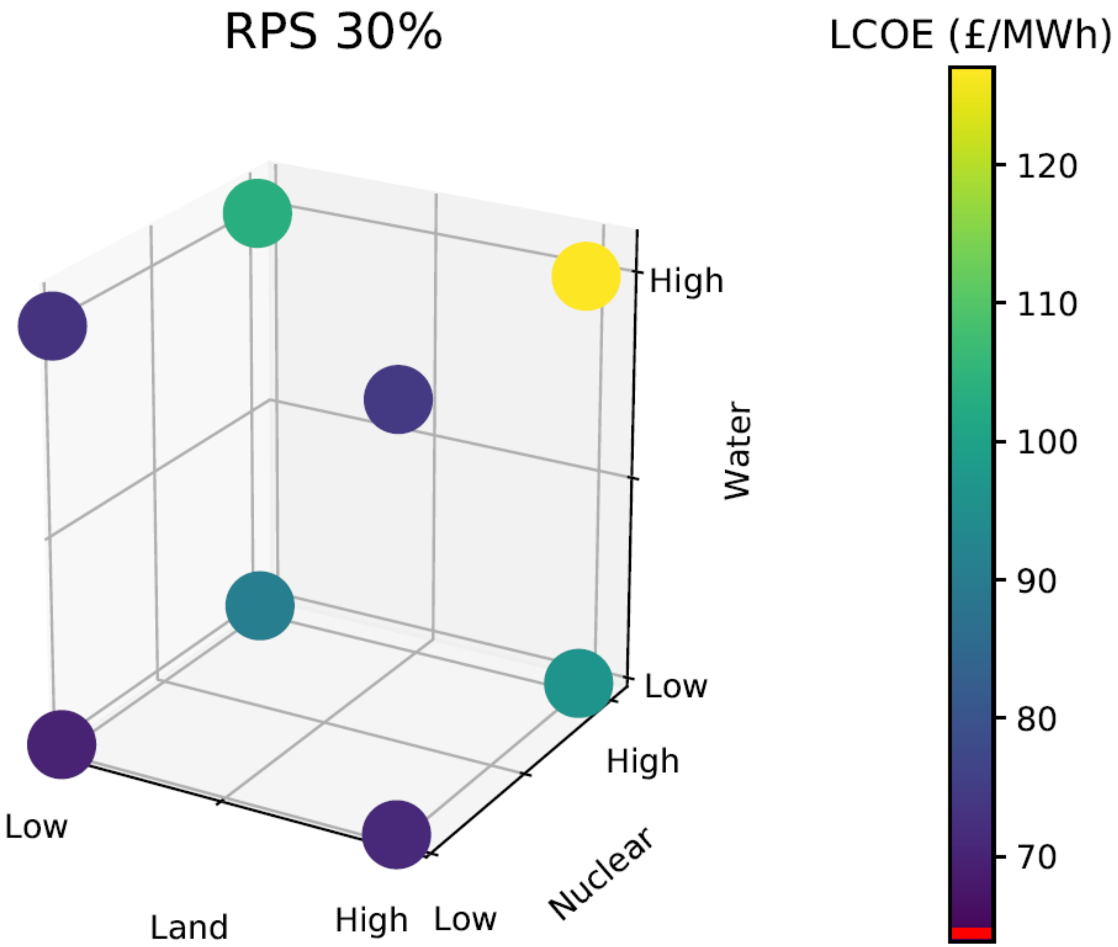
=

81 highRES runs

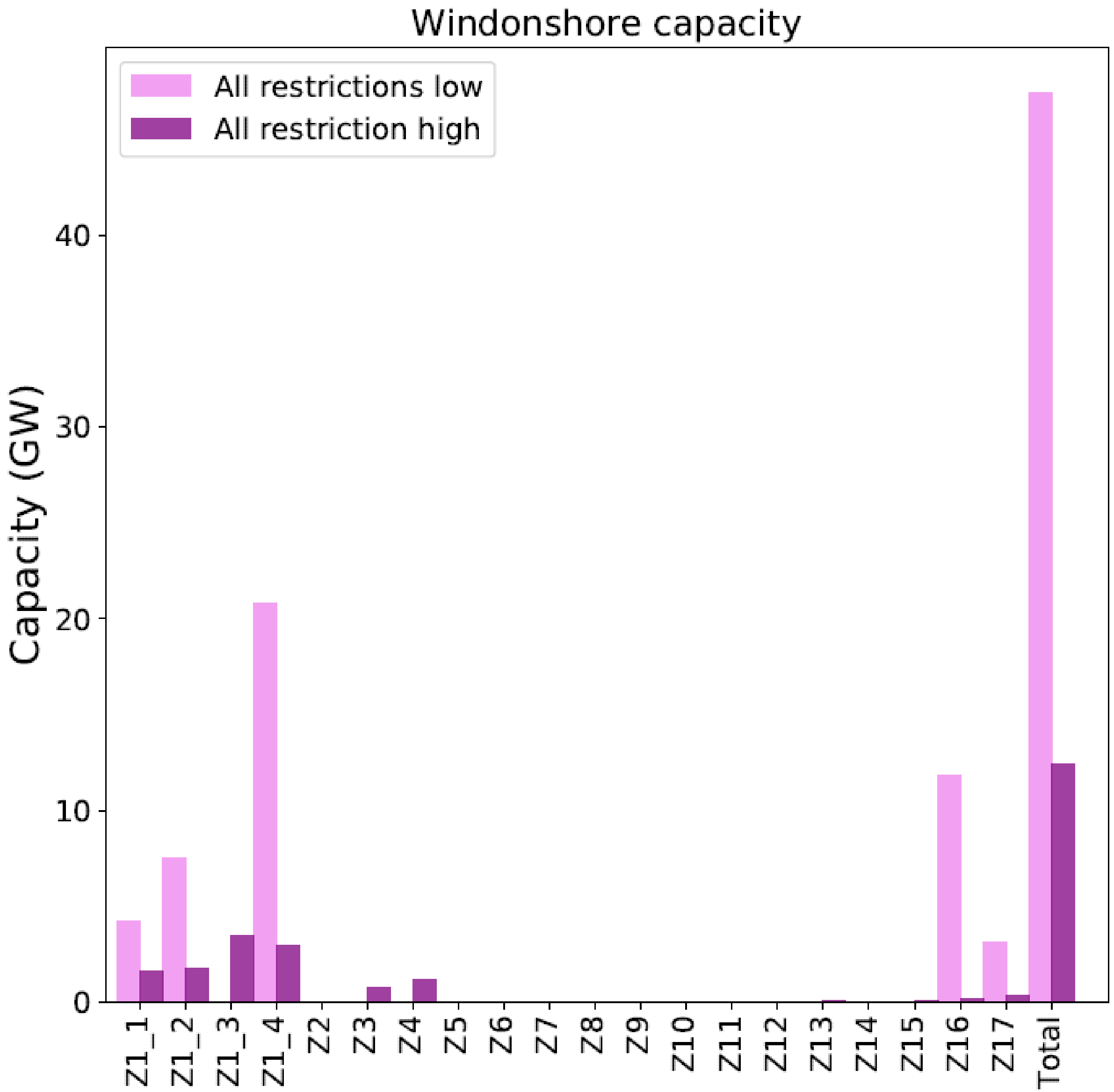
(Here focus on results from low/high combinations)

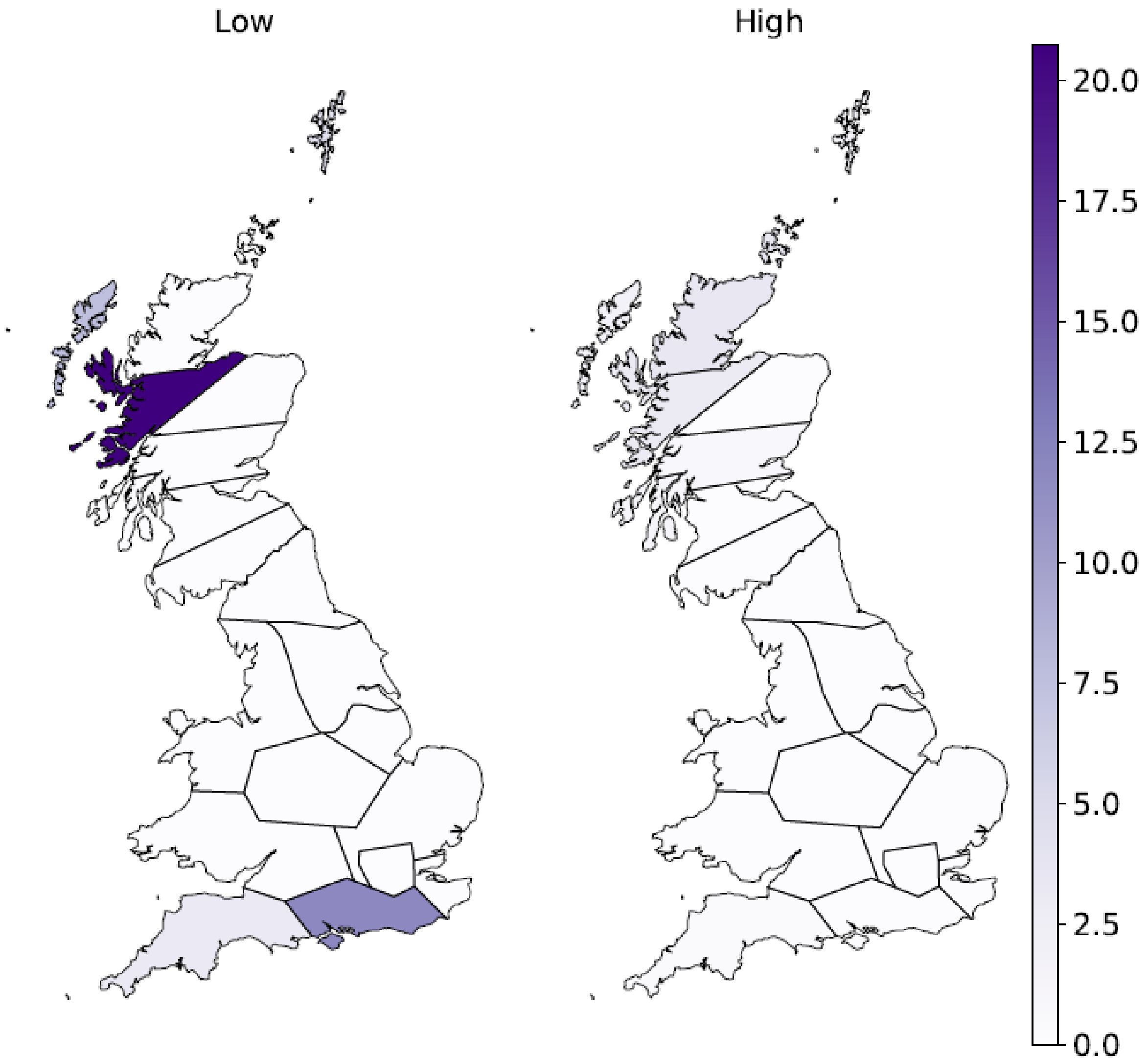
Results – LCOE (8 combinations of low/high)



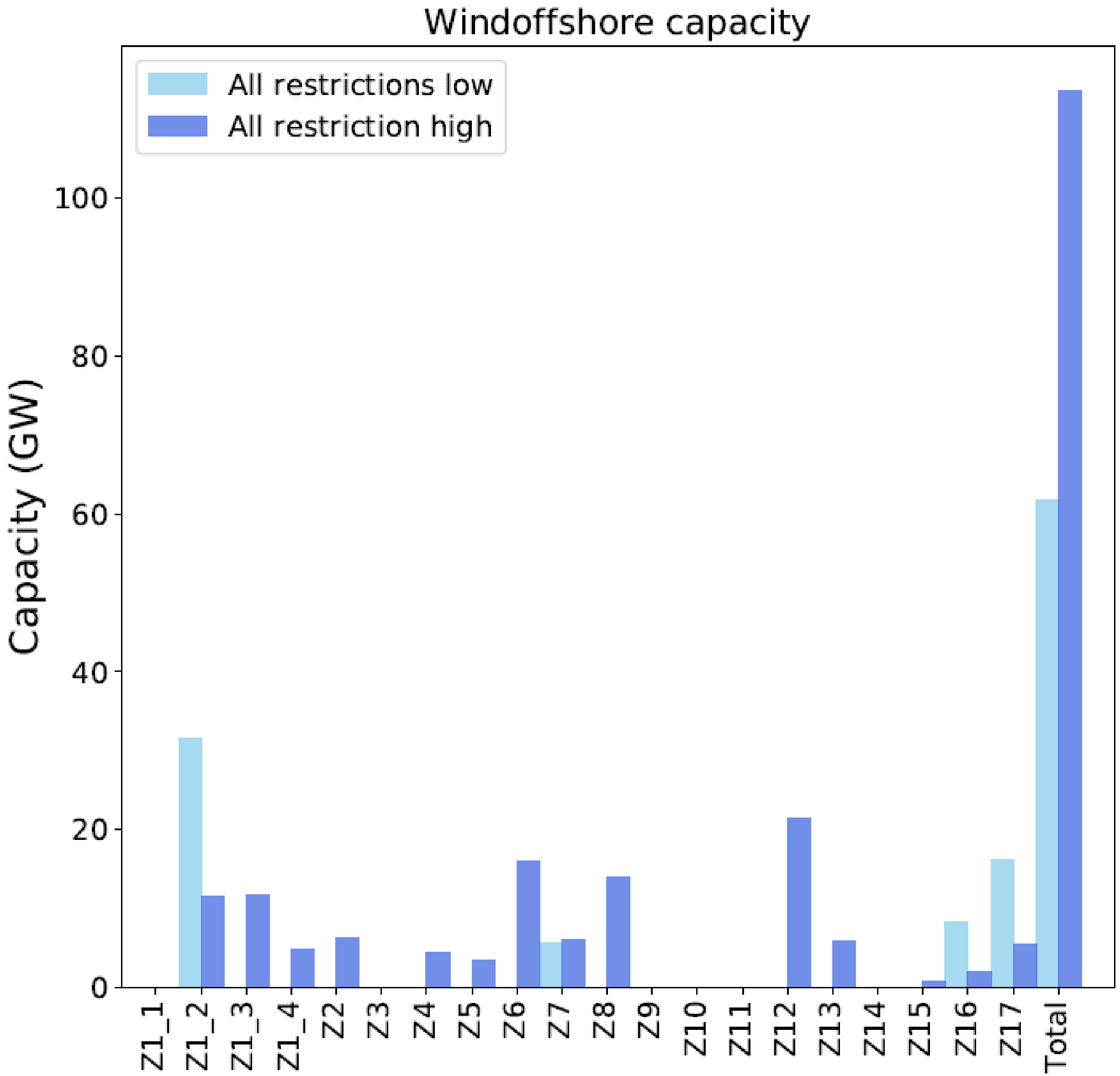


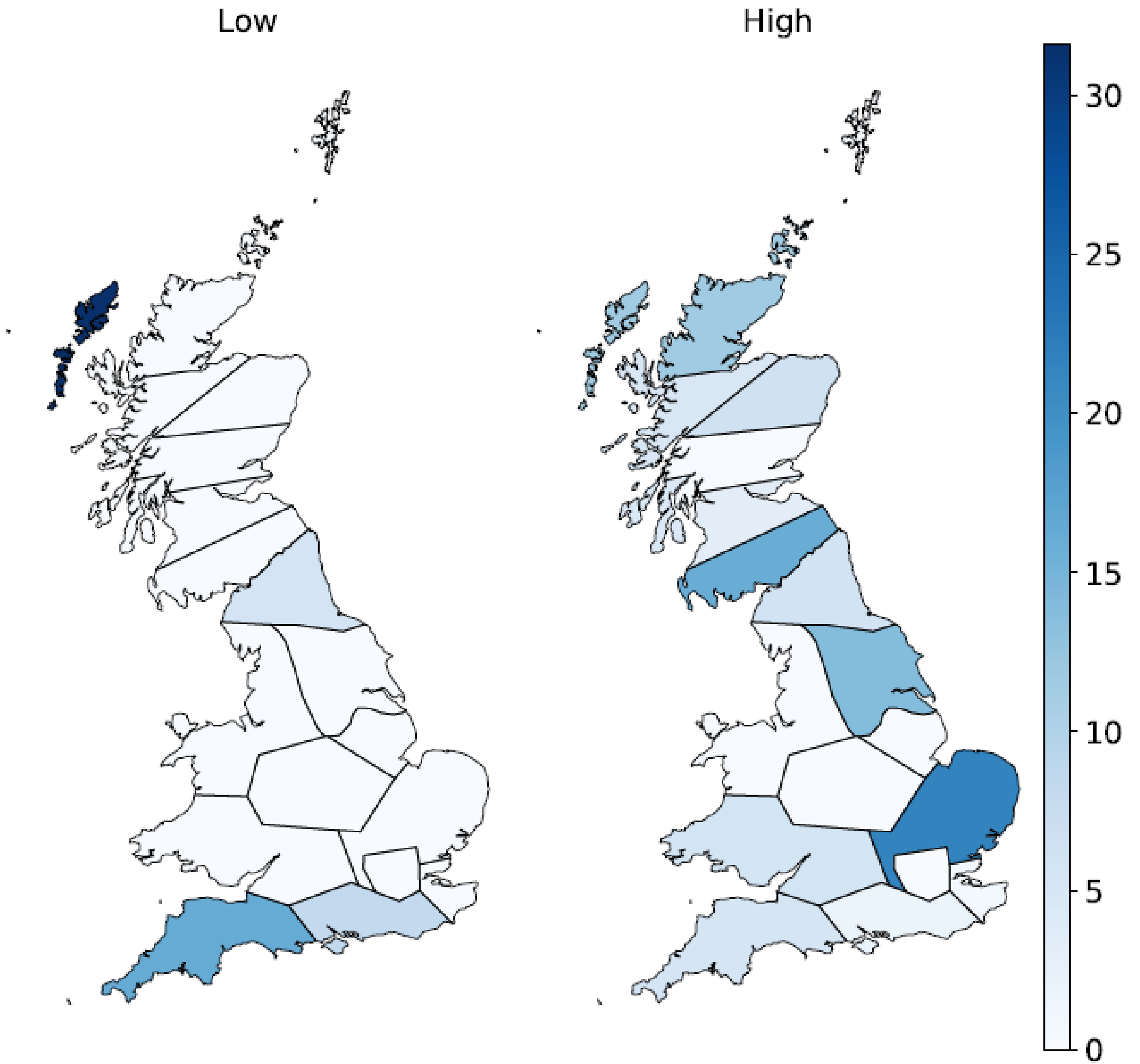
Results – VRE deployment (80% RPS)



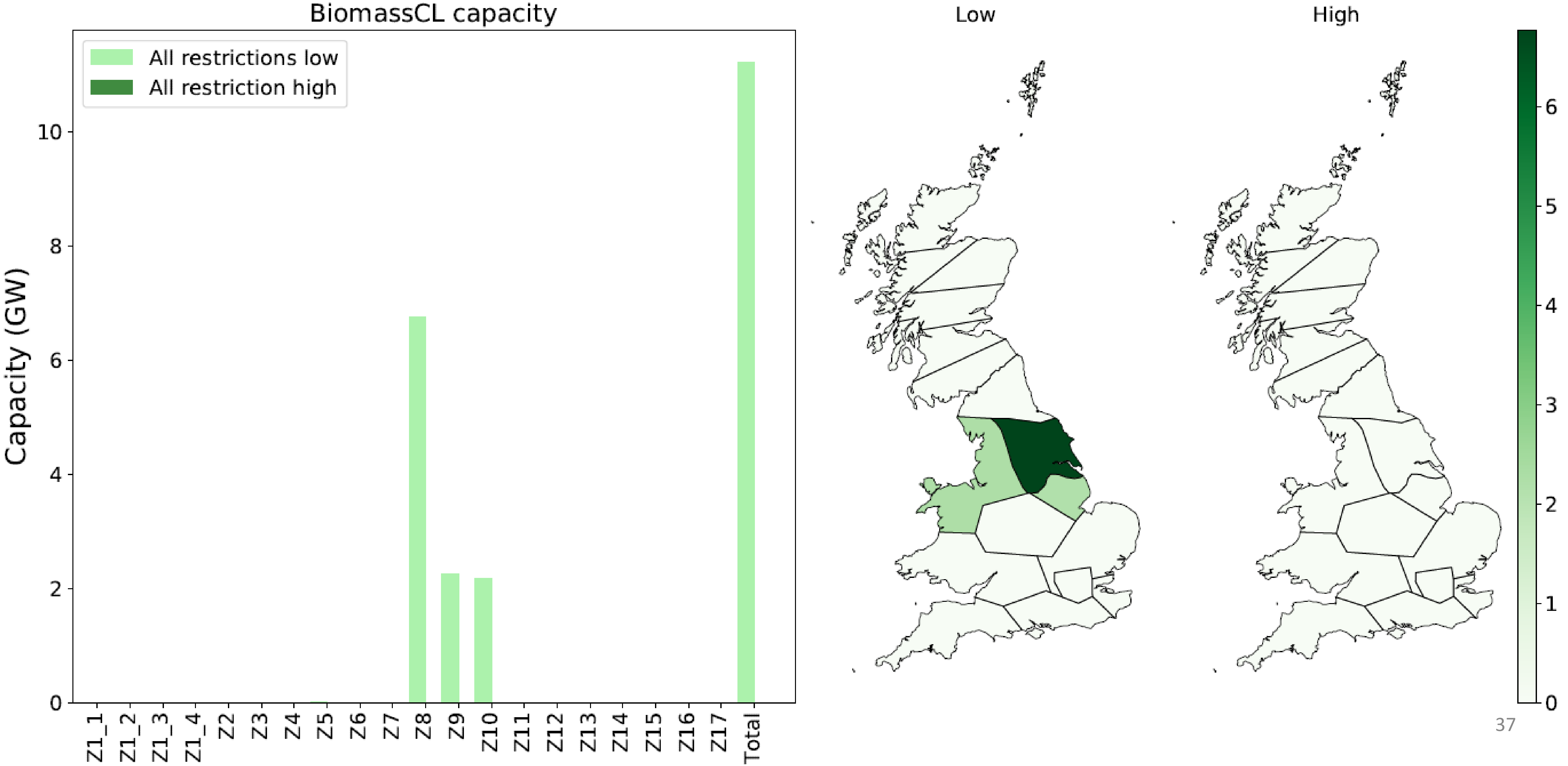


Results – VRE deployment (80% RPS)

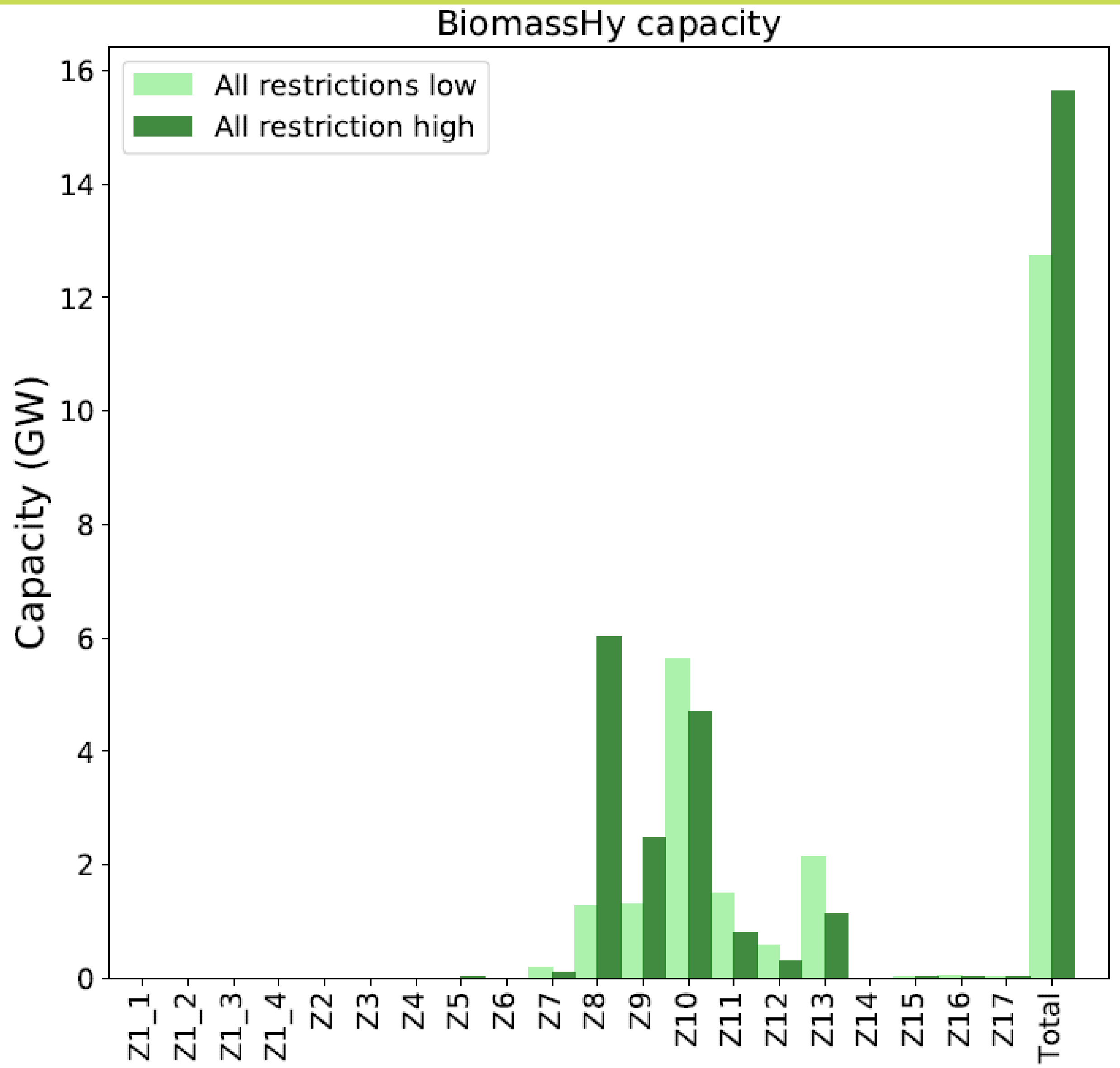


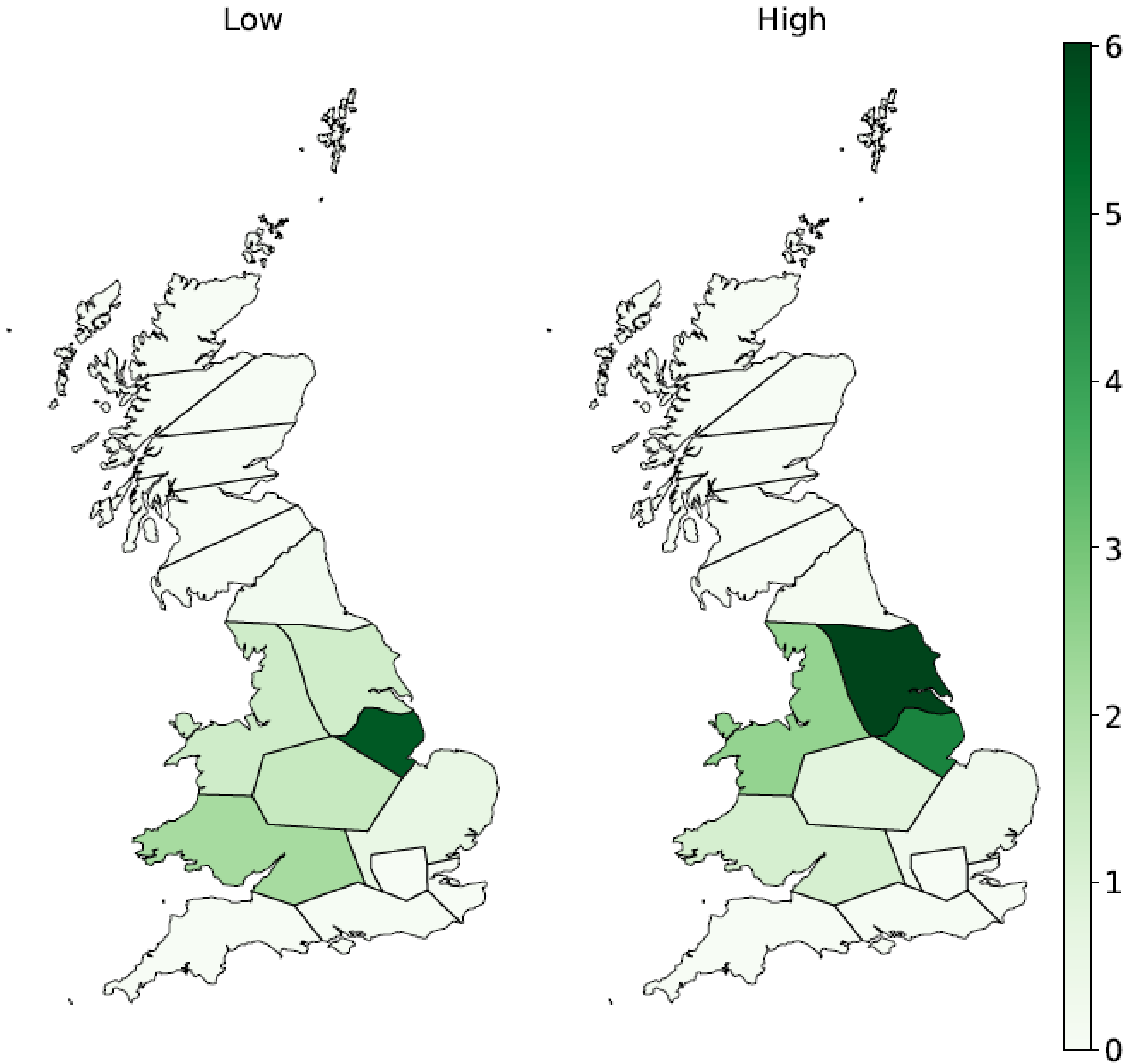


Results – Biomass deployment (30% RPS)



Results – Biomass deployment (30% RPS)





Conclusions

- The inclusion of land, water and nuclear constraints has sizable impact on system design:
  - Costs
  - Spatial deployment patterns
  - Technology choices (e.g. biomass cooling)
  - VRE integration options - storage and transmission reinforcement (not shown due to time restrictions)

- Sensitivity analysis demonstrates under what circumstances certain factors become important.

- Linking and integrating models is challenging but worthwhile.

Overarching conclusions

Conclusions

- Linking models with the aim of representing technical, environmental and social issues is challenging: different concepts, disciplines, modelling approaches

- For this project we developed two approaches of integrating models:

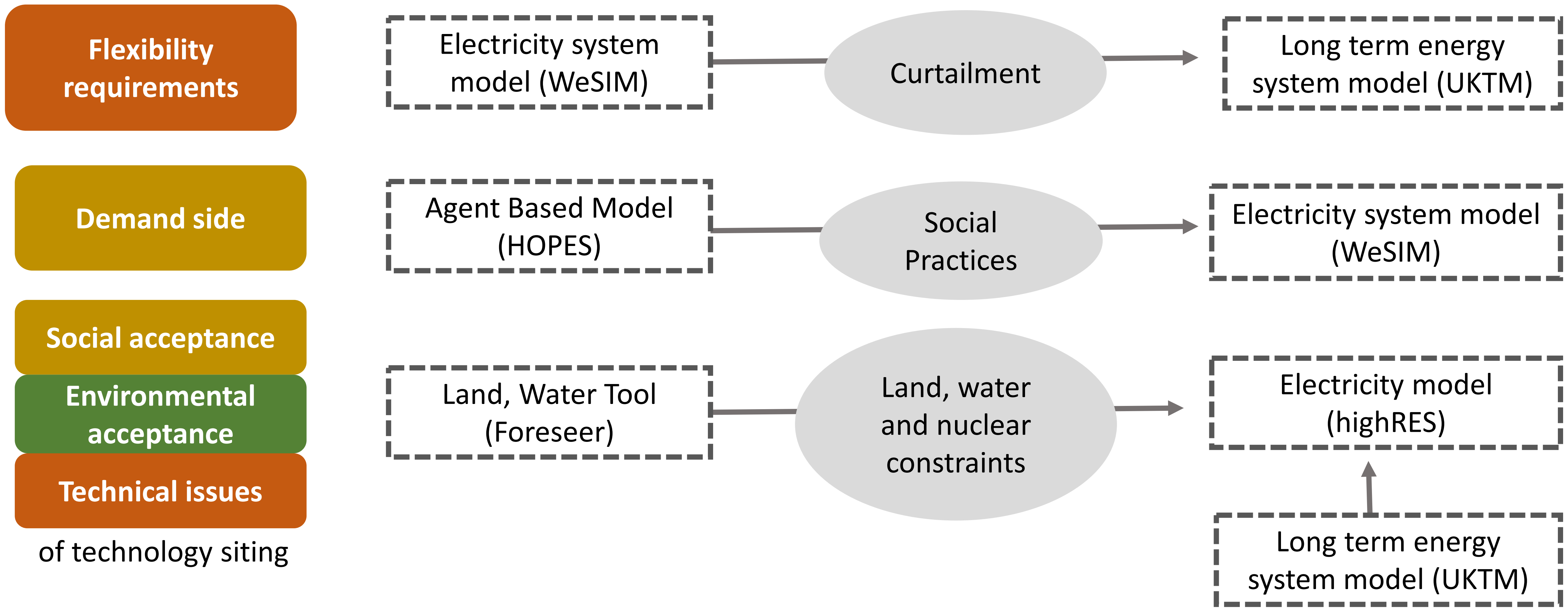
  - Using one model to come up with a parameterisation to be used in another model (Flexibility and Social Practices Case studies)

  - Integrating significant parts of one model into another (Nexus Case study)

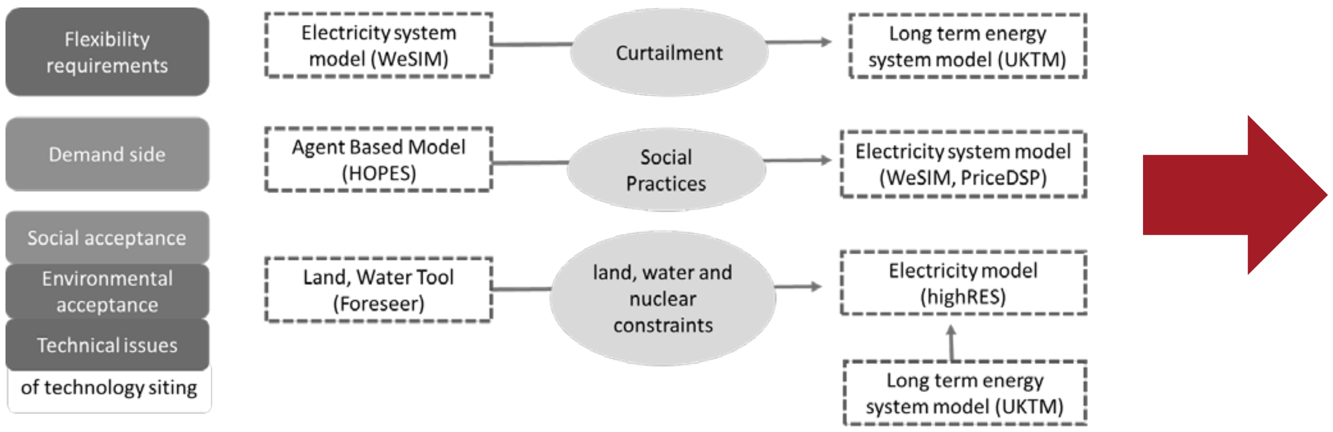
wholeSEM

Conclusions

Case studies represent three novel approaches to improve the representation of



Conclusions



Linking and integration allows us to:

1. add social, environmental and technical realism leading to different results in terms of system design and insights that one model alone would not produce

2. better explore and understand the complex, multi-faceted problem of transitioning to a low carbon electricity system


UCL
Characterising and integrating
demand response within a
long-term energy system analysis
Dr. Pei-Hao Li
MØLLER
CENTRE

The 'Adapt-elements' process
MØLLER
CENTRE
CHURCHILL COLLEGE
UNIVERSITY OF CAMBRIDGE

Thank you!