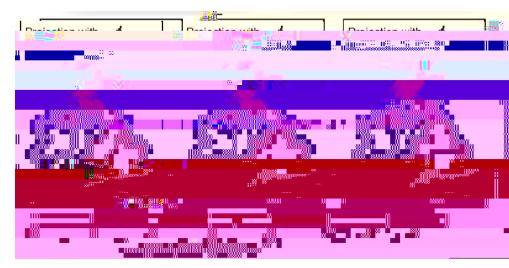
The design process

for 2050, 2100 and beyond



Project demands in a hotter world - +2 oC, +5 oC?

Select available technologies and configure

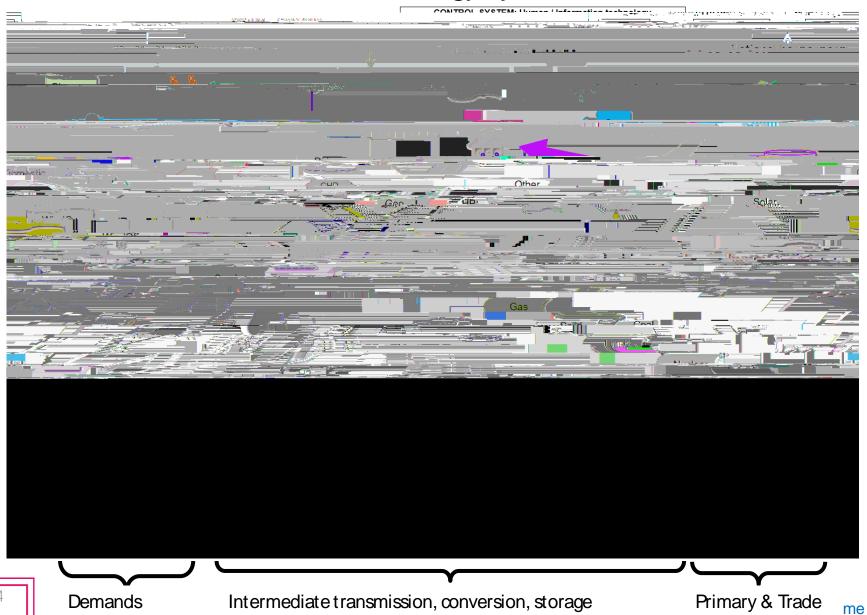
Smulate system hourly performance with historic meteorology to ensure designs actually work

Optimise to find least cost system designs

Explore 11 variant scenarios with different heat shares, dimate etc.

Conclusions

A national energy system



DH20%: Transition - demands

Insulation and climate change:

Heat demand decreases Cooling demand increases

5

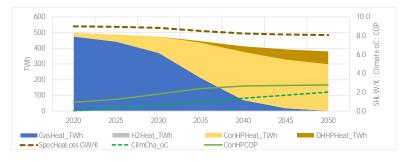
Heat/cool supply shift to electric HPs and DH

New demands: EVs, hydrogen, ammonia for ships, DACS negative emissions

2.5 1200 2 1000 1.5 800 600 400 0.5 200 0 0

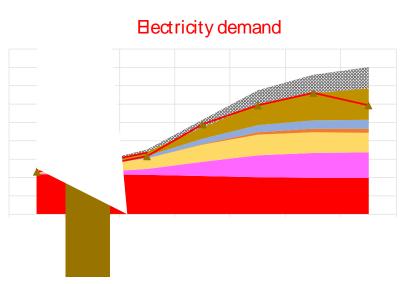
Demands

Heat supply shift from gas to HPs and DH



Eectricity demand increases from about 300 to 800 TWh.

Peak demand increases from about 60 GW to about 150 GW.



Primary energy: nuclear and renewable reliability

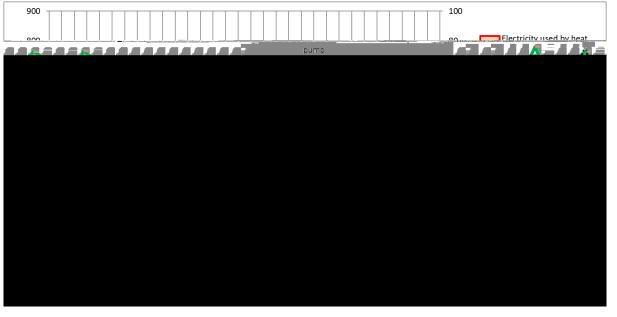
31 years annual renewable output variation Wind off +/-9%

Wind on +/- 20% Solar +/- 11%

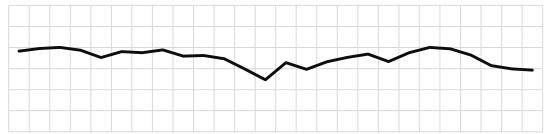
Offshore wind capacity factors projected for 55-65%

Annually, wind + solar is more reliable than nuclear

Nuclear: 25 years annual output ~70-83% average capacity factor Dip to <50% in some years Nuclear is not baseload even if operating properly 31 years annual demand and renewable output



25 years annual nuclear output



Primary: renewables and nuclear costs

Renewables mass produced, costs falling, privately financed, no insurance subsidy

Nuclear

Final cost Hinkley C? 30 £bill?

Decommissioning nuclear fleet?

Nuclear Decommissioning Authority (NDA): somewhere between £99 billion and £232

<u>Nuclear Provision: the cost of cleaning up Britain's</u> <u>historic nuclear sites - GOV.UK (www.gov.uk)</u>

Insurance for UK operator liability About 1 £bn from operator Fukushima cost 100-200 £bn

Proliferation?

Central cost assumptions

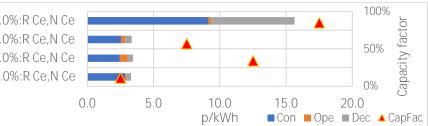
Generator	Solar	Wind On	Wind Off	Nudear
Capacity MW	30	8	12	3300
Construction Yrs	4	4	5	12
Operate Yrs	30	25	30	50
Decommission Yrs	1	1	1	100
CapFac	11%	34%	57%	85%
Generation kWh/kW	964	2978	4993	7446
Const Capital £/kW	350	1020	1430	6500
Decom £/kW	50	150	300	2500
O&M £/kW/a	2.5%	2.5%	2.2%	2.0%
0&M £/MWh	1.0	6.0	3.0	2.0
Fuel p/kWh				0.5
Tech. specific rate	6.5%	6.5%	7.5%	8.9%

Indifferent discount rates: nuclear decommissioning rate 0%/a



Technology specific discount rates 0%/a nuclear decommissioning rate

Nuc:C8.9% O3.5% D0.0%:R Ce,N Ce WOf:C7.5% O3.5% D1.0%:R Ce,N Ce WOn:C6.5% O3.5% D1.0%:R Ce,N Ce Sol:C6.5% O3.5% D1.0%:R Ce,N Ce



DH20%: Operation in 2050:

Sample days

How will the electricity and energy markets build and operate this?

What prices to consumers?







Meteorology

Demands

Winter heat peak, summer cooling peak

Generation

-

Winter wind peak, summer solar peak

DH20%: 2050 year

Stores, renewables, flexible

Surplus/deficit, H2 electrolysis and DAC

Heat pump COPs



DH20%: Transition to optimised system - electricity

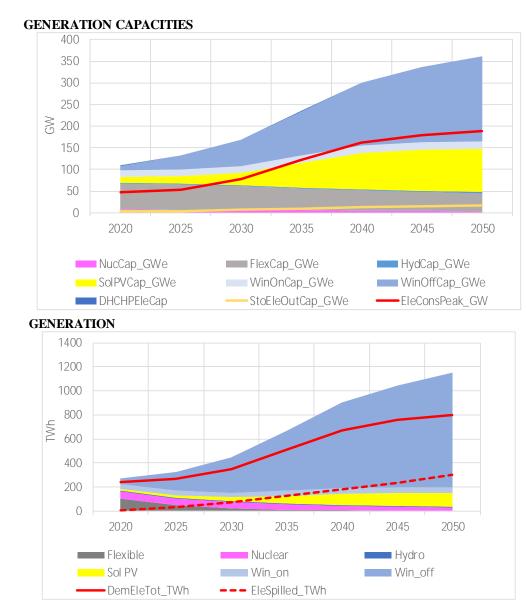
Primary electricity:

84% from wind, mainly offshore10% solar2% nuclear4% other

About 50 GW of gas/bio flexible generator used with capacity factor of ~1%

20-30% of generation is spilled without interconnectors

~300 GW of new generation capacity – what policies and markets will deliver this?



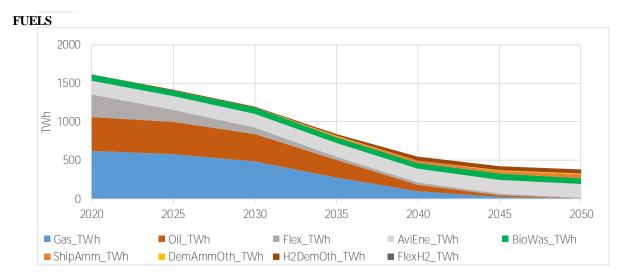


DH20%: Transition fuels and CO2e emission

Chemical fuel consumption reduced to: Waste biomass Hydrogen Ammonia ships

Gas peaking generation

Fossil kerosene aviation



CO2 emission largely eliminated apart from:

Fossil kerosene and aviation altitude warming A little flexible gas generation

CO2e emission balanced by negative emission with unproven DACS (Direct Air Capture and Sequestration)

4

CO2e EMISSION

DH20%: Transition system costs

System costs similar to current, assuming ~2022 fuel prices.

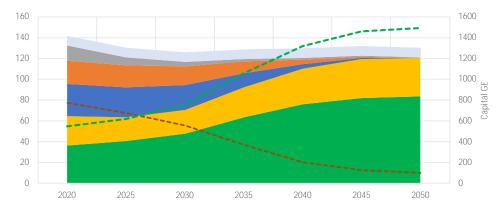
Future costs are dominated by capital and fixed O&M, so little volatility and high security

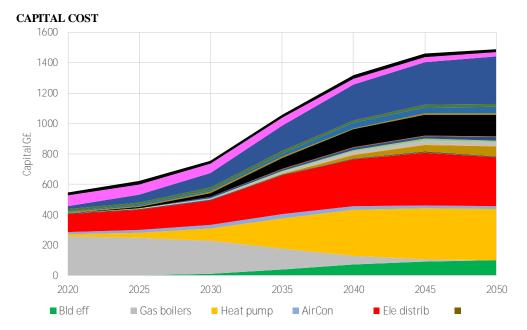
Capital investment about 2% of annual GDP

The largest capital costs are:

Heat pumps Electricity network Offshore wind Direct air carbon capture and storage

Aviation about 20% of total system cost





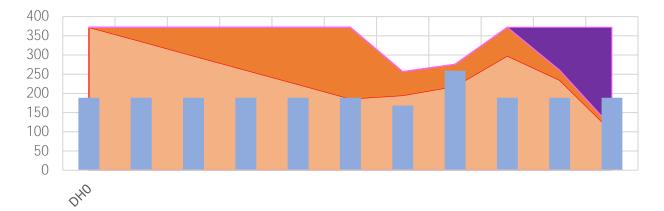
Heat and cool in 11 system designs

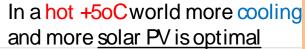
We need to plan beyond 2050 given the lives of buildings and infrastructure

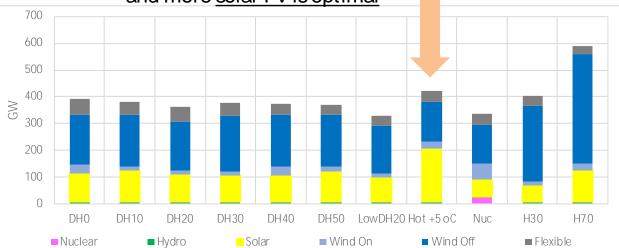
With climate change: Heat demand will fall, cooling will increase

Reversible heat pumps in buildings or district heat and cooling provide resilience

The more cooling, the more solar PV and less wind is optimal

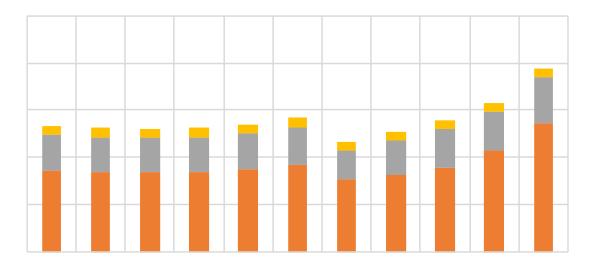








2050 costs in 11 system designs





Aviation

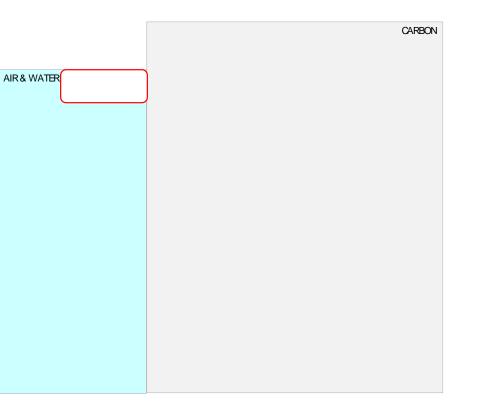
How to balance aviation altitude warming?

Negative emissions CO2 from the atmosphere

DACCS?

Direct Air Capture and Carbon Storage







Conclusions

Heat demand will reduce, cooling will increase Heating and cooling with consumer and DHC reversible heat pumps the lowest cost

Economy largely electrified; electricity demand triples

Renewables give supply and price security

Nuclear is more expensive and less reliable than renewables

Net zero systems have a similar total cost to the current system

Renewable systems economically and technically secure

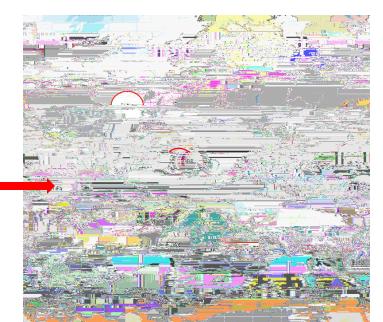
Some hard questions:

How to fuel aviation and balance high altitude warming? How to provide negative emissions? How to install heat pumps and district heating fast? What is the potential role for interconnector trading?

How will a future energy market function?

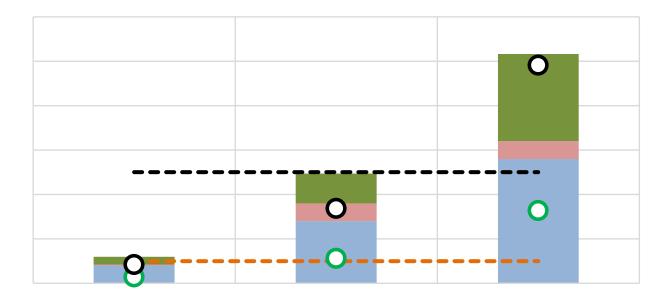


Thanks for listening



Aviation environmental cost

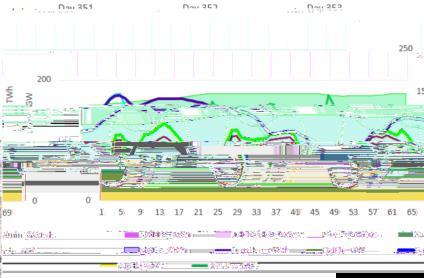
Cost of flying doubled or tripled ~300 £/tCO2 or electrokerosene Return flight to Spain = average African emission Return flight to USA = average UK person emission



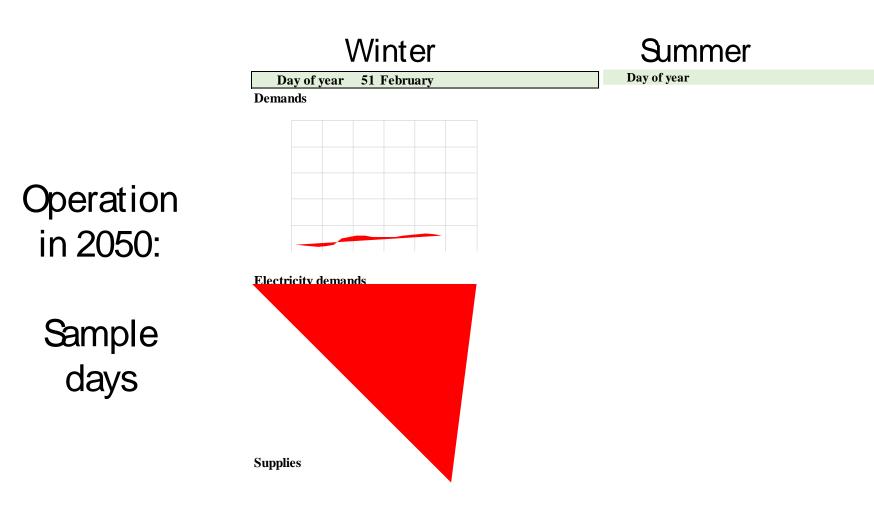


Designing a system to connect demands and renewables across time and space



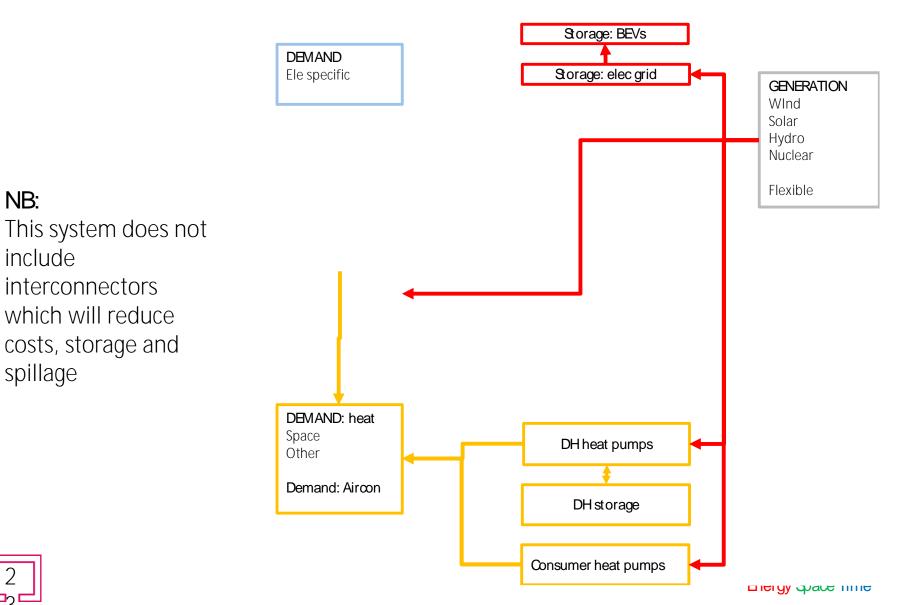








Energy system diagram



2

NB:

include

spillage

Model algorithm

Demands	Weather independent	(Use pattern) x (average demand)	
	Weather dependent	(Use pattern) x (Tint_oC - Tamb_oC) (Specific heat loss) - (IncGain)	
	Elec: general	(Use pattern) x (average demand)	
	Elec: BEVs	(vehicle use pattern) x (average demand) x (weather sensitivity)	
	Hydrogen demand	Variable demand for heat + average demand for industry/NH3	
	Ammonia demand	Average demand	
Generation	Hydro	follows general use pattern	
	Sol PV	hourly varying resources	
	Win_on	hourly varying resources	
	Win_off	hourly varying resources	
	Nuclear	base load	
	Flexible	dispatched if shortage	
BEV	Charge	if battery nearly empty	
Heat supply	Consumer HP	(Heat demand) (HP heat share)	
	Elec use - cons HP	Consumer HP / COP(Tdemand, Tamb)	
	District heating	(Heat demand) (DH heat share)	
		1 Heat from store	
		2 Heat from heat pumps to demand if store empty	
		B Heat and elec from CHP if more heat nee((1)2)e)-123dETBT/F3 1205	

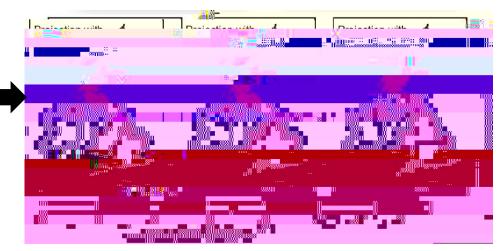
UK climate projection for late 21st century

UKCP18 National Climate Projections. MetOffice, 2018

"A greater chance of warmer, wetter winters and hotter, drier summers long with an **increase in the frequency and intensity of extremes**." (high emission scenario: summer +0.9-5.4°C summer, winter +0.7-4.2°C)

Consequences for comfort, heating and cooling and renewables?

Variability in rainfall is increasing: What impact on hydro, biomass etc?





Designing low emission energy systems for a changed climate

How might multi-vector, dynamic energy systems integrate at different spatial and temporal scales? How can we model these complex, fractal systems?

Scales

Building to city to national to international

Demands

Heat, cool, power, electricity... Domestic, services, industry, transport

Energy sources

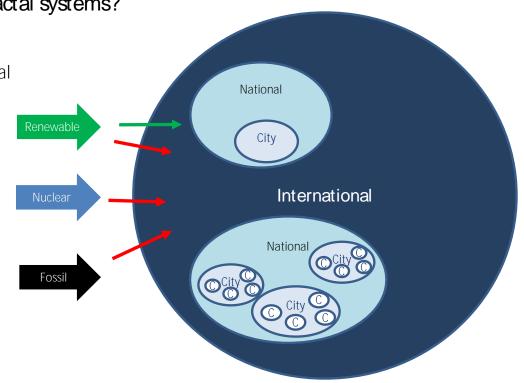
Renewable

Nuclear

Fossil

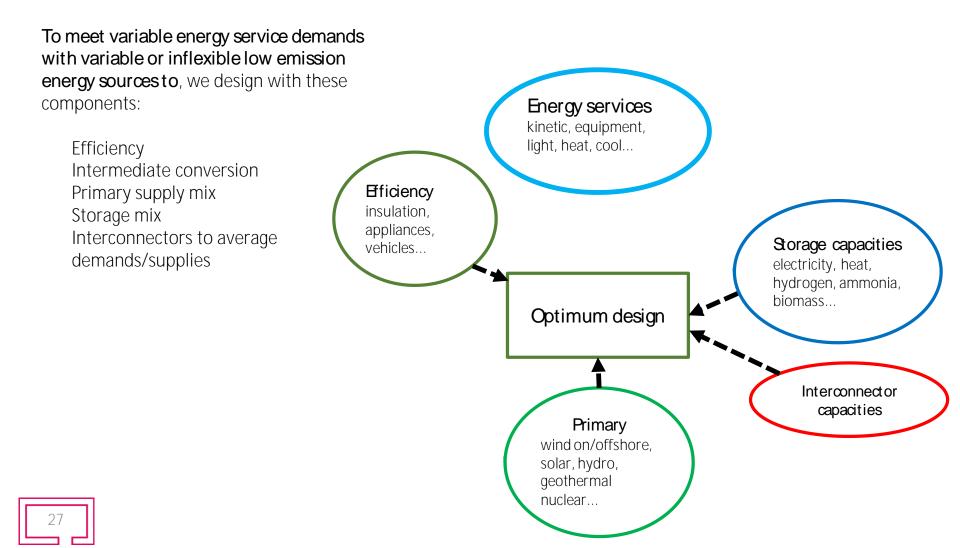
Vectors

Primary chemical: fossil, biomass Secondary chemical (H2, NH3...) Electricity Heat





Designing zero emission systems



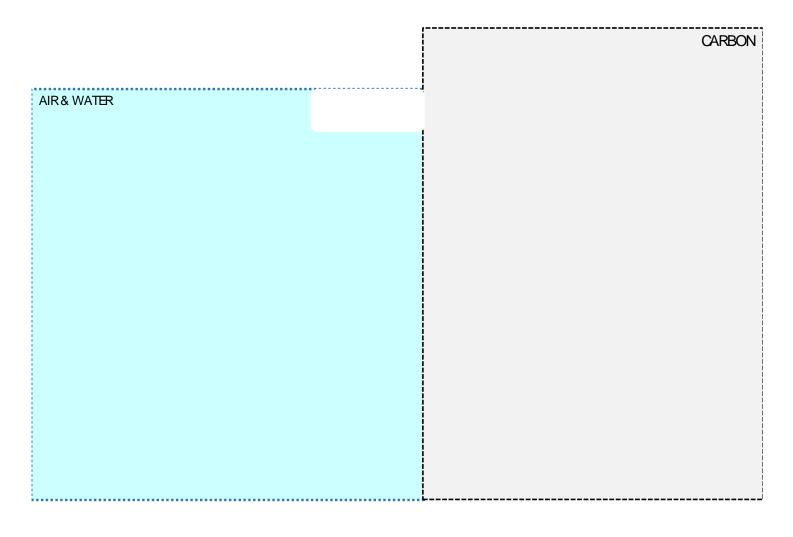
Key options explored

- 1. Consumer heat pumps (HP), district heating (DH) and hydrogen heating (H2)
- 2. Aviation fuelling assumed to be mainly fossil
- 3. All other non heat/cool demands met with electricity, e-hydrogen or e-ammonia
- 4. Primary energy: renewable electricity, waste biomass, nuclear
- 5. Direct Air Capture Sequestration (DACS) negative emissions to balance aviation CO2 and high altitude global warming

Systems with different combinations of options: Optimised for 2050 Transition 2020-2050 emulated with logistic functions Simulated 2020-2050 at 5 year intervals



Synthetic fuels





KEY

y Space Time

Selected publications

Barrett, M, Gallo Cassarino, T, (2021), Heating with steam methane reformed hydrogen, Research Paper, <u>https://www.creds.ac.uk/publications/heating-with-steam-methane-reformed-hydrogen-a-survey-of-the-emissions-security-and-cost-implications-of-heating-with-hydrogen-produced-from-natural-gas/</u>

Gallo Cassarino, T. (2019) 'Is a 100% renewable European power system feasible by 2050?', . Elsevier, 233–234(January 2018), pp. 1027–1050. doi: 10.1016/j.apenergy.2018.08.109.

Gallo Cassarino, T. and Barrett, M. A. (2021) 'Meeting UK heat demands in zero emission renewable energy systems using storage and interconnectors', . Elsevier Ltd, 306(PB), p. 118051. doi: 10.1016/j.apenergy.2021.118051.

Gallo Cassarino, T., Sharp, E. and Barrett, M. (2018) 'The impact of social and weather drivers on the historical electricity demand in Europe', , 229. doi: 10.1016/j.apenergy.2018.07.108.

Park, M., Barrett, M. and Gallo Cassarino, T. (2019) 'Assessment of future renewable energy scenarios in South Korea based on costs, emissions and weather-driven hourly simulation', , 143. doi: 10.1016/j.renene.2019.05.094.

Siddiqui, S., Barrett, M. and Macadam, J. (2021) 'A high resolution spatiotemporal urban heat load model for gb', 14(14). doi: 10.3390/en14144078.

Siddiqui, S., Macadam, J. and Barrett, M. (2020) 'A novel method for forecasting electricity prices in a system with variable renewables and grid storage', , 27(Special Issue), pp. 51–66. doi: 10.5278/ijsepm.3497.

Siddiqui, S., Macadam, J. and Barrett, M. (2021) 'The operation of district heating with heat pumps and thermal energy storage in a zero-emission scenario', . Elsevier Ltd, 7, pp. 176–183. doi: 10.1016/j.egyr.2021.08.157.

