Some environmental impacts of Green Light net zero greenhouse gas emission energy system designs for the UK

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Green Light

Eleven variant net zero greenhouse gas emission scenarios to 2050

Directly electrify: heating and cooling in a hotter world (+2 oC, +5 oC);
: other services and land based transport

Fossil fuel in aviation, 50% efficiency savings, assumed aviation growth rate halved
(behaviour change !! ha ha ha !!)

Ammonia in ships, hydrogen in industry

Direct Air Capture negative emissions to balance aviation and other processes

Primary energy: renewable and nuclear electricity, biowaste

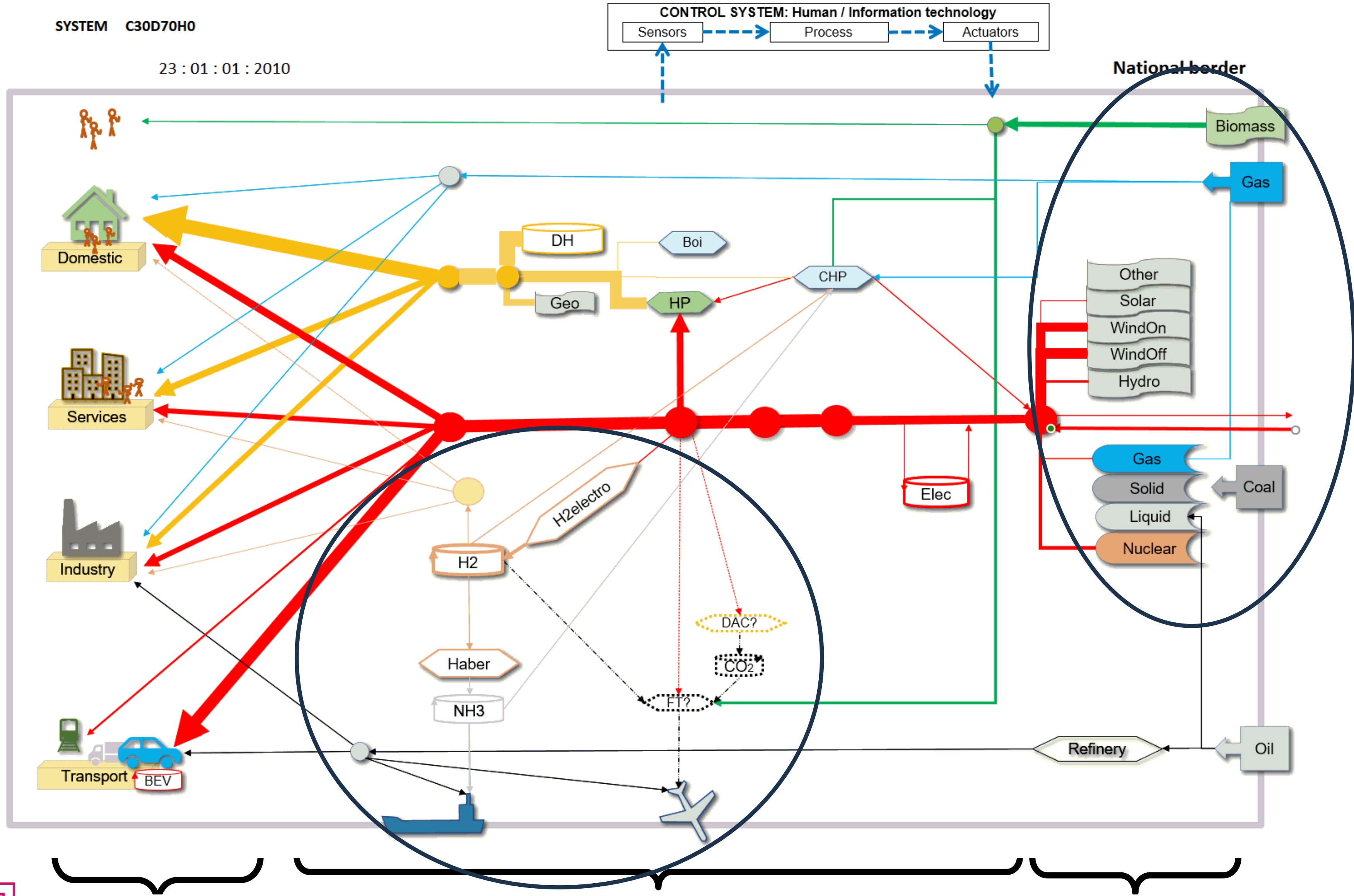
Excluded: biocrops, biomass import, hydrogen from gas

Reports here: Net zero energy system designs for the UK| UCL Energy Institute - UCL – University College London
SMR hydrogen (including methane leakage) https://www.creds.ac.uk/wp-content/uploads/CREDS-Heating-steam-methane-reformed-hydrogen.pdf

2050 energy system

SYSTEM C30D70H0

23 : 01 : 01 : 2010



Demands

Intermediate transmission, conversion, storage

Primary & Trade

me

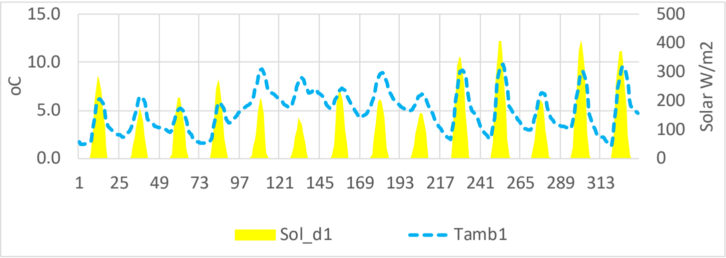
DH20%: Operation in 2050:

Winter fortnight

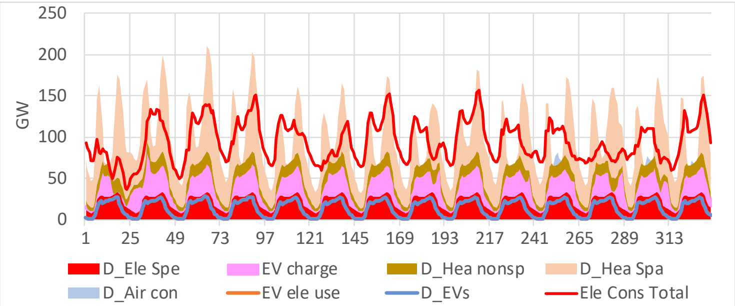
Will the system work every hour of the year?

Fortnight from day	51	February	2010 met year

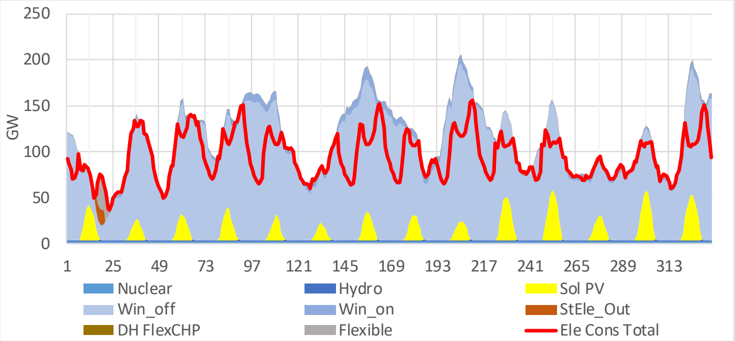
Meteorology



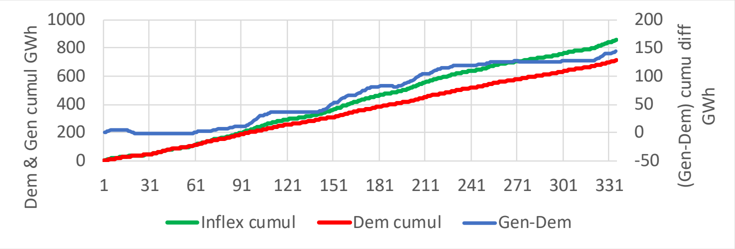
Demands



Supplies

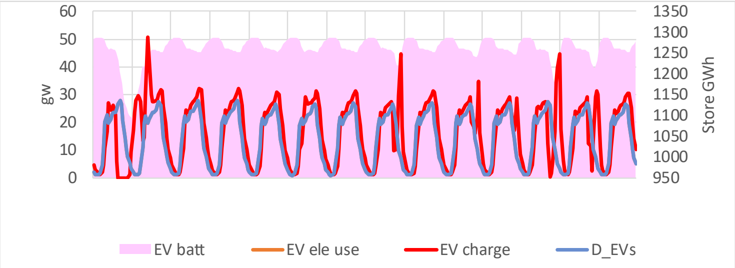


Cumulative demand and supply

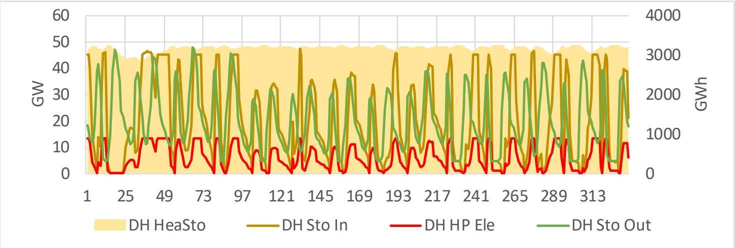


Fortnight from day	51	February	2010 met year

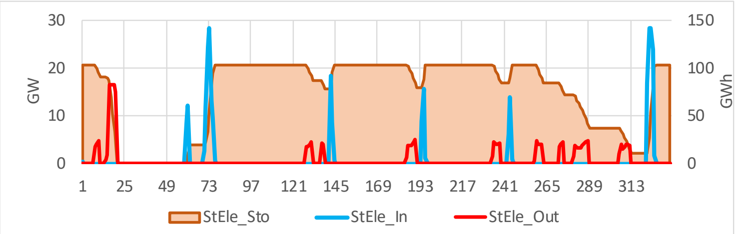
BEV storage



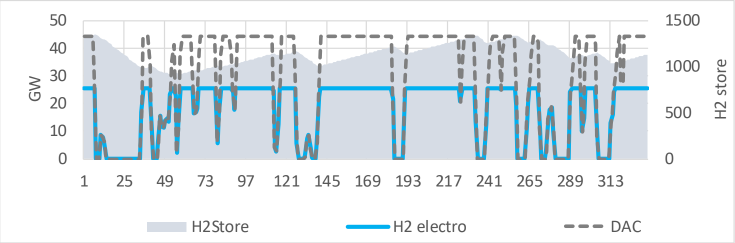
District heating



Electricity storage



H2 electrolysis and DACCS



DH20%: Transition to optimised system - electricity

Primary electricity

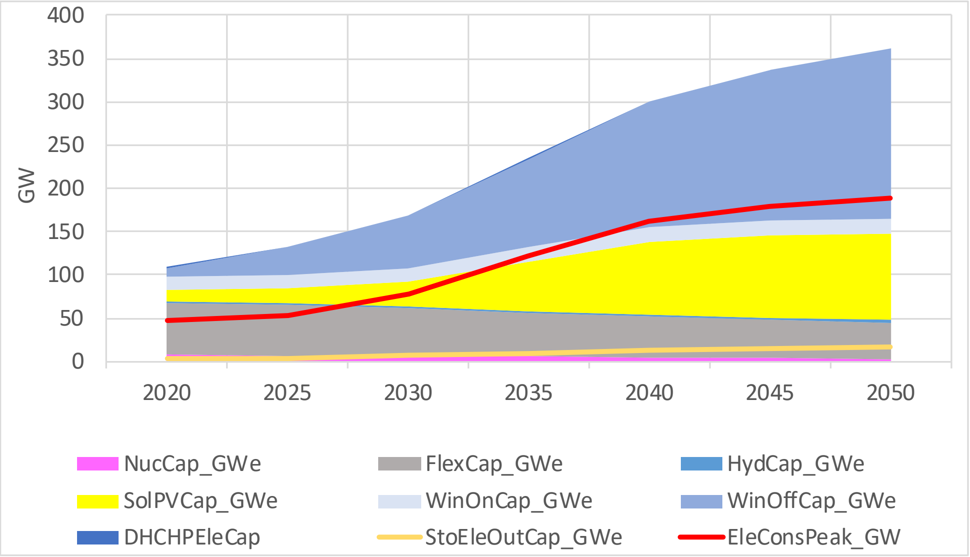
- 84% from wind, mainly offshore
- 10% solar
- 4% hydro
- 2% nuclear

Some biowaste fuel

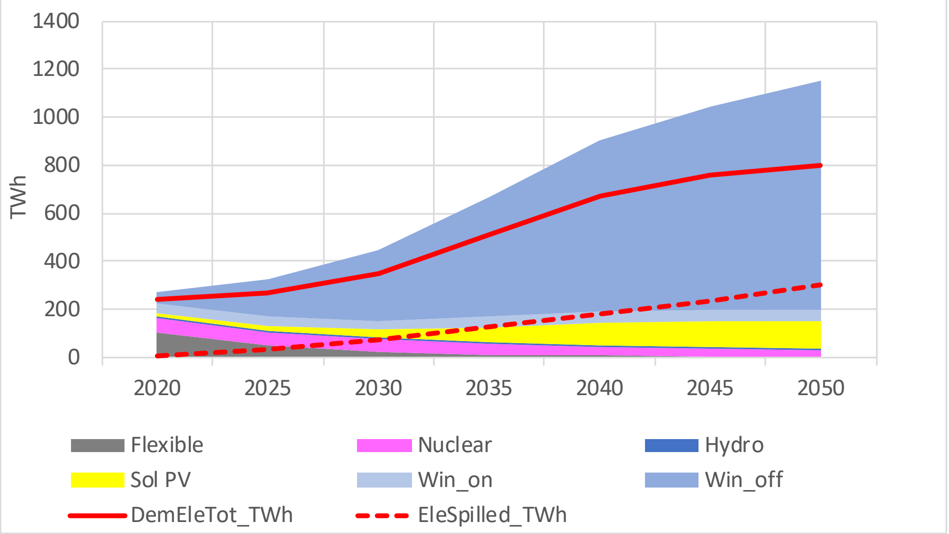
About 50 GW of gas/bio flexible generator used with capacity factor of ~1%

20-30% of potential generation is spilled/unused without interconnectors

GENERATION CAPACITIES



GENERATION



Space

Land use

- Contact area - land exclusively covered by technology
- Resource area – accounting for spacing of wind turbines etc. to access renewable resource
- Visual impact area

	Energy	**Capacity**	**Mass**	**Resource area**	
	TWh	**GW**	**Mt**	**km2**	
Biocrops (aviation)	*350*		*126*	*79909*	*46.5% UK agric*
Solar	115	110		1097	0.4% UK (all urban, no rural)
Wind offshore	891	185		46226	8.1% North sea
Wind onshore	40	11		1893	0.8% UK
Hydro	4	2			?

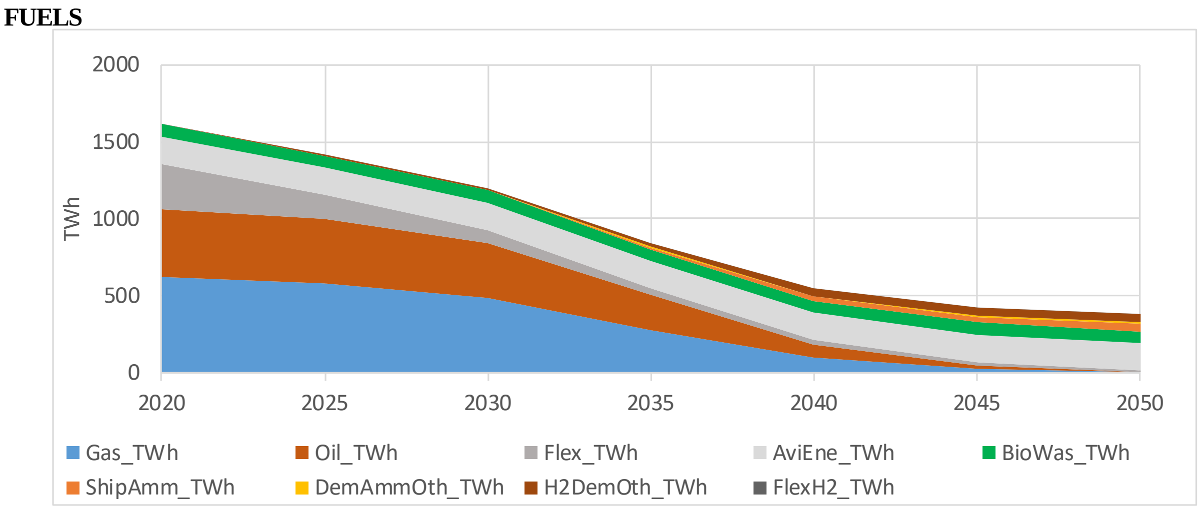
Many other technologies with (small) contact area needs: hydro (UK), transmission, stores, …

https://www.ucl.ac.uk/bartlett/energy/sites/bartlett_energy/files/ucl_ei_net_zero_land_use_for_cpre_barrett_scamman_180523.pdf

DH20%: Transition fuels and CO2e emission

Chemical fuel consumption reduced to:

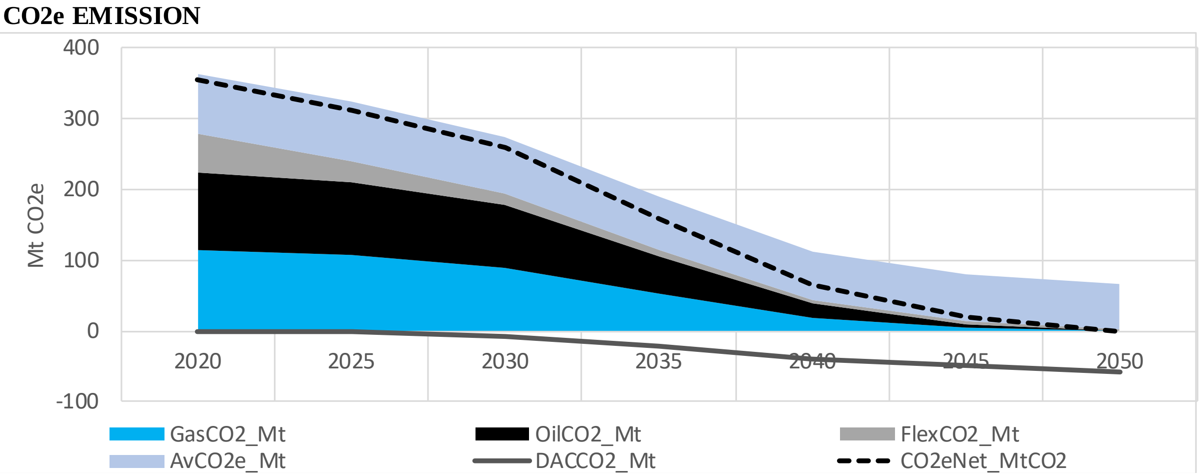
- **Aviation fossil kerosene**
- **Ship ammonia**
- Waste biomass
- Hydrogen



CO2e emission largely eliminated apart from:

- **Aviation fossil kerosene and high altitude warming**
- Back-up generation

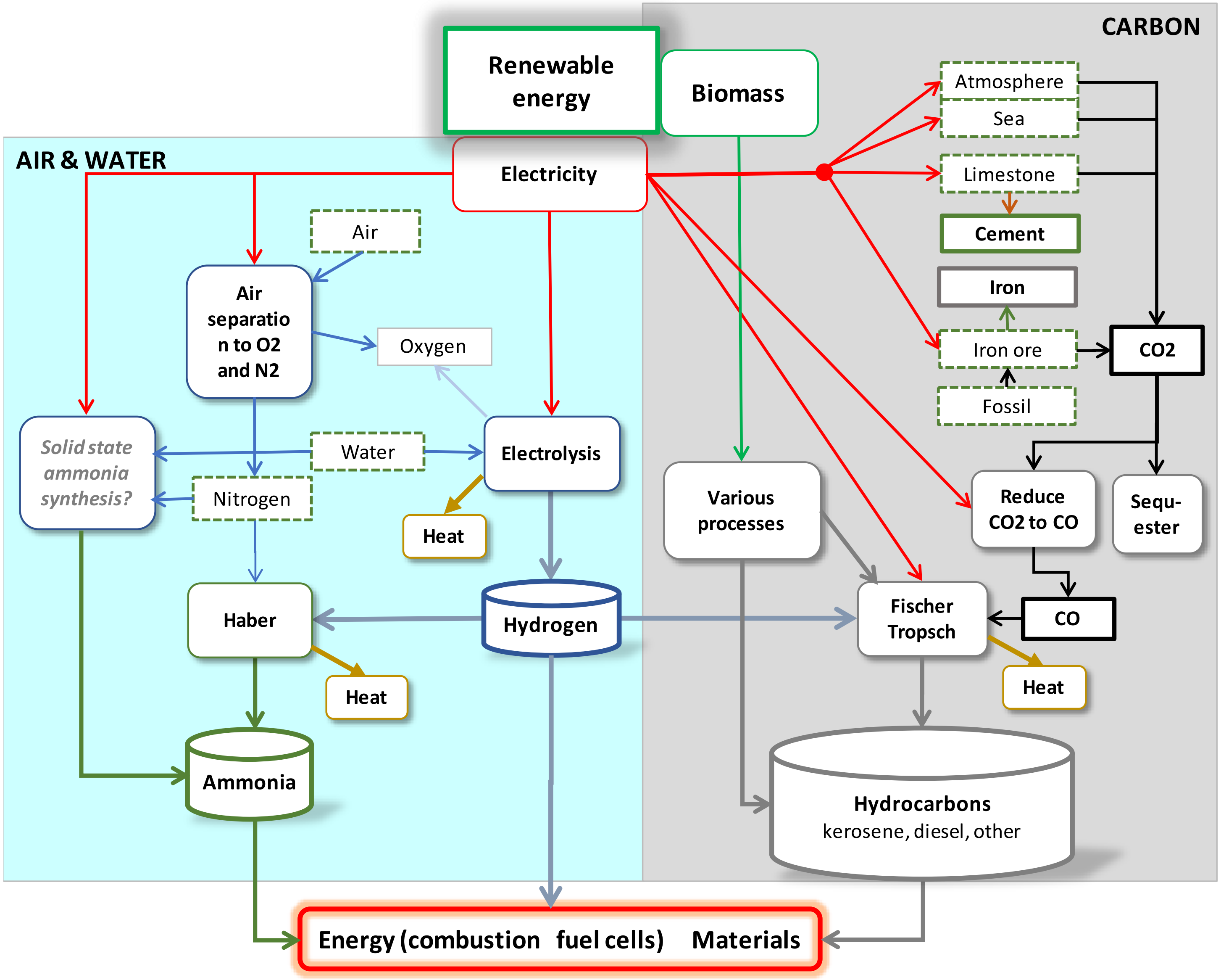
CO2e emission balanced by negative emission with DACS (Direct Air Capture Sequestration)



Renewable fuel production pathways

Aviation
Kerosene
(Hydrogen)
(Electricity)

Shipping
Ammonia?
Hydrogen?
Hydrocarbon?
(Electricity)



Aviation and shipping

Aviation

High altitude => ~25-50 Mt CO2e for fossil or renewable kerosene
=> Need negative emission (DAC?)

Aviation fuel

1. **Fossil kerosene =>~50 Mt CO2e**
2. Biomass => 68% UK agricultural land (Royal Society)
3. Power-to-liquid: e.g. renewable DAC and hydrogen? => net 400+ TWh electricity
4. Electricity - short range only

Shipping

1. **Ammonia. Easily stored, can be used in diesel engines, but emissions**
2. Hydrogen. Difficult to store can be used in fuel cells/turbines
3. Hydrocarbon - bio or power to liquid
4. Electricity – short range only

Negative emission of CO2

Negative emission (any process)
minimum 2500 tAir /tCO2

Engineering

- Direct air capture (and sequestration) – small area, water, chemicals
- Rock weathering
- ?

Biological – <u>large land areas</u>

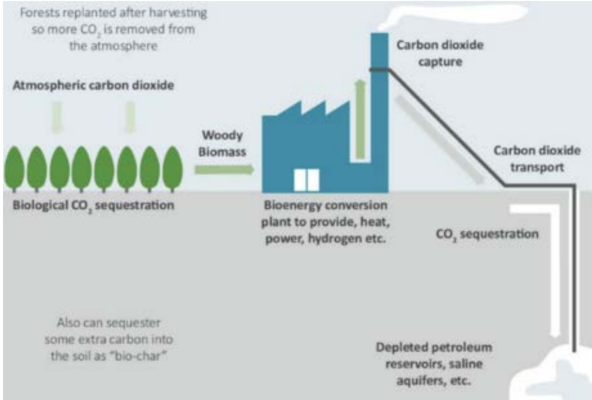
- Short cycle: algae, sea seeding, BECCS etc.
- Long cycle: forest, soil
- Habitat recovery

DACS?

Direct Air Capture and Carbon Storage

BECCS?

Bioenergy and carbon capture and storage



Major chemical plant

AIR POLLUTANTS
(but also solid, liquid)

Refinery
Crude oil

shutterstock.com · 1452861395

Aviation
Kerosene
Residual oil?
Sulphur etc.

Aircraft
NOx, CO, HC, VOC, PM…

Electrolysis
Electricity
Water
Chemicals

Hydrogen
Oxygen

Hydrogen engine/fuel cell
Industry, generation, ships?
NOx

Haber
Air
Hydrogen
Chemicals

Ammonia (ships)
Oxygen

Ammonia engine or fuel cell?
NH3, NOx
Secondary PM
N2O (GHG)
Leakage
Process, storage, transport

Direct air capture
Electricity
Air **Gt!**
Water
Chemicals

Air **Gt!**
Conc. CO2
Pollution?

Chemicals?

SMR hydrogen analysis here: https://www.creds.ac.uk/wp-content/uploads/CREDS-Heating-steam-methane-reformed-hydrogen.pdf**:**

2050 chemical mass flows

				Inputs			
	Energy TWh	Mass Mt	CO2 Mt	Water Mt	Nitrogen Mt	Hydrogen Mt	Air process Mt
Flexible	14	1	3				
Aviation - mainly fossil	175	14	62				
Hydrogen	125	3		28.5			
Ammonia	55	9			7.2	1.6	36.2
Biowaste	80	29					
Direct air capture (DAC)	115		-57	?? 229			**Min: 143181**
Biocrops (aviation)	*350*	*126*		?			?

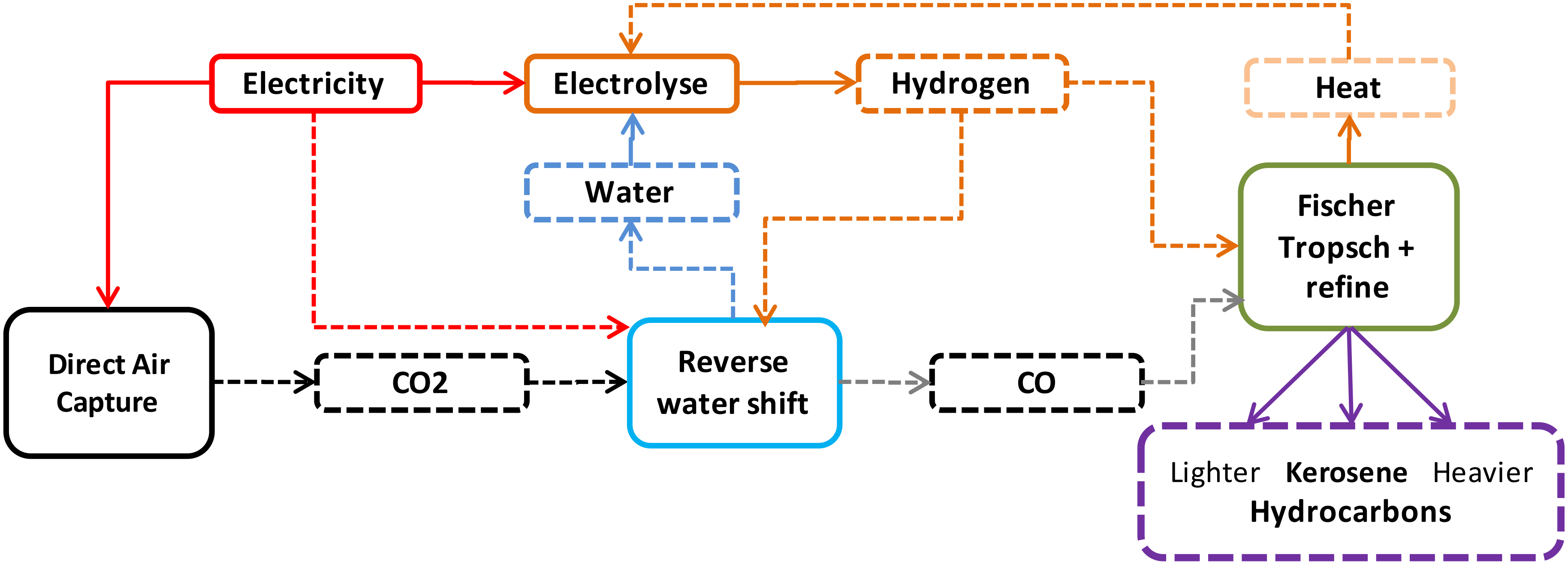
Notes

- Mass flows are minima assuming no waste/leakage
- Negative emission (any) process a minimum of 2500 tAir /t CO2
- Water use of DAC?

Renewable: power to liquid, electrokerosene

(if we don't want to use fossil oil)

- About 50% of Fischer-Tropsch hydrocarbon product is kerosene
- Other 50% products could be used in ships, vehicles, industry, generation…
- High capital and operational costs
- About 800 TWh gross of electricity needed, but ~400 TWh savings



Power to liquid – electrokerosene

	Formula	Wt	%Ker Wt	Kerosene Mt	HC Total Mt	Elec TWhe	Source	Energy per mass
Kerosene	**$C_{12}H_{26}$**	**170**		**15.0**	**31.9**			13 kWhc/kgKer
	C	144	85%	12.7	27.0			
FT input	H	26	15%	2.3	4.9	256	Electrolysis	53 kWhe/kgH
RWSG input	CO_2	528	311%	46.6	99.1	198	DAC	2 kWhe/kgCO2
RWSG input	H	24	14%	2.1	4.5	237	Electrolysis	53 kWhe/kgH
FT input	CO	336	198%	29.6	63.1			
Miscell: heat, compress, crack…					**31.9**	128	Refine	4 kWhe/kgHC
						819	**Total**	
				Total HC out	**31.9**	**410**	TWhc	13 kWhc/kgHC
				Kerosene out	15.0	193	TWhc	13 kWhc/kgKer
				DAC not required for fossil kerosene emission		-93	TWhe	
				Residual mixed HC RMHC	16.9	-217	TWhc	(Diesel:112 TWh)
				H2 electrolysis displaced by RMHC		-289	TWhe	
				Aviation fuel net additional electricity		**436**	**TWhe**	
				Waste heat for district heating etc?		*155*	*TWhth*	

	kWhe/kWhcHC	Efficiency
Total HC	26	50%
Kerosene	29	44%

Conclusions and questions

Aviation

- Fossil kerosene, renewable kerosene, ?
- Requires negative emission - any process 2500 tAir / tCO_2
- Comprises ~20% total energy system costs

Shipping

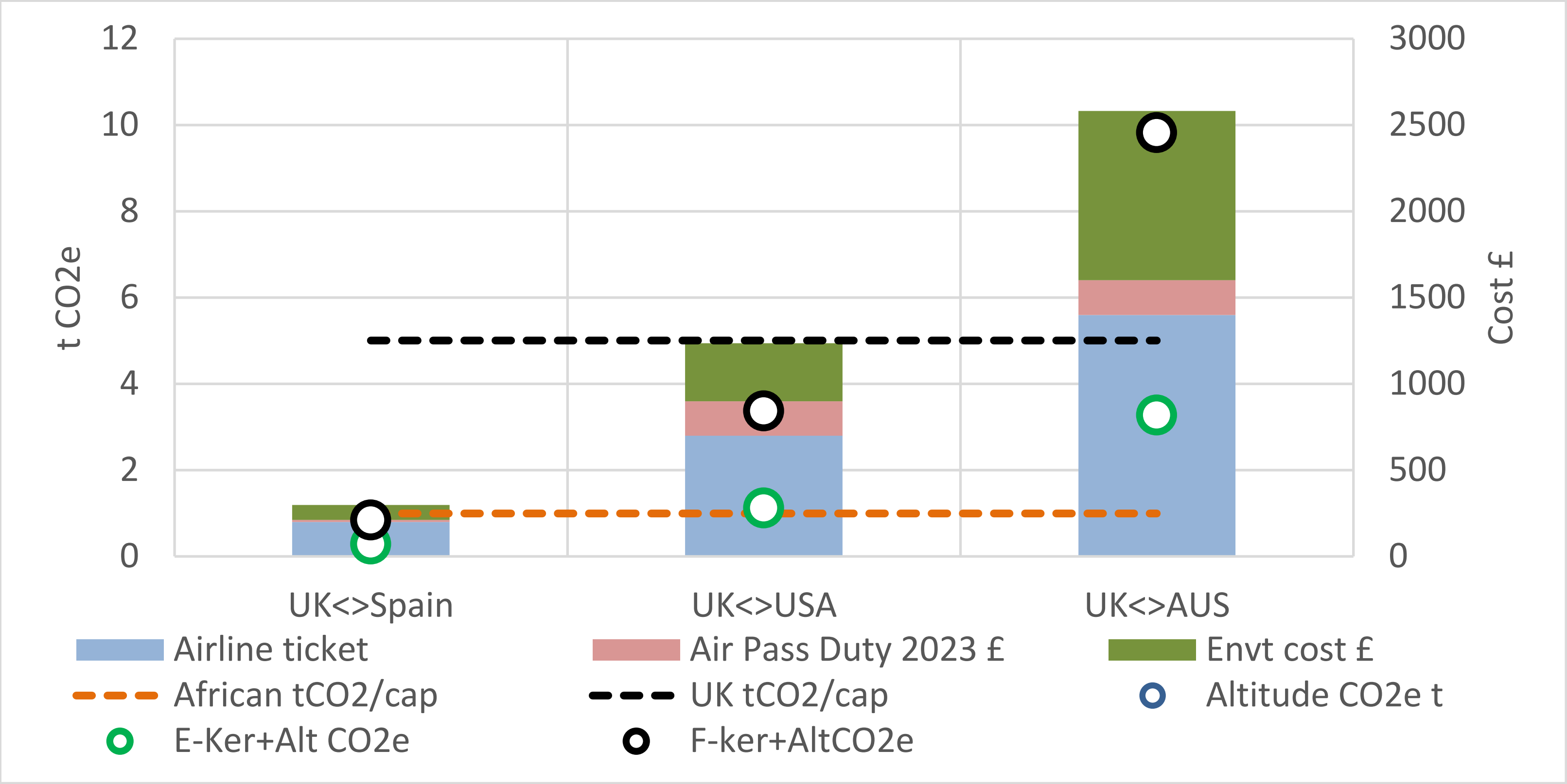
- Ammonia
- Hydrogen?
- Hydrocarbon?
- ?

Renewables

- Solar - little land area, urban roofs and car parks sufficient
- Wind – large resource area, small contact
- Biomass – large contact area per energy produced

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



Further materials

Designing low emission energy systems for a changed climate

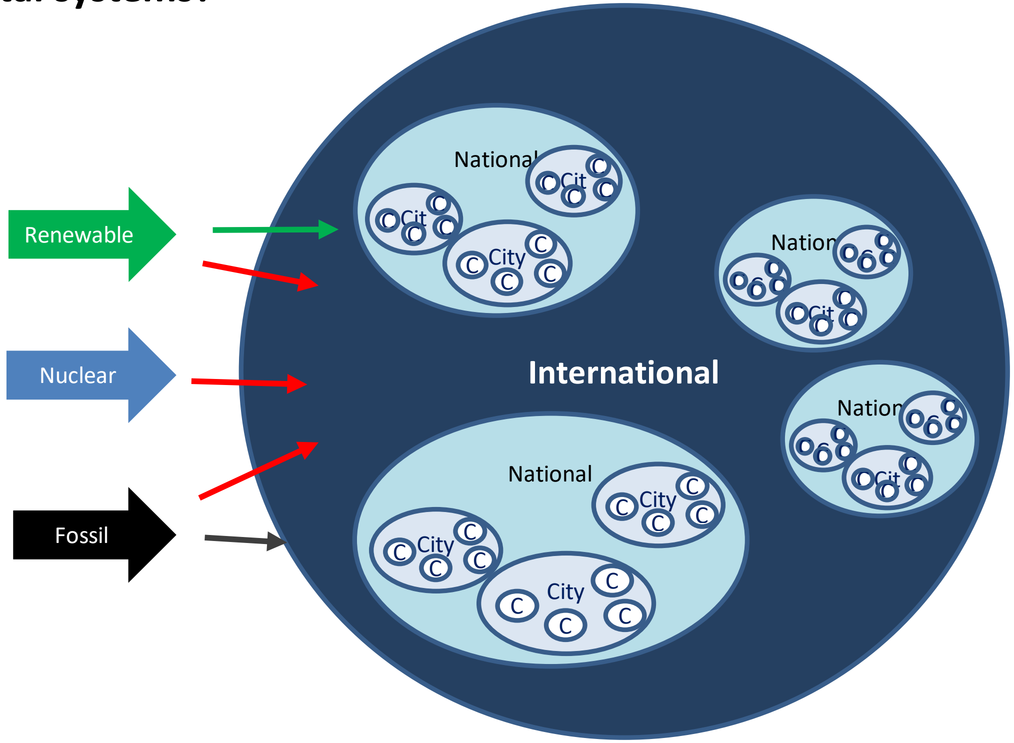
How might multi-vector, dynamic energy systems integrate at different spatial and temporal scales?
How can we model these complex, fractal systems?

Scales
- Building to city to national to international

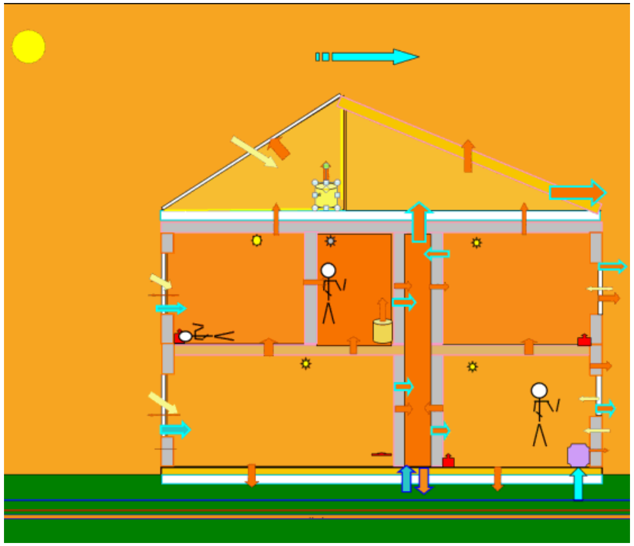
Demands
- Heat, cool, power, electricity…
- Domestic, services, industry, transport

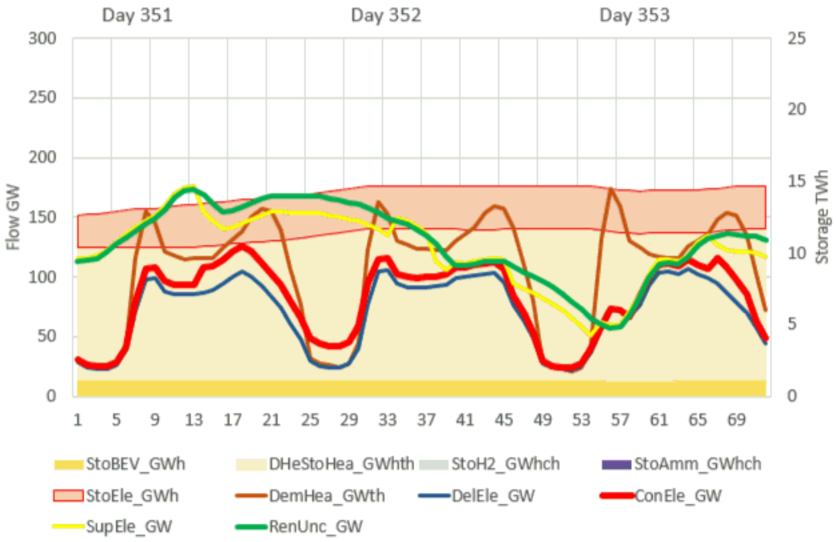
Energy sources
- Renewable
- Nuclear
- Fossil

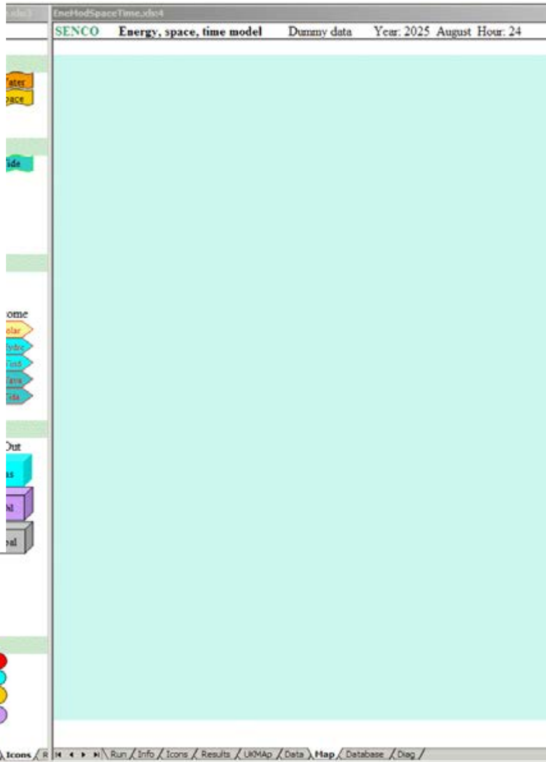
Vectors
- Primary chemical: fossil, biomass
- Secondary chemical (H2, NH3…)
- Electricity
- Heat



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







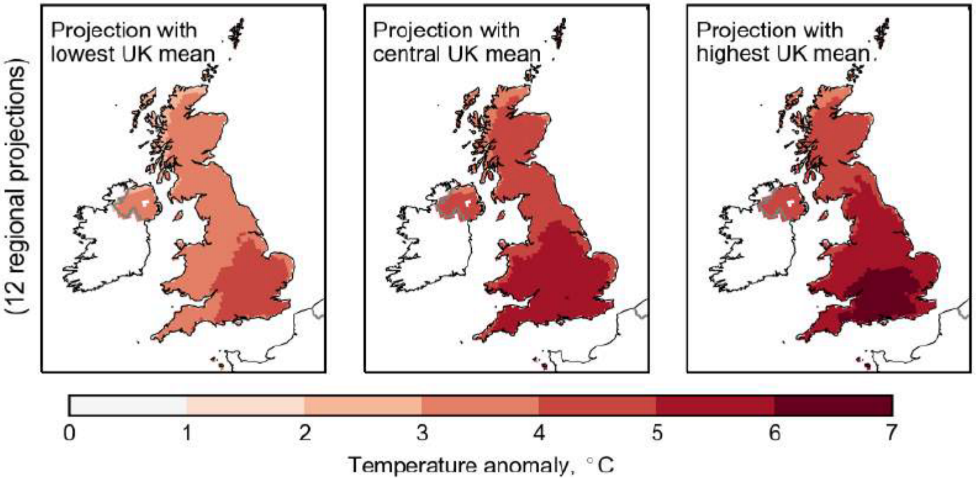
EneModSpaceTime.xlsx

SENCO Energy, space, time model Dummy data Year: 2025 August Hour: 24

Transmission
Electricity
Gas
Heat
Liquid

The design process

for 2050, 2100 and beyond



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

Select available technologies and configure

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

Optimise to find least cost system designs

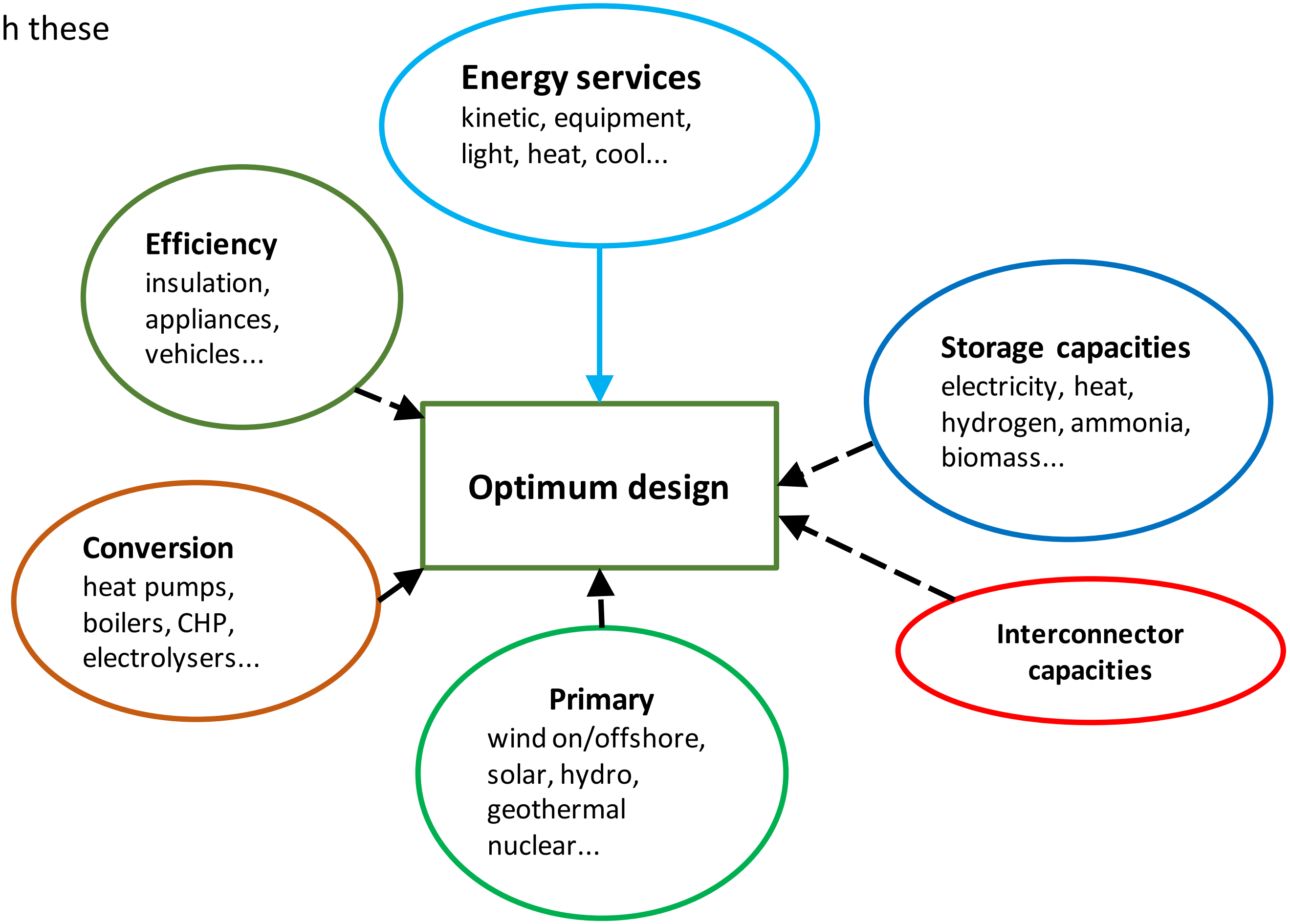
Explore 11 variant scenarios with different heat shares, climate etc.

Conclusions

Designing zero emission systems

To meet variable energy service demands with variable or inflexible low emission energy sources to, we design with these components:

- Efficiency
- Intermediate conversion
- Primary supply mix
- Storage mix
- Interconnectors to average demands/supplies



Energy services
kinetic, equipment, light, heat, cool...

Efficiency
insulation, appliances, vehicles...

Optimum design

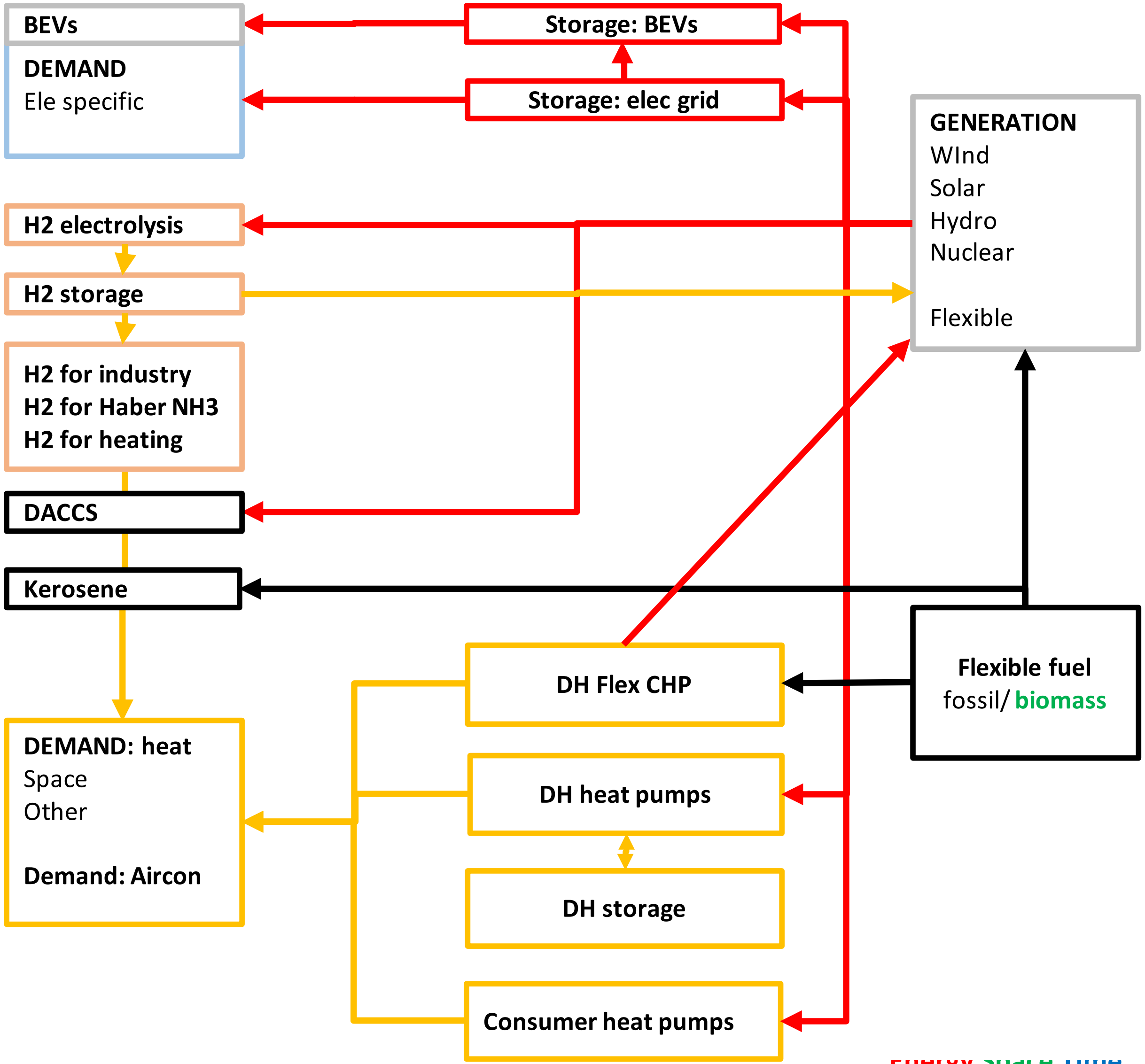
Storage capacities
electricity, heat, hydrogen, ammonia, biomass...

Conversion
heat pumps, boilers, CHP, electrolysers...

Interconnector capacities

Primary
wind on/offshore, solar, hydro, geothermal nuclear...

Energy system diagram



BEVs

DEMAND
Ele specific

Storage: BEVs

Storage: elec grid

H2 electrolysis

H2 storage

H2 for industry
H2 for Haber NH3
H2 for heating

DACCS

Kerosene

GENERATION
WInd
Solar
Hydro
Nuclear

Flexible

Flexible fuel
fossil/ **biomass**

DH Flex CHP

DH heat pumps

DH storage

Consumer heat pumps

DEMAND: heat
Space
Other

Demand: Aircon

NB:
This system does not include interconnectors which will reduce costs, storage and spillage

DH20% : Transition - demands

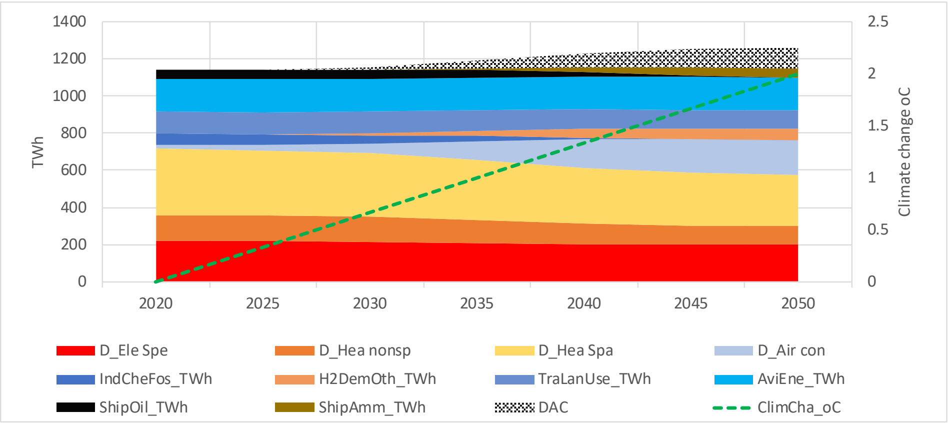
Insulation and climate change:

- **Heat demand** decreases
- **Cooling** demand increases

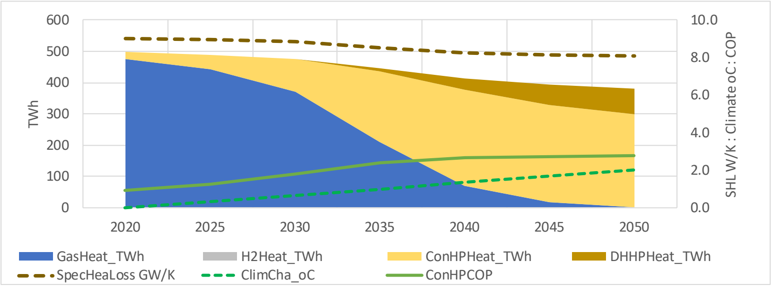
Heat/cool supply shift to electric HPs and DH

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

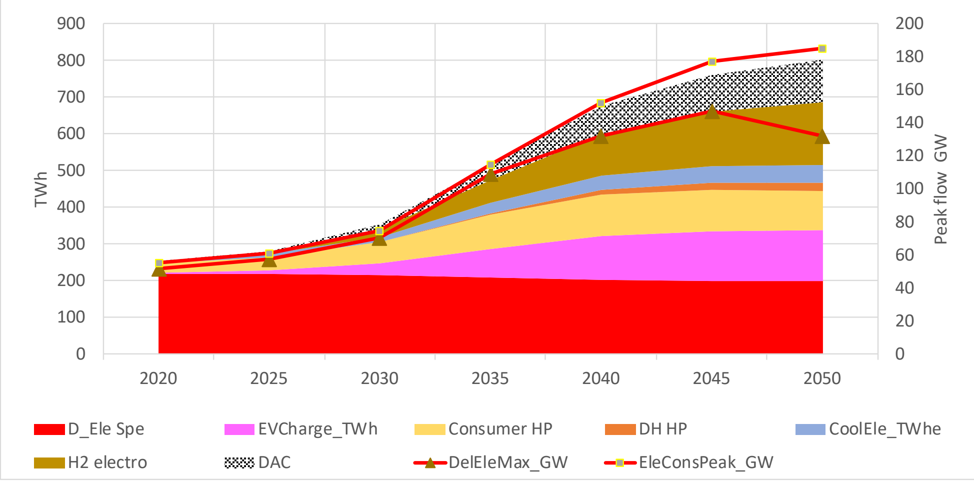
Demands



Heat supply shift from gas to HPs and DH



Electricity demand



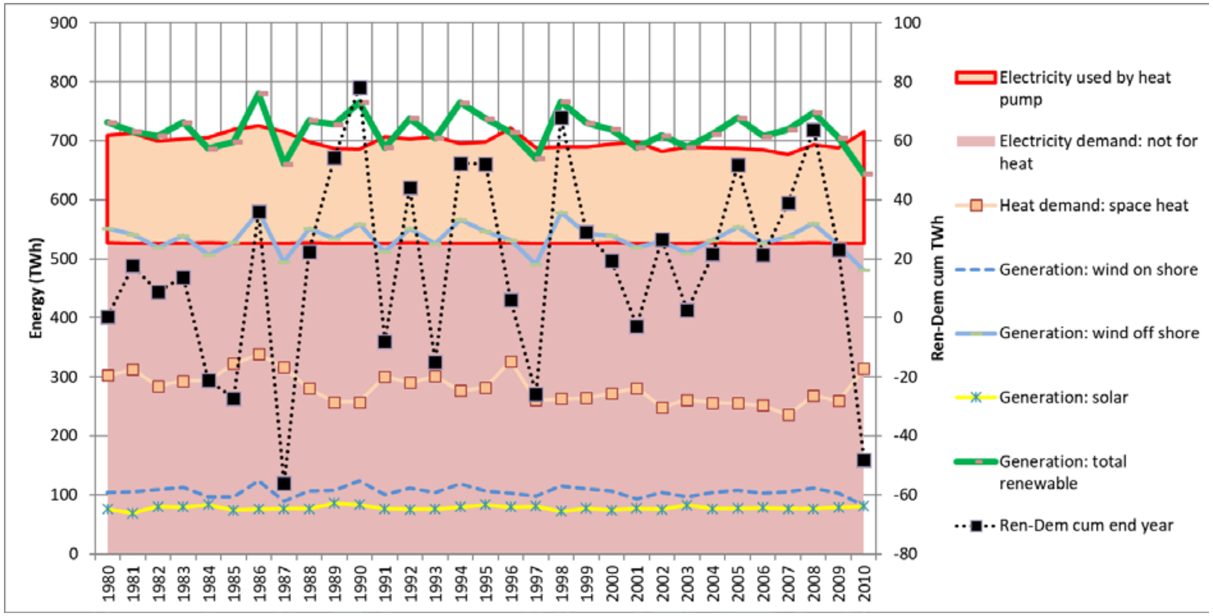
Electricity demand increases from about 300 to 800 TWh.

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%

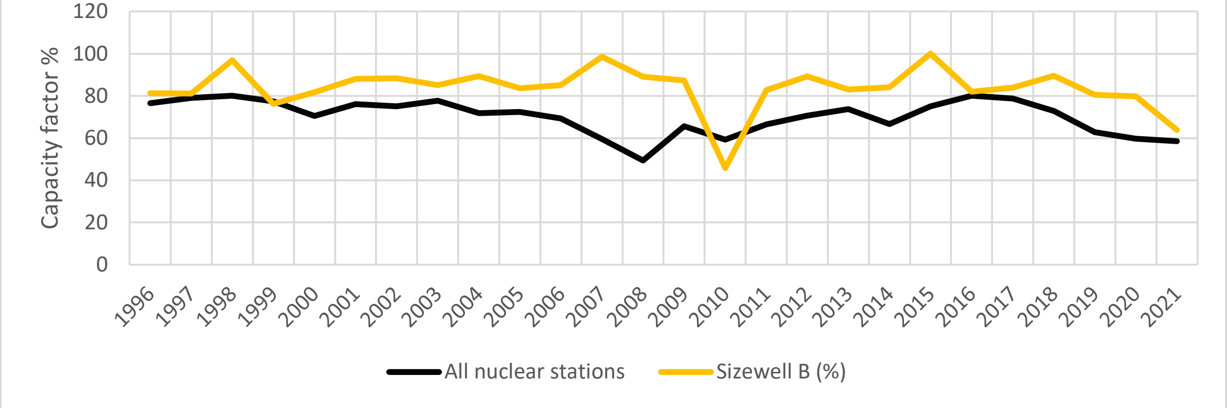
Offshore wind capacity factors projected to be 55-65%



31 years annual demand and renewable output

Annually, wind + solar varies less 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



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 billion.' => 2500 £/kW?**
Nuclear Provision: the cost of cleaning up Britain's historic nuclear sites - GOV.UK (www.gov.uk)

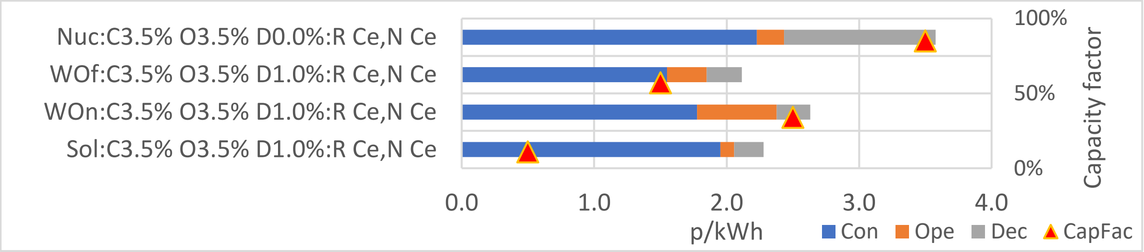
Insurance for UK operator liability About 1 £bn from operator
Fukushima cost 100-200 £bn

Proliferation?

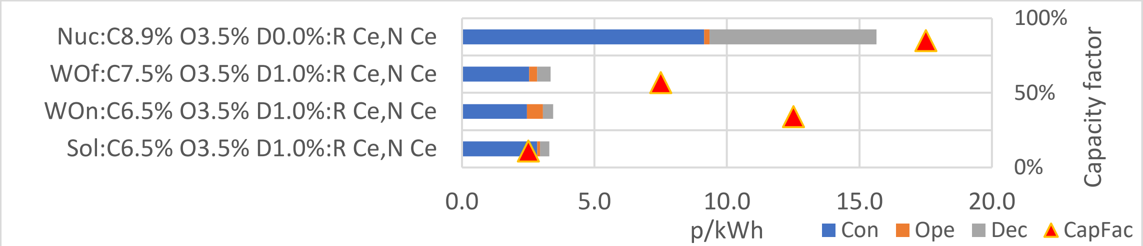
Central cost assumptions

Generator	Solar	Wind On	Wind Off	Nuclear
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%
O&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

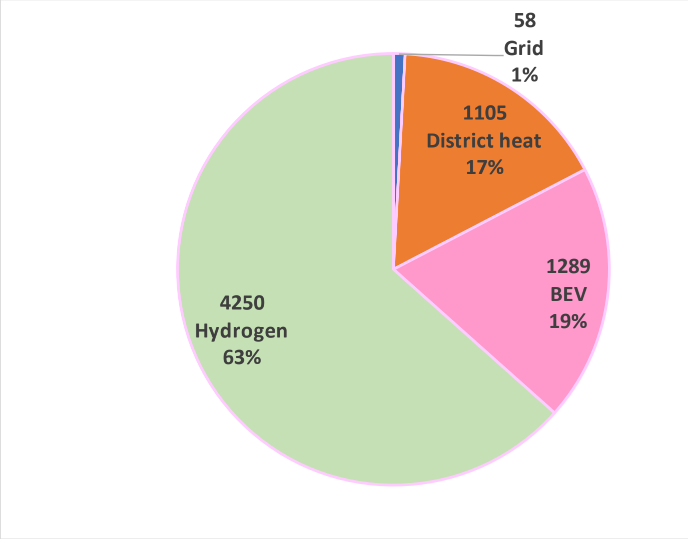


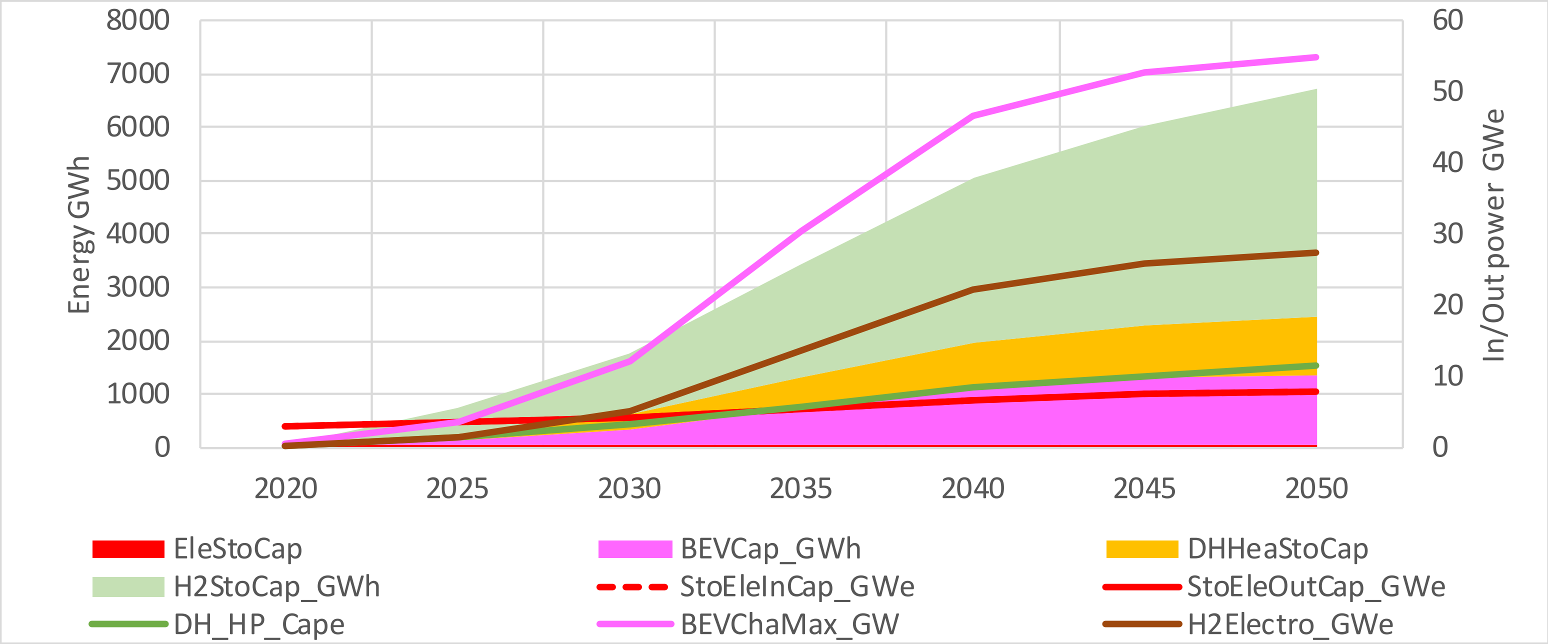
DH20%: Transition - storage

To help match demands and supplies, storage is needed.

- **Grid storage** ~ 100 GWh/10 GWe electricity in/electricity out
- **Vehicle battery storage** – 1300 GWh/ 60 GW charge
- **Hydrogen** (for industry only) storage – 4300 GWh / 30 GWe electrolyser
- **DH Heat storage** ~ 1100 GWh/ 10 GWe heat pump heat in/heat out

- **Fuel storage:** peaking generation: 10 TWh gas/H2? ~ 60 GWe





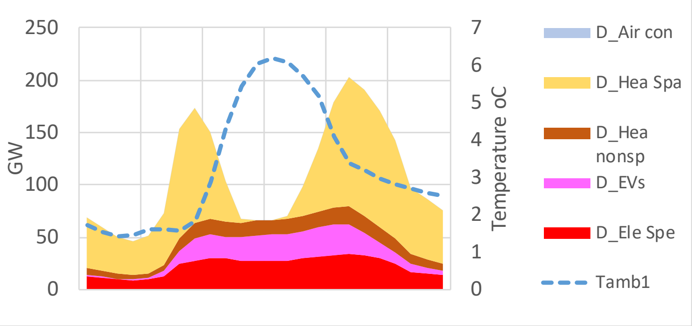
Operation in 2050:

Sample days

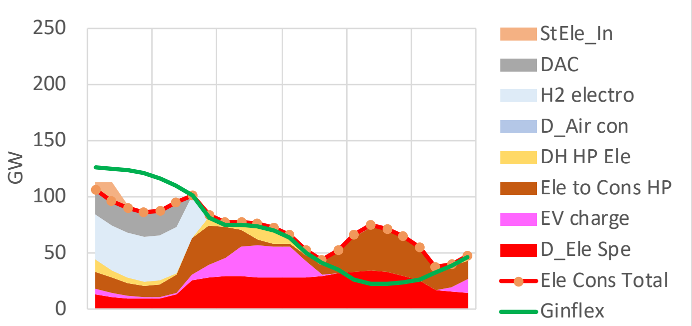
Winter

Day of year 51 February

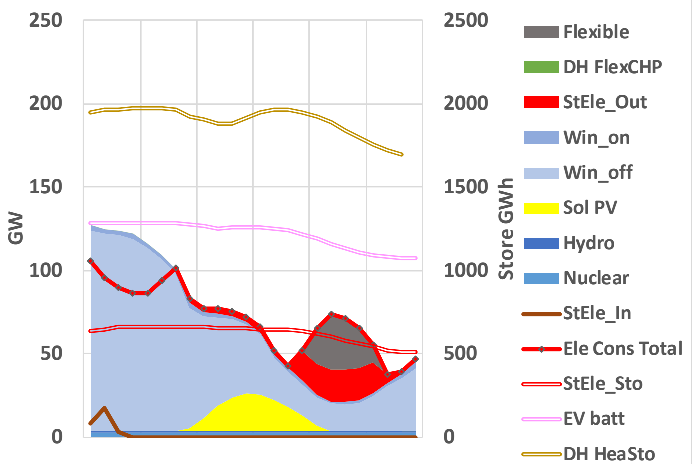
Demands



Electricity demands



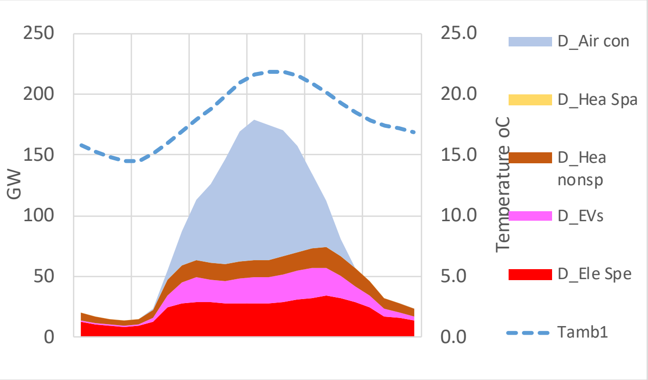
Supplies



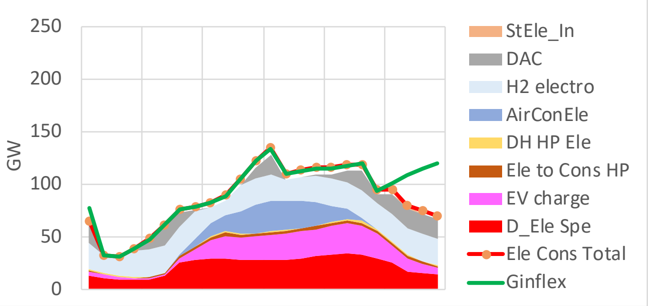
Summer

Day of year 194 July

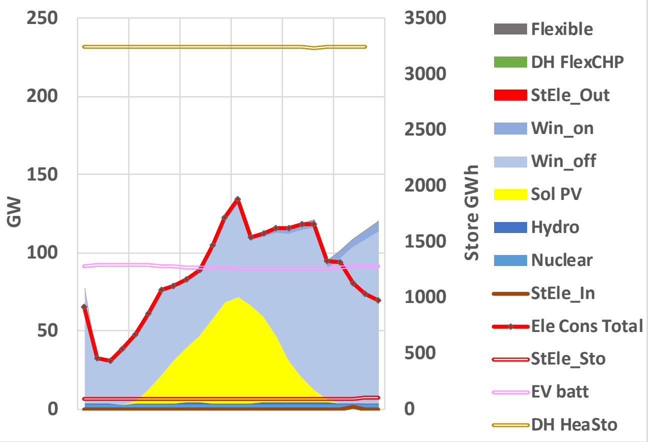
Demands



Electricity demands



Supplies



DH20%: Operation in 2050:

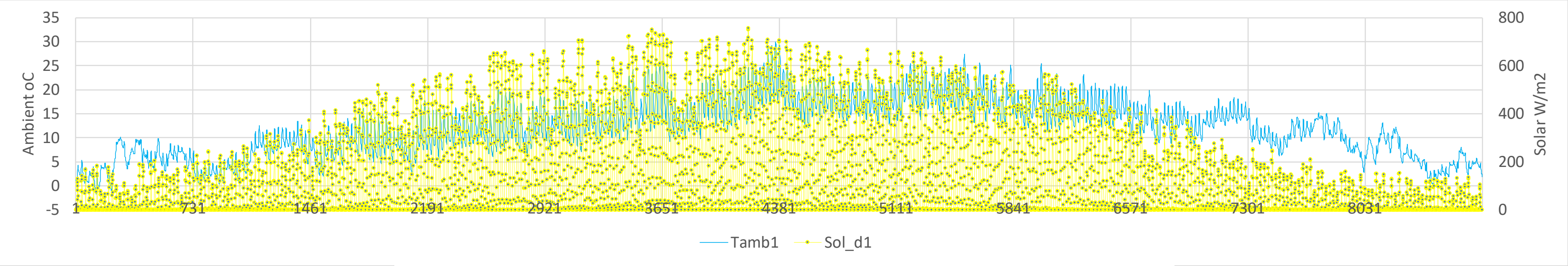
Sample days

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

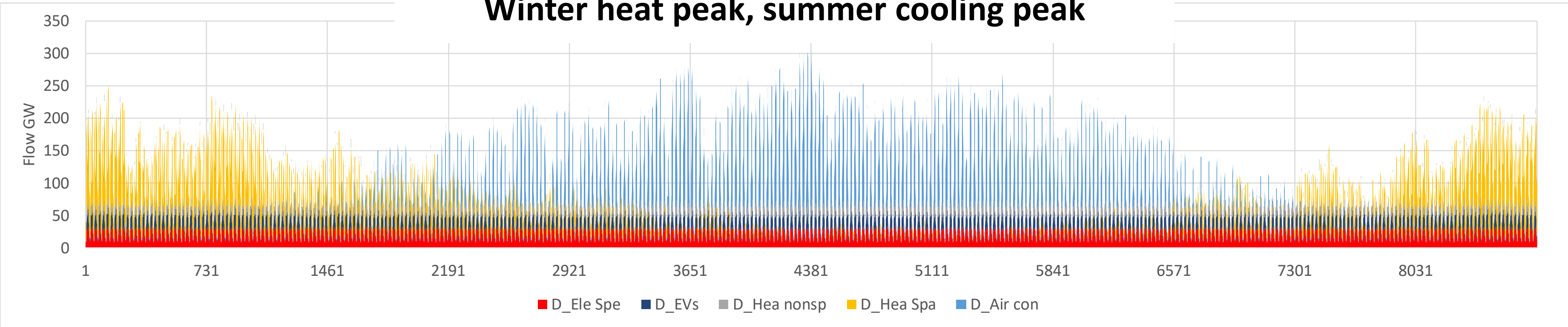
What prices to consumers?

DH20% : Year’s operation in 2050

Meteorology

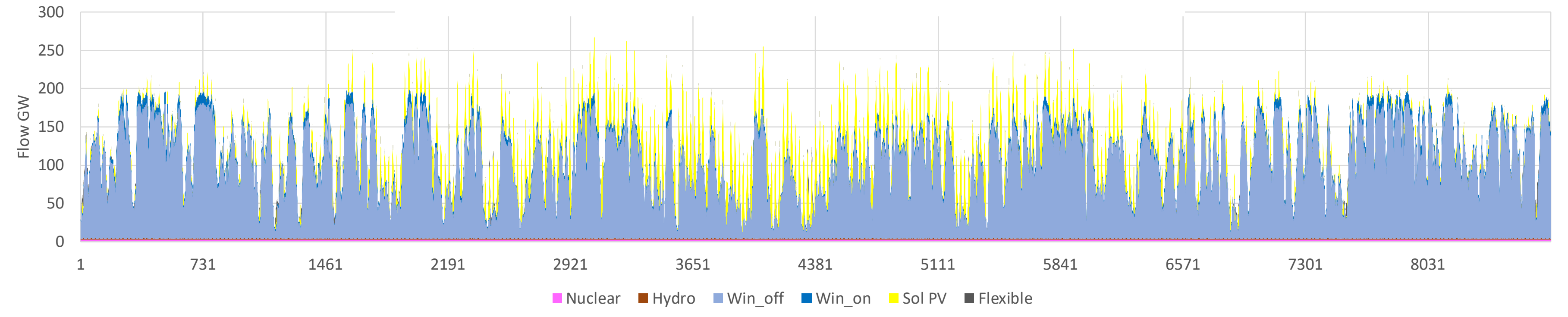


Demands



Winter heat peak, summer cooling peak

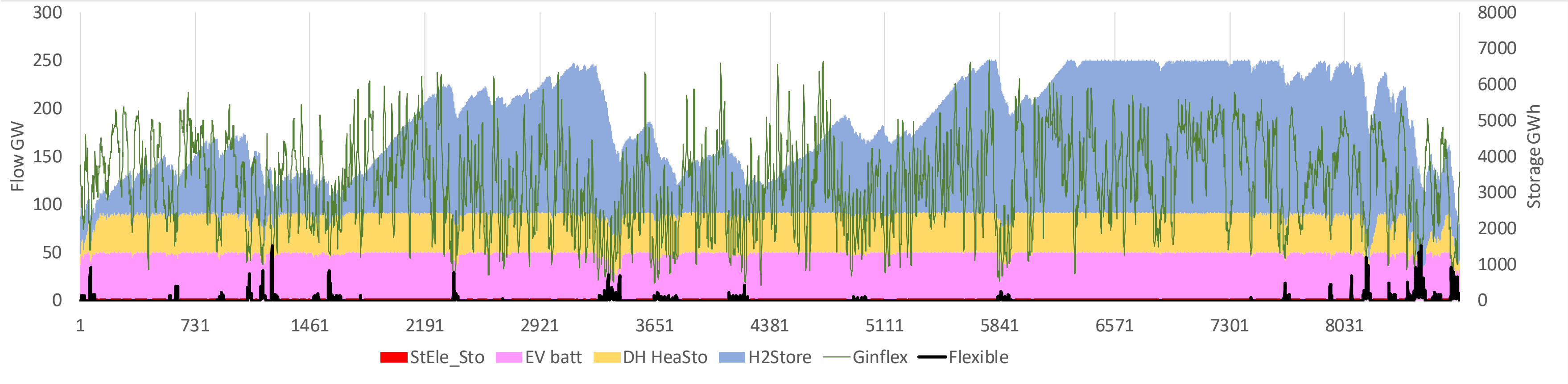
Generation



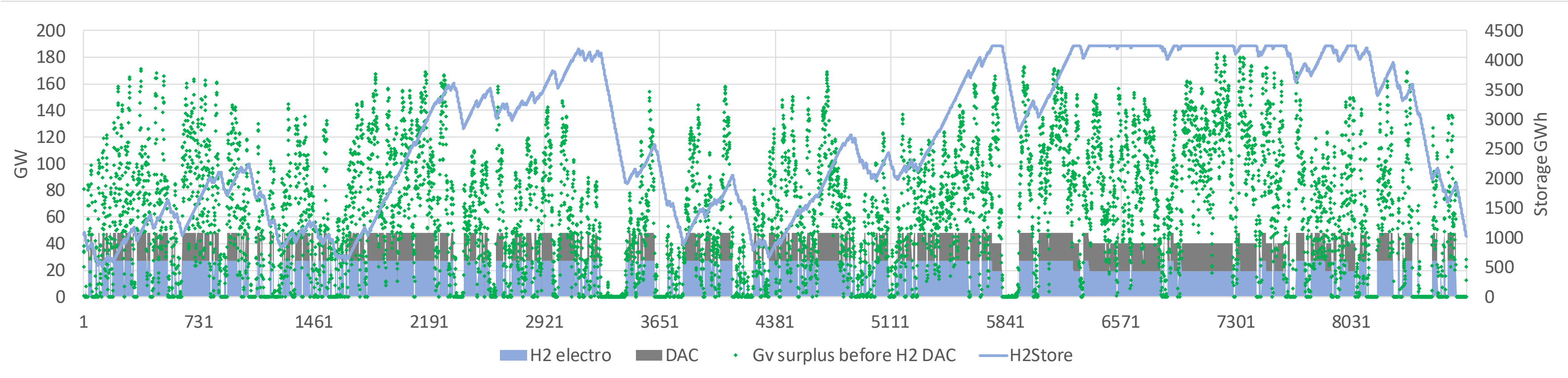
Winter wind peak, summer solar peak

DH20%: 2050 year

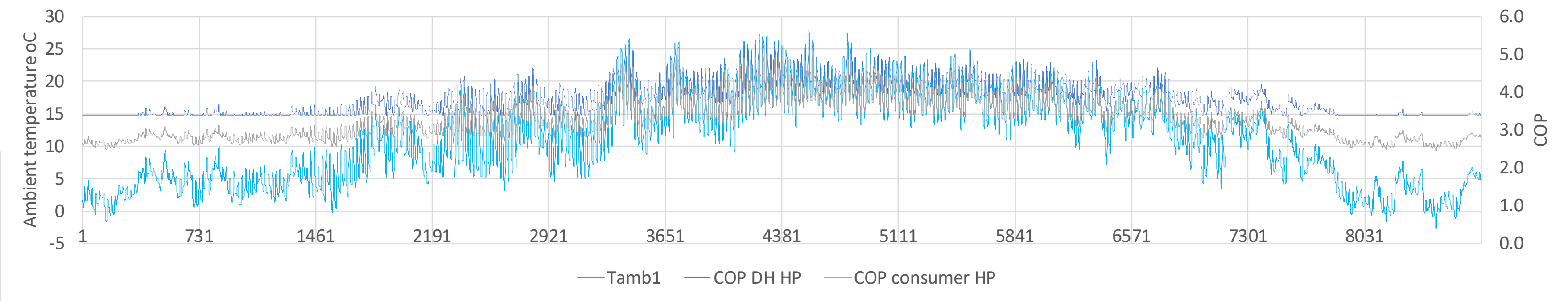
Stores, renewables, flexible



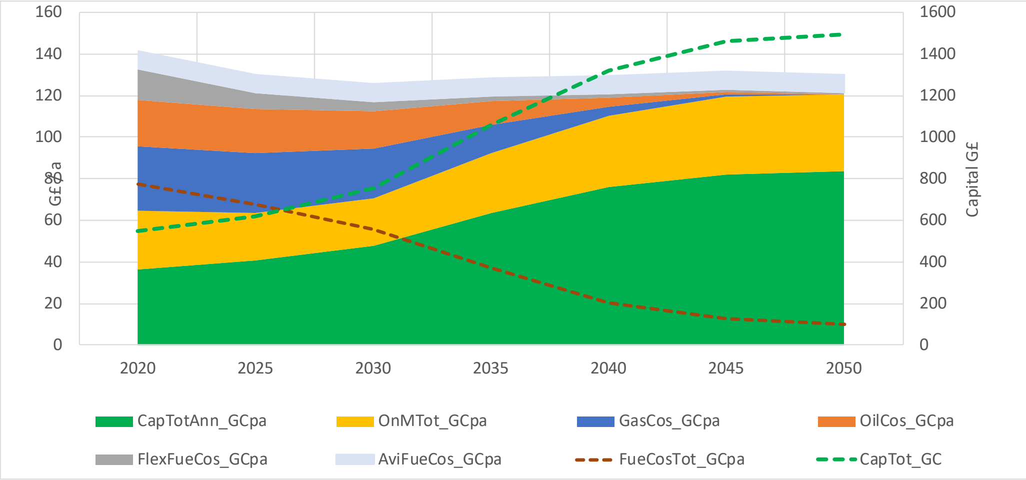
Surplus/deficit, H2 electrolysis and DAC



Heat pump COPs



DH20%: Transition system costs



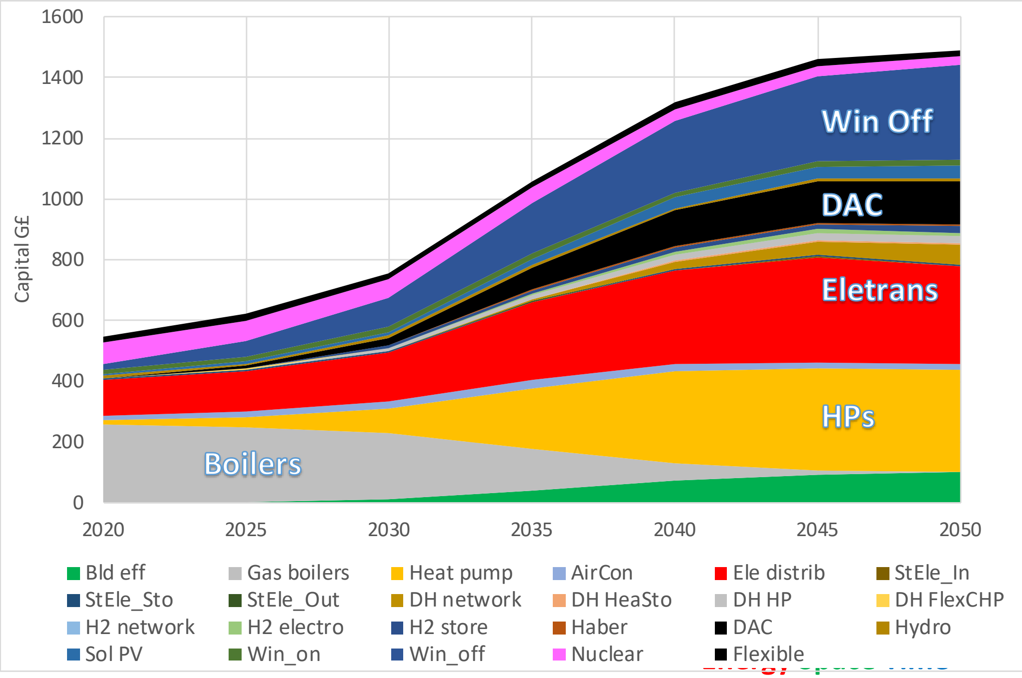
System costs similar to current, assuming ~2022 fuel prices.

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

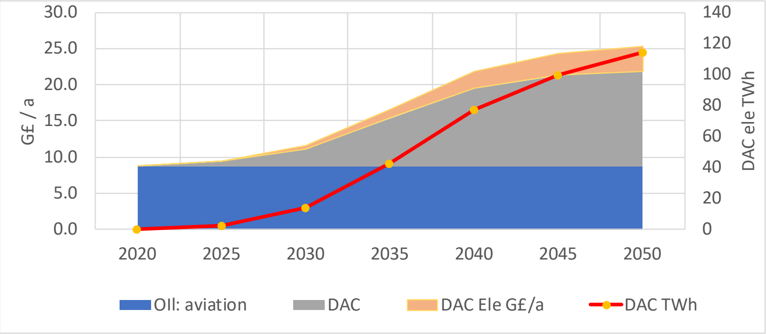
Capital investment about 2% of annual GDP

The **largest capital costs** are:

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


CAPITAL COST

Aviation about 20% of total system cost



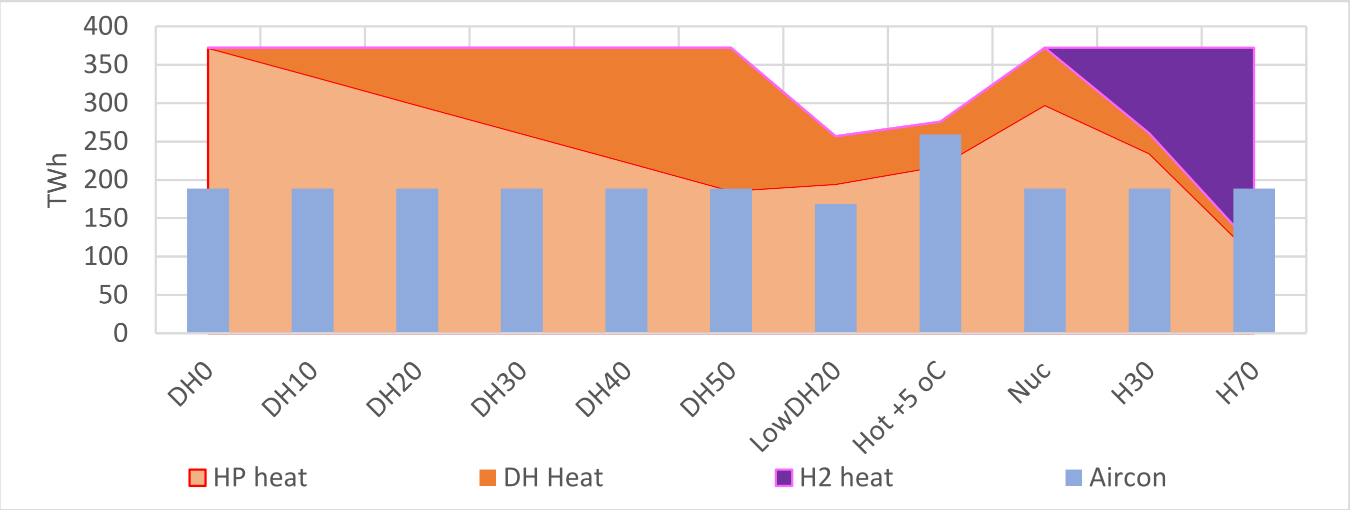
Heat and cool in 11 system designs

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

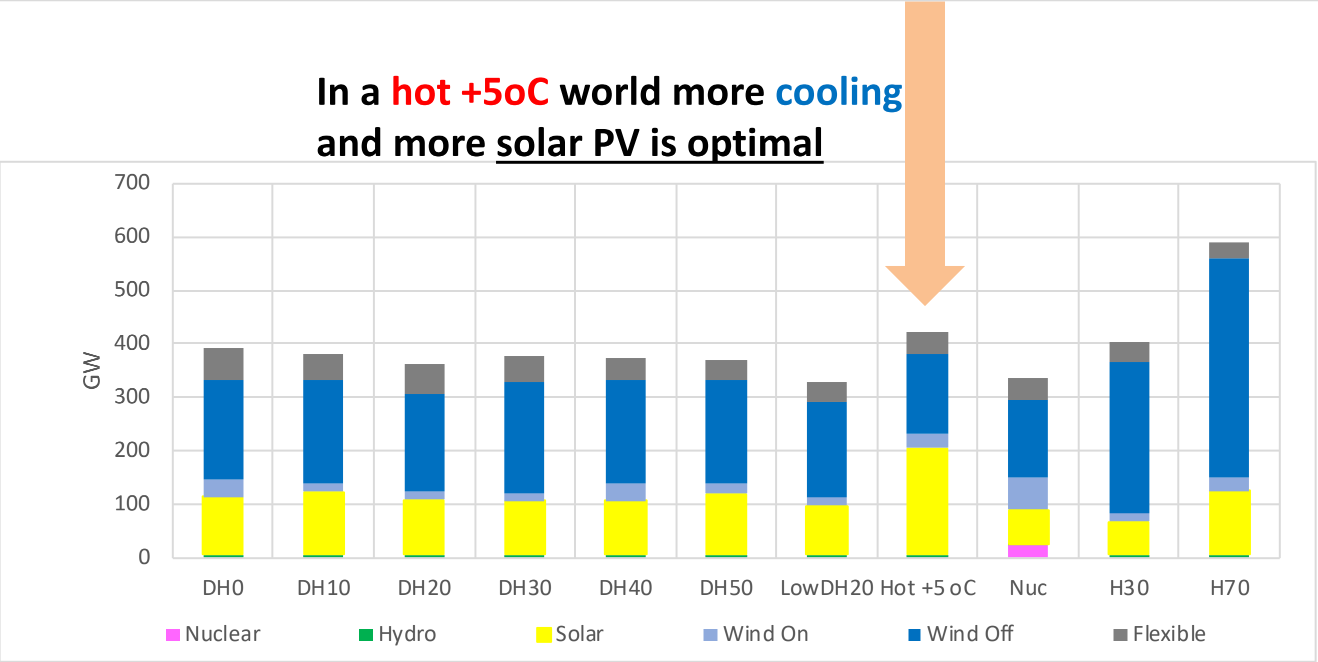
With climate change:
Heat demand will fall, **cooling will increase**

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

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



In a hot +5oC world more cooling and more solar PV is optimal

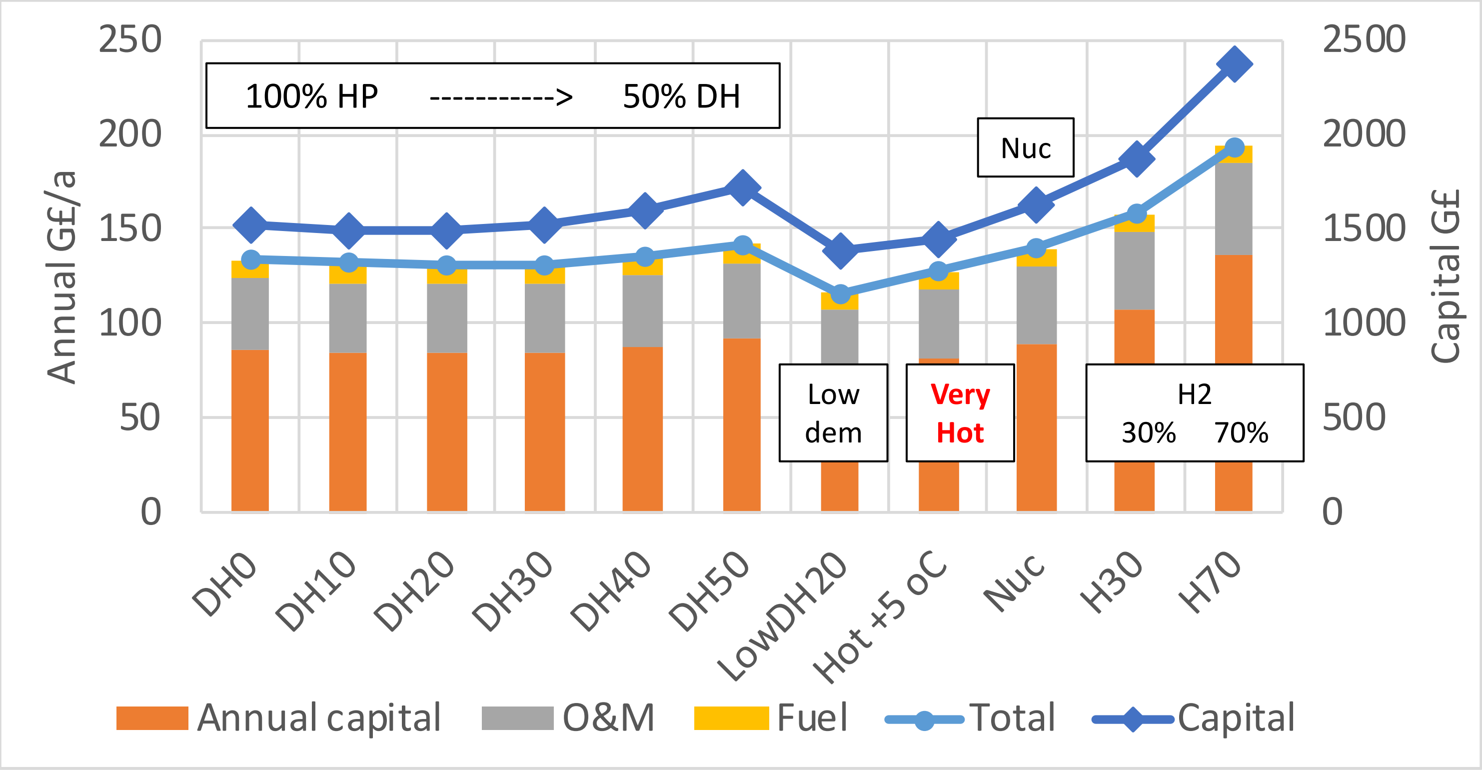


2050 costs in 11 system designs

Different fractions of consumer heat pumps (HP), district heating (DH) and hydrogen heating (H2)

Zero emission electricity is all renewable except Hinkley, or 24 GW in the nuclear variant

- HP and DH similar costs, but DH slightly lower cost and more storage for system management
- Nuclear more costly
- H2 heating much more costly for 30% and 70% heat shares



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

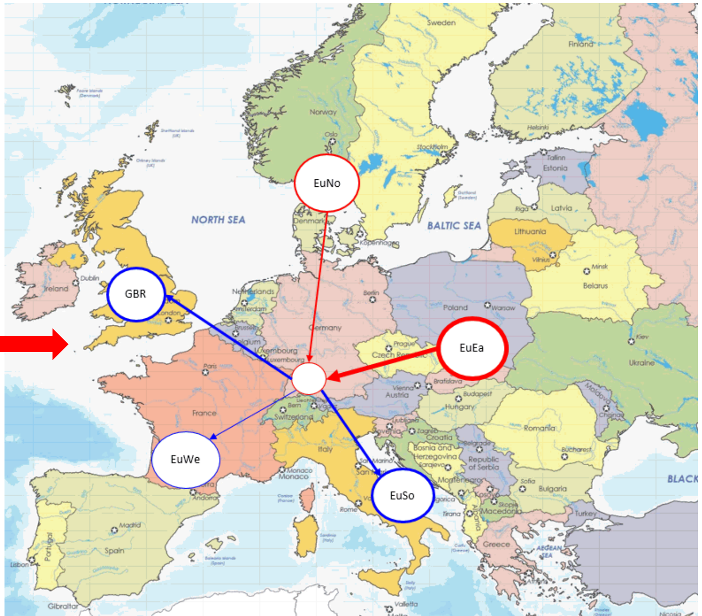
Renewables give supply and price security

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

Model algorithm

x

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
		3 Heat and elec from CHP if more heat needed
Surplus	If surplus electricity	1 To EV battery
	and store not full	2 To electricity store
		3 Put heat into DH store using DH heat pumps
		4 To H2 electrolyser
		5 To DACCCS
Deficit	If deficit electricity	1 From electricity store
		2 From flexible generator

Selected publications

Barrett, M, Gallo Cassarino, T, (2021), Heating with steam methane reformed hydrogen, Research Paper, 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/

Gallo Cassarino, T. *et al.* (2019) 'Is a 100% renewable European power system feasible by 2050?', *Applied Energy*. 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', *Applied Energy*. 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', *Applied Energy*, 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', *Renewable Energy*, 143. doi: 10.1016/j.renene.2019.05.094.

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Siddiqui, S., Macadam, J. and Barrett, M. (2020) 'A novel method for forecasting electricity prices in a system with variable renewables and grid storage', *International Journal of Sustainable Energy Planning and Management*, 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', *Energy Reports*. Elsevier Ltd, 7, pp. 176–183. doi: 10.1016/j.egyr.2021.08.157.