Green Light

Least cost net zero energy system designs for the UK

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UCL Energy Institute: EnergySpaceTime group

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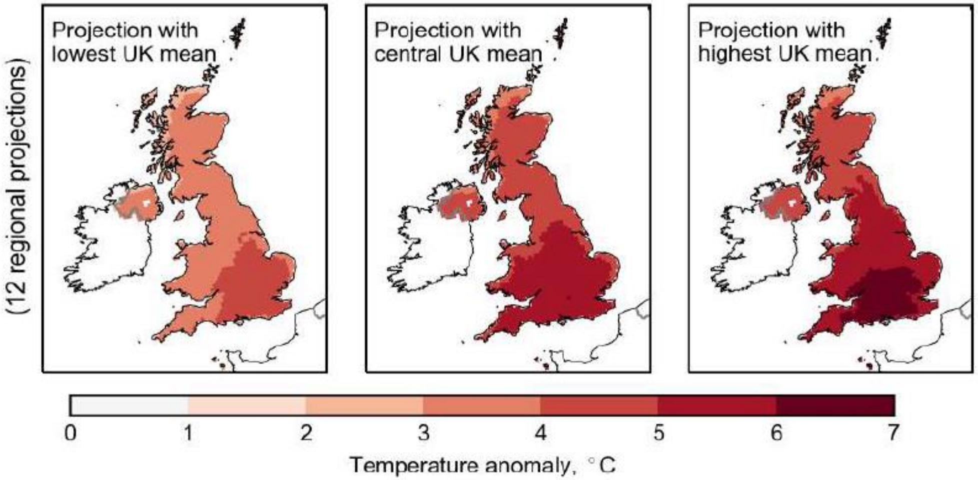
The design process

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

Options included

Manage demands with efficiency

Electrify directly:

- Heating and cooling with consumer heat pumps, district heating and hydrogen
- Transport – electric road and rail vehicles

Renewable 'electro' fuels:

- Electrolytic hydrogen for industry
- Ammonia for ships

Aviation:

- **Fossil kerosene with negative emissions**

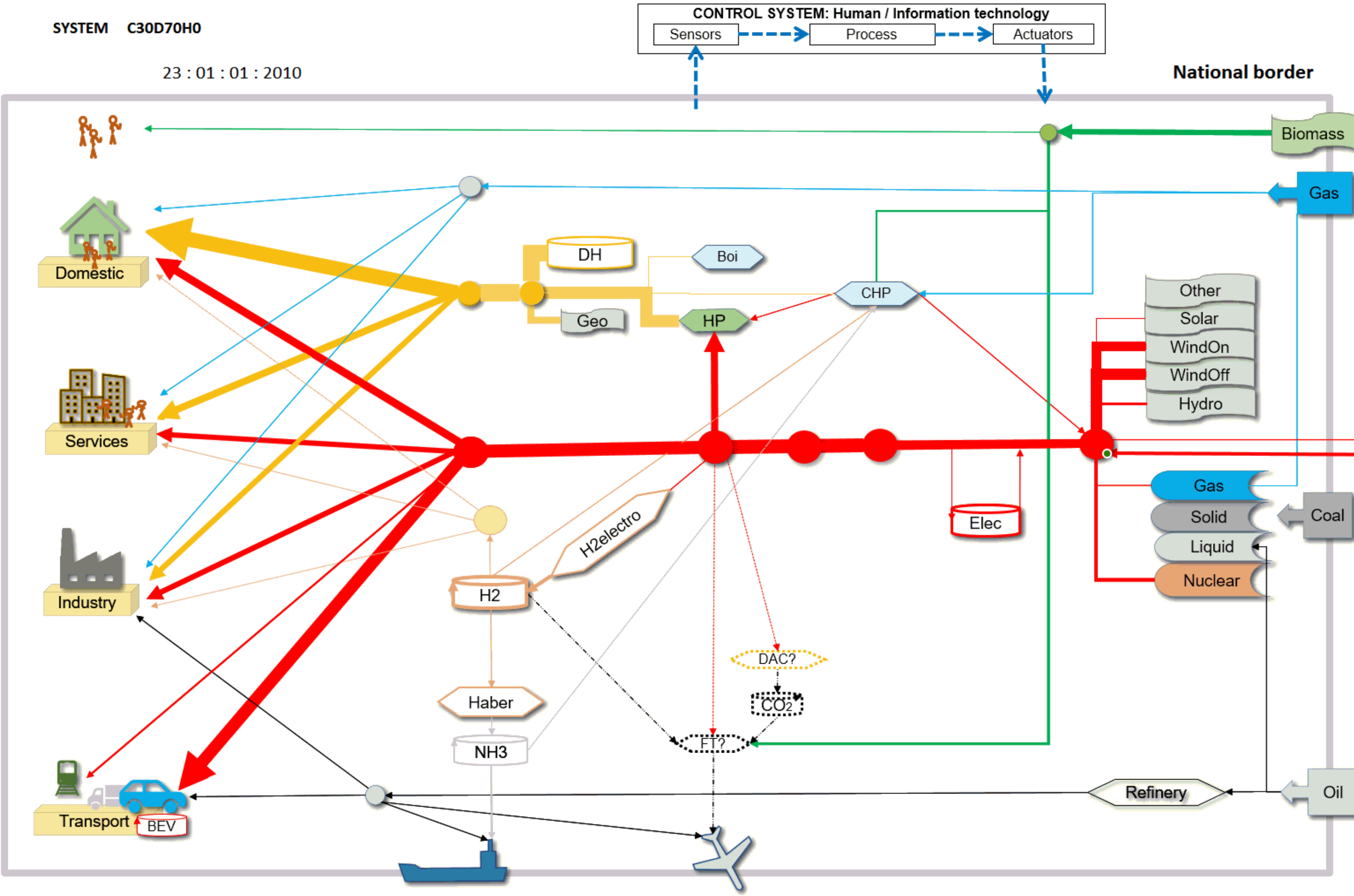
Direct Air Capture negative emissions to balance aviation and other emissions

Primary energy

- Renewable electricity from wind and solar
- Biowastes
- Nuclear – Hinkley C assumed operating in 2050

Excluded: biocrops, biomass import, hydrogen from gas, fossil fuels with CCS, etc.

A national energy system



Demands

Intermediate transmission, conversion, storage

Primary & Trade

me

DH20% : Transition - demands

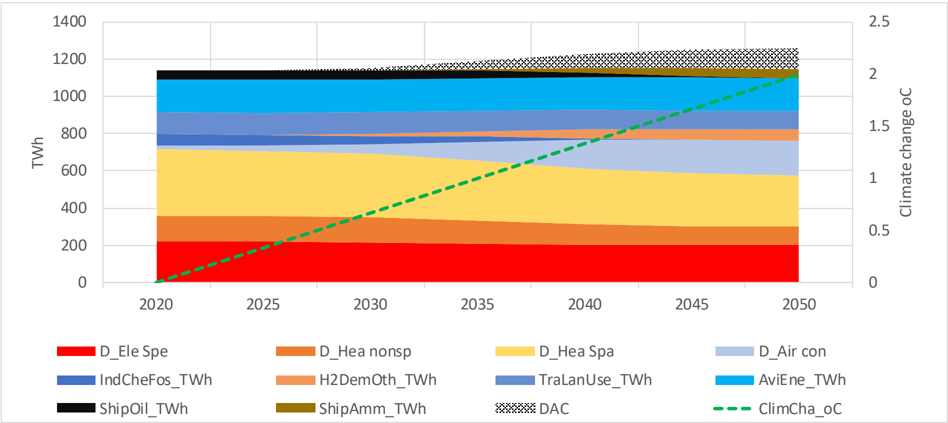
Insulation and climate change:

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

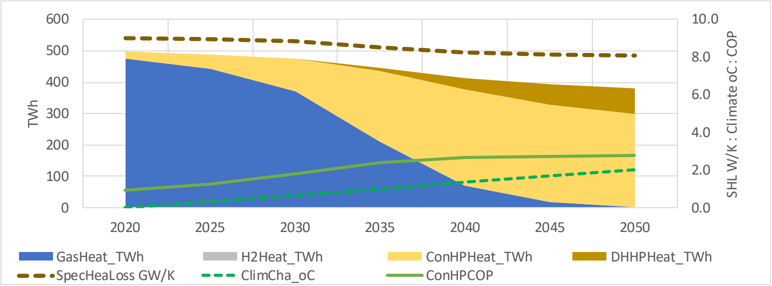
Heat/cool supply shift to electric HPs and DH

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

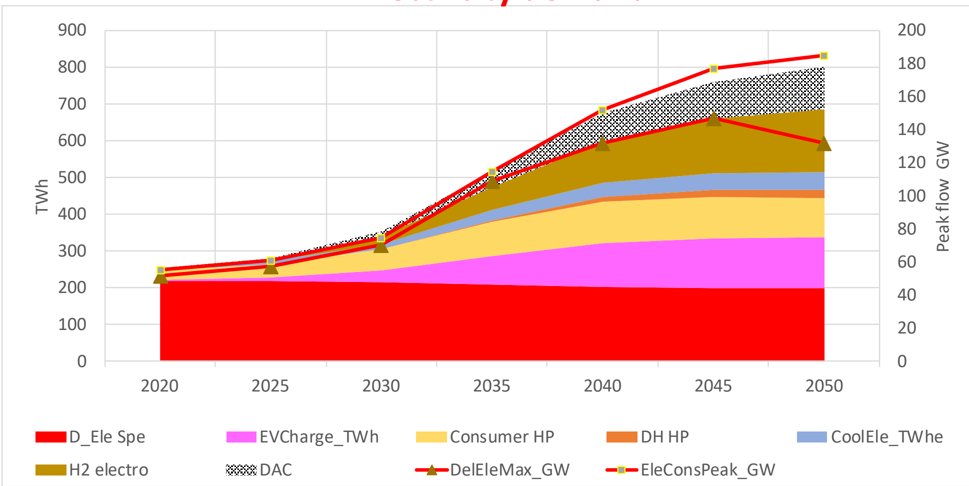
Demands



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

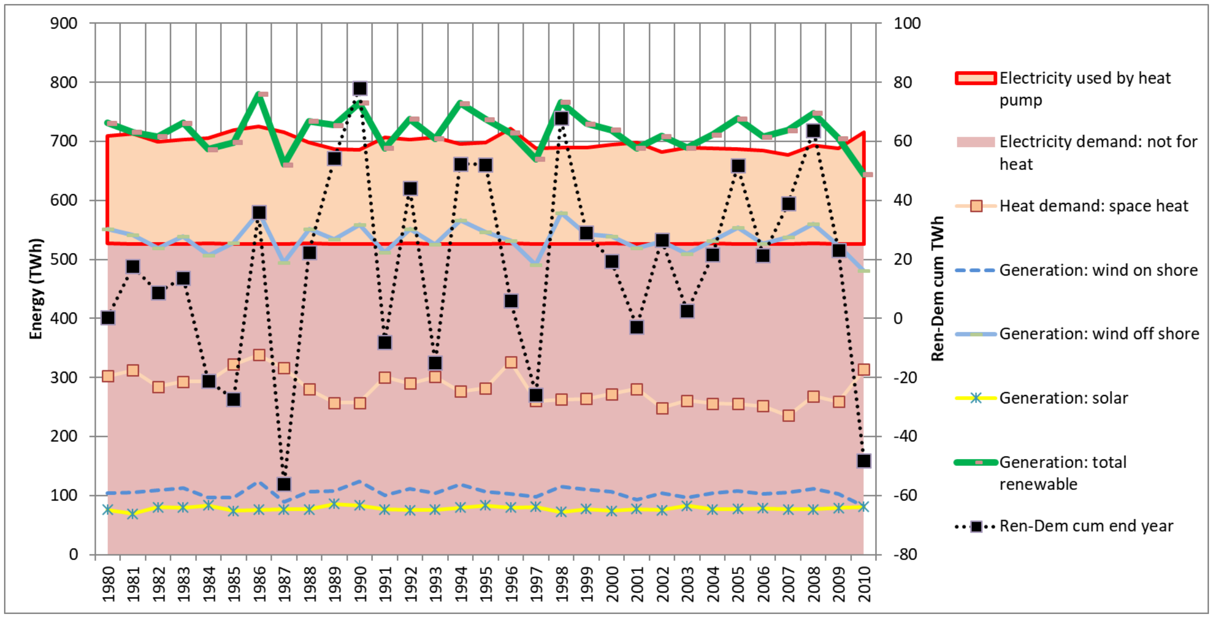
31 years annual renewable output variation
Wind off +/-9%
Wind on +/- 20%
Solar +/- 11%

Offshore wind capacity factors projected for 55-65%

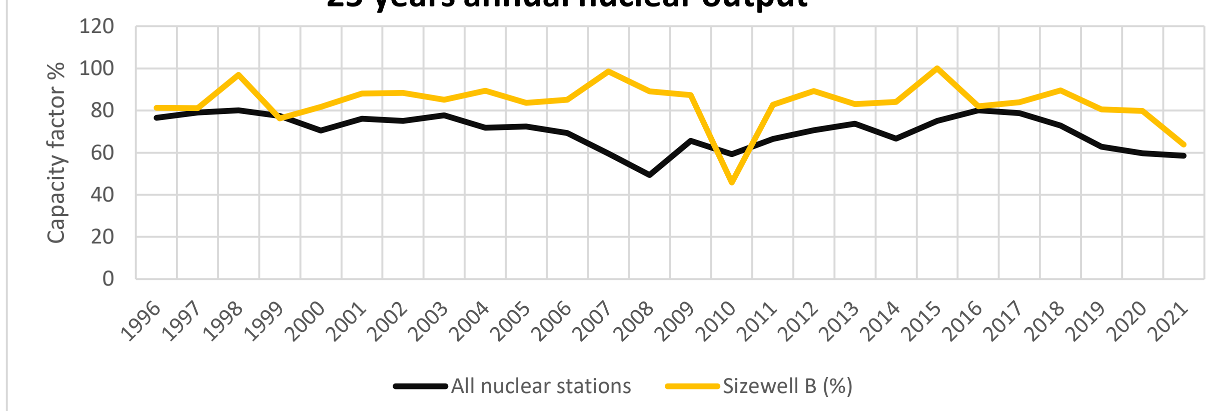
Annually, wind + solar is more reliable than nuclear

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

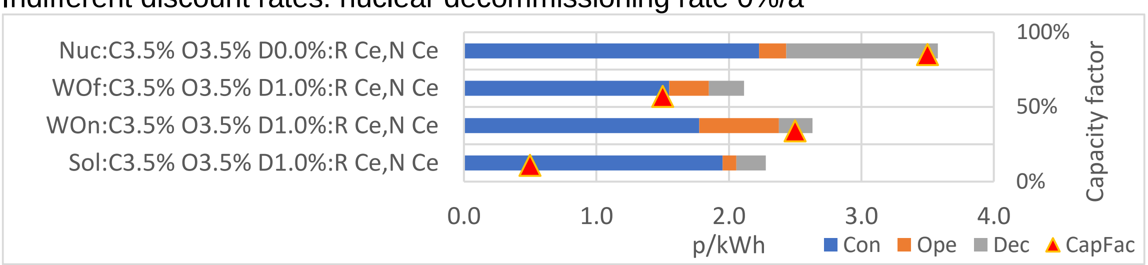
Insurance for UK operator liability About 1 £bn from operator
Fukushima cost 100-200 £bn

Proliferation?

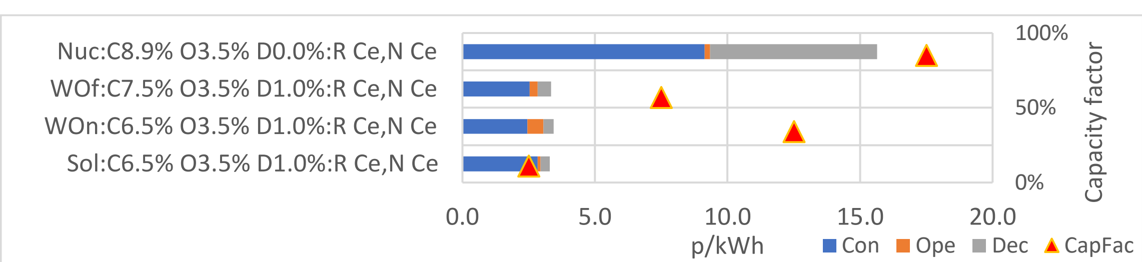
Central cost assumptions

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

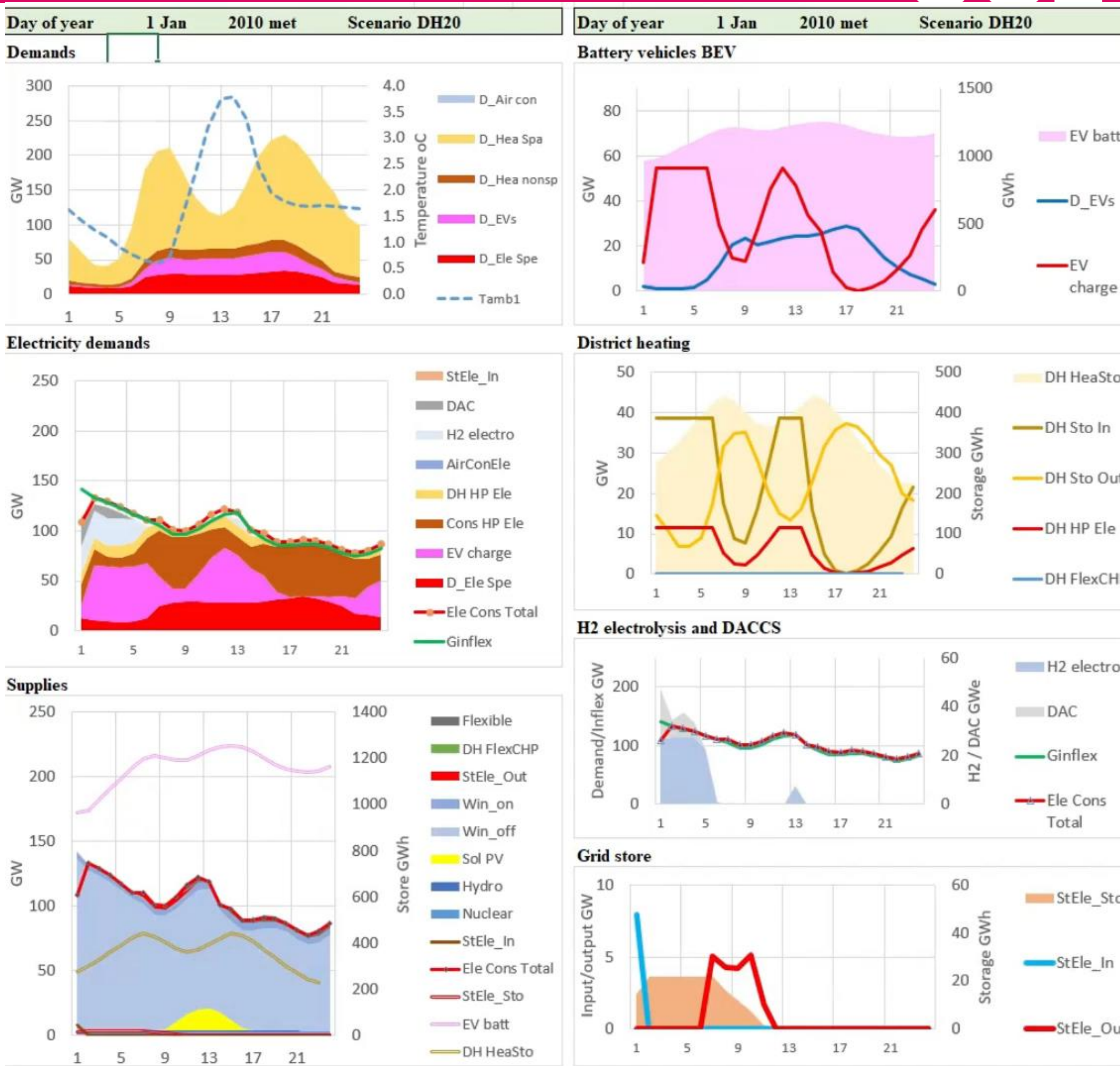


DH20%: Operation in 2050:

Sample days

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

What prices to consumers?

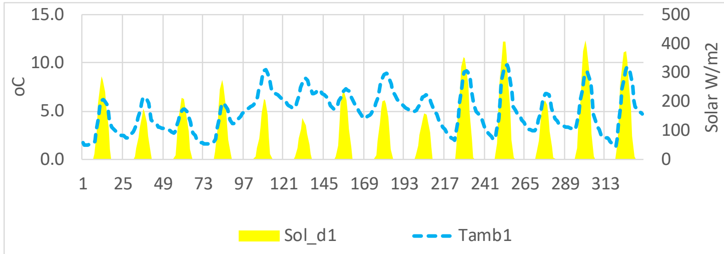


DH20%: Operation in 2050:

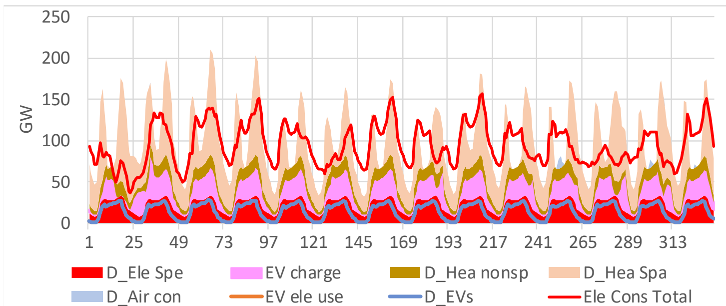
Winter fortnight

Fortnight from day	51	February	2010 met year

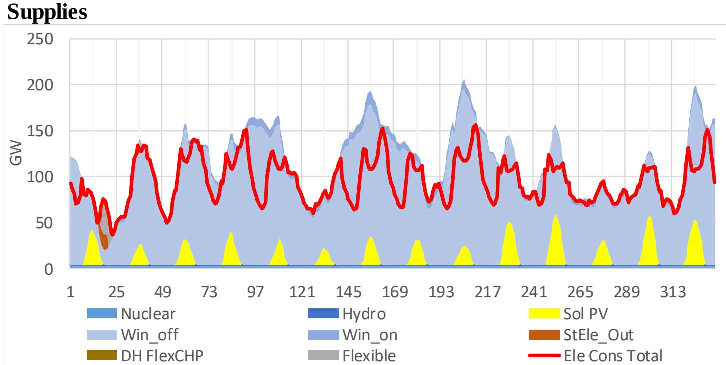
Meteorology



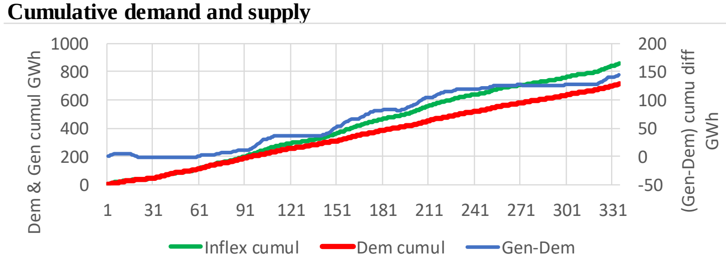
Demands



Supplies

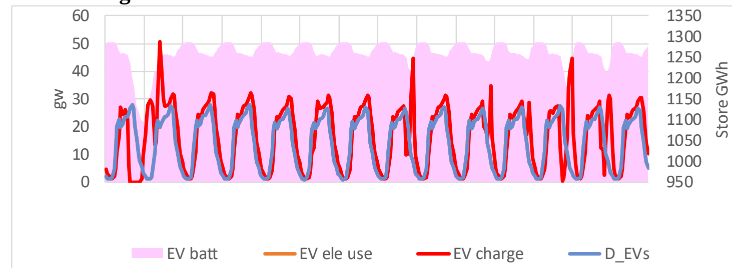


Cumulative demand and supply

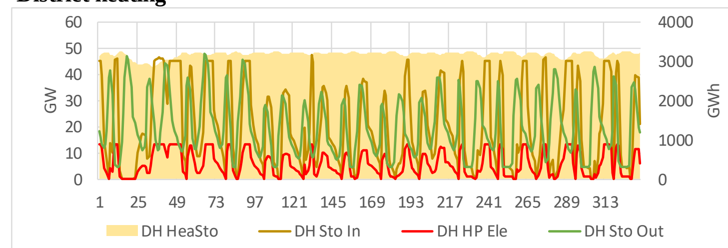


Fortnight from day	51	February	2010 met year

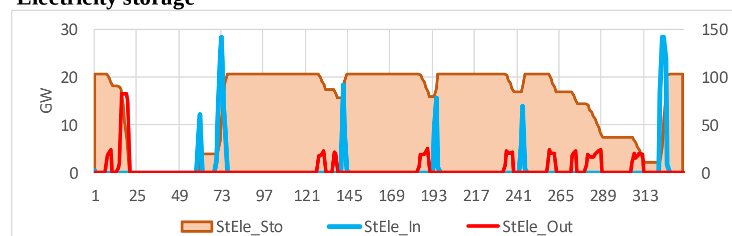
BEV storage



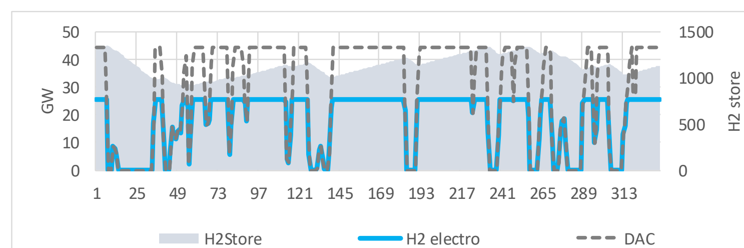
District heating



Electricity storage

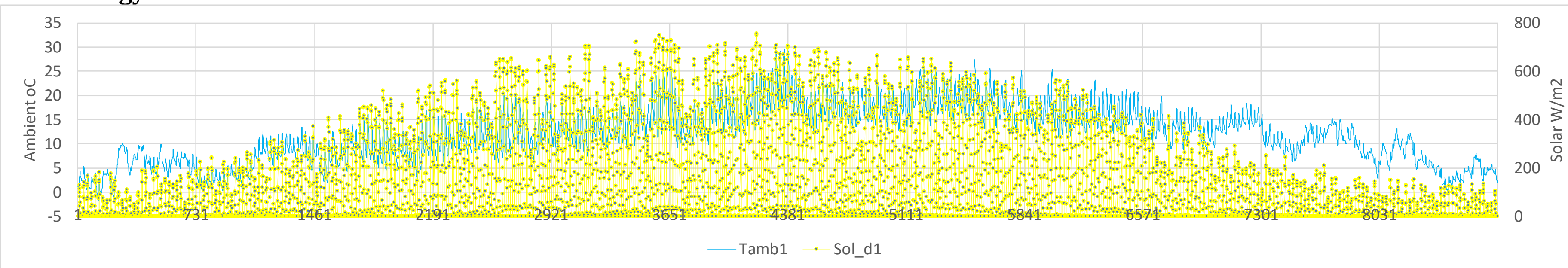


H2 electrolysis and DACCS



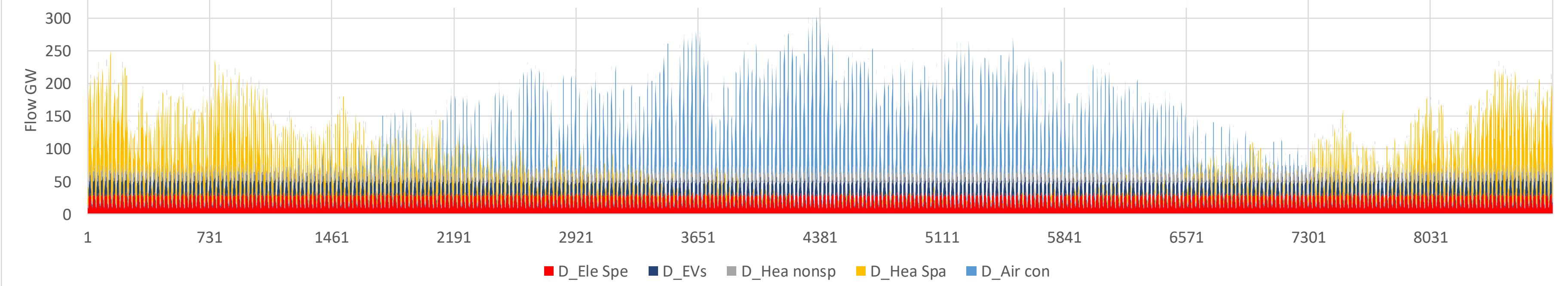
DH20% : Year's operation in 2050

Meteorology



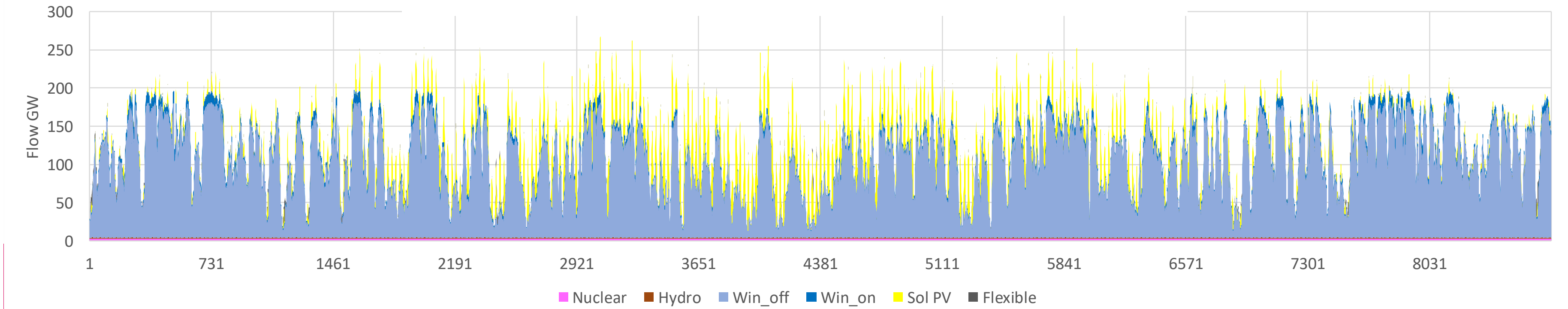
Demands

Winter heat peak, summer cooling peak



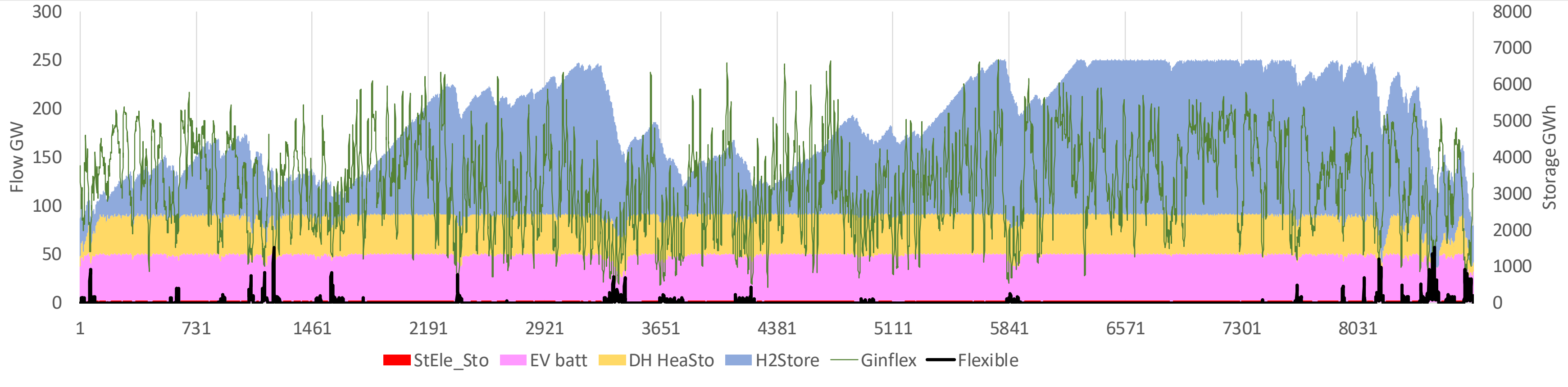
Generation

Winter wind peak, summer solar peak

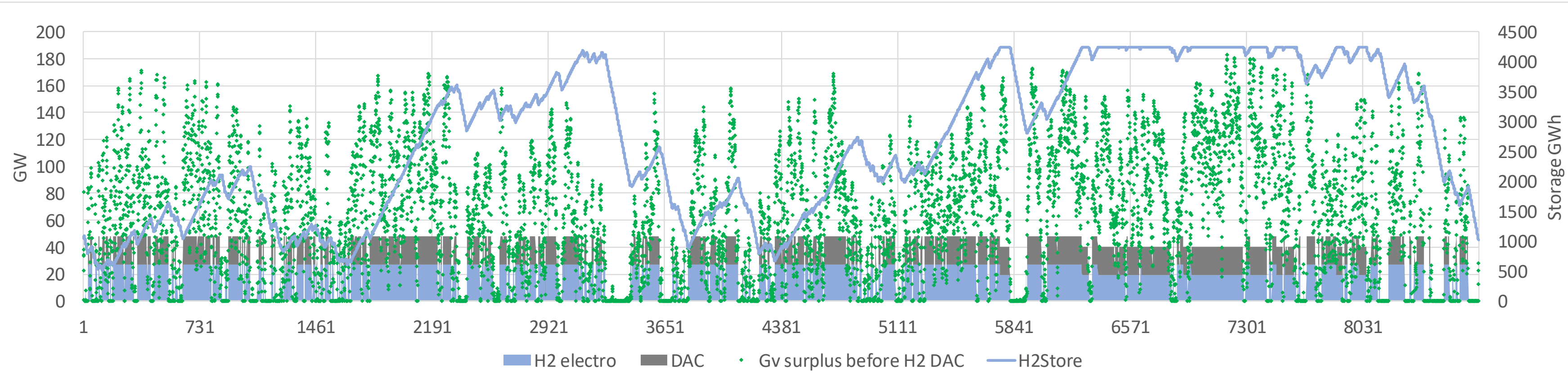


DH20%: 2050 year

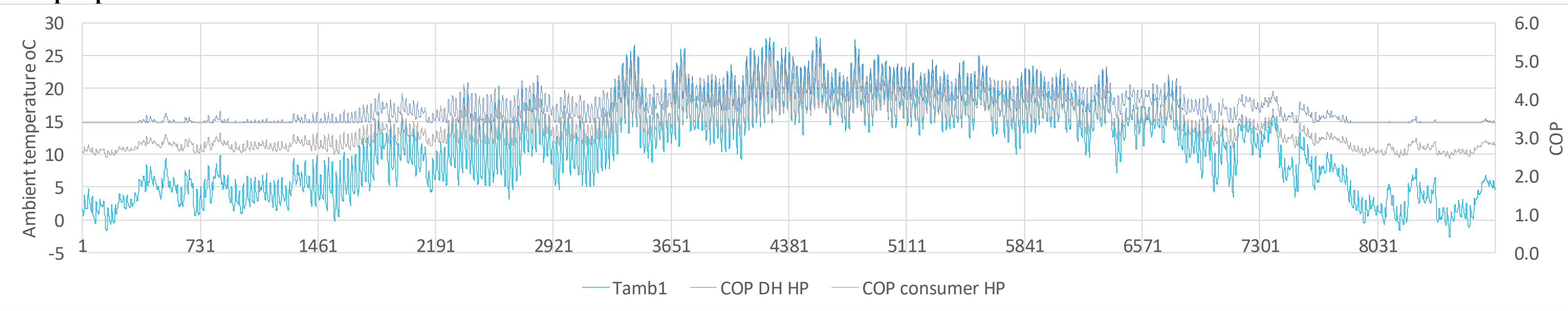
Stores, renewables, flexible



Surplus/deficit, H2 electrolysis and DAC



Heat pump COPs



DH20%: Transition to optimised system - electricity

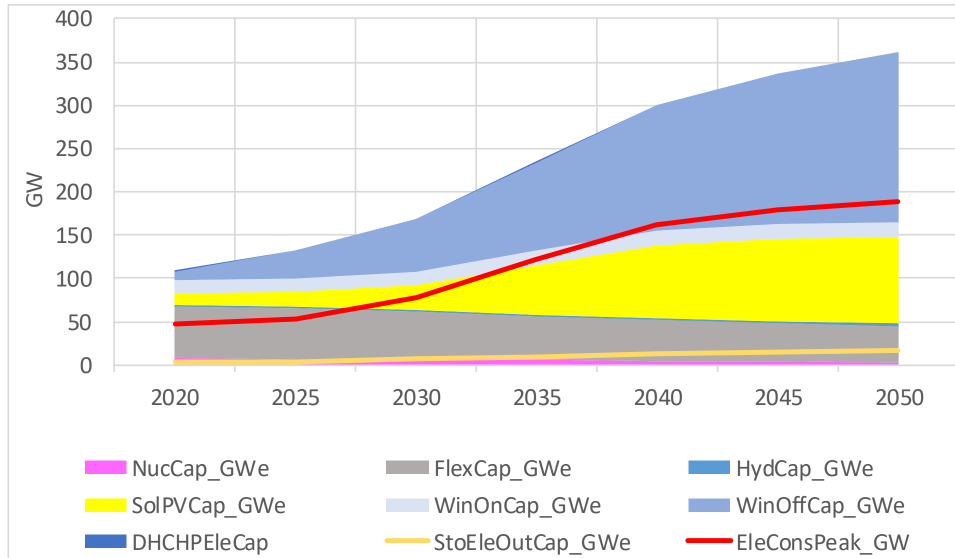
Primary electricity:
- 84% from wind, mainly offshore
- 10% solar
- 2% nuclear
- 4% other

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

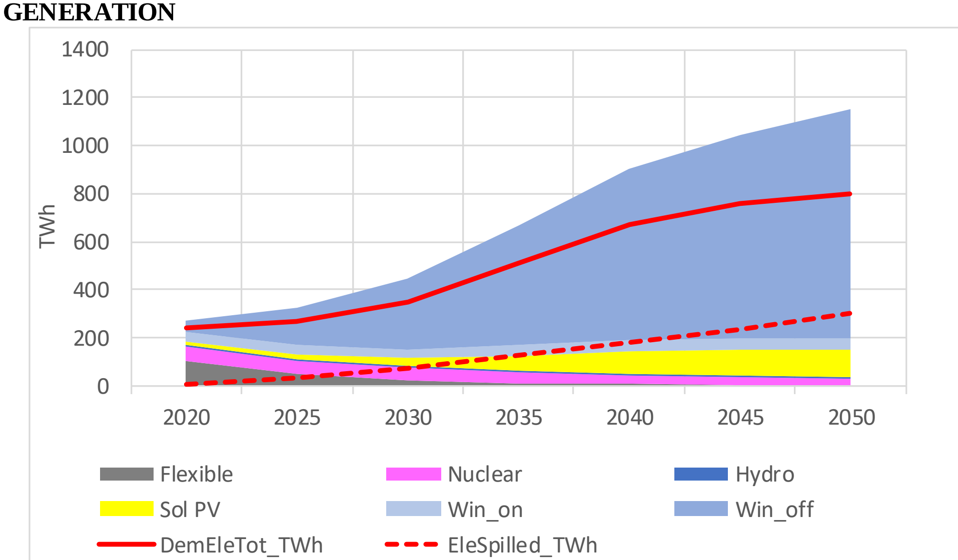
20-30% of generation is spilled without interconnectors

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

GENERATION CAPACITIES



GENERATION

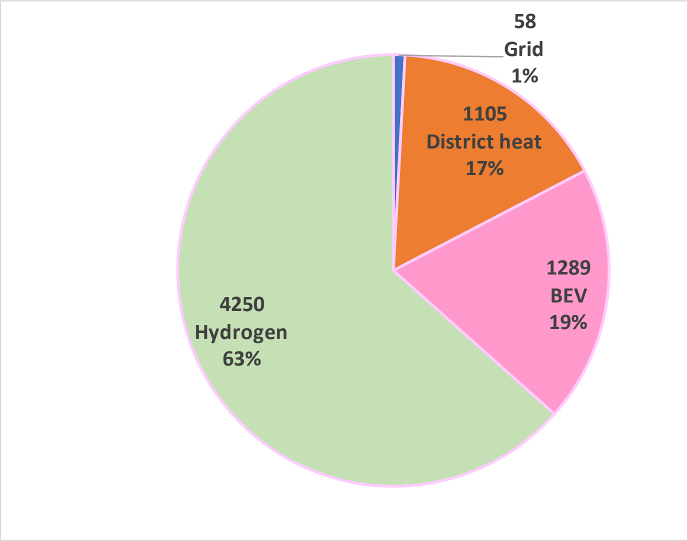


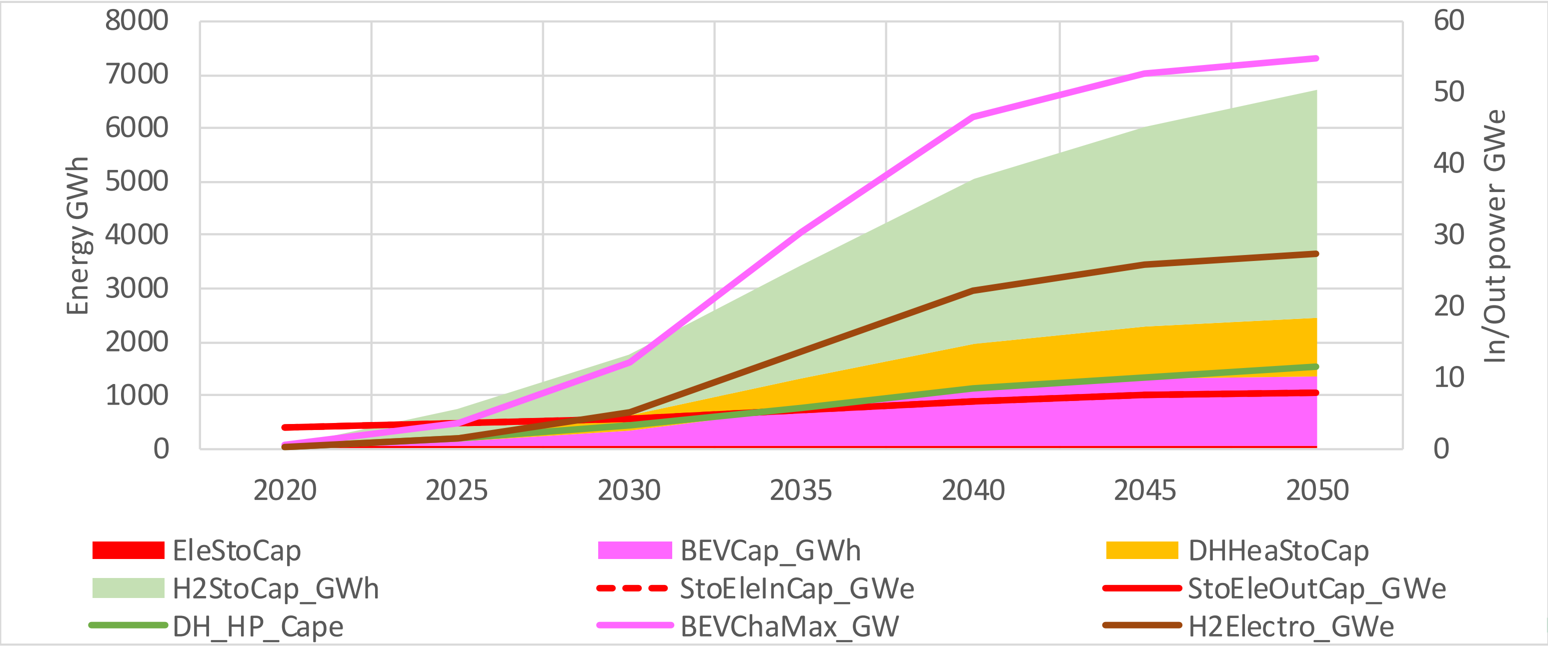
DH20%: Transition - storage

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





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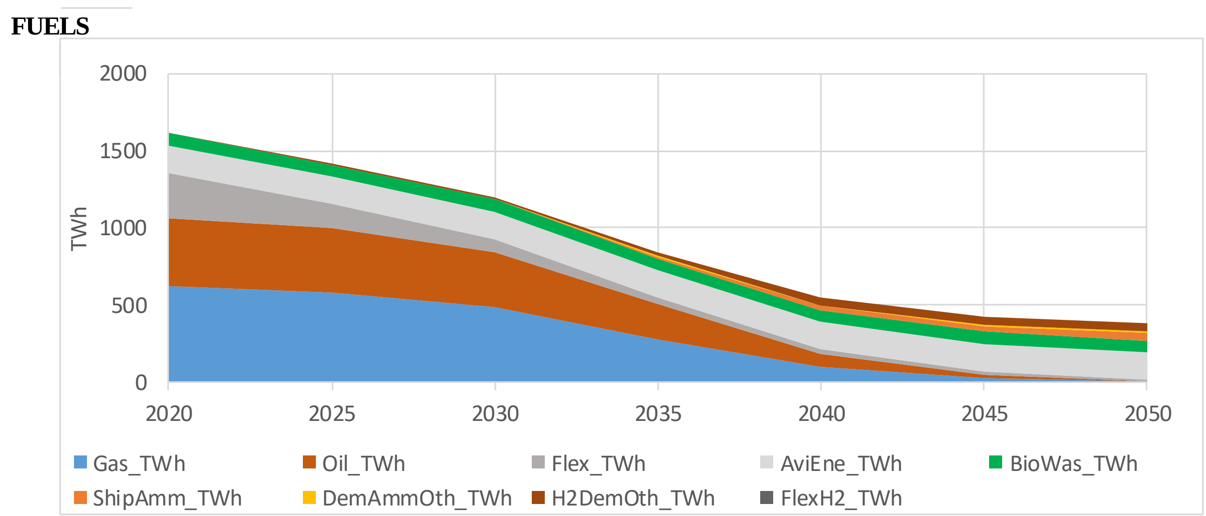
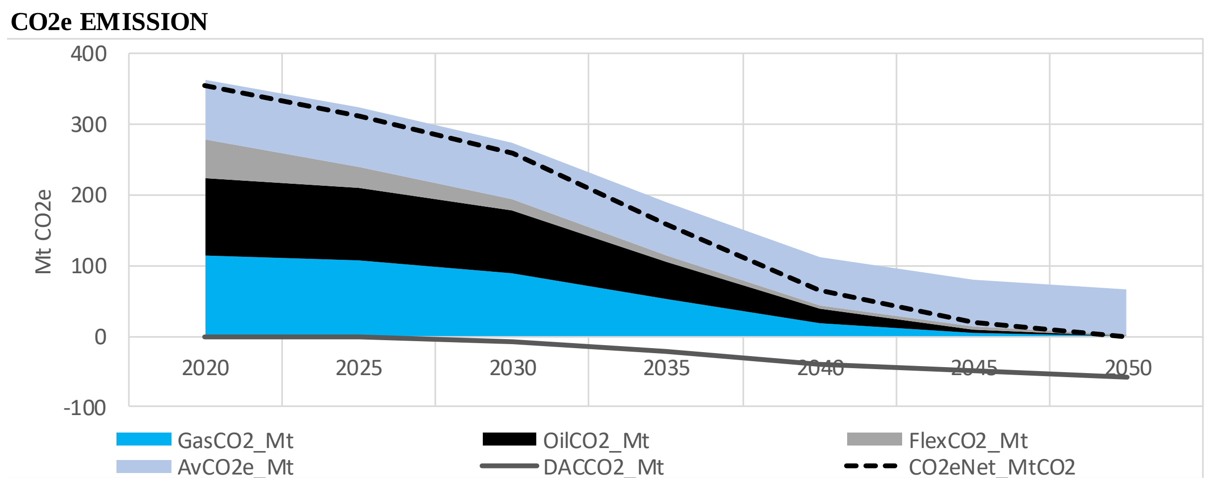
DH20%: Transition fuels and CO2e emission

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)



DH20%: Transition system costs

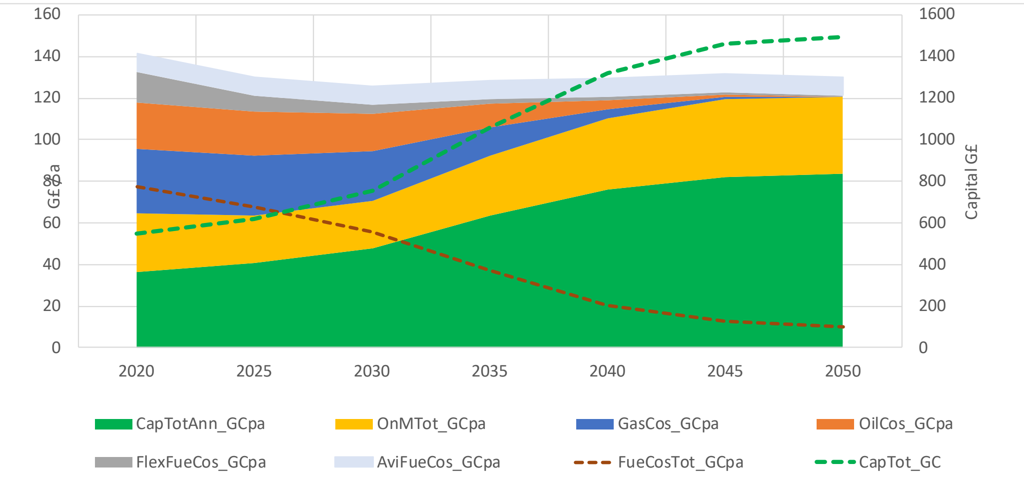
System costs similar to current, assuming ~2022 fuel prices.

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

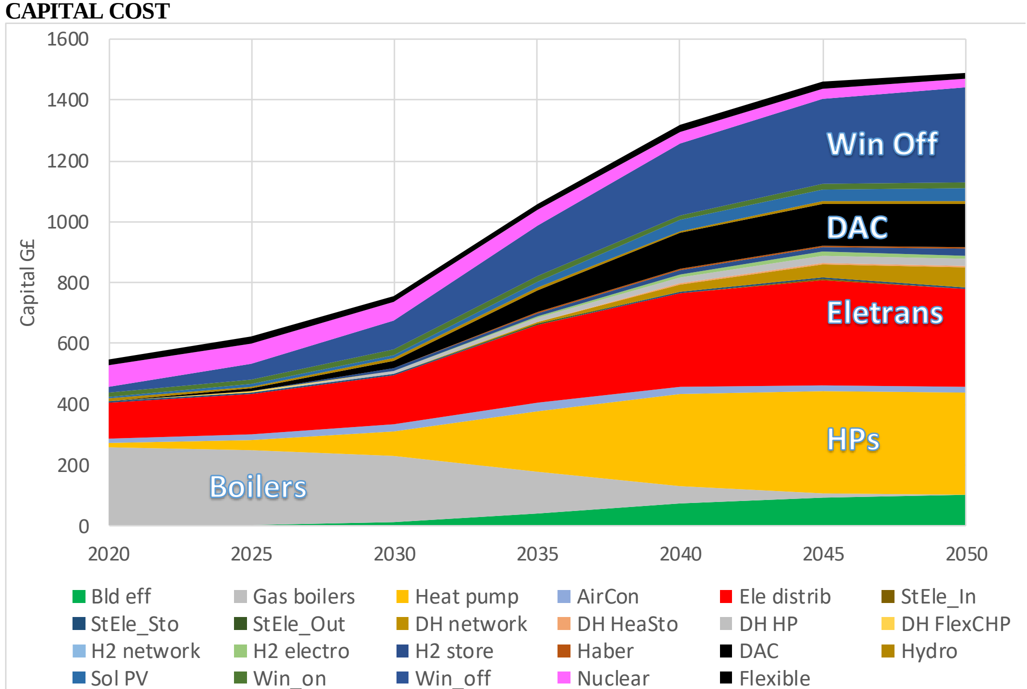
Capital investment about 2% of annual GDP

The **largest capital costs** are:

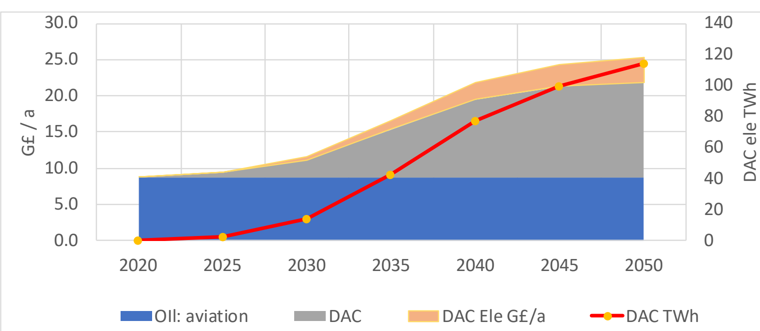
- Heat pumps
- Electricity network
- Offshore wind
- Direct air carbon capture and storage



CAPITAL COST



Aviation about 20% of total system cost



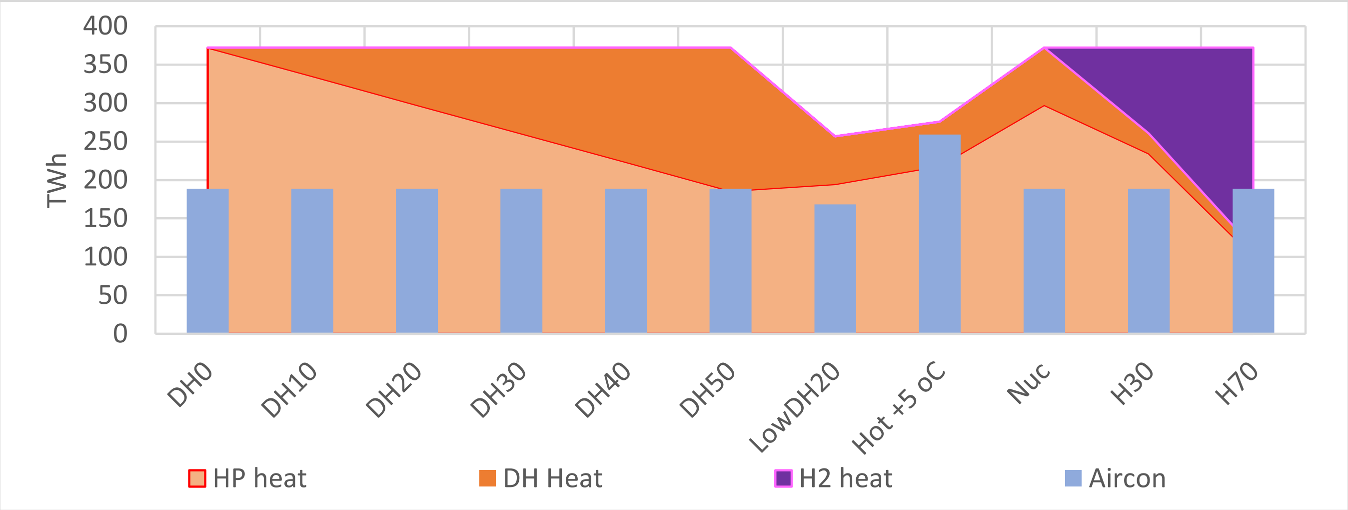
Heat and cool in 11 system designs

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

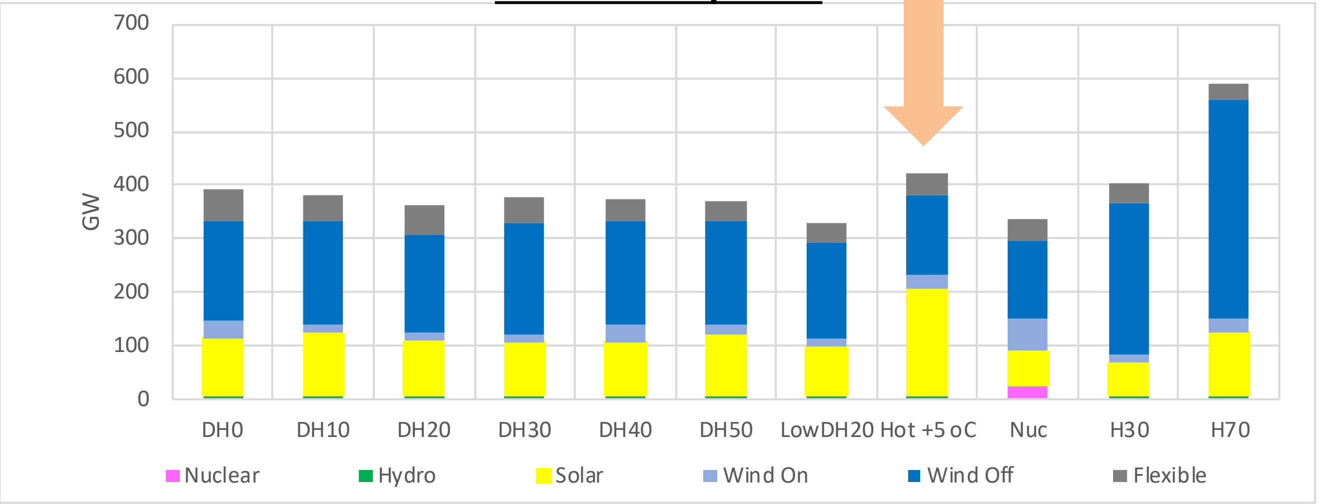
With climate change:
Heat demand will fall, **cooling will increase**

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

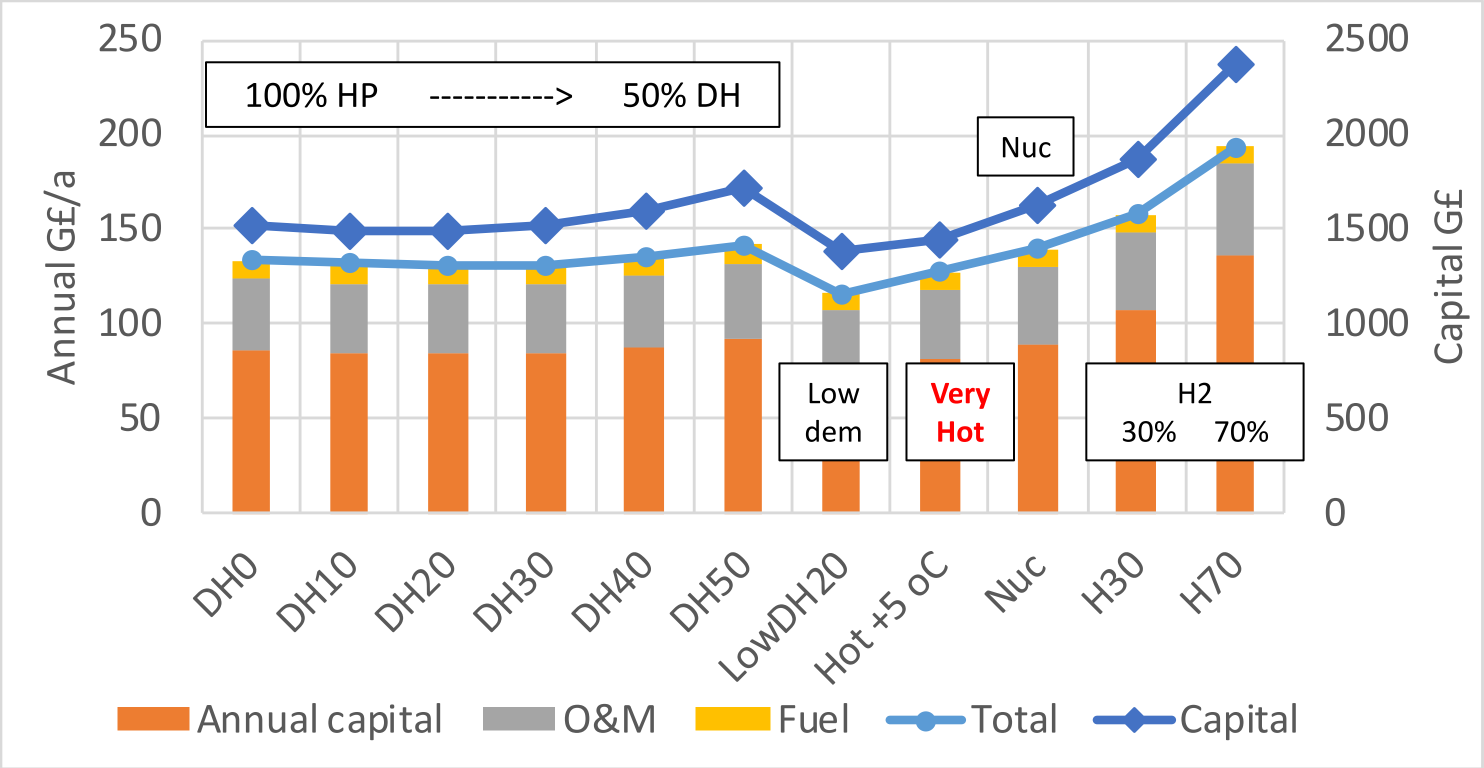


2050 costs in 11 system designs

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



Aviation

Remaining large emitter, even if growth rate halved
20+% of total system cost so the cost of flying needs to increase

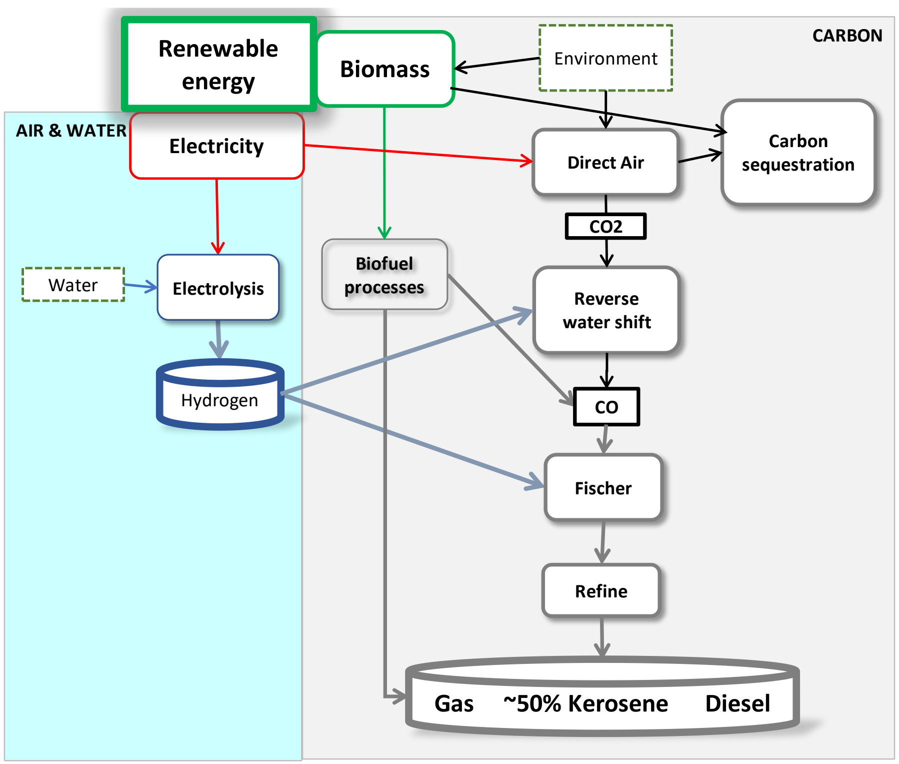
What fuel for aviation?

- **Fossil fuel kerosene + high altitude => ~50 Mt CO2e**
- **Biomass? => 68% UK agricultural land**
- **Renewable DAC and hydrogen? => 400+ TWh electricity**

Electrokerosene

Made from electrolytic H2 and atmospheric CO2

- Complex
- Very expensive

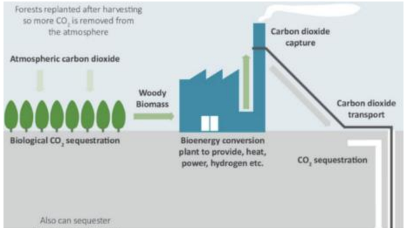


How to balance aviation altitude warming?

Negative emissions CO2 from the atmosphere

DACCS?

Direct Air Capture and Carbon Storage



BECCS?

Bioenergy and carbon capture and 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

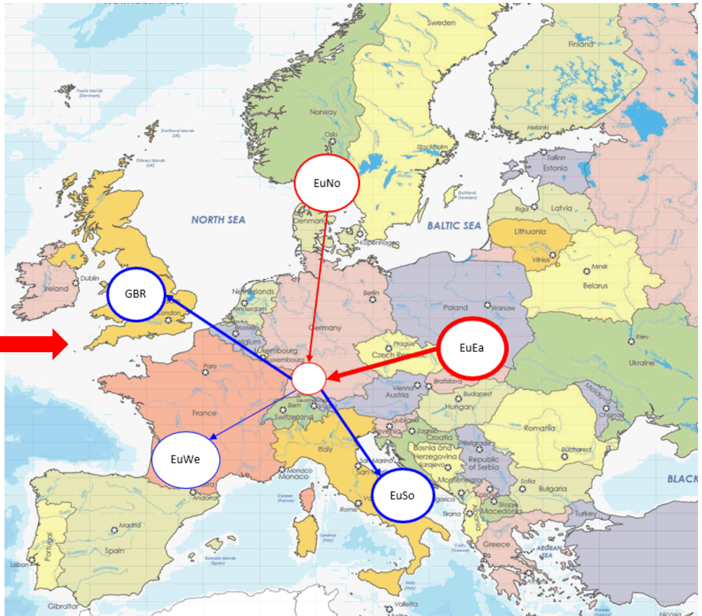
Renewables give supply and price security

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?

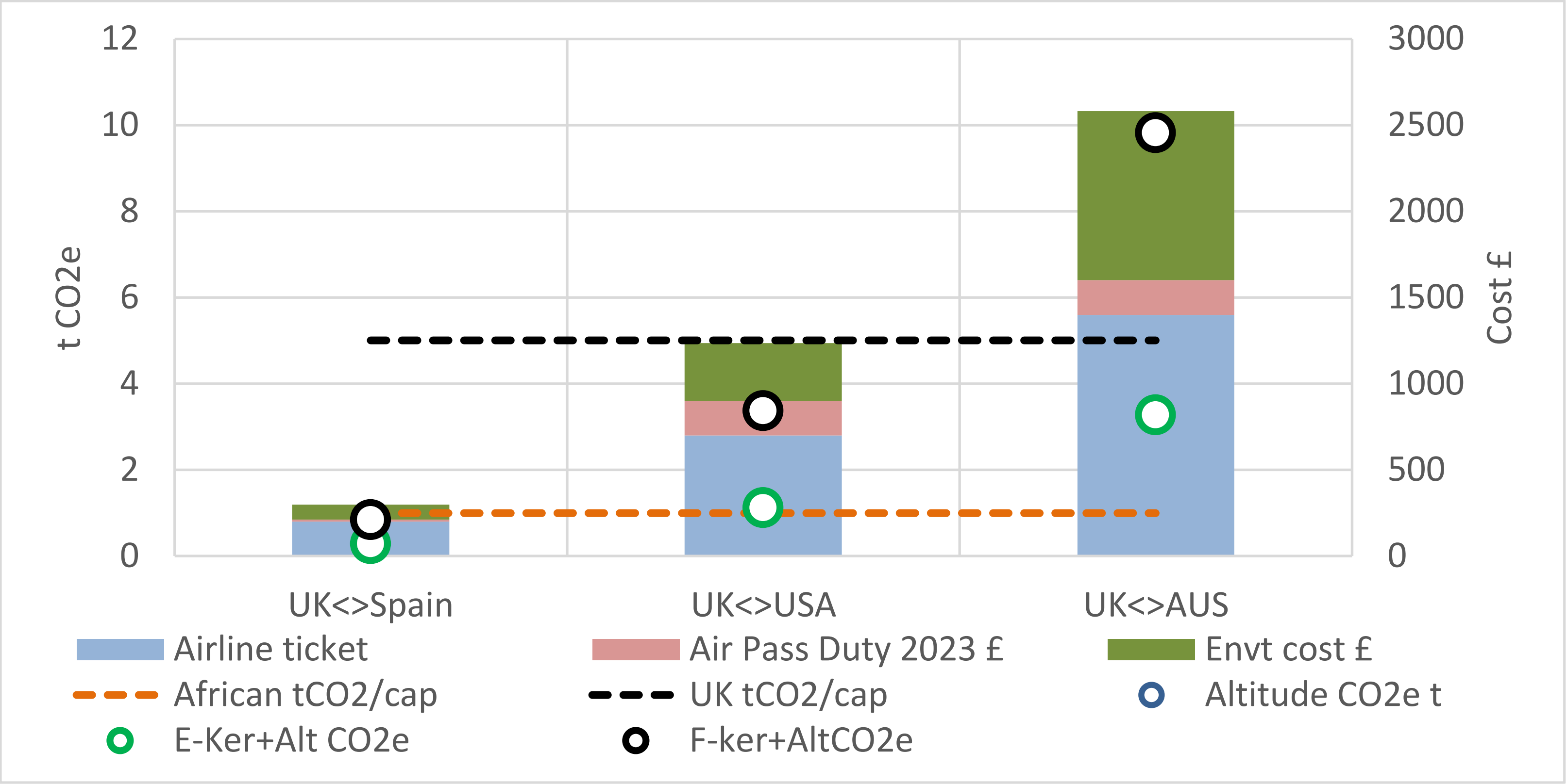


How will a future energy market function?

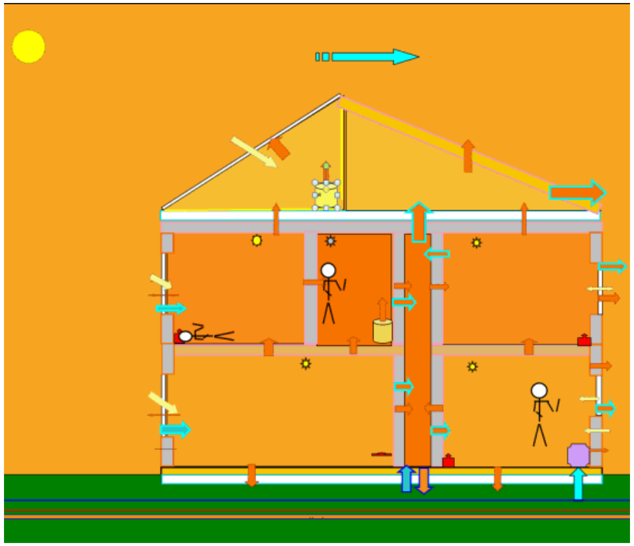
Thanks for listening

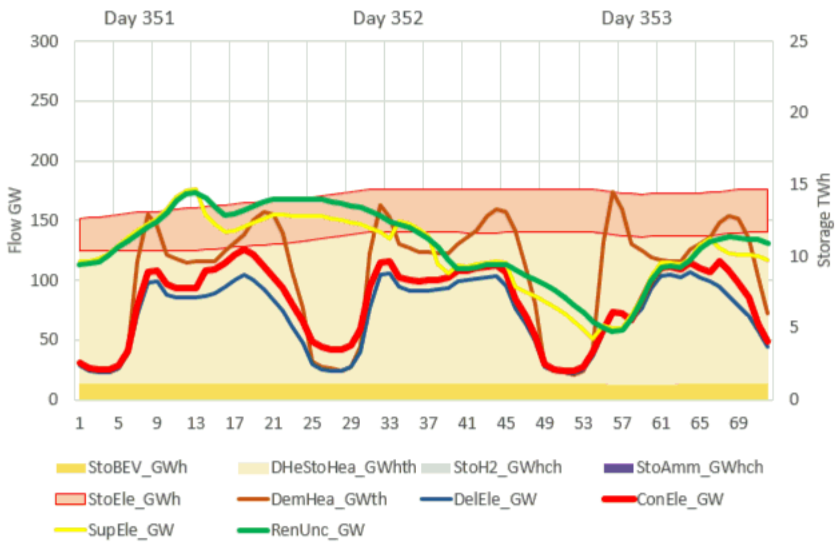
Aviation environmental cost

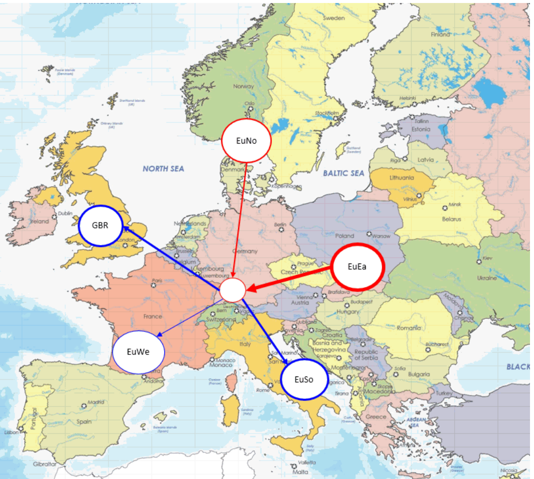
Cost of flying doubled or tripled ~300 £/tCO2 or electrokerosene
Return flight to Spain = average African emission
Return flight to USA = average UK person emission

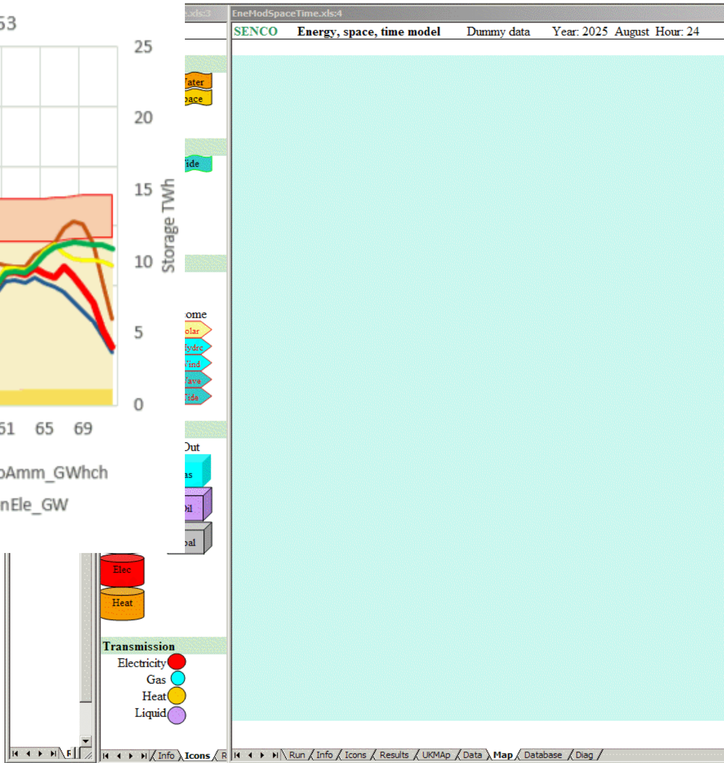


Designing a system to connect demands and renewables across time and space









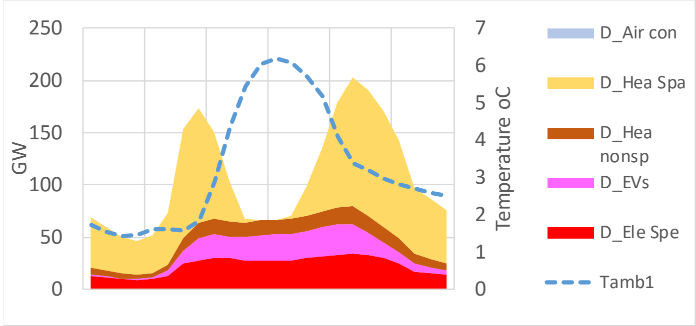
Operation in 2050:

Sample days

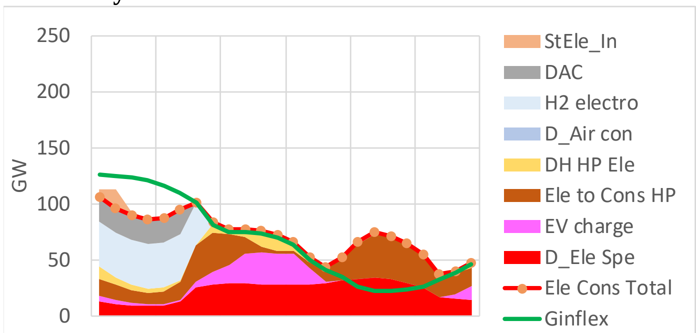
Winter

Day of year 51 February

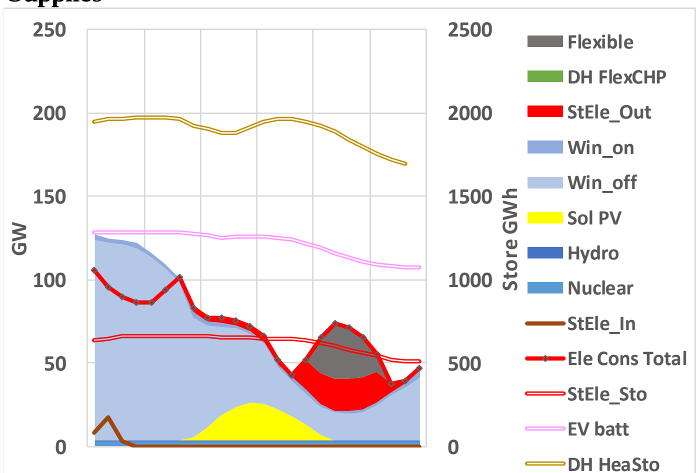
Demands



Electricity demands



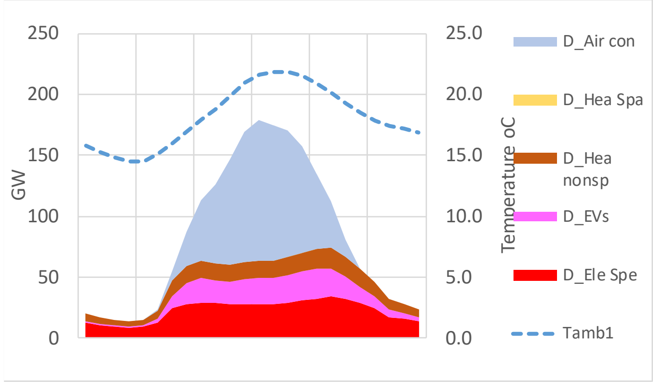
Supplies



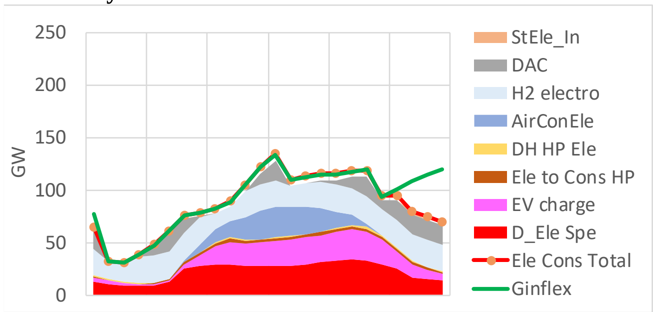
Summer

Day of year 194 July

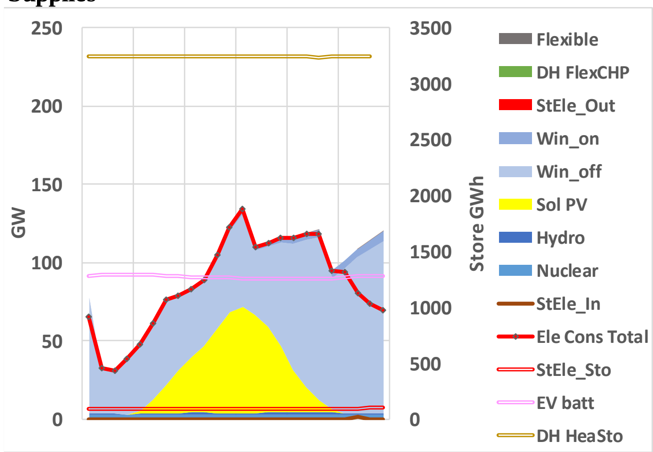
Demands



Electricity demands

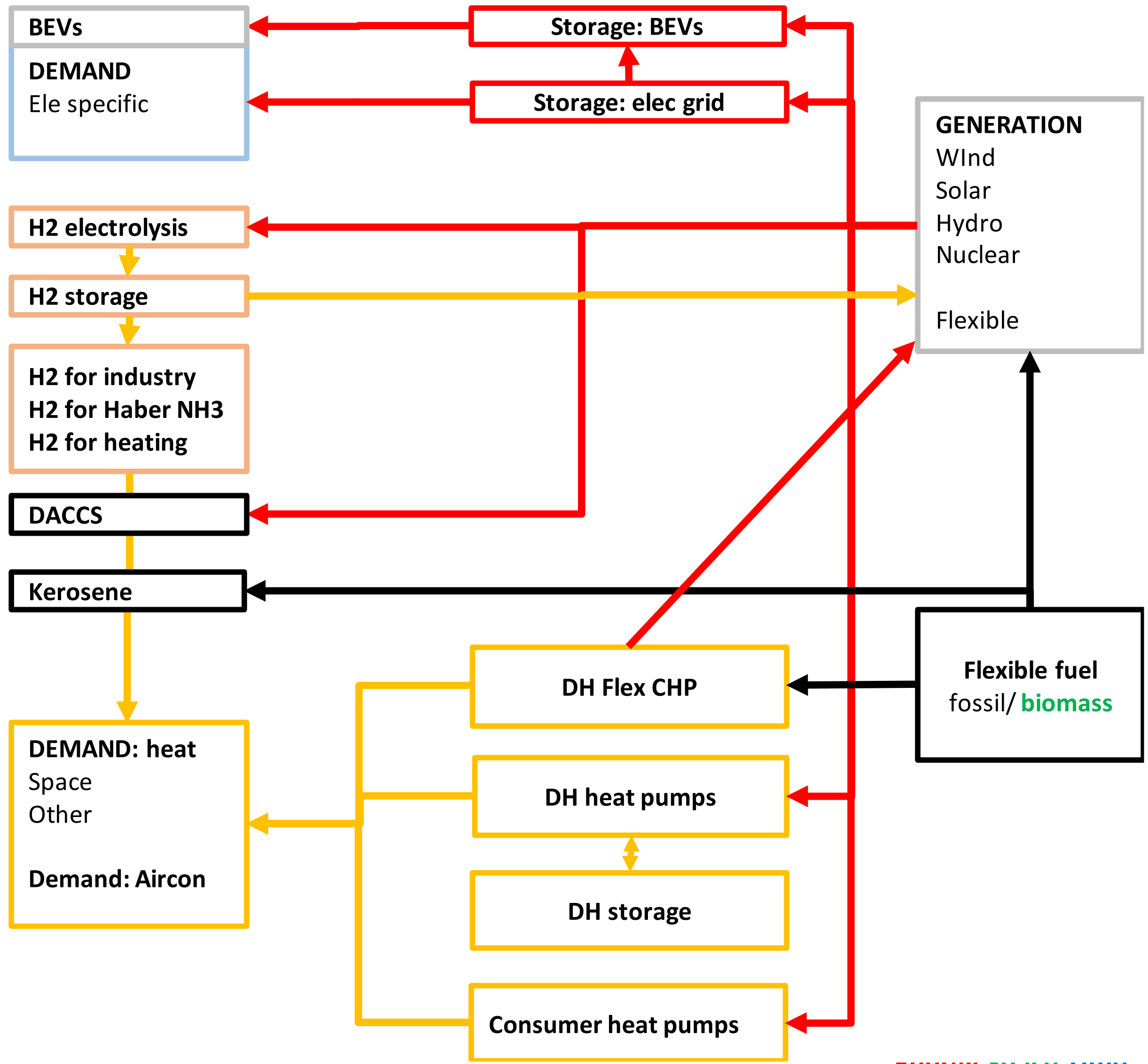


Supplies



Energy system diagram

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



Model algorithm

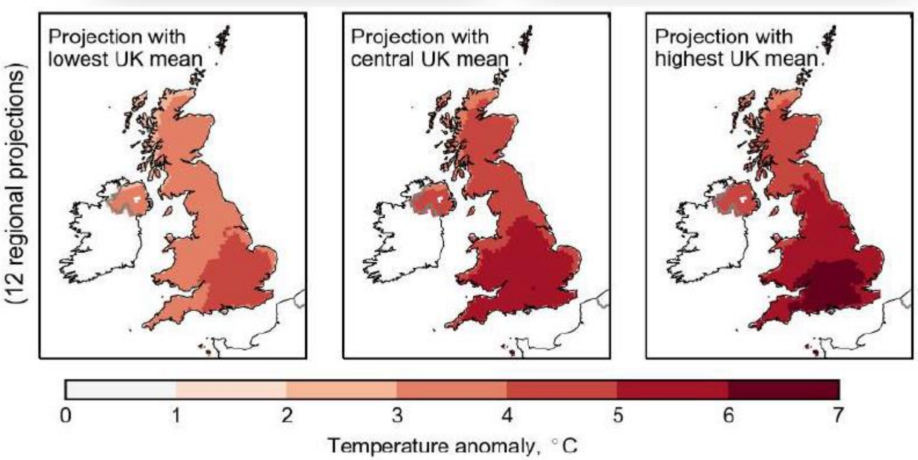
x

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 and store not full	1 To EV battery
		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

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

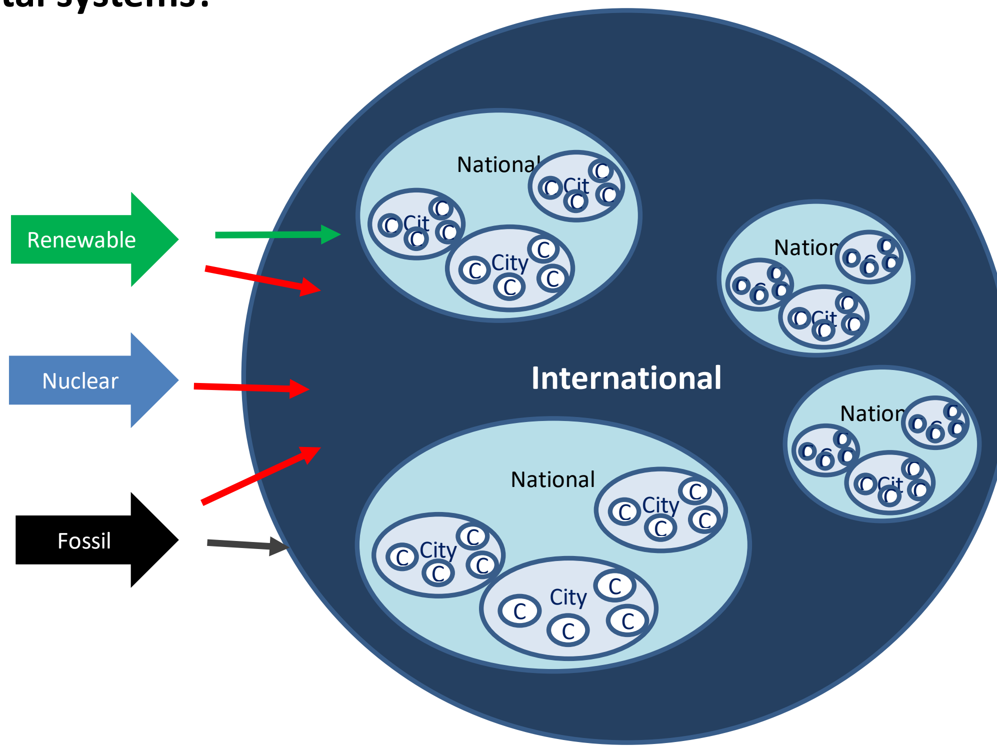
How might multi-vector, dynamic energy systems integrate at different spatial and temporal scales?
How can we model these complex, fractal systems?

Scales
- Building to city to national to international

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

Energy sources
- Renewable
- Nuclear
- Fossil

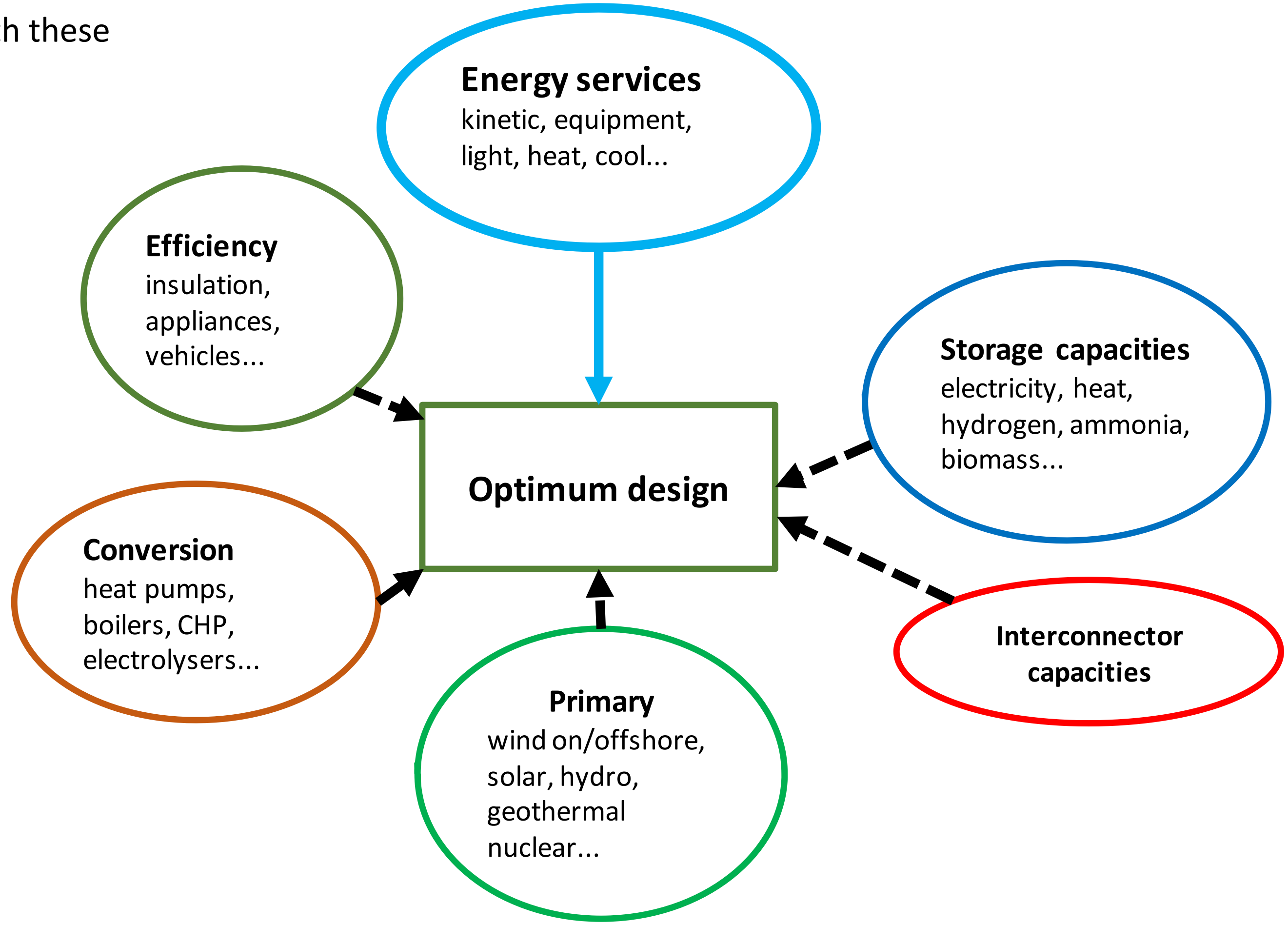
Vectors
- Primary chemical: fossil, biomass
- Secondary chemical (H2, NH3…)
- Electricity
- Heat



Designing zero emission systems

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



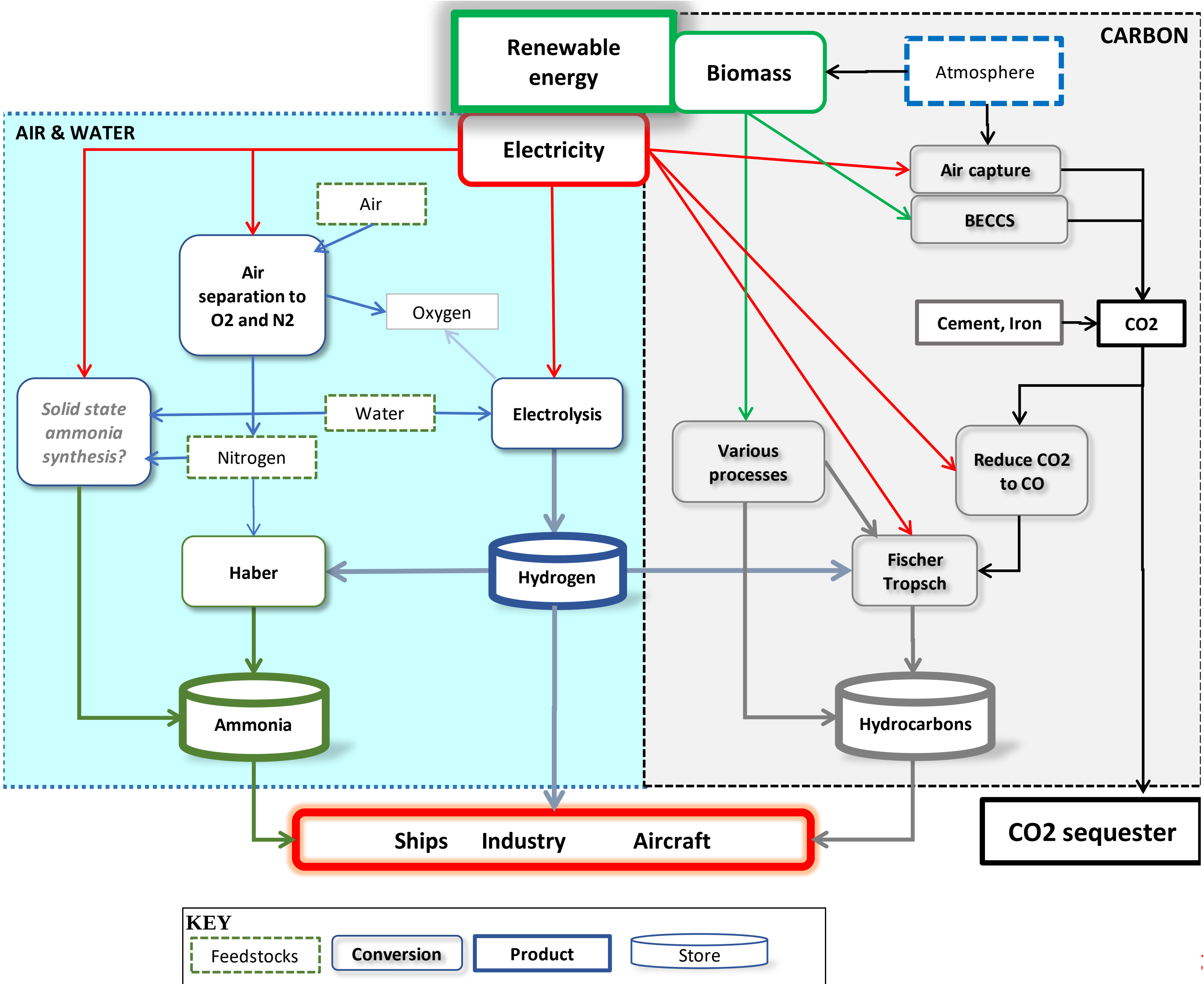
Key options explored

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



Selected publications

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