Zero greenhouse gas emission energy system designs for the UK and Europe

Mark Barrett, Tiziano Gallo Cassarino

UCL Energy Institute: EnergySpaceTime group

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Run presentation to see animations

Energy Space Time

Introduction

Aim: design zero greenhouse gas emission energy systems with a focus on heat

How will climate change (+2 +5 +? oC) impact on demands for heat and cool?

Test whether designs work in engineering terms, and determine costs

Nine systems are designed with different:
- **building efficiencies**
- **shares of heating** with consumer heat pumps, district heating and electrolytic hydrogen
- **capacities** of renewables, stores and interconnectors
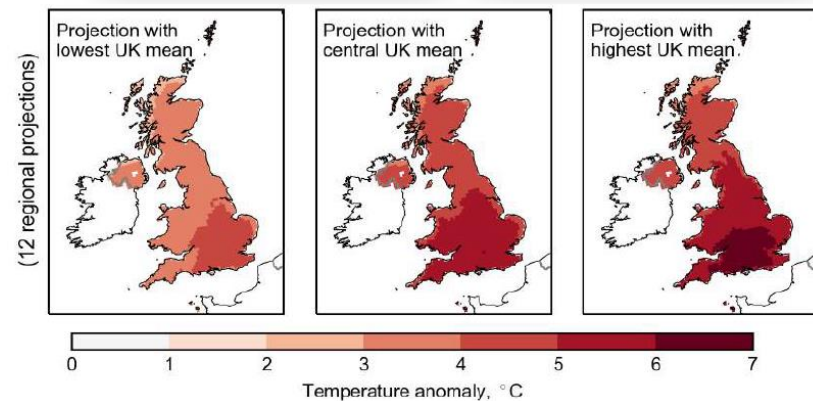
A national energy system

A national energy system comprises four basic parts:

- Demands
- Intermediate conversion, storage and transmission
- Primary and trade
- A control system

ESTIMO models the energy flows hourly (across the days, months and years) as driven by social activities and meteorology.

ESTIMO dynamically controls the intermediate system, storage and trade

Energy Space Time
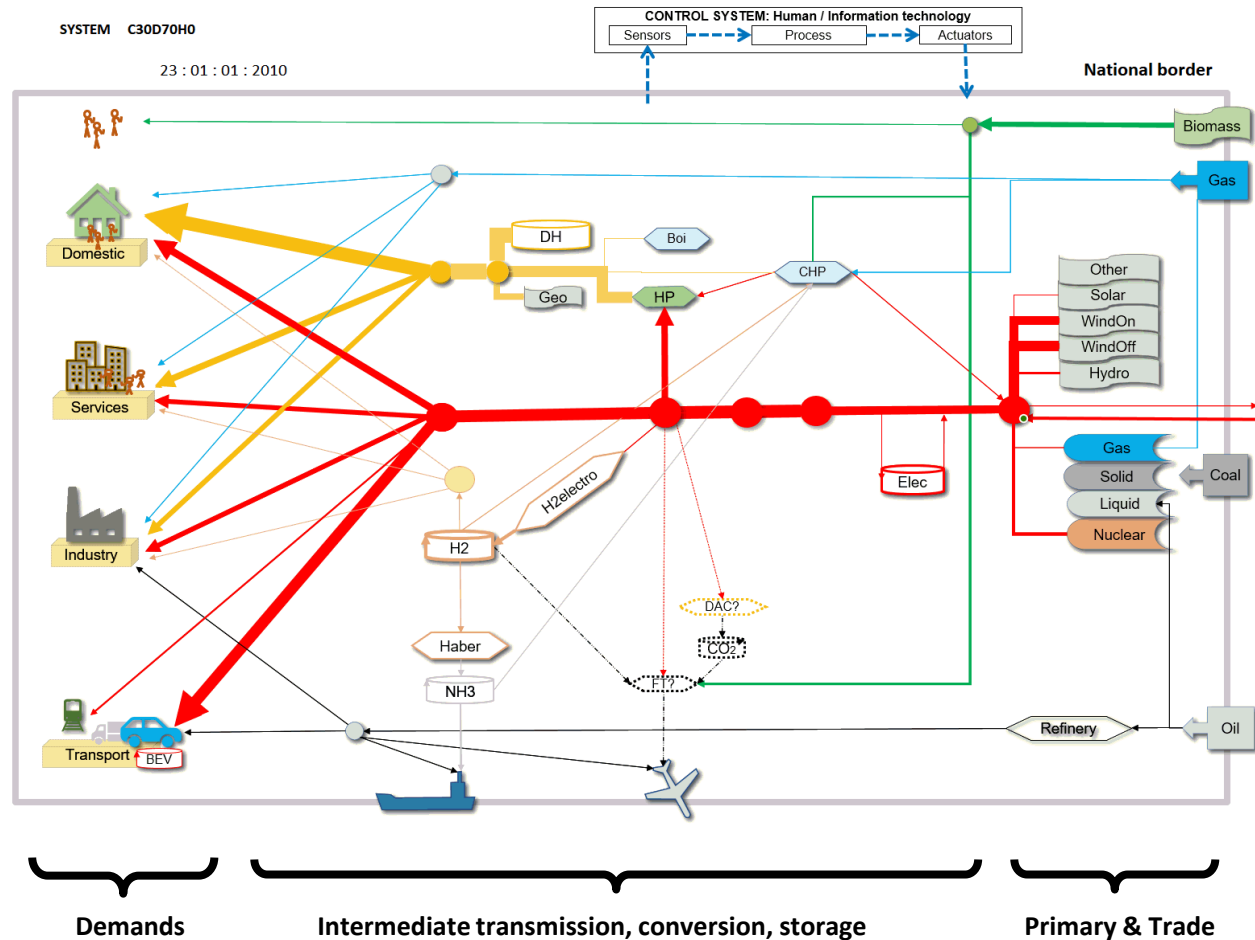
Geographical connection

- Energy demands in different places are different because of local meteorology and local time

- Renewables - wind and solar – different because of meteorology

- Interconnecting different places averages out demands and renewables so less storage is needed

Primary supply example: France and the UK
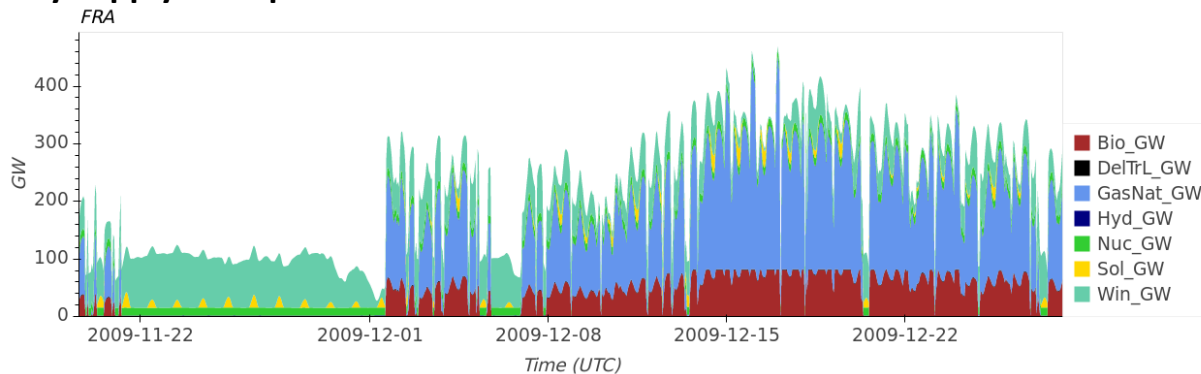
DelTrL: fossil liquid fuels (petrol, diesel etc.) for transport

Bio: generic biomass

Energy Space Time
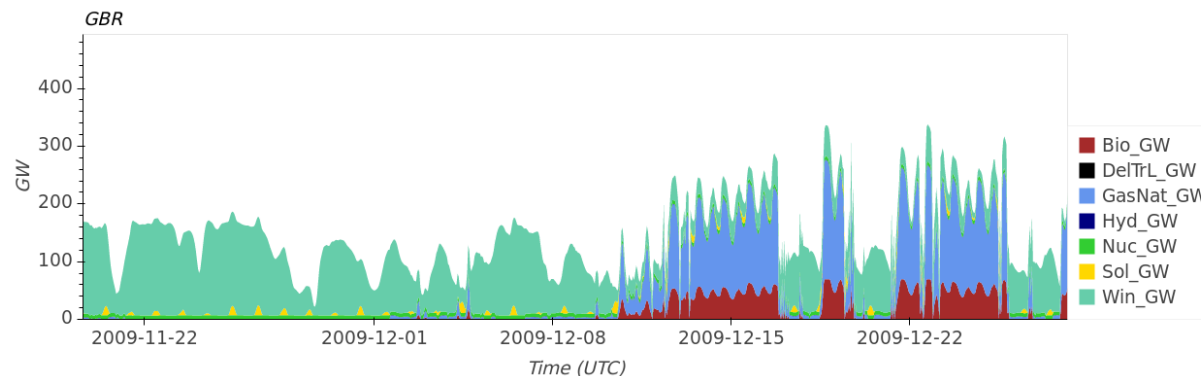
Interconnector trade

ESTIMO concurrently simulates:

Energy systems at each node with different simultaneous:
- Demands because of local weather and time zone differences
- Renewable supply because of local meteorology

Interconnector transmission trade of renewable surpluses and deficits at different nodes, this can greatly reduce storage need.

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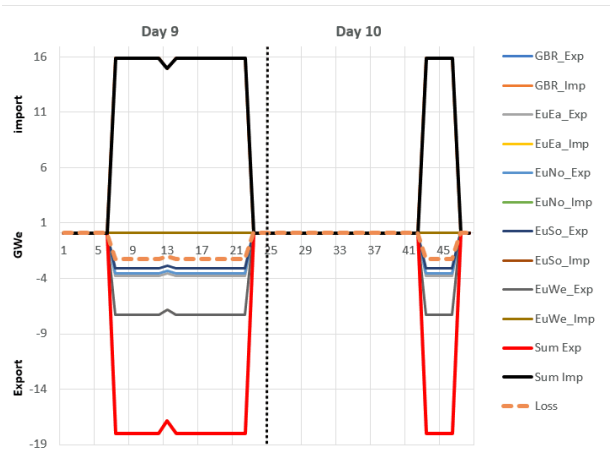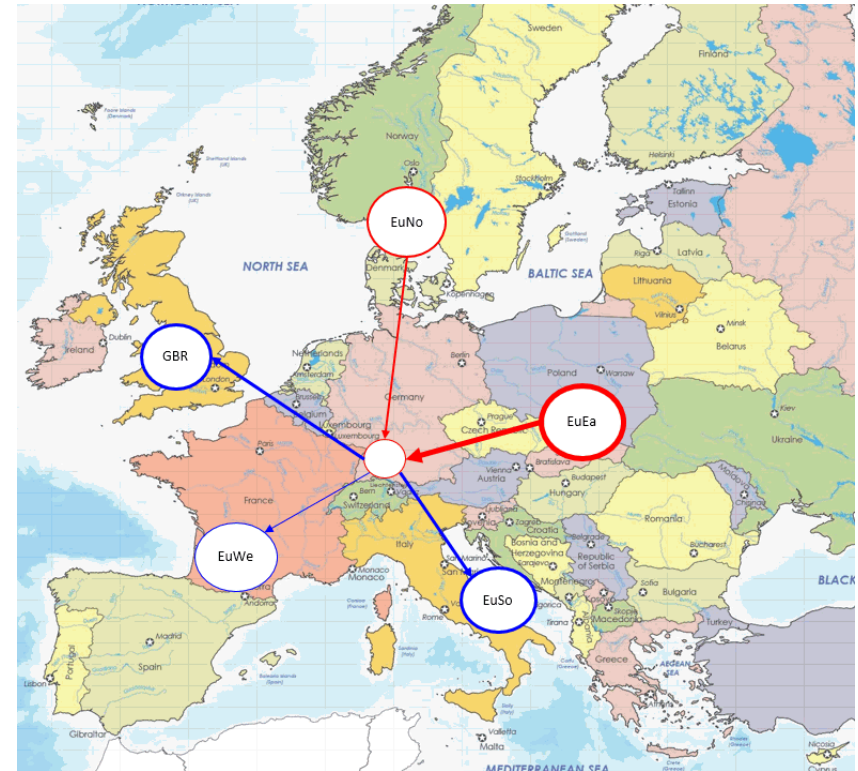
Screening of primary supply

- **Fossil** fuels produce greenhouse gas and are excluded
- **Renewable** solar and wind resources are very large; biomass, hydro, geothermal etc. are limited
- **New nuclear is excluded** beyond committed build for reasons including waste, cost and generic risk
- **Biomass** is restricted to waste and reserved to synthesis **kerosene substitute** for long range aircraft.

	Renewables									Nuclear
	Solar	Wind On	Wind Off	Hydro river	Hydro dam	Biowaste	Biocrop	Tidal dam	Tidal flow	Nuclear
Climate change mitigation	10	10	10	9	7	10	5	8	10	10
Air pollution	10	10	10	10	10	7	5	10	8	9
Ecosystem	9	9	9	4	3	9	3	3	9	8
Land use	5	9	10	8	2	10	0	10	10	1
Visual	5	2	9	5	1	9	3	3	10	5
Chemical	10	10	10	10	10	10	5	10	10	8
Water	10	10	10	3	3	10	5	10	10	8
Nuclear waste/risk	10	10	10	10	10	10	10	10	10	0
Potential impact outside UK	10	10	10	10	10	10	10	10	10	0
Use of global resources	10	10	10	10	10	10	5	10	10	5

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Heat and cool demand with climate change

- **Climate change** was simply modelled by adding +2 oC and +4 oC to historic ambient temperature data.

- **Air conditioning** was assumed limited to the services sector.
- The model indicates that **AC is increased by climate change** as much as space heat is reduced
- **Climate change** will affect the seasonal variation in demand – more in summer, less in winter – and this will alter the optimal capacities of wind and solar.
- **Reversible consumer or DHC heat pumps** can provide heat and cool.

HEAT AND COOL (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo +2 oC	DH-CChHi +4 oC
Space heat	287	287	287	287	287	287	287	303	271	225	169
Ser: Aircon	59	59	59	59	59	59	59	61	56	128	197
All: Space heat	100%	100%	100%	100%	100%	100%	100%	106%	94%	78%	59%
Ser: Aircon	100%	100%	100%	100%	100%	100%	100%	103%	95%	217%	334%

Note: these are heat/cool demands, not electricity
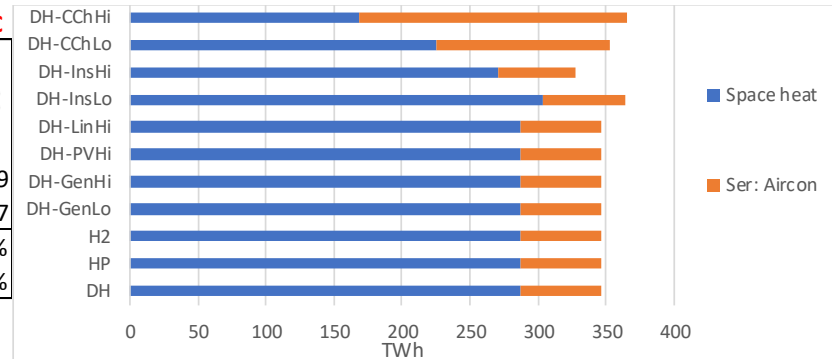
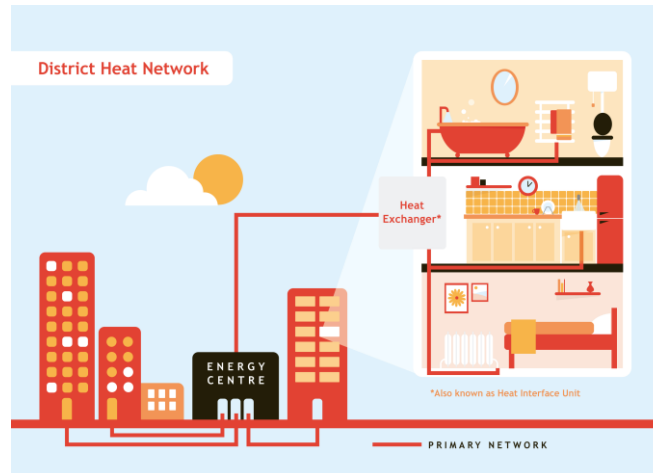# Heating technologies using zero emission electricity

Many resources and technologies can produce heat – solar, geothermal, biomass etc. etc.

Selected: heat pumps (**HP**), district heating (**DH**) and electrolytic hydrogen (**H2**) boilers; all widely used except H2.

Heat pumps (HP)

District heating (DH)

(Electrolytic) H2

Nine zero emission designs explored
- UK Systems

Three core heat shares are explored:

- **District heat: 70%;** consumer heat pumps 30%
- **Consumer heat pumps 70%;** district heat: 30%;
- **Electrolytic hydrogen: 70%**; consumer heat pumps 30%

Then:

- **6 DH designs** with **varying insulation**, generation and interconnector mixes
- **2 variant climate scenarios** with +2 oC and +4 oC ambient temperature increment

Each design has different capacities of:

- Renewables
- Storage
- Interconnector

Architecture acronyms used in this presentation

Core scenarios

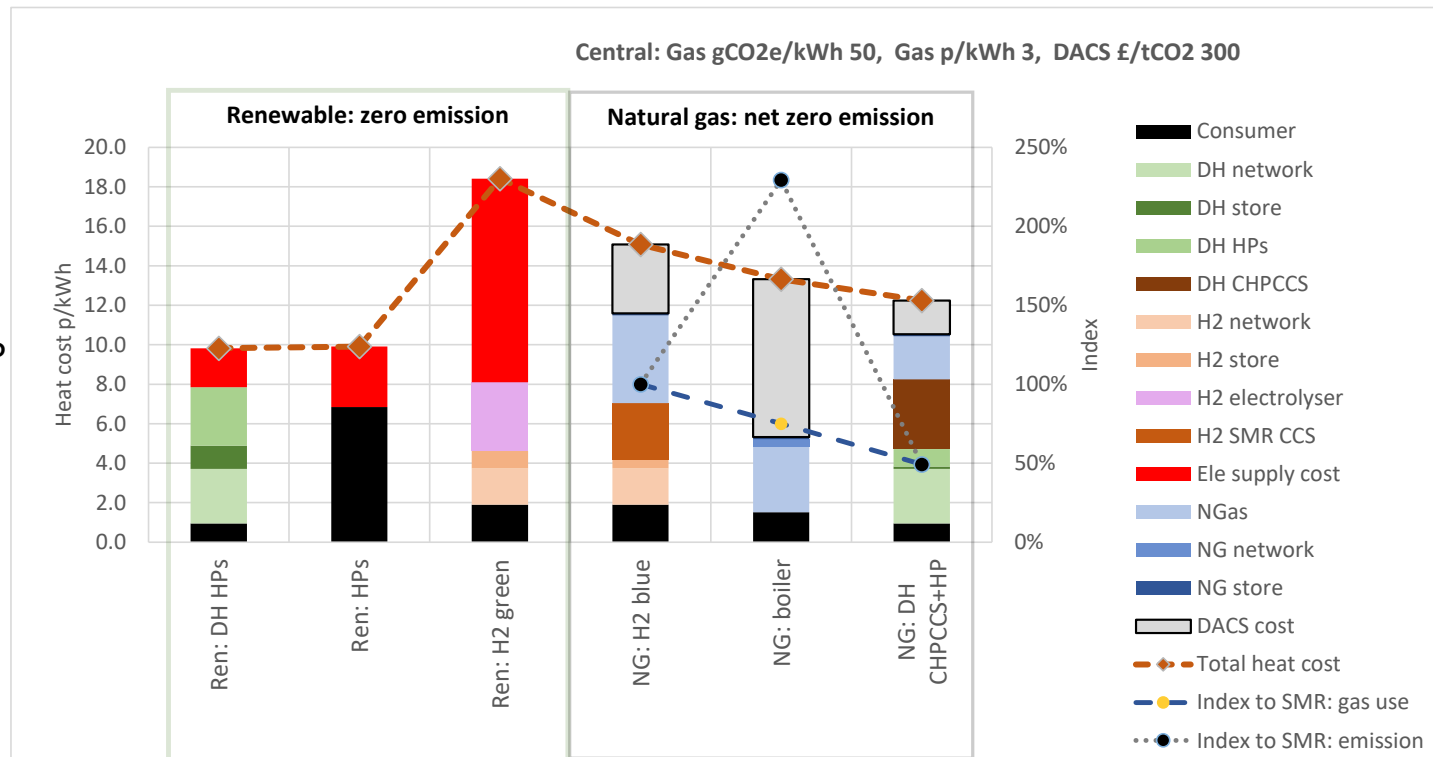|	Variable	DH	HP	H2	DH GenHi	DH GenLo	DH PVLo	DH LinHi	DH InsLo	DH InsHi	DH CChLo	DH CChHi
heat shares	HP share (%)	30	70	30	30	30	30	30	30	30	30	30
	DH share (%)	70	30	0	70	70	70	70	70	70	70	70
	H2 boiler share (%)	0	0	70	0	0	0	0	0	0	0	0
System design	Storage H2 (GWh)	0	0	15737	0	0	0	0	0	0	0	0
	Storage grid (GWh)	2300	3020	2275	1150	4599	2300	1150	2300	2300	2300	2300
	DH storage heat (GWh)	13869	10489	0	7013	27739	13869	7013	13869	13869	13869	13869
	PV capacity (GW)	105	114	173	131	79	79	105	105	105	105	105
	Wind onshore capacity (GW)	52	57	86	52	52	52	52	52	52	52	52
	Wind offshore capacity (GW)	136	148	277	147	126	147	136	136	136	136	136
	Interconnector capacities UK (GW)	25	25	25	25	25	25	53	25	25	25	25
	Building heat loss (%)	-10	-10	-10	-10	-10	-10	-10	-5	-15	-10	-10
Climate	T mean annual change (oC)	0	0	0	0	0	0	0	0	0	+2	+4

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Renewable and natural gas heating costs and emissions

Systems

- **Zero emission:** HP, DH, electrolytic H2 most costly

- **Zero net emission with negative emissions:** 3 natural gas systems: boiler, gas to H2, gas CHP

Natural gas uncertainties:
- future gas prices
- upstream gas emissions
- technologies: DACS, SMRCCS, CHPCCS

Central: Gas gCO2e/kWh 50, Gas p/kWh 3, DACS £/tCO2 300

Legend:
- Consumer
- DH network
- DH store
- DH HPs
- DH CHPCCS
- H2 network
- H2 store
- H2 electrolyser
- H2 SMR CCS
- Ele supply cost
- NGas
- NG network
- NG store
- DACS cost
- Total heat cost
- Index to SMR: gas use
- Index to SMR: emission

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Achieving zero or negative global warming

Renewable wind and solar are low impact reversible technologies, but a range of zero GHG technologies and processes need research into impacts.

Energy system designs use no fossil fuels so no GHG from these, but still:
- Global warming from aviation high altitude water and NOx
- Possible emissions and global warming from iron, cement, agriculture, land use change etc etc

Aviation
- UK waste biomass has about enough carbon to synthesise about 50% of aviation fuel
- Use carbon capture to provide additional carbon for kerosene synthesis with Fischer Tropsch?

Or use carbon capture and sequestration to balance the above?

Negative emissions

High impact biomass competes with food, high impact, uncertainty of productivity with climate change

- **Forests, soil etc.**

- **BECCS** Biomass combusted and CO_2 or char buried/sequestered

DAC Direct air capture of CO_2 from atmosphere – unproven, costly, chemical inputs, water use, but best?

Non GHG impacts of zero GHG systems

Need a comprehensive review of non GHG impacts; life cycle production, operation, decommissioning

Air pollution emission (anthropogenic)
- PM from vehicle (BEVs, trains/trams) tyre/wheel, brake, resuspension. BEVs heavier but regenerative braking.
- Ammonia during production, storage and use in ships
- Industry, agriculture, waste processes
- Biomass – biowaste only, processing and use
- Indoor air pollution - no indoor fossil appliances

Other impacts
- Heat pump fluids – can be zero GWP
- Hydrogen from electrolysis – water, chemicals
- Biowaste processing – methane, etc
- Battery production and disposal
- Solar PV - land use
- Wind onshore – bird strike, land use and visual amenity
- Wind offshore - ?
- Nuclear – risk, waste

Thank you for your attention

The first version of **ES**T**IMO** was coded by Mark Barrett in python and then greatly expanded and made operational by Tiziano Gallo Cassarino. The scenarios in this presentation were mainly prepared by Tiziano.

If you have comments or would like to discuss the work, please contact us:

t.cassarino@ucl.ac.uk

mark.barrett@ucl.ac.uk

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.

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/

Energy **Space** **Time**

Next steps being considered

Include :

- **Aviation fuel** production from biomass, atmospheric carbon, hydrogen and electricity

- **Negative emissions -** Direct Air Capture and Sequestration

- **Detail on efficiency** – insulation, personal comfort systems potential and costs

- **Hydrogen for iron production**

- **Domestic air conditioning** and **district heating and cooling**

- **Building storage**: passive fabric, active thermal, battery

Develop better design procedures including optimisation
Extend modelling to west Asia and north Africa to reduce storage?
Prepare less technical, accessible report for the public

Energy Space Time

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
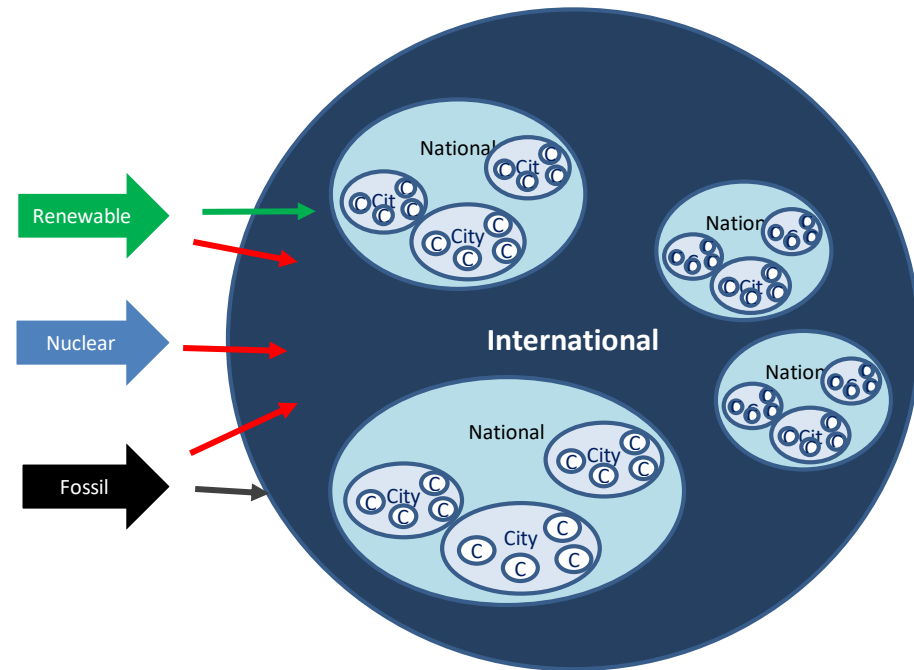- Building to city to national to international

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

Energy sources
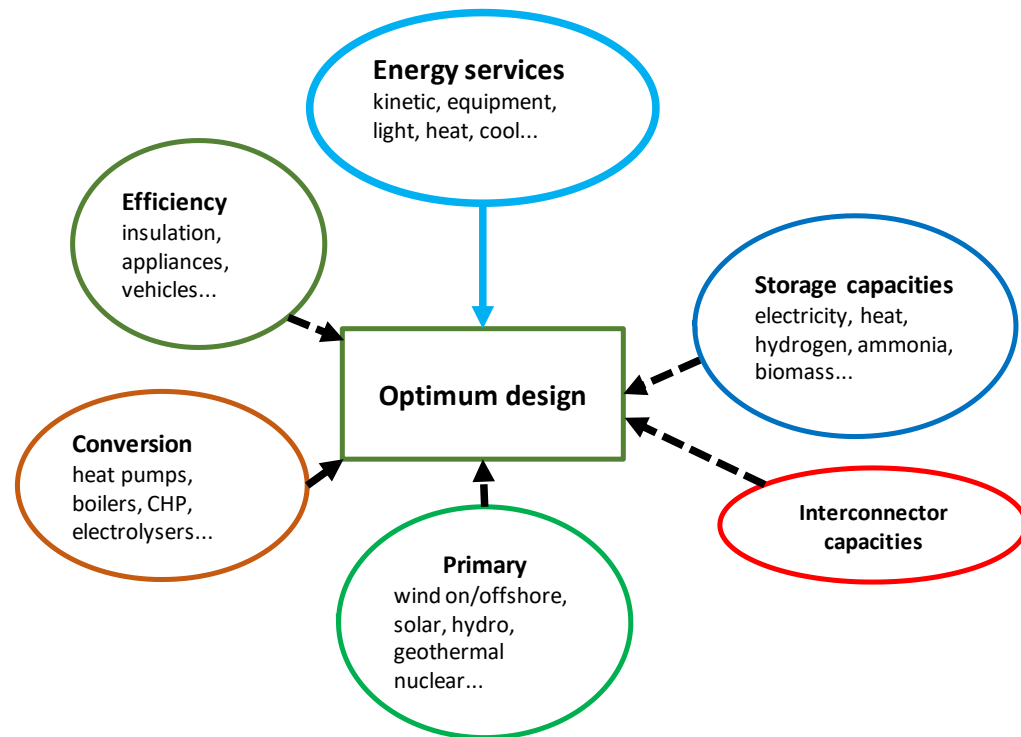- Renewable
- Nuclear
- Fossil

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

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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...

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

Optimum design

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

Interconnector capacities

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

Energy Space Time

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)
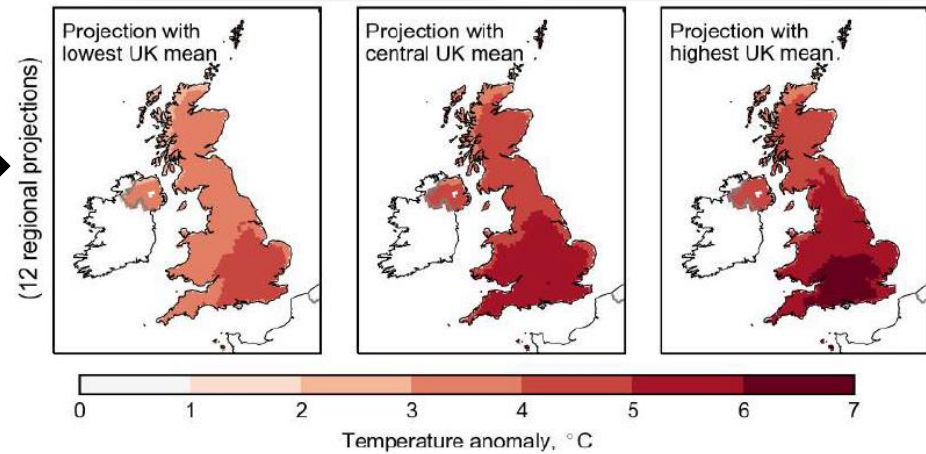
Consequences for comfort, heating and cooling and renewables?

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

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ESTIMO – winter day's service demands and deliveries

**Each end use is simulated hourly, as driven by:**

- **socioeconomic activity** patterns

- **weather** affecting heating, cooling, and lighting loads in buildings and vehicles

# Security and resilience of zero emission systems

- **Hourly demands are met** over 35 years' of historic weather

- No fossil or biomass energy import, and interdependent international electricity trading

- For **resilience to climate change**, reversible heat pumps can provide heat and cool, unlike hydrogen boilers.

- **Widespread electricity failure** can occur due to transmission faults, cyber attack, or environmental conditions.

- **Nuclear capacity** is small so its risk to the system is low.

- **To insure against extreme meteorology causing high demand and low renewables** 'backstop' capacity might be built. For example, 100 GW of natural gas turbines would add about 4% to total system capital cost and 2% to annual system cost. Gas storage would additionally be required.

Energy Space Time

Varying demands and generation - storage, transmission

Energy Space Time
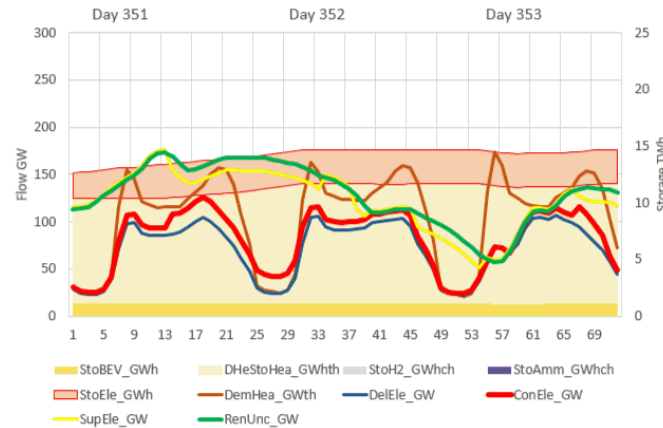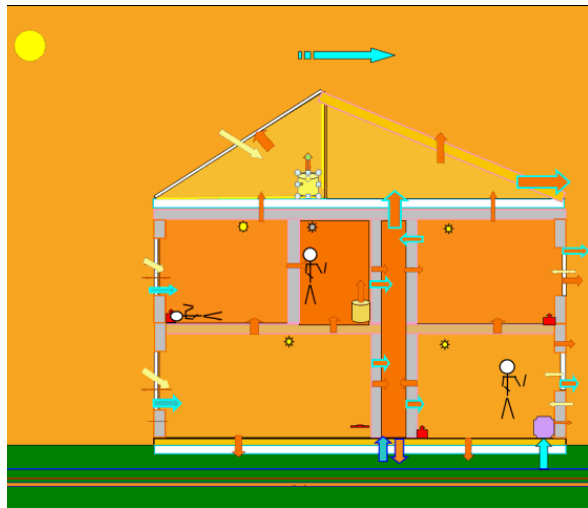
ES**T**IMO– electricity system integration (simulation hourly for one month)

Demand, supply, storage, import/export flows are different in GBR and FRA because of local time difference and weather.

Energy Space Time
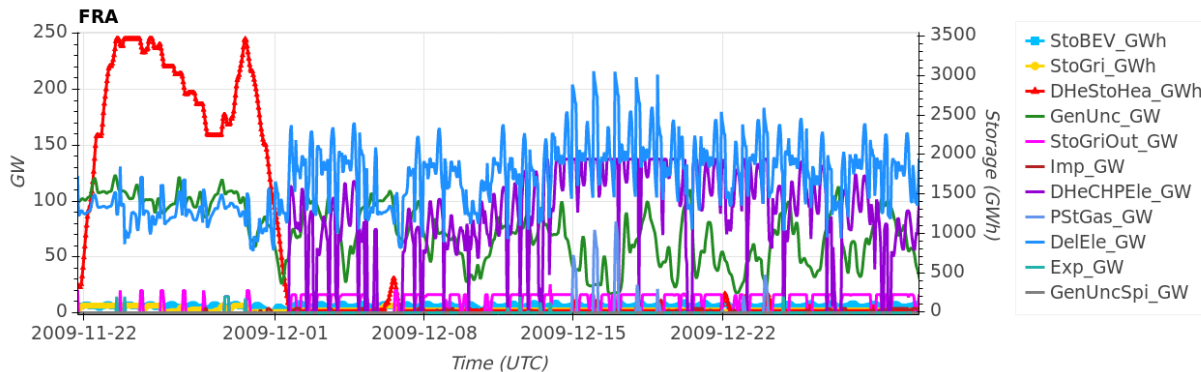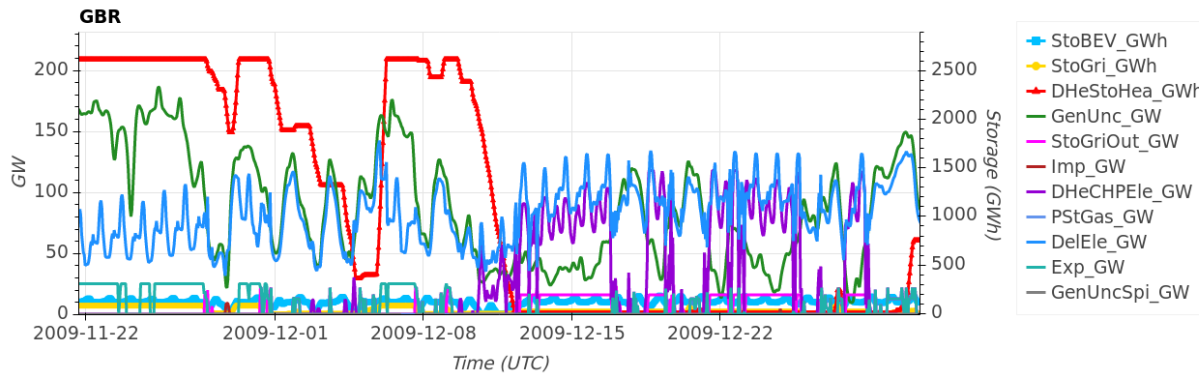
Energy service demands - the starting point

Energy service demand is the minimum energy required to perform a task

Domestic, services, industry, transport sectors

Eight energy services modelled: space heat/cool, other heat, lighting, equipment, cooking, refrigeration, transport.

All service demands are driven by **hourly social use patterns** for each sector and end use

Weather independent demands only vary with use patterns

Weather dependent space heating and cooling depend on:
- **use pattern**
- **ambient temperature** and **solar radiation**
- **internal temperature** of the building or vehicle, **heat loss factor of building/vehicle,** and **heat gains** from people, appliances and solar radiation

ESTIMO – system control algorithm

The **Global Optimal Dispatch (GOD) algorithm** in ESTIMO operates the system so as to minimise fossil fuel use. The algorithm is an engineering proof of concept for a **dynamic energy market**

The basic algorithm comprises three phases:

A. Each node – try to meet demand locally and store any surplus
1. Calculate demands, and uncontrollable (no storage) renewable and inflexible nuclear generation
2. Try to meet all demands with uncontrollable generation, and then stores
3. Try to absorb surplus with stores

B. All nodes: trade surpluses and deficits via transmission
1. From nodes with surplus uncontrollable to nodes with deficits
2. From nodes with surplus storage to nodes with deficits
3. From nodes with surplus uncontrollable to nodes with spare storage capacity

C. Each node– use stored fuel if still remaining demand
1. If remaining electricity demand and spare heat storage, run DH CHP using electrofuel/biofuel/natural gas
2. If remaining heat demand run DH CHP, store surplus electricity if possible
3. If remaining heat demand run DH natural gas boilers
4. If remaining electricity demand run dispatchable electricity only plant using natural gas

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Meteorology

- Decades of MERRA global hourly data at 0.5 degree Lat/Lon resolution available; data collated for Europe 1980-2015

- Data used: **temperature, wind, solar**

- **Temperature and solar** weighted by population distribution for demand and solar PV modelling

- **Wind speeds** at wind farm locations for generation modelling

This data collation and modelling by Dr Ed Sharp
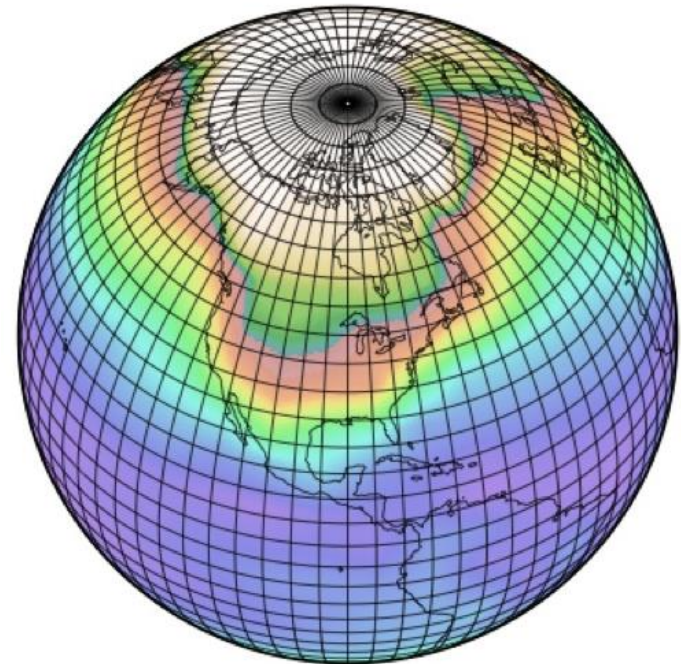
Heat demand variation

Variation driven by:
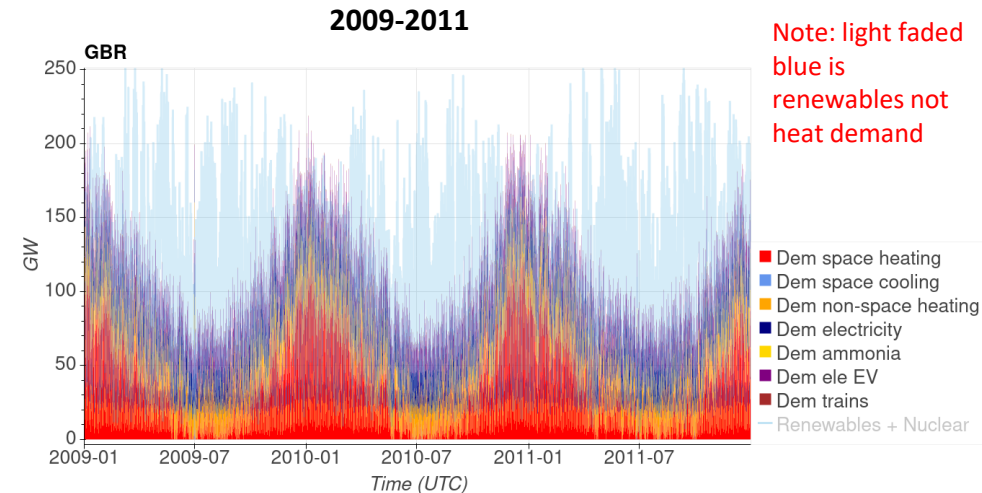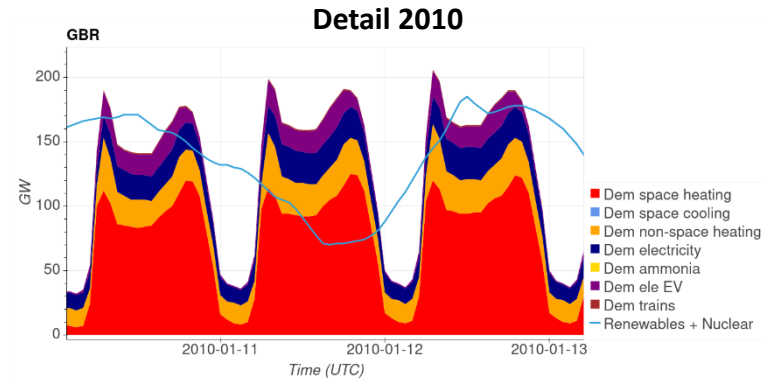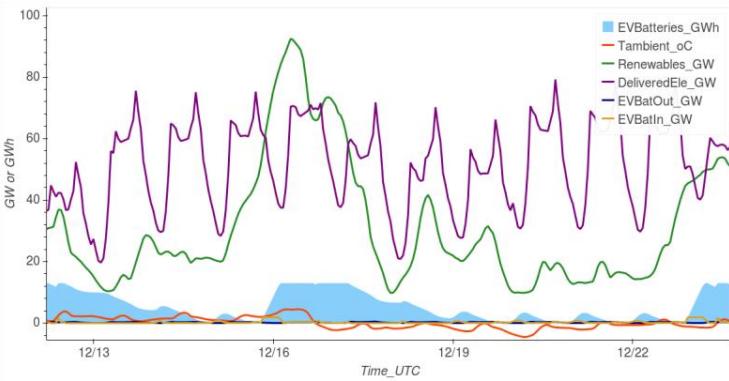- Social activities
- Meteorology

Stationary:
- Buildings
- Industry

Detail 2010

Electric vehicles:
- Buildings on wheels need heating/cooling!

2009-2011

Note: light faded blue is renewables not heat demand

Energy Space Time

Primary supply illustration

Wind and solar have no integral storage
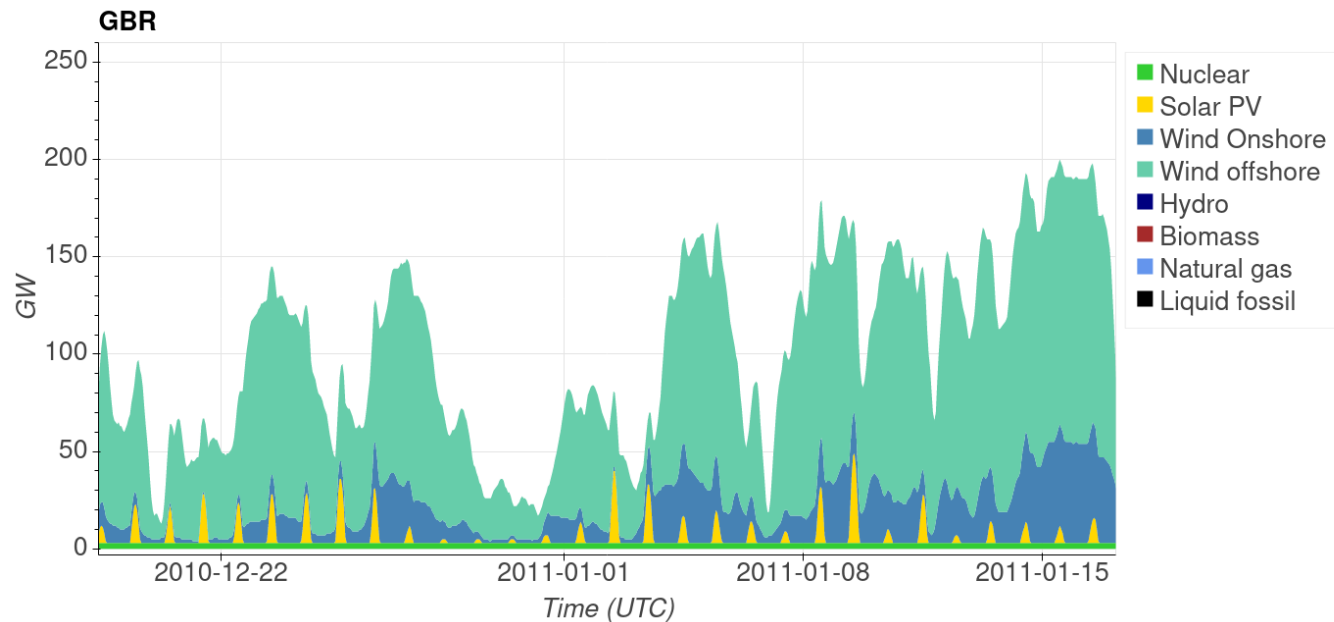
Wind varies, generally more in the winter than summer

Solar: none at night (!) and less in the winter than summer

Hydro: has some storage but varies with precipitation

Nuclear generation is fairly constant except when maintenance or fault

Detail 2010-2011

GBR

Legend:
- Nuclear
- Solar PV
- Wind Onshore
- Wind offshore
- Hydro
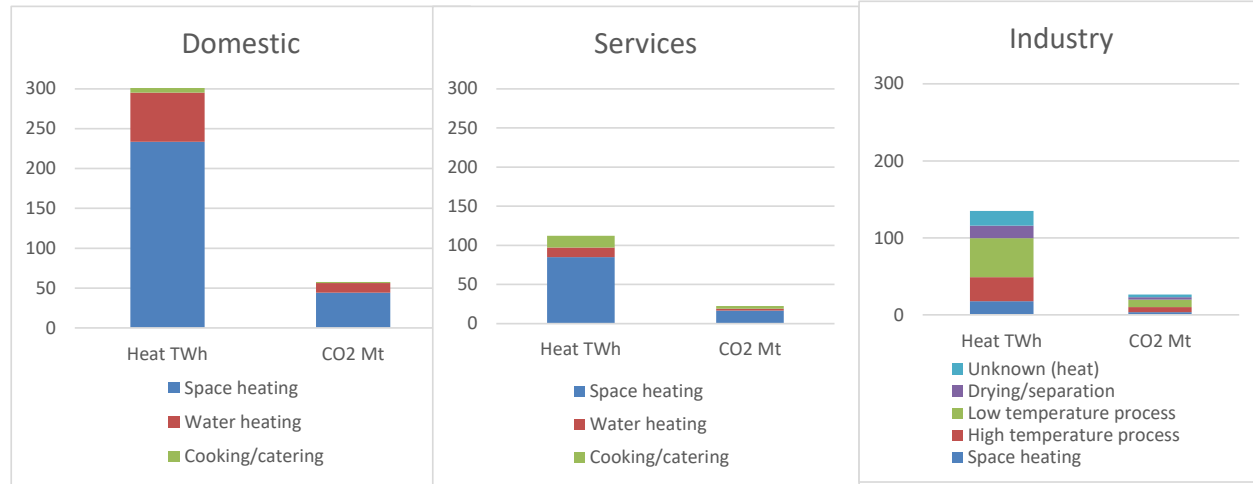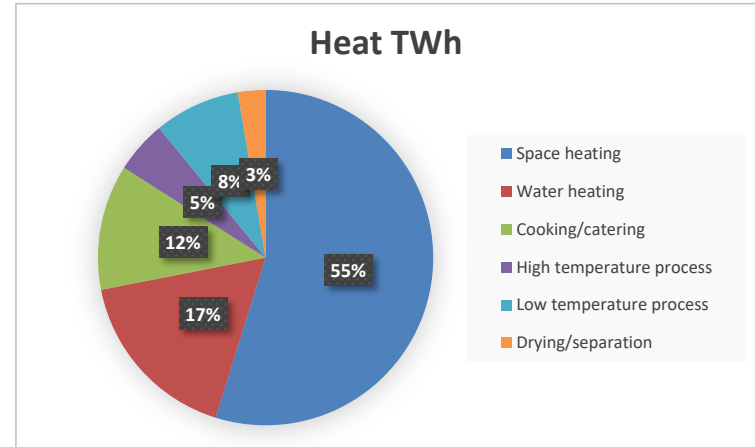- Biomass
- Natural gas
- Liquid fossil

Heat demand and emissions

We can estimate heat **emitted** from boilers etc. But this is not service, as **not all emitted heat is useful**. We want comfort not heated buildings.

Heat accounts for about half of UK energy CO2 emissions.

Future heat demand will be affected by population and economic growth, efficiency (insulation) and climate change.

Personal Comfort Services (heated/cooled furniture etc.) might radically affect space heat/cool demand.

Heat TWh pie chart: Space heating 55%, Water heating 17%, Cooking/catering 12%, High temperature process 5%, Low temperature process 8%, Drying/separation 3%

Domestic — Heat TWh and CO2 Mt (Space heating, Water heating, Cooking/catering)

Services — Heat TWh and CO2 Mt (Space heating, Water heating, Cooking/catering)

Industry — Heat TWh and CO2 Mt (Unknown (heat), Drying/separation, Low temperature process, High temperature process, Space heating)

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Primary resources scope

Resources and technologies currently in widespread use:

- **Renewable** solar and wind resources are very large; biomass, hydro, geothermal etc. are limited

- **New nuclear beyond Hinkley** is excluded for reasons including waste, cost and generic risk

- **Fossil** fuels produce greenhouse gas and are excluded

- There is no proven **kerosene substitute** for long range aircraft, so biomass is reserved for this.

Energy Space Time

Annual: heat and cooling demands

Total heat demand in the core scenarios is 464 TWh, similar to today's demand. This falls to 402 and 346 TWh in the climate change scenarios of +2 oC and +4 oC respectively.

Heat demand sensitivity
Building insulation: 3 TWh/SHL_%
Climate Change: -30 TWh/oC

Electricity demand for cooling
Building insulation: 0.6 TWh/SHL_%
Climate change: 35 TWh/oC

Electricity demand for BEVs
Climate change: -1.5 TWh/oC

HEAT DEMAND (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Res: Water heat	42	42	42	42	42	42	42	42	42	42	42
Res: Space heat	212	212	212	212	212	212	212	224	201	167	126
Ser: Water heat	20	20	20	20	20	20	20	20	20	20	20
Ser: Space heat	53	53	53	53	53	53	53	56	50	41	30
Ind: Process	116	116	116	116	116	116	116	116	116	116	116
Ind: Space heat	22	22	22	22	22	22	22	23	21	17	13
TOTAL	**464**	**464**	**464**	**464**	**464**	**464**	**464**	**480**	**448**	**402**	**346**
Index	100%	100%	100%	100%	100%	100%	100%	103%	97%	87%	75%

| DEMANDS (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Ser: Aircon	59	59	59	59	59	59	59	61	56	128	197
BEV	124	124	124	124	124	124	124	124	124	121	119
Rail	2	2	2	2	2	2	2	2	2	2	2

Electricity consumption

Electricity consumption includes that by:

- **Consumers**, the **intermediate** system (DH, hydrogen electrolysis etc.) and **losses** in stores and transmission

Electric transport is about 25% of total consumption
H2 requires 4x electricity per heat output so about 75% more consumption

ELECTRICITY CONSUMPTION (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Tra: BEVs	124	124	124	124	124	124	124	124	124	121	119
Tra: Rail	5	5	5	5	5	5	5	5	5	5	5
Del: Res	144	174	144	144	144	144	144	145	143	139	136
Del: Ser	70	78	70	70	70	70	70	70	69	68	68
Del: Ind	58	75	58	58	58	58	58	58	58	57	56
DH: HPu	100	43		103	97	99	98	103	96	85	72
H2: Electrolysis	1	1	484	1	1	1	1	1	1	1	1
Ele: Sto loss	3	3	2	5	2	3	4	3	2	2	2
Ele: Tra loss	36	36	62	36	36	36	36	36	36	34	33
Ele: Int Loss	1	1	1	2	1	1	2	1	1	1	1
Total	**541**	**541**	**951**	**549**	**538**	**541**	**542**	**547**	**535**	**515**	**493**
Index	100%	100%	176%	101%	99%	100%	100%	101%	99%	95%	91%
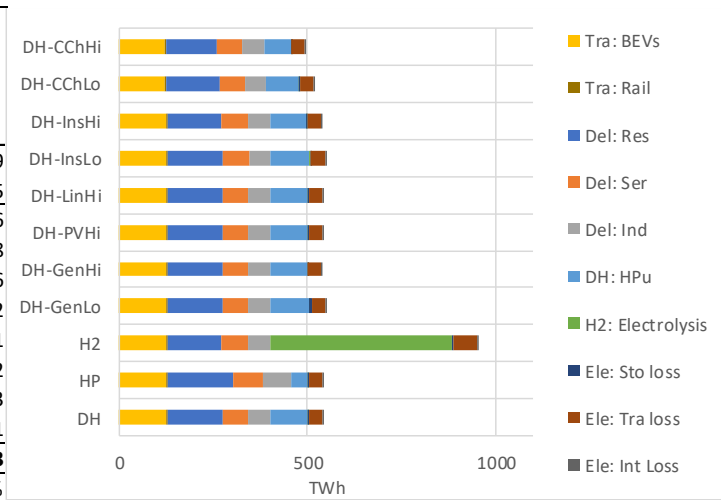
# Primary renewable capacities and annual production

Hydrogen requires about 80% more primary capacity than DH and HP

Generation **spillage** ranges from 40% to 50%.

Decreasing spillage would require more **storage, interconnector** or other capacity such as electroysers.

The UK systems here all **net export** electricity to Europe.

PRIMARY CAPACITIES (GW)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Wind: off	136	148	277	126	147	147	136	136	136	136	136
Wind: on	52	57	86	52	52	52	52	52	52	52	52
Solar PV	105	114	173	79	131	79	105	105	105	105	105
Hydro	2	2	2	2	2	2	2	2	2	2	2
Nuclear	3	3	3	3	3	3	3	3	3	3	3
TOTAL	298	324	541	262	335	283	298	298	298	298	298
	100%	109%	181%	88%	112%	95%	100%	100%	100%	100%	100%
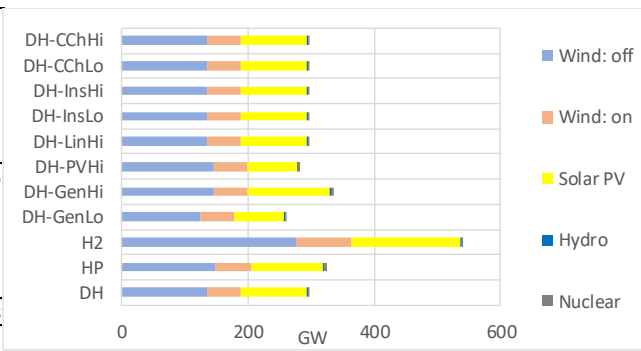
PRIMARY (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Wind: off	676	735	1372	624	728	728	676	676	676	676	676
Wind: on	169	184	279	169	169	169	169	169	169	169	169
Solar PV	124	135	205	93	156	93	124	124	124	124	124
Hydro	2	2	2	2	2	2	2	2	2	2	2
Nuclear	25	25	25	25	25	25	25	25	25	25	25
Biomass				0			1	1			
Gas											
TOTAL	996	1082	1883	913	1079	1017	997	997	996	996	996
TOTAL ELE	996	1082	1883	913	1079	1017	996	996	996	996	996
Index	100%	109%	189%	92%	108%	102%	100%	100%	100%	100%	100%
Net import	-25	-20	-33	-47	-15	-31	-40	-26	-24	-22	-19
Elec spillage	46%	50%	50%	41%	51%	47%	46%	46%	47%	49%	51%

Energy Space Time
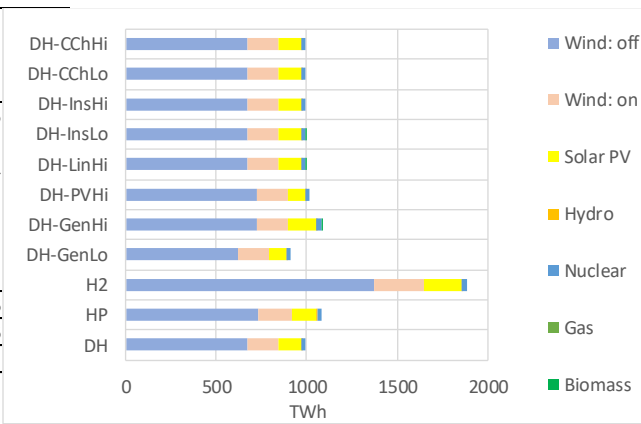
# Hourly flows and storage 2009-2011

a: **Hourly heat storage** level (right axis) and delivered heat from heat pumps, heat storage, CHPs, boilers (left axis).

b: **Hourly hydrogen storage** level (right axis) and delivered hydrogen for ammonia production and for boilers (left axis).

c: **Hourly electricity storage** level (right axis) and system electricity consumption (left axis).

They have similar patterns, but electricity storage is used to also meet non-heat demands

**There are few hours when stores are empty**

Energy Space Time
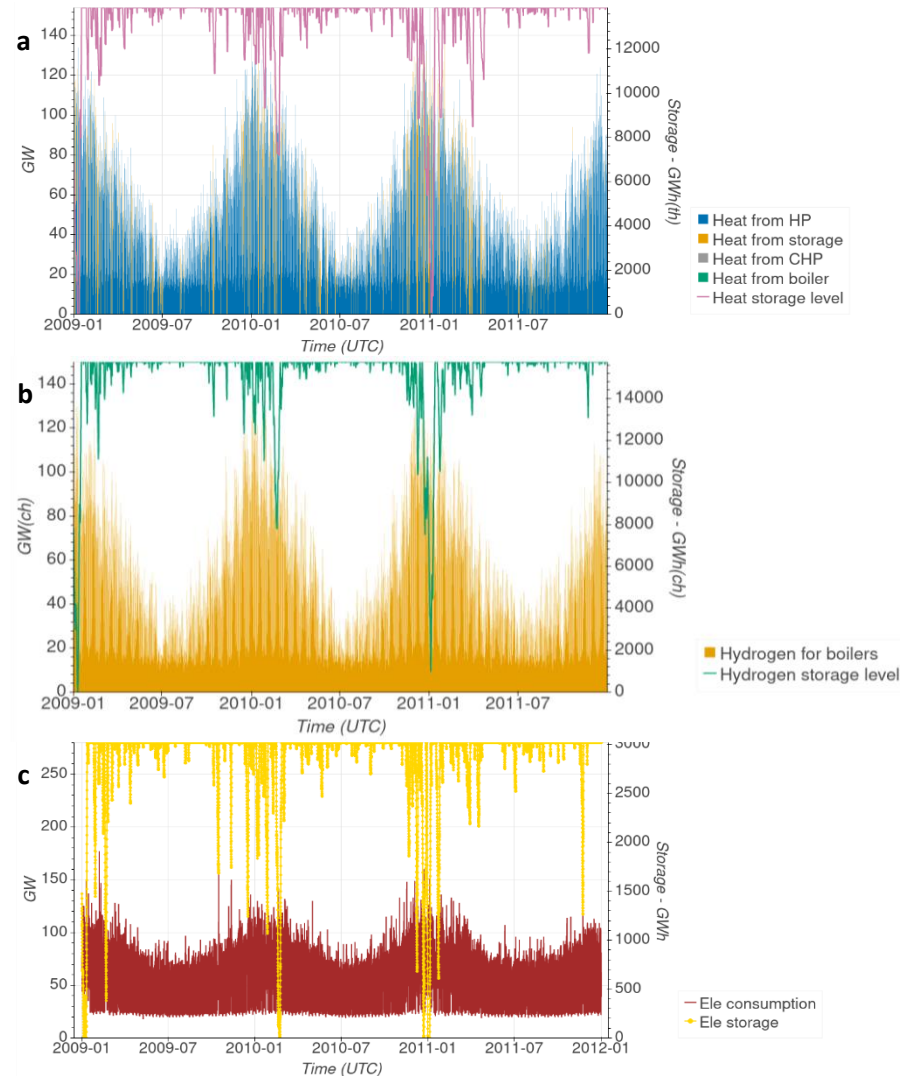
Storage

The amounts and types of storage varies with heat share, renewable capacities and interconnectors.

Increasing one of renewable, storage and interconnector capacity can allow reductions in the other two.

The amount of total storage in the designs varies; **the more renewable capacity the less storage is needed**.
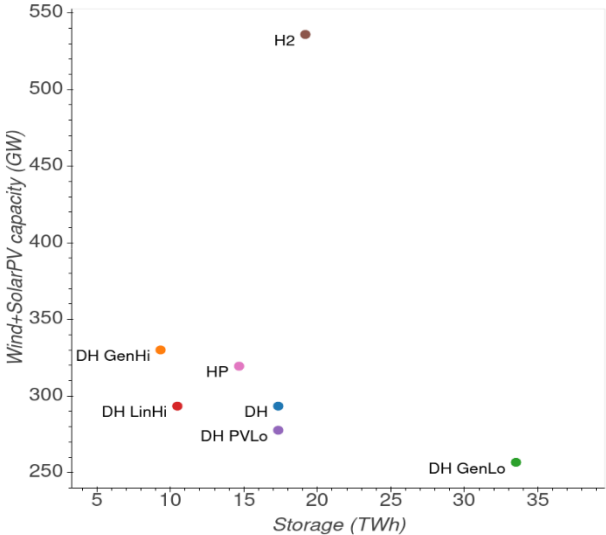
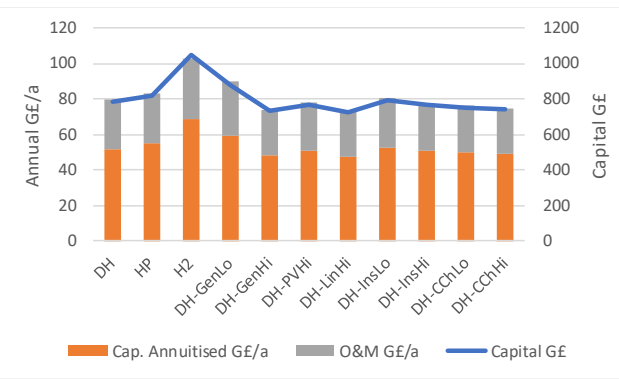| STORAGE (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
BEV batteries	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
DH heat	13.9	10.5		27.7	7.0	13.9	8.2	13.9	13.9	13.9	13.9
Grid store	2.3	3.0	2.3	4.6	1.1	2.3	1.1	2.3	2.3	2.3	2.3
Hydrogen			15.7								
Ammonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**17.3**	**14.7**	**19.2**	**33.5**	**9.3**	**17.3**	**10.5**	**17.3**	**17.3**	**17.3**	**17.3**
	100%	85%	111%	193%	54%	100%	60%	100%	100%	100%	100%
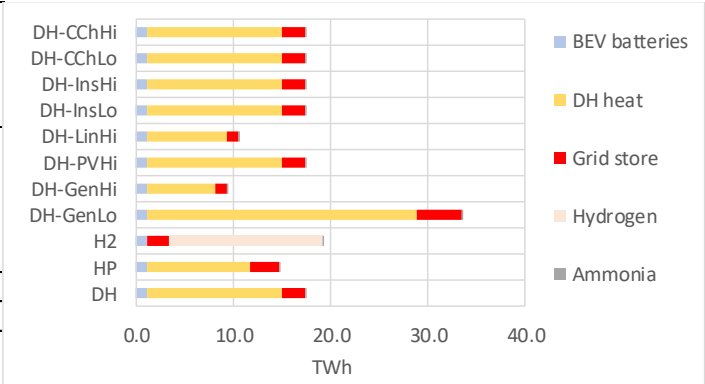
# Costs: whole system and electricity subsystem

Capital costs are annuitized using technology unit costs (£/kW, £/kWh), life (yrs) and interest rate 5%/a.

O&M costs are about 35% of the total annual cost.

SYSTEM COSTS	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Capital G£	783	816	1045	875	733	763	727	791	764	752	738
Cap. Annuitised G£/	52	55	69	60	48	51	48	53	51	50	49
O&M G£/a	28	28	34	30	26	27	26	28	27	26	26
Total G£/a	**73**	**81**	**103**	**84**	**72**	**74**	**73**	**80**	**73**	**73**	**72**
O&M %total G£/a	38%	35%	33%	36%	36%	37%	36%	35%	37%	36%	36%
Capital G£	100%	104%	133%	112%	94%	97%	93%	101%	98%	96%	94%
Cap. Annuitised G£/	100%	106%	133%	114%	92%	97%	92%	101%	97%	96%	94%
O&M G£/a	100%	102%	121%	110%	94%	97%	94%	101%	97%	96%	93%
Total G£/a	**100%**	**111%**	**140%**	**114%**	**98%**	**100%**	**99%**	**109%**	**99%**	**99%**	**98%**

| ELECTRICITY COSTS G£/a	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Consump: ele	520	519	898	524	517	520	518	525	515	496	474
Network	4.86	7.94	8.13	4.36	5.35	4.65	4.86	4.86	4.86	4.86	4.86
Storage	8.9	11.7	8.8	17.8	4.4	8.9	4.4	8.9	8.9	8.9	8.9
Primary generators	26.8	28.9	48.5	24.8	28.8	27.3	26.8	26.8	26.8	26.8	26.8
CHP etc											
Total cost	**40.5**	**48.5**	**65.4**	**46.9**	**38.6**	**40.8**	**36.1**	**40.5**	**40.5**	**40.5**	**40.5**
Gen: p/kWh	2.7	2.7	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Consumed: p/kWh	7.8	9.4	7.3	9.0	7.5	7.9	7.0	7.7	7.9	8.2	8.5
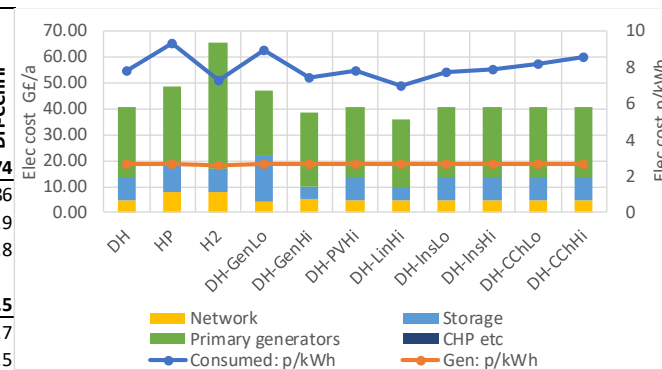
Costs cumulated across the system

The costs may be cumulated from consumer through intermediate to primary system components.

Consumer heat pumps have higher capital costs for the consumer than hydrogen boilers or DH connections.

Upstream of the consumer, the main difference in costs occurs because of the greater primary energy consumption of H2, and therefore costs of primary supply.
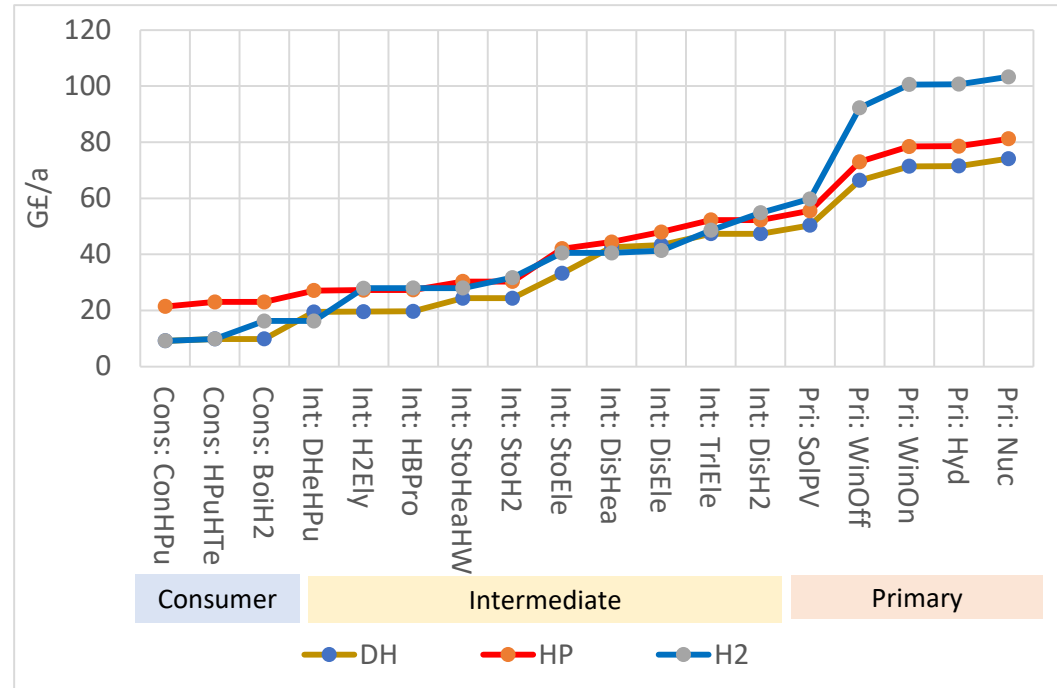
Summary

Nine zero emission energy systems have been designed that:

- **Use current commercial technologies**, except hydrogen boilers and networks

- **Have zero emission:** renewable (excluding biomass) and nuclear electricity

- **Meet demands hour by hour** across 35 years of weather without and with climate change

- **Have net exports** – but nuclear fuels imported

- **Hydrogen heating** has higher primary energy needs and costs than consumer heat pumps or DH.

- **Require major changes** to consumer and public supply systems.

It is not claimed the systems are the best, least cost designs – further work is needed…

Supplementary information follows

On heat scenarios:

- New slides
- More commentary

Illustrative results for other scenarios and countries

Energy Space Time

Consumer heat and cool supply – reversible electric heat pump

Climate change will bring warmer years and more extreme hot and cold spells. Can a single system manage in these conditions?
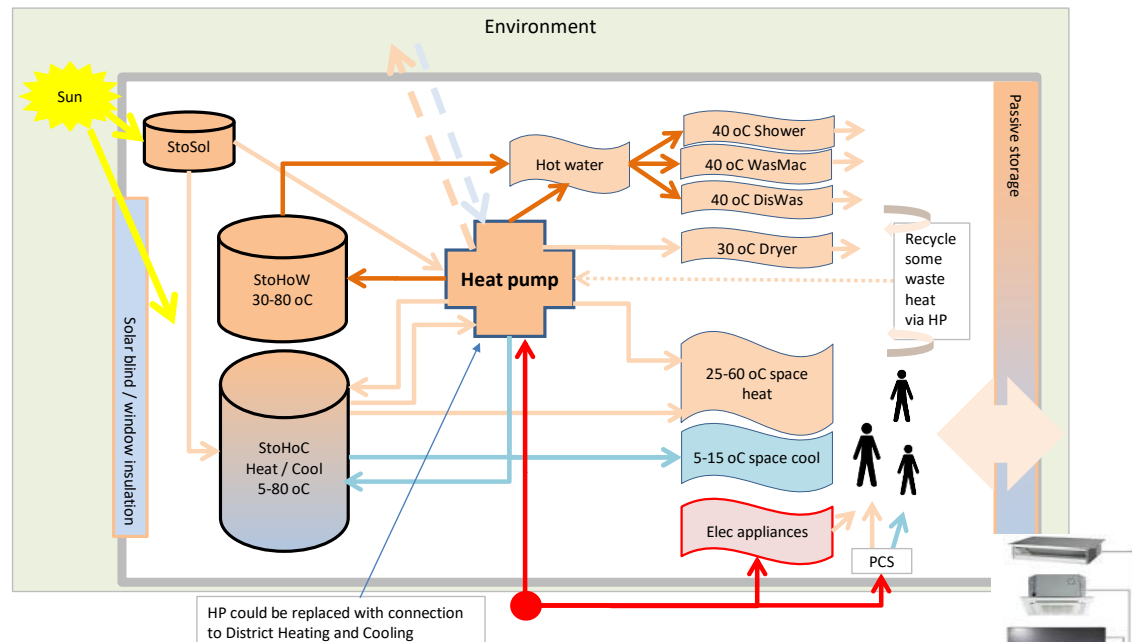
A reversible electric heat pump provides:
- Space heating **and** cooling
- Hot water
- Heat for appliances

Storage:
- Small tank for hot water
- Large heat or cool storage : or perhaps a battery

What is the potential **for personal comfort systems (PCS)**?

Environment

Sun

StoSol

Solar blind / window insulation

StoHoW 30-80 oC

StoHoC Heat / Cool 5-80 oC

Heat pump

Hot water

40 oC Shower
40 oC WasMac
40 oC DisWas

30 oC Dryer

Recycle some waste heat via HP

25-60 oC space heat

5-15 oC space cool

Elec appliances

PCS

Passive storage

HP could be replaced with connection to District Heating and Cooling

Split reversible air conditioner/heater heat pump?
- Flexible, multi-function, spatiotemporal control.
- Hot water and heat storage in some systems.
- Millions installed

Energy Space Time

Consumer heat and cool supply simulation – peak design conditions

Human health requires air temperature around 16-26 °C. Climate change will mean UK summers 1-5 °C hotter, but still cold spells.

A reversible heat pump can provide comfort in extreme cold and hot conditions

1. How will demand conditions be correlated with renewable supply?

2. What impact will millions of such systems have on electricity and other supply?

3. How can heat and cool storage be used for national system management?

Simulation with separate CoHeCo model =>

Energy Space Time
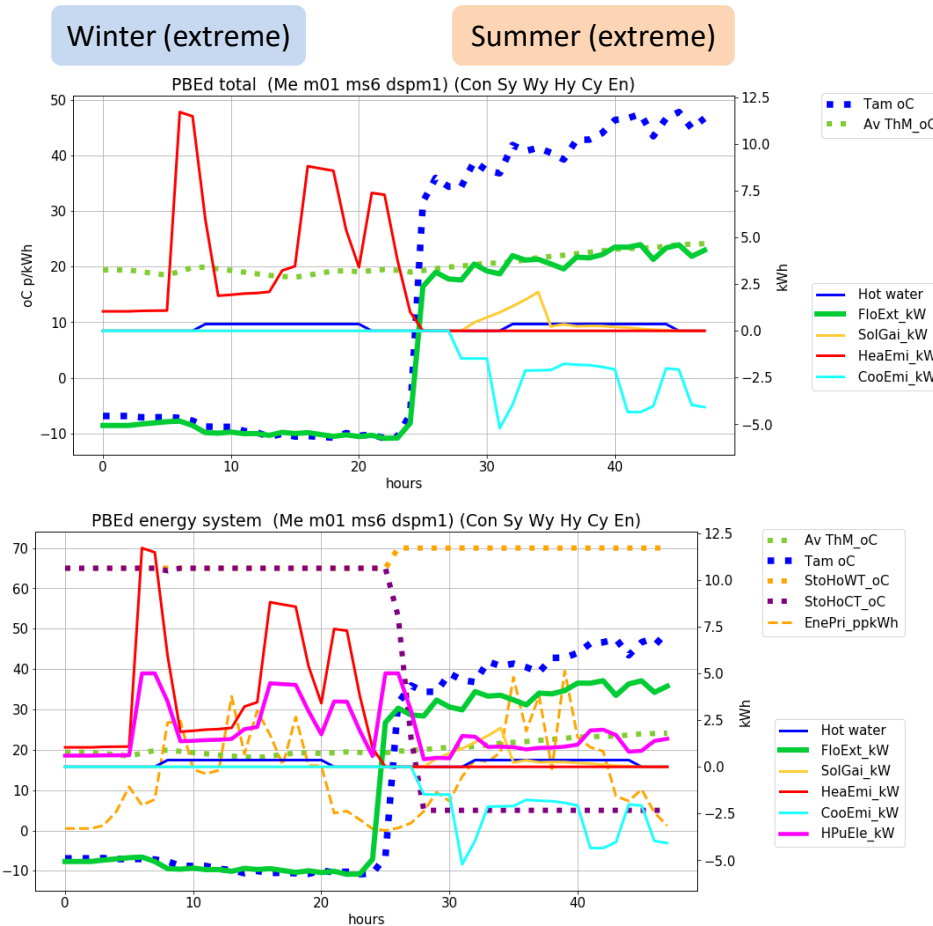
District heat – a flexible, multi heat source system

District heating has a major system balancing role using:
- low cost heat **storage**
- **multiple heat sources** (heat pumps, CHP, boilers)

These may be adjusted to conditions of renewable surplus or deficit.

Surplus: run HPs

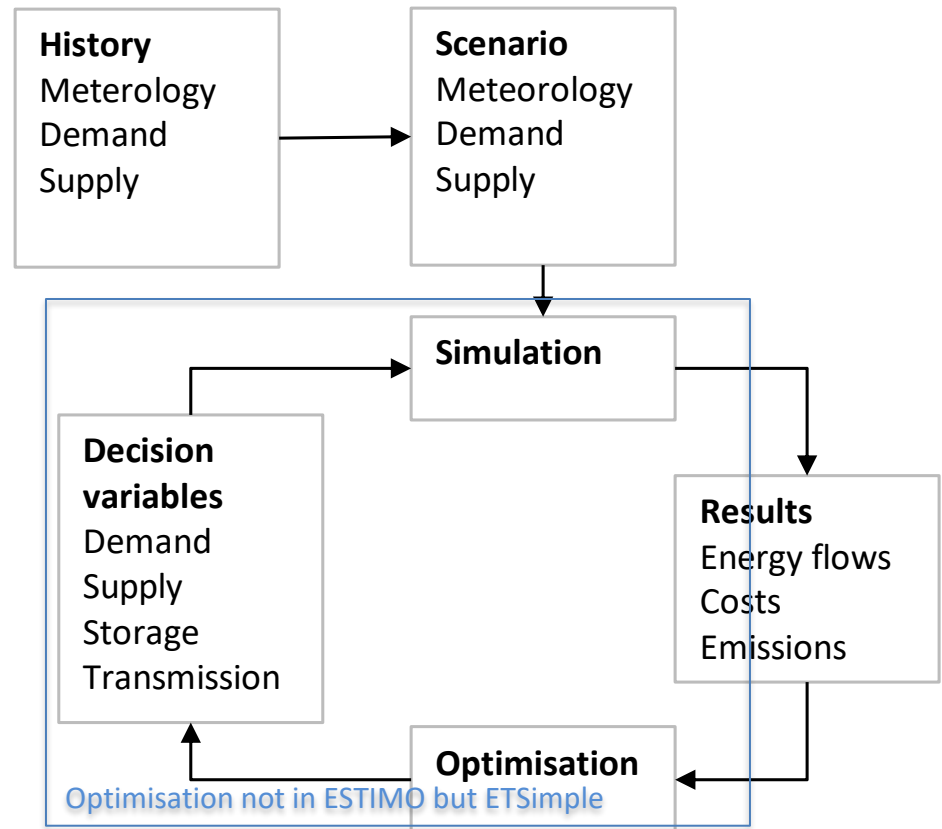**Deficit**: use storage, run CHP, boilers

District cooling is also an option
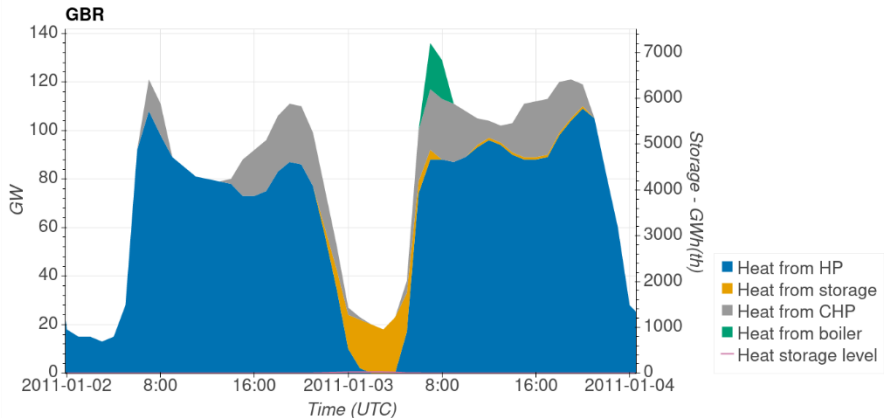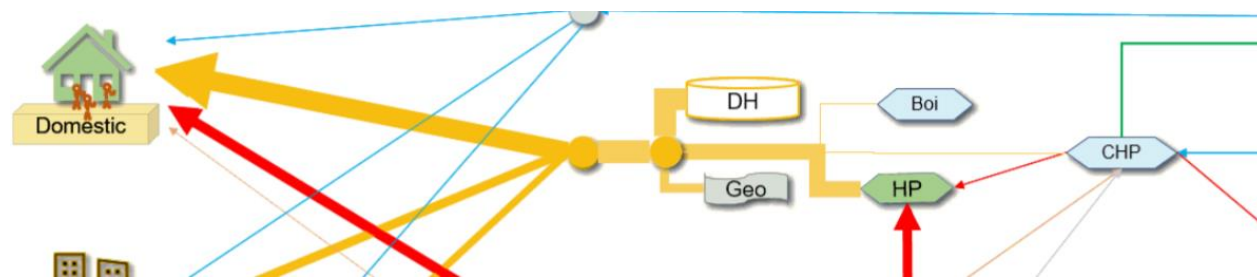
ESTIMO – Energy Space Time Integrated Model Optimiser

ESTIMO is a national/international scale dynamic model.

For each hour and each European region, ESTIMO concurrently simulates :

- **Service demands** driven by social activity and weather
- **Renewable and nuclear**, zero emission supplies
- **Intermediate** energy conversion
- **Storage** flows and levels
- **Trade** between GBR and European regions

History
Meterology
Demand
Supply

Scenario
Meteorology
Demand
Supply

Simulation

Decision variables
Demand
Supply
Storage
Transmission

Results
Energy flows
Costs
Emissions

Optimisation

Optimisation not in ESTIMO but ETSimple

ESTIMO – interconnector network topology

How to achieve the best balance between computability and accuracy?
Initially a star formation is chosen: a year's hourly simulation takes ~5 minutes per node on a laptop.

Mesh
Realistic
Requires hourly optimisation
Computation increases non-linearly with N of nodes

Star
Simplification, unrealistic but engineering feasible
Computation increases linearly with N of nodes
Can inform real time dynamic markets

Energy Space Time
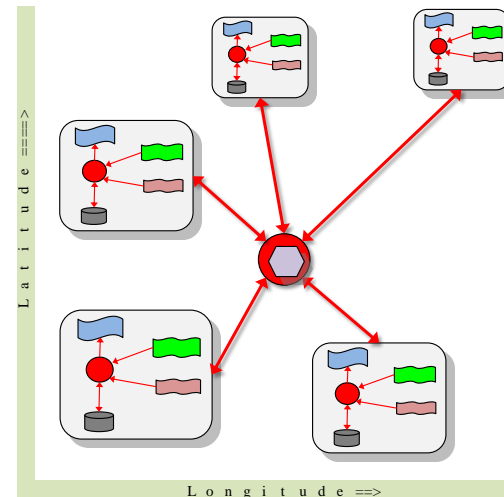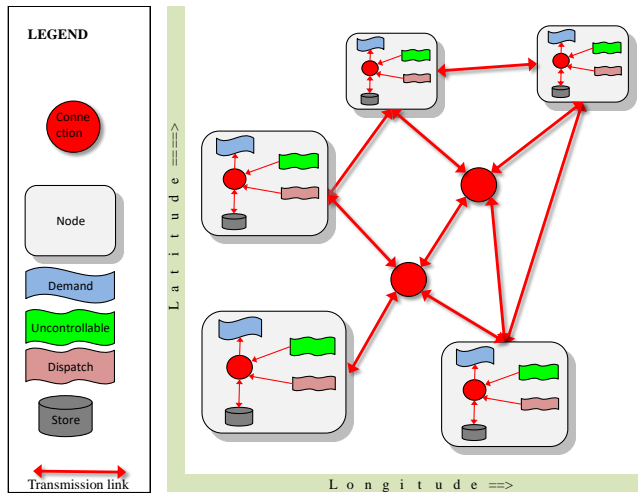
ESTIMO – energy service demands

Energy service demands may be defined as the minimum energy required to perform a task; however this definition is generally difficult to implement, so service demand is often equated with the energy input to a device such as a refrigerator, or the energy output from a device such as a heat pump. It is especially hard to define a service demand for comfort provision (space heating and cooling) as it depends so much on clothing levels, temperatures and the spatiotemporal control of systems. Energy service demands are divided by the last conversion efficiency to give the energy input (delivered) to devices.

Four sectors are modelled (domestic, services, industry, transport) and eight energy services are included: space heat and cool, lighting, other heat (water, process), equipment, cooking, refrigeration, transport. Service demands are driven by different normalised hourly use patterns (U(h)) for each sector and end use including building occupancy and transport.

Weather independent demands D_i are modelled simply: $D_i(h) = U(h)$ (Average annual demand) Watts

Weather dependent demands D_w are primarily driven by ambient temperature (T_a oC) and solar radiation (Sol W/m2). 35 years of hourly MERRA data by 0.5 oLat/Lon have been assembled and weighted by population to derive weather data for each European country. Space heat/cool demands are dependent on the occupied internal temperature (T_i oC), specific heat loss (SHL) of the building or vehicle, and incidental gains (I) from people, appliances and solar radiation: $D_w(h) = U(h)$ [SHL (T_i-T_a) – I] Watts. This enables the exploration of varying internal temperatures and efficiency (insulation etc.), as well as past and future climates.

If $D_w > 0$ then there is a space heat load, if $D_w < 0$ a cooling load. Currently it is assumed that air conditioning is confined to the services sector. ESTIMO does not yet account for the thermal mass of buildings and the use of this to store heat or cool for limited periods.

Energy Space Time

Heat demand and emissions

The ECUK (2019) gives estimates of energy delivered by end use. These deliveries may be multiplied by nominal efficiencies for each fuel for converting energy into underlined emitted heat. Emitted heat can be used as a proxy for heat services, but services will be less than emitted due to inefficiencies such as heating unoccupied houses. Total heat emitted (2019) is about 492 TWh. This excludes heat in washing appliances.

Energy deliveries may be multiplied by emission factors to estimate CO_2 emission: heat accounts for about half of energy emissions; this fraction is growing rapidly as electricity decarbonises, but not gas.

We have assumed future heat demand to be similar to today but with improved efficiency (insulation) reducing space heating more than increases due to population and economic growth.

ECUK 2019		Gas	Oil	Solid	Elec	Heat	BioWas					
Emission factors gCO2/kWh		187	275	348	173	293	110					
Emitted heat TWh		Gas	Oil	Solid fuel	Electricity	Heat	Bio&waste	Total	% UK heat	% UK Del Energy	CO2 Mt	% UK CO2
Domestic	Space heating	175	17	3	18	3	18	233	47%	20%	44	23%
	Water heating	52	4	0	5	0	1	62	13%	5%	12	6%
	Cooking/catering	4	0	0	4	0	0	8	2%	1%	1	1%
	Clothes/dishwasher							0	0%	0%	0	0%
	Space + water	227	20	4	22	3	19	295	60%	25%	56	29%
Services	Space heating	53	13	0	9	3	7	85	17%	7%	17	9%
	Water heating	7	2	0	2	0	1	12	2%	1%	2	1%
	Cooking/catering	3	5	0	7	0	0	15	3%	1%	3	2%
	Space + water	60	15	0	11	3	8	97	20%	8%	19	10%
Industry	Space heating	9	1	1	7	0	0	18	4%	2%	3	2%
	High temperature process	16	1	5	9	0	0	31	6%	3%	7	3%
	Low temperature process	31	2	2	16	0	0	51	10%	4%	10	5%
	Drying/separation	9	1	1	6	0	0	16	3%	1%	3	2%
	Unknown (heat)	0	0	0	0	8	11	19	4%	2%	4	2%
	Space + LT process	48	4	4	29	8	11	104	21%	9%	13	7%
STATIONARY	Space heating	237	31	4	34	6	24	336	68%	29%	65	34%
	Water heating	59	6	0	6	0	2	74	15%	6%	14	7%
	Low temperature process	31	2	2	16	0	0	51	10%	4%	10	5%
	High temperature process	16	1	5	9	0	0	31	6%	3%	7	3%
	Heat	343	41	11	65	6	26	492	100%	42%	95	50%

Resources and technology scope

The overall aim is net zero GHG emission. Fossil fuels, even with CCS, produce GHG and so these are excluded. Negative emissions can be achieved with processes such as DACS, BECCS and afforestation. However, these are either unproven in technical, commercial and environmental terms, or constrained. Furthermore, carbon from such sources will be required for producing synthetic kerosene as there is no current substitute fuel for long range aircraft. So negative emissions are not included in the modelling here.

Primary sources with near zero operational emissions include most renewables and nuclear. The embedded GHG incurred in technology construction and installation are assumed to reduce to zero with industrial decarbonisation. Biomass is assumed to be constrained and generally reserved for carbon based fuels such as kerosene. Hydro is also constrained. It is assumed the resources of wind and solar are sufficient for any feasible demand.

There are many resources and technologies and combinations thereof for producing heat services. There are innumerable types and combinations of technologies; these commonly proposed options are currently excluded:

Vector	Comment
Biomass	Reserved for aviation
Geothermal	Constrained
Reversible heat pumps	Cooling model incomplete
Consumer ground/water sourced heat pump	Cost
Solar heating	Cost
Hybrid hydrogen/heat pump	Cost?

Energy Space Time

District heat – low storage period

Scenario: DH core

Illustration of dynamically changing heat supply mix.
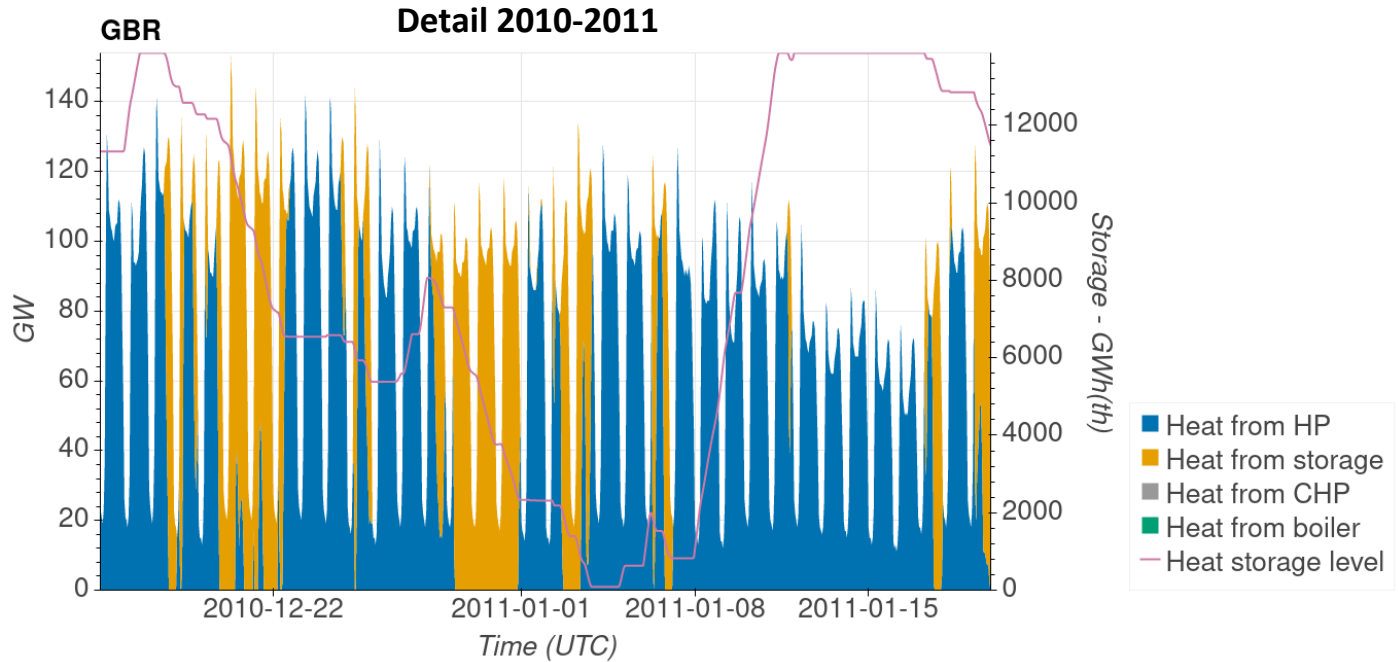
District heat

Scenario: DH core

District heating (and cooling) potentially has a major system balancing role to play in managing variable uncontrollable supplies by using low cost heat storage, and multiple heat sources (heat pumps, CHP, boilers) which can dynamically adjust to conditions of renewable surplus or deficit.

Surplus: run HPs

Deficit: use storage, run CHP, boilers

Detail 2011

2009-2011

Energy Space Time
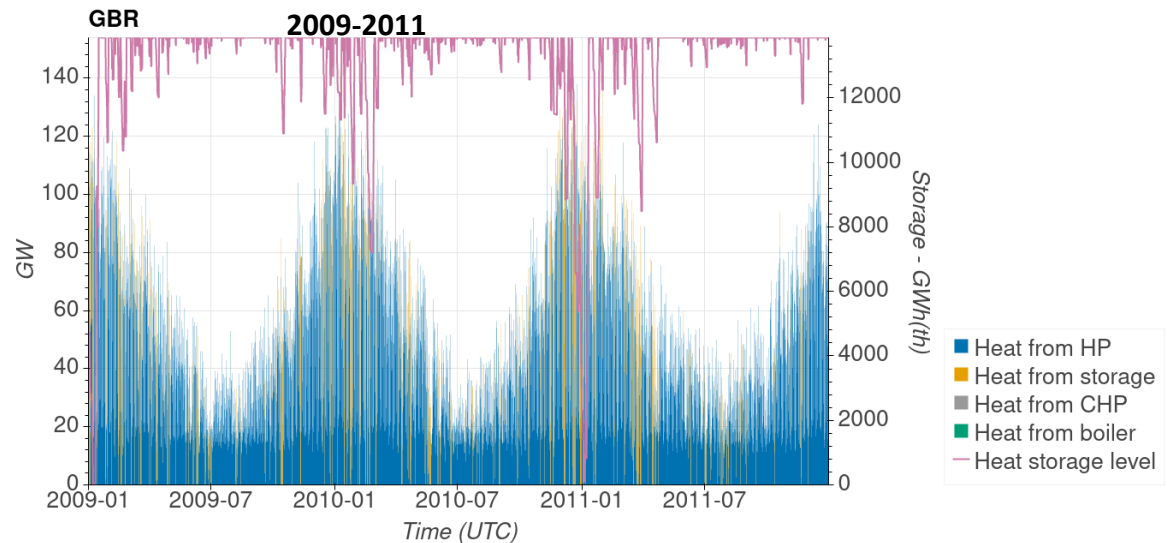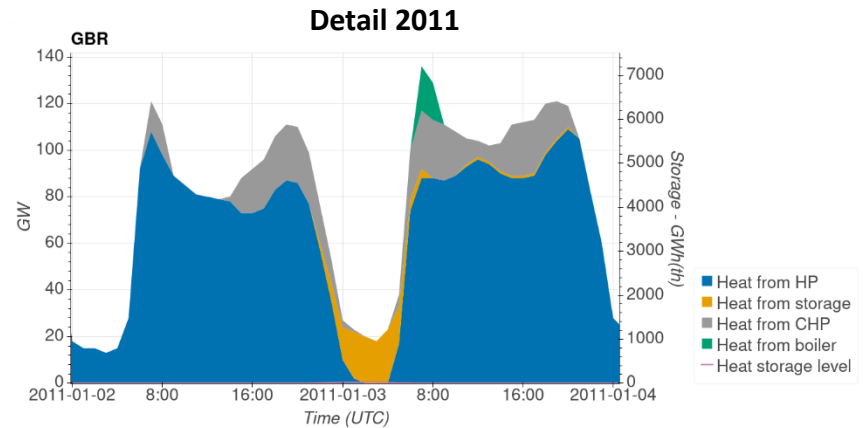
District heat – storage in scenarios

Top: DH GenHi scenario with 33% more wind and solar capacities, and 50% less storage size than the core

Middle: core DH architecture.

Bottom: DH GenLo scenario with 33% less wind and solar capacity, and 100% more storage than the core DH architecture.
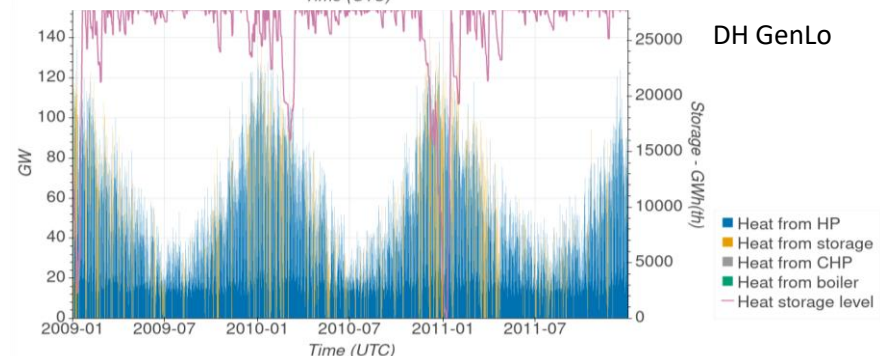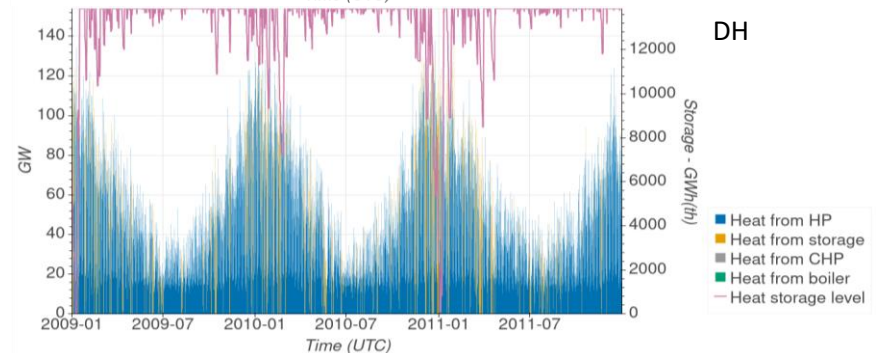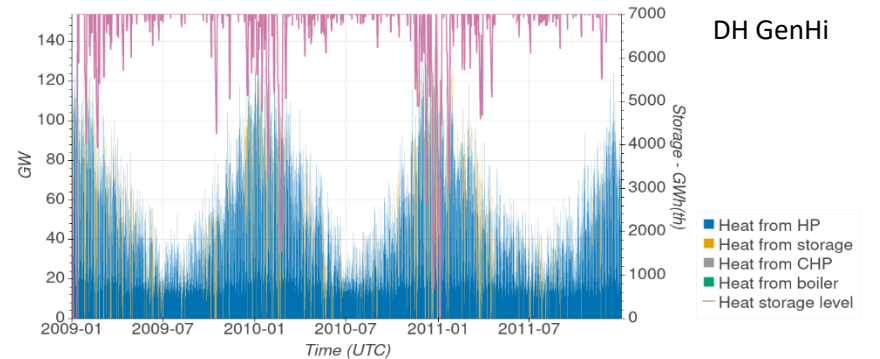
Storage over 35 years

Hourly simulation of the storage output over 35 years (1980-2015) of historic meteorology for the three core scenarios

a: Frequency distribution of the hourly output from the hydrogen storage (H2 core scenario), the heat storage (DH core scenario), and the electricity storage (HP core scenario).
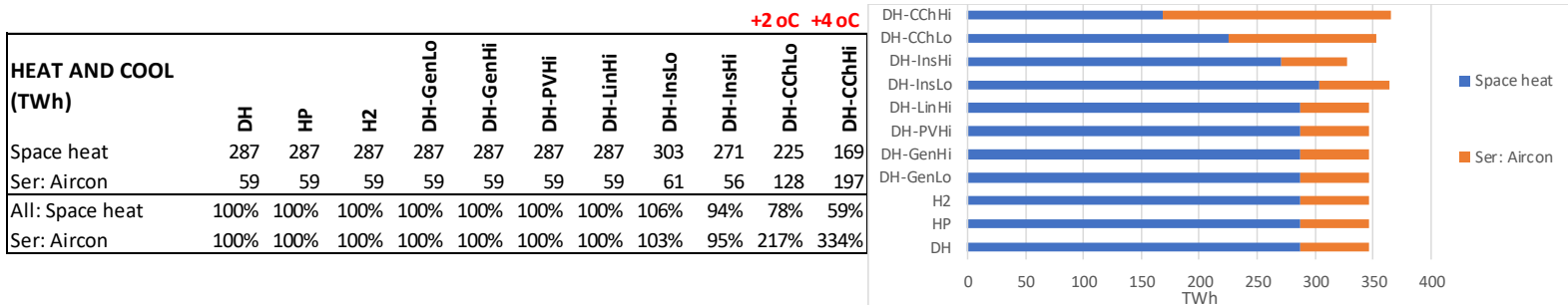
b: Annual distribution of the hourly heat storage output in the DH scenario.
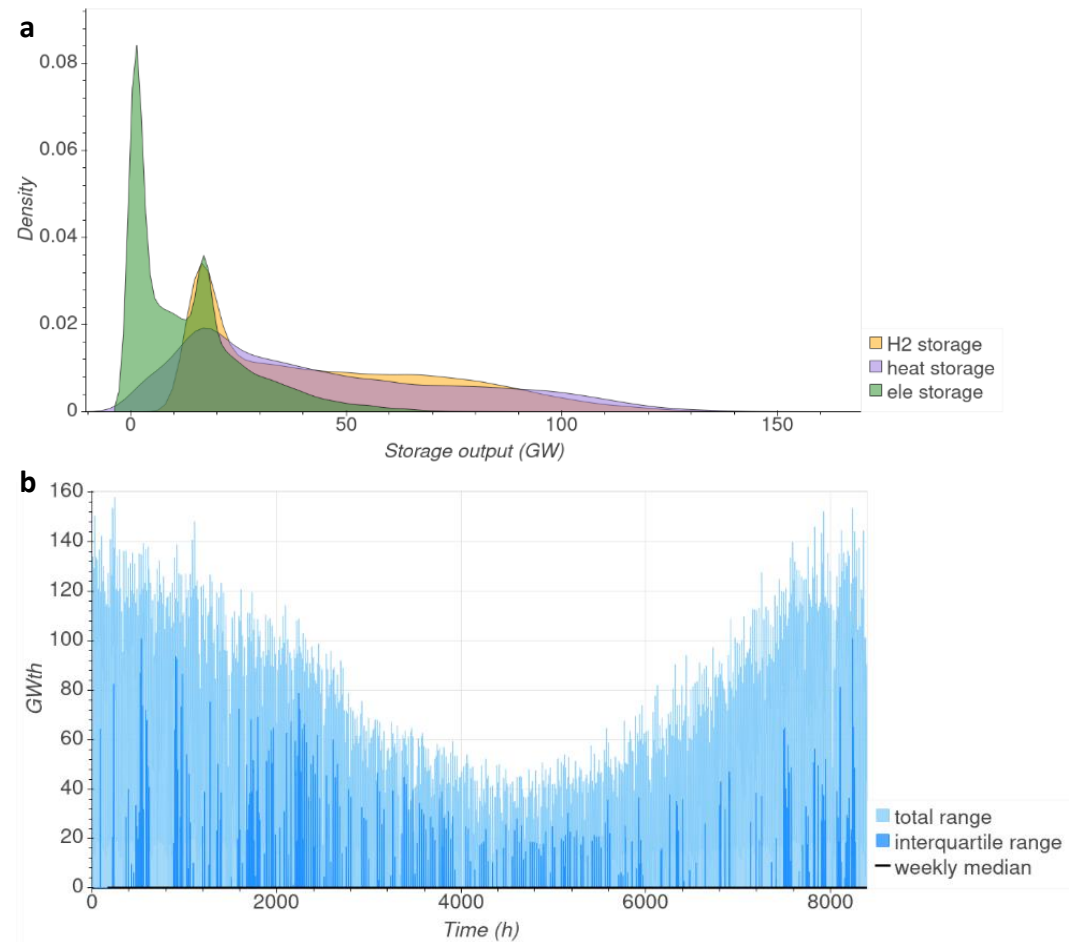
Commentary: climate change

The focus has been on heat, so the modelling of air conditioning is less developed and the results are indicative only. Inward heat flows through a building envelope and incidental gains from people, equipment and the sun can drive building temperatures above comfortable levels. Depending on design details, insulation can moderate or exacerbate overheating. Air conditioning (AC) heat pumps transfer heat from the interior to the outside to maintain comfort.

Climate change was modelled by simply adding temperature increases of +2 oC and +4 oC to historic MERRA data. Air conditioning was assumed limited to the services sector. The model indicates that AC is increased more by climate change than space heat is reduced, such that decreases in total UK space heat demand are roughly balanced by increases in the service sector AC load (cool, not electricity). The effect on BEV demand is not very large. Climate change will affect the seasonal variation in electricity demand – more in summer, less in winter – and this will alter the optimal capacities of wind and solar. Reversible heat pumps provide heat and cool. These may be in buildings (e.g. split AC/heater) or in District Heating and Cooling (DHC) systems

HEAT AND COOL (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Space heat	287	287	287	287	287	287	287	303	271	225	169
Ser: Aircon	59	59	59	59	59	59	59	61	56	128	197
All: Space heat	100%	100%	100%	100%	100%	100%	100%	106%	94%	78%	59%
Ser: Aircon	100%	100%	100%	100%	100%	100%	100%	103%	95%	217%	334%

+2 oC +4 oC

Note: these are heat/cool demands, not electricity

Energy Space Time

Annual: deliveries by distribution networks

Deliveries reported here are direct to consumers but exclude electrofuels to ships. Consumption by intermediate facilities such as DH and H2 electrolysers are also excluded.

The total deliveries of electricity, district heat and hydrogen through distribution networks are similar though differentiated by consumer conversion efficiencies: consumer heat pump efficiency > consumer DH connection efficiency > consumer hydrogen boiler efficiency.

| DELIVERIES (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Electricity	416	472	414	417	416	417	416	418	415	406	398
DH heat	377	162	0	377	377	377	377	391	364	325	278
Hydrogen	0	0	374	0	0	0	0	0	0	0	0
Total	**794**	**634**	**788**	**795**	**793**	**794**	**794**	**809**	**779**	**731**	**676**
Index	100%	80%	99%	100%	100%	100%	100%	102%	98%	92%	85%

Energy Space Time
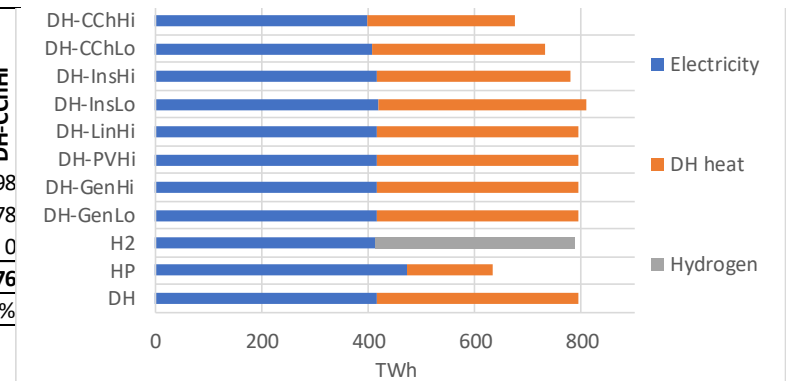
Annual: electricity delivered for heat

Deliveries of electricity for heat include all flows to consumers in the network with voltages less than long distance transmission voltages of 400 kV and 275 kV.

This includes smaller domestic and non-domestic consumers (mostly 230 V), and larger consumers at voltages of up to 33 kV. Electricity to facilities producing secondary energy (DH heat, electrolysis, ammonia etc.) is excluded.

The total deliveries of electricity for heat are highest in HP and the same in DH and H2 as they have the same HP fraction.

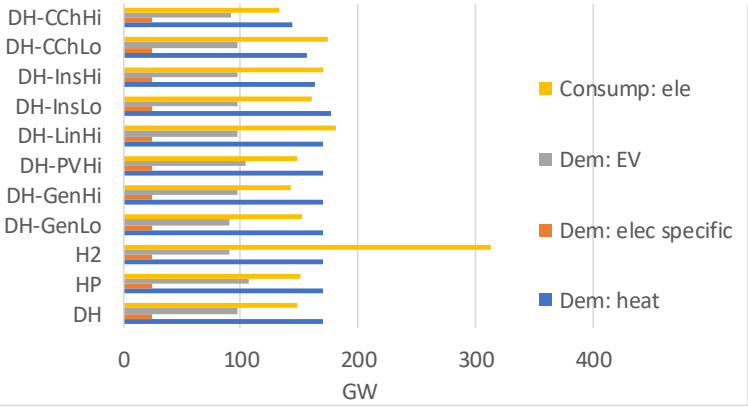| ELECTRICITY DELIVERED FOR HEAT (TWh)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Res : Space : HP	19	45	19	19	19	19	19	20	18	15	11
Res : HW : HP	2	9	2	2	2	2	2	2	2	2	2
Ser : Space : HP	4	11	4	4	4	4	4	4	4	3	2
Ser : HW : HP		3									
Ind : SWhea : HP	1	5	1	1	1	1	1	1	1	0	0
Ind : Pro HT : HP	10	25	10	10	10	10	10	10	10	10	9
Total	36	97	36	36	36	36	36	37	34	29	24
% of delivered	9%	21%	9%	9%	9%	9%	9%	9%	8%	7%	6%
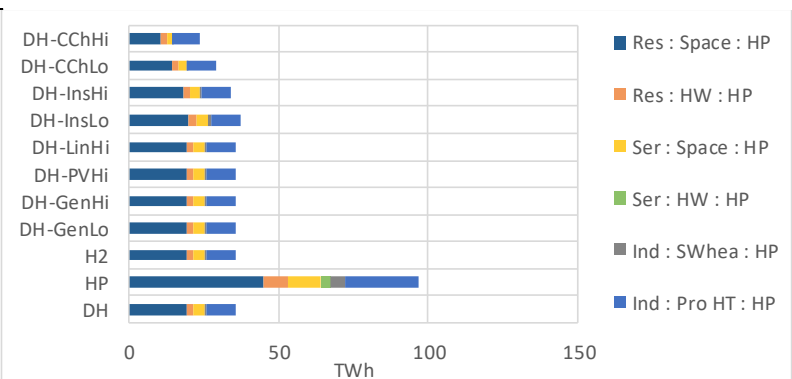
Peak flows

The peak flows at various points in the system are recorded. Note that those presented may not occur at the same time so they cannot be added.

The peak heat demand in the core scenarios is 170 GW. This increases if less insulation, and falls if more insulation or climate change.

The peak electricity consumption is highest in H2 because of overall supply, losses and electrolyser demand. Lowering the capacity of electrolysers would reduce this peak, but mean that less surplus electricity could be absorbed and stored.

PEAK FLOWS (GW)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Dem: heat	170	170	170	170	170	170	170	177	163	157	145
Dem: elec specific	25	25	25	25	25	25	25	25	25	25	25
Dem: EV	98	107	91	91	97	104	98	98	97	98	92
Del: electricity	142	148	121	147	136	142	166	144	155	150	127
Consump: ele	148	151	313	153	143	149	182	161	170	174	133
DH HP input	58	25		58	58	58	58	58	58	58	58
H2 electrolyser	3	3	250	3	3	3	3	3	3	3	3
Generate: renew	254	277	471	227	282	248	254	254	254	254	254
Generate: total	257	280	474	230	285	251	257	257	257	257	257

Technical and cost data

ESTIMO calculates capital, O&M and fuel costs.
The current performance, capital and operational costs of many individual technologies are fairly well known. Most performance and cost data used here are projected for 2040, from the Danish technology database*. Uncertainties are generally large for hydrogen for which there are no extant large scale distribution and use systems. Projected costs are uncertain. The economies of scale are accounted for in terms of efficiency and unit cost. Nuclear costs are uncertain and opaque, but nuclear capacity is small in the scenarios so has little effect on total costs.

Perhaps the greatest uncertainties concern the costs of new and upgraded distribution networks. These have been calculated as a capital cost per consumer increasing for different consumer fractions served by DH/HP/H2 to reflect heat load density decreasing. Network losses as a fraction will partially depend on network length per consumer.

* https://ens.dk/en/our-services/projections-and-models/technology-data

Conversion and storage costs

Heat pump efficiencies are fractions of Carnot efficiency

| Technology	Unit	Tech Size	Effi-ciency	Capital Projection Index	O&M £/unit	O&M Fixed £/cap/a	Life yrs
Consumer heat pump	kW(th)	10	60%	74%	696	2.0%	25
DH Heat pump	kW(th)	10000	78%	74%	637	2.0%	25
Hydrogen boiler	kW(th)	10	85%	83%	247	2.0%	25
DH CHP (heat eff)	kW(e)	10000	58%	99%	788	2.0%	25
Hydrogen electrolyser	kW(ch)	10000	80%	75%	526	2.0%	25
Heat store	kWh(th)	1000000	95%	94%	3	1.0%	25
Hydrogen storage	kWh(ch)	1000000	98%	75%	2	1.0%	25
Electricity store	kWh(e)	1000000	92%	70%	35	1.0%	20
Solar PV	kW(e)	10000	20%	81%	355	2.0%	35
Wind off	kW(e)	10000		77%	1240	1.0%	30
Wind on	kW(e)	5000		45%	936	1.0%	30
Hydro	kW(e)	100000	90%	85%	767	1.0%	50
Nuclear	kW(e)	2000000	40%	100%	8000	2.0%	35
Electricity transmission			98%			3.0%	50
Electricity distribution			95%			5.0%	50
Hydrogen distribution			98%			5.0%	50
District heat network			93%			5.0%	50

Network costs

Energy Space Time
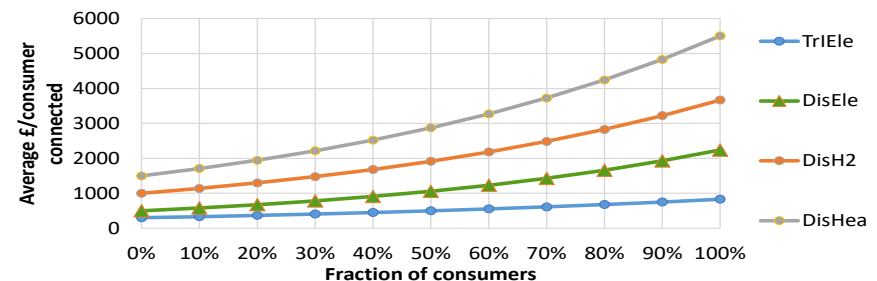
Costs: disaggregated

ESTIMO calculates capital, O&M and fuel costs.

- Capital costs are annuitized using unit capacity costs (£/kW, £/kWh), technology life (yrs) and an interest rate of 5%/a.
- H2 total system costs are 30% higher than DH and HP, mainly because primary capacity is higher due to the inefficiency of heating with electrolytic hydrogen as compared to heat pumps.

| Total G£/a	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Consumer conversio	9.8	23.0	16.2	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
DH conversion	9.6	4.1		9.6	11.8	9.6	15.1	15.9	9.2	8.8	8.4
DH store & network	13.2	5.4		17.2	11.3	13.2	11.6	13.2	13.2	13.2	13.2
H2 electrolyser	0.1	0.1	11.7	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
H2 store & network			9.2								
Ammonia prod & sto	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Elec storage	8.9	11.7	8.8	17.8	4.4	8.9	4.4	8.9	8.9	8.9	8.9
Elec network	4.9	7.9	8.1	4.4	5.4	4.6	4.9	4.9	4.9	4.9	4.9
Nuclear	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Renewables	24.1	26.3	45.9	22.2	26.1	24.6	24.1	24.1	24.1	24.1	24.1
Trade	-0.7	-0.6	-1.0	-1.4	-0.5	-0.9	-1.2	-0.8	-0.7	-0.6	-0.6
TOTAL exc. BEV	73.5	81.2	102.6	83.8	71.7	73.7	72.9	79.7	73.0	72.7	72.3
Index to 1st system	100%	111%	140%	114%	98%	100%	99%	109%	99%	99%	98%

Energy Space Time
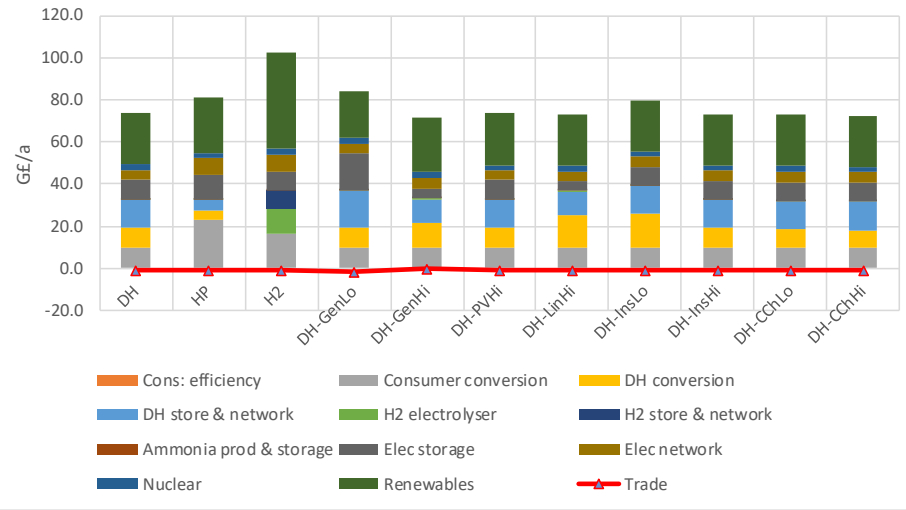
Costs of heat and electricity

Energy systems are interconnected systems with some components serving multiple demands. Estimation is needed to separate out the cost of heat, but note that these are for 70:30 mixed DH/HP/H2 systems:

- The costs of components solely or mainly for heating may be summed – these include consumer heaters, heat and hydrogen networks, DH components, and H2 electrolysers.

- The cost of electricity supply for heating (heat pumps, electrolysis) may be estimated as the fraction of electricity consumption for heat times the total cost of electricity supply.

These two elements may then be summed. The sums may then be divided by heat demand to derive the unit cost of heat. 70% H2 heat costs about 70% more than DH or HP heat.

Similarly for electricity. The total cost of electricity in H2 is higher because of the greater consumption, but there is little variation in unit p/kWh costs.
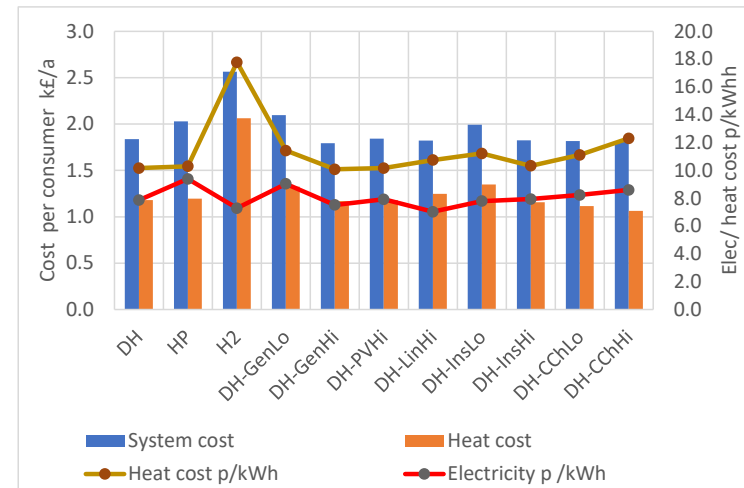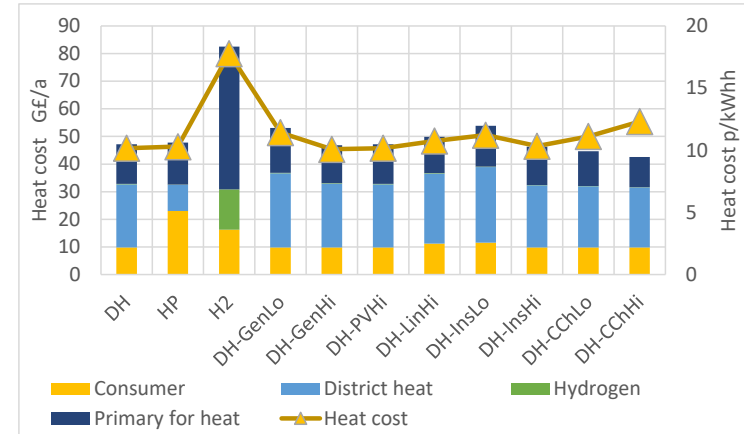
Indicative implementation rates

The **possible development path** from the current system to a zero emission system has not been analysed here.

How fast can the installation rate of consumer and public systems be ramped up given the needed skilled labour, financing and so on?

What regulatory or market measures are required?

The rates of implementation required to <u>maintain</u> the capacities the core systems given technology lifetimes are shown.
The **rate of primary capacity build for H2 is about 70% higher** than for DH and HP, because H2 requires much more electricity.

Energy Space Time
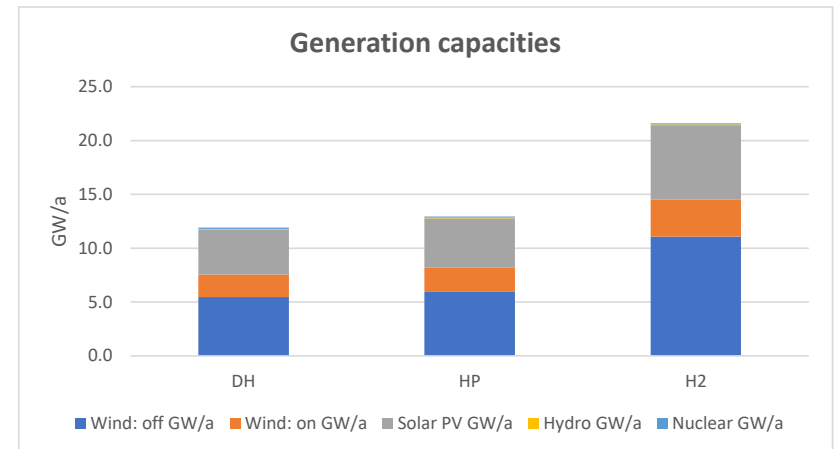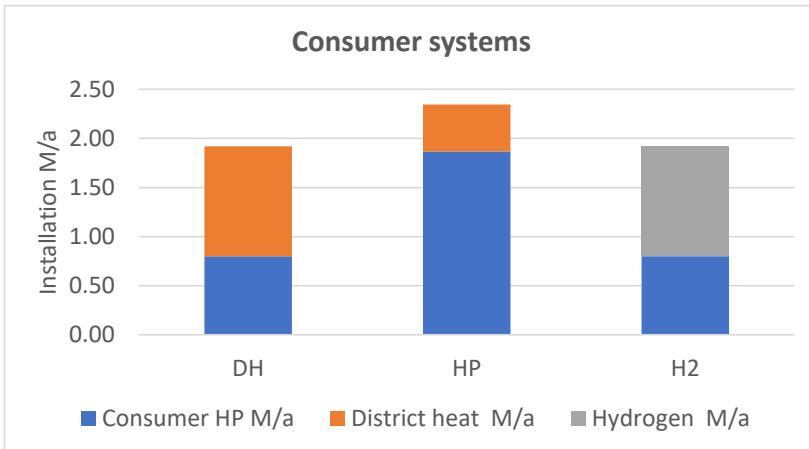
Heating systems comparison

Building types and heat load density affect costs and practicalities

DH and H2 are mainly urban options; HPs may be used more widely

Consumer and district heat pumps can heat and cool

Heat pumps might replace boilers and then later the loads connected to DH

		ELECTRIC: ZERO EMISSION OPTIONS		
		Consumer HP	**District heat**	**Hydrogen**
Technologies	Heat generator	HP (reversible)	HP (reversible)	Boiler
	Function	Heat (cool)	Heat (cool)	**Heat**
	Primary sources	Renew/nuclear	Renew/nuclear	Renew/nuclear
	H2 production			Electrolysers
	Heat per electricity	3.0	3.5	**0.7**
Environment GHG	Primary reduction	100%	100%	100%
	Air pollution			**Boiler NOx**
Noise	External noise	**~50 dB**		
	Internal noise	~50 dB		*~50 dB*
	Other impacts	condensate		*water, chem*
Space	Space: outside bldg	**1 m3**		
	Space: inside bldg	**1 m3**	0.25 m3	0.5 m3
Cost	Urban heat cost p/kWhh	10	10	**18**
	Consumer capital cost k£	**10**	2	3
Installed	UK consumers 2021	~0.2 M	~0.2 M	**0**
M - million	Europe consumers 2021	~10 M	~30 M	**0**
	New installation	one by one	**by area**	**by area**

Energy Space Time

Cost comparisons: single zero emission vectors

- The core scenarios have mixes of heat shares **DH** (DH-70:HP-30:H2-0); **HP** (DH-30:HP-70:H2-0); **H2** (DH-0:HP-30:H2-70). Therefore the cost comparisons do not relate to single vectors.

- As shown below, an attempt has been made to separate out the costs for each vector, with one difficulty being the estimation of additional electricity network and storage costs incurred by each vector.

- Green hydrogen heating costs about 80% more than heat pumps or district heating

Separate DH/HP/H2 vector costs			DH only	HP only	H2 only
DH connection, heat pump, boiler	G£/a	Consumer	3.2	23.0	6.4
District heat	G£/a	DH network	9.3		
	G£/a	DH HPs	10.0		
	G£/a	DH store	4.0		
Hydrogen	G£/a	H2 network			6.2
	G£/a	H2 store			3.0
	G£/a	H2 electrolyser			11.7
Total cost for heat only components	G£/a	**Heat only cost**	**26.4**	**23.0**	**27.2**
Vector: ele consumed for heat	TWh	Heat elec consu	99.5	101.3	484.3
Vector: % total UK ele	%	Ele % of UK	18%	19%	51%
Total UK ele cost	G£/a	UK elec cost	40.5	48.5	65.4
Vector: adjustment for network	G£/a	Network Ele	-1.8	5.4	5.4
Vector: adjustment for storage	G£/a	Store Ele	-2.8	0.9	-2.8
Vector: adjusted total	G£/a	UK elec cost adju	36.0	54.9	68.0
Vector: 70% of total ele cost	G£/a	**Ele supply cost**	**6.6**	**10.3**	**34.7**
	G£/a	**Total vec cost**	**33.0**	**33.3**	**61.9**
Vector: % UK heat	%	Heat %	70%	70%	70%
Vector: UK heat	TWh	Heat supplied	336	336	336
Vector: heat unit cost	p/kWh	**Heat cost p/kWh**	**9.8**	**9.9**	**18.4**
		Index to DH	100%	101%	188%
		Index to HP			186%

Commentary: electricity network

The current UK peak electricity demand is about 55 GW. Modelled peak flows account for storage use in general; but consumer storage apart from in EVs is not modelled; however several cold days with low renewables would deplete most practicable consumer stores. Delivered peak flows are 142 (DH), 148 (HP) and 121 GW (H2) or an increase of about 2.5 times the current peak. The H2 distribution peak is 27 GW or 20% less than for HP.

A major contributor to this peak is EV charging at about 100 GW; about 40% of dwellings have no off-road parking, so a fraction of this would be to charging stations, some of which would have high voltage supply. The peak consumption on the high voltage grid is 148 (DH), 151 (HP) and 313 GW (H2), with the H2 peak being largely driven by electrolyser capacity which is assumed connected to high voltage transmission. Transmission is assumed to accommodate the maximum generation of 257 (DH), 280 (HP) and 474 GW (H2).

In all scenarios, the capacities of the distribution and transmission electricity networks will have to be greatly increased, with much of the network being upgraded. Assuming a 60 year asset life, half the existing network will be replaced by 2050 in any scenario. In the minimum 30% HP heat share scenario, HPs may mainly be in off-gas-grid and low load density areas where the network length per consumer is high, but a fraction of this will be overground and underground installation per metre may cost less than in cities.

PEAK FLOWS (GW)	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Dem: heat	170	170	170	170	170	170	170	177	163	157	145
Dem: elec specific	25	25	25	25	25	25	25	25	25	25	25
Dem: EV	98	107	91	91	97	104	98	98	97	98	92
Del: electricity	142	148	121	147	136	142	166	144	155	150	127
Consump: ele	148	151	313	153	143	149	182	161	170	174	133
DH HP input	58	25		58	58	58	58	58	58	58	58
H2 electrolyser	3	3	250	3	3	3	3	3	3	3	3
Generate: renew	254	277	471	227	282	248	254	254	254	254	254
Generate: total	257	280	474	230	285	251	257	257	257	257	257

Energy Space Time

Commentary: technology uncertainties

Technologies

Heat pump and district heat technologies are well known. In the UK in 2021, about 0.3 M consumers have heat pumps and some 0.2 M consumers have DH; tens of millions of consumers in Europe are served with these.

There is no extant large scale application of new or adapted hydrogen distribution networks, building internals and boilers, so there is uncertainty about implementation and cost.

The scenarios here use costs projected for 2040. These are generally uncertain, but particularly for wind, solar and batteries as these technologies are still being rapidly developed technically and mass production increases so cost reductions are usually assumed to continue, albeit more slowly.

Distribution networks

A major uncertainty is the cost of new, upgraded or adapted distribution networks comprising transmission (cable, pipe) and ancillary gear (transformers, compressors etc.). Electricity and DH network transmission costs depend on many factors, perhaps most important are network length and the cost in laying equipment underground.

For hydrogen, the costs of adapting existing gas networks, including in consumers' premises are not well known.

Energy Space Time

Commentary: supply security and resilience

Electricity transmission is the spine of the systems designed and there is the possibility of widespread failure due to cascading faults, cyber attack, or extreme environmental conditions. A significant system wide risk is sustained low ambient temperature, and therefore high demand, coupled with low renewable output. The systems explored meet hourly demands as driven by weather of the last 35 years, including the stress year 2010. The systems have zero operational emission and do not rely on imported fossil or biomass fuels, and they net export electricity. Biomass consumption is zero for heating and electricity, and is assumed reserved for aviation fuelling. Nuclear capacity is small so its generic risk to the system is low.

Climate change will in general decrease space heat demand and increase space cooling demand in buildings and vehicles. Climate change may not reduce the severity of stress periods for heating but will increase cooling loads. To offer resilience to climate change, reversible consumer or DH heat pumps can provide heat and cool, unlike hydrogen boilers. Climate change will alter wind and solar resources and correlations with demand, but research so far indicates little climate change impact on these renewables. Increased temperatures will impact on the cooling of thermal plant (mainly nuclear).

As the system evolves over the coming decades under varying meteorological conditions, there will be a decreasing frequency and magnitude of GHG emission. The demand, intermediate and primary system components should be developed in a reasonably coordinated way. If it looks like there is a risk of a supply shortfall in forthcoming years because of lack of coordination, or perhaps to meet a 1 in 100 year meteorology, then back-stop supply could be deployed, such as multi-fuelled DH CHP or non-CHP open cycle gas turbines (OCGT) using natural gas. Since the system is primarily electric, this provides security for most services. For example, 100 GW of OCGT with a unit cost of 300 £/kW would have a capital cost of 30 G£ and an annuitized cost of 2 G£/a. This represents about 4% of total system capital cost and 2% of annual system cost. Demand reduction through interruptible contracts is an additional option.

Energy Space Time

Commentary: optimisation and system dynamic control

Ideally, the system configuration – component capacities and connections - and the dynamic control algorithm (Global Optimum Dispatcher, GOD, in ESTIMO) - should be optimised at the same time, as they are co-dependent. But this is generally beyond current capability for complex multi-node systems with trading. Here, GOD and the connectivity of components is the same for all systems, but the capacities of the components are adjusted.

The approach taken has been to separately and iteratively generate 'good' designs using optimisation with simpler models (ETSimple) coupled with manual adjustments to the component capacities, followed by simulation in ESTIMO. It is clear that considerable inter-substitution between renewable, storage and interconnector capacities is possible. The next step here is to optimise using ESTIMO rather than simpler models. It may be that much lower cost designs can be found. Plainly optima will depend on the relative costs of components, and the huge reductions in wind, solar and battery costs have radically transformed optima just in the past 15 years or so.

The dynamic control algorithm functions effectively in that it makes good use of available low emission supply hour by hour through controlling storage and trade flows. However it may not be optimal, particularly as it uses information for the current hour only – how much might the use of weather and renewable forecasts improve the algorithm?

GOD is an 'engineering proof' and may help informing the construction of practical operational markets that include pricing and competition. Constructing and modelling practicable dynamic markets is a most difficult problem.

Energy Space Time

Commentary: renewable spillage

A notable outcome of the architectures designed is the fraction of 40-50% of electricity, mainly renewable, that is spilled because it cannot be used, stored, or exported given the component capacities and operation of the designs. Reducing spillage would mean less investment in renewable generation, but generally more in conversion, storage and some transmission components; this is an optimisation question and ancillary analysis with a simpler model (ETSImple) has shown that significant spillage leads to lower total cost.

It may be that some of this spilled electricity could be used for purposes not modelled here, such as to power facilities for aviation fuel production or Direct Air Capture and Storage (DACS) of CO_2, which can include other storage such as of aviation fuel and CO_2. However the same question arises of balancing the capital costs of facilities for these purposes against the costs of renewables. In general, the higher the fraction of renewables absorbed, the more storage is needed, and the lower the capacity factors of plant using the electricity, and therefore the higher capital cost per unit of production of these facilities.

Extending the interconnector system geographically beyond Europe would further average demands and renewables and thereby reduce spillage and storage needs. In the systems explored here, the cost of the UK interconnector (crudely calculated) to central Europe is less than 1% of the total UK system cost, whereas storage is around 10% of total cost.

This is a complex optimisation problem.

Energy Space Time

Consumer system implementation

A key issue is the speed and ease of changing the energy system to transit to zero emission.
The most difficult part of the system to change is that owned by consumers because of capital costs, acceptance, disruption and therefore choice. Changing the public intermediate and primary parts of the system is less problematic as the rapid increases in wind and solar generation have demonstrated.

Consumer heat pumps require space and access to environmental heat, and noise and visual obtrusion can be problematic especially in high density areas and particular dwelling types. Heat pumps have higher consumer end capital cost than DH and H2, and about 63% of dwellings are owner-occupied for which there is the problem of capital financing; whereas in the remaining 37% of dwellings, the capital costs can be paid through rent.

District heating. Most DH would be new and installed on an area basis. DH has little impact at the consumer end in terms of space and noise.

A HP to DH development path might be:
1. Replace gas boilers (life about 15 years) as they 'die' with reversible heating/cooling heat pumps.
2. Connect DH(C) to the HP internal system as and if DH(C) arrives at the consumer.

Hydrogen boilers would be similar to gas boilers but may be constrained such as in high rise flats. H2 is assumed to largely use the existing gas network, and would be implemented on an area basis with all current gas consumers having to switch from natural gas to H2 or HP.

The economics of DH and H2 are partially dependent on the fraction of consumers who connect to these networks within an area. A question is then how to ensure an adequate fraction do connect.

Energy Space Time

Indicative implementation rates

The rates at which technologies need to be installed depends on the lifetimes of the current and future technologies and the total capacity of each required by a certain date (e.g. 2050).

The table indicates the rates of implementation required to <u>maintain</u> the capacities in a net zero system given technology lifetimes. It is notable that the rate of primary capacity build for H2 is 80% to 70% higher than for DH and HP respectively.

To calculate the year by year installation rate to build the system by 2050 requires more detailed stock modelling coupled with assumptions about future implementation rates given the evolution of industrial building capacity elements – workforce, finance, factories, installers, etc..

RATES	DH	HP	H2	DH-GenLo	DH-GenHi	DH-PVHi	DH-LinHi	DH-InsLo	DH-InsHi	DH-CChLo	DH-CChHi
Consumer HP M/a	0.80	1.87	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
District heat M/a	1.12	0.48	0.00	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Hydrogen M/a	0.00	0.00	1.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DH heat GWh/a	0.46	0.35		0.92	0.23	0.46	0.27	0.46	0.46	0.46	0.46
Grid store GWh/a	0.08	0.10	0.08	0.15	0.04	0.08	0.04	0.08	0.08	0.08	0.08
Hydrogen GWh/a			0.52								
Ammonia GWh/a	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind: off GW/a	5.4	5.9	11.1	5.0	5.9	5.9	5.4	5.4	5.4	5.4	5.4
Wind: on GW/a	2.1	2.3	3.5	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Solar PV GW/a	4.2	4.6	6.9	3.1	5.2	3.1	4.2	4.2	4.2	4.2	4.2
Hydro GW/a	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Nuclear GW/a	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Energy Space Time

Vector comparison summary

The main drawbacks of the options are highlighted.

The relative performance and costs of options depend on many assumptions - particularly uncertain are gas upstream emission, gas prices and DACS costs.

Building types and heat load density affect costs and practicalities

HP, DH and H2 are mainly urban options; elsewhere HP

Consumer and district heat pumps can heat and cool

			ELECTRIC: ZERO EMISSION OPTIONS			NATURAL GAS: NET ZERO OPTIONS	
			Consumer ASHPs	District heat/cool	Hydrogen: green	Hydrogen: blue	DH: CHP + HP
Technologies		Heat generator	HP (reversible)	HP (reversible)	Boiler	Boiler	CHP, HP
		Function	Heat (cool)	Heat (cool)	Heat	Heat	Heat (cool)
		Primary sources	Renew/nuclear	Renew/nuclear	Renew/nuclear	Imported/UK gas	Imported/UK gas
		H2 production			Electrolysers	SMR+CCS / other	
		Heat per electricity	3.0	3.5	0.7		
		Heat per gas				0.7	1.3
Environment	GHG	Primary reduction	100%	100%	100%	78%	85%
		DACS cost p/kWhh	0	0	0	3.5	1.7
		Air pollution	0	0	Boiler NOx	Boiler NOx	small
	Noise	External noise	~50 dB	~0	~0	~0	~0
		Internal noise	~50 dB	~0	~50 dB	~50 dB	~0
		Other impacts	condensate	~0	Water, chem	Water, chem	Water, chem
	Space	Space: outside bldg	1 m3	~0	~0	~0	~0
		Space: inside bldg	0.5 m3	0.25 m3	0.5 m3	0.5 m3	0.25 m3
		Space: bldg HW tank	0.5 m3	0.25 m3	?	?	0.25 m3
Cost		Urban heat cost p/kWhh	10	10	18	14	11
		Consumer capital cost k£	10	2	3	3	2
Installed		UK consumers 2021	~0.2 M	~0.2 M	H2~0 (NG~23 M)	H2~0 (NG~23 M)	~0.2 M
M - million		Europe consumers 2021	~10 M	~30 M	H2~0 (NG~95 M)	H2~0 (NG~95 M)	~30 M
New		New installation	one by one	by area	by area	by area	by area

HP - heat pump
ASHP - air source heat pump
DH - district heating
SMR - steam methane reforming
CHP - combined heat and power

NG - Natural Gas
GHG - greenhouse gas
CCS - carbon capture and storage
DACS - direct air capture storage (to balance GHG)
NOx - nitrogen oxides

Gas assumptions	
Price	3 p/kWh
Supply emission	50 gCO2e/kWh
DACS	300 £/tCO2

Natural gas for net zero heating

- Natural gas is convenient for heating but it emits greenhouse gases. The practicalities and costs of negative emissions to balance emissions engender a wide range of opinions and estimates. The long term price and emissions of natural gas are necessarily uncertain.

- The UK is increasingly dependent on imported gas over which the UK has no price control, so natural gas imports present technical and economic security questions over the time period to, say 2100, over which new heating infrastructures will operate. At some point the decline in global natural gas reserves will impact on price.

- Natural gas can be used directly in **NG plant** including consumer boilers or CHP plant, or in processes such as steam methane reforming (SMR) to make 'blue' hydrogen for use in boilers or CHP.

- The production and transport in the supply of natural gas results in CO_2 arising from the energy used in these processes, and methane emissions from leakage. These upstream GHG emissions cannot be captured by **NG plant**.

- CHP and SMR can have carbon capture and storage (CCS) which captures perhaps 80-90% of the CO_2 emissions at the plant, but CCS reduces plant efficiency, and therefore increases gas use and upstream emissions.

- Thus **NG plant** cause GHG emission which, for net zero emission, have to be balanced by the capture and storage of environmental CO_2; one such system is direct air capture and storage (DACS).

Natural gas supply

An increasing fraction of UK supply is imported via pipe or LNG. The GHG emission (gCO2e/kWh) of natural gas supply from different sources (e.g. UK, Qatar LNG, Siberia pipe) may be estimated from leakage and combustion, and applying global warming potentials (GWP) for different time horizons. Estimates made by Barrett of these range from around 50 to 150 gCO2e/kWh. For analysis here a low figure of **50 gCO2e/kWh** (30 methane + 20 CO2) is assumed, this being the minimum emission of using gas.
Estimates from *Heating with Steam Methane Reformed Hydrogen*, 2021, Mark Barrett, Tiziano Gallo Cassarino. DOI: 10.21203/rs.3.rs-638496/v1 https://www.researchsquare.com/article/rs-638496/v1
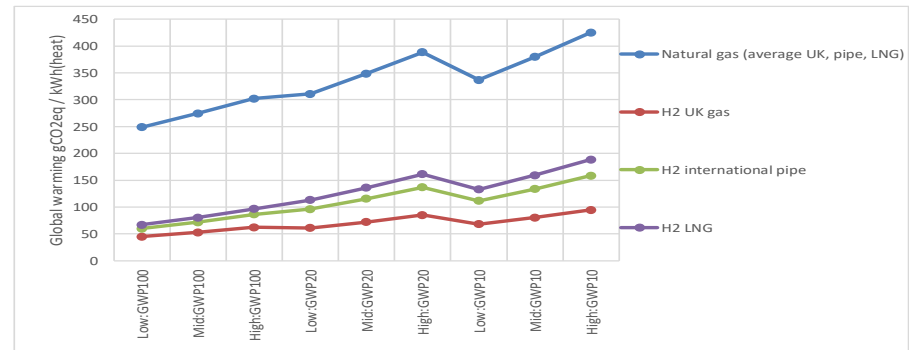
Gas prices are increasingly driven by international markets as UK imports increase. Prices have been volatile and BEIS projections to 2035 bracket historic ranges. For the period 2040-2100 over which DH or H2 systems might be appraised, a price of **3 p/kWh** (88 p/therm) is assumed in analysis. Volatility is exemplified by the 2021 gas price increase from 1.7 p/kWh to 3.4 p/kWh, and further rises because of the Ukraine war.

BEIS 2017 Fossil fuel price assumptions.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663101/BEIS_2017_Fossil_Fuel_Price_Assumptions.pdf
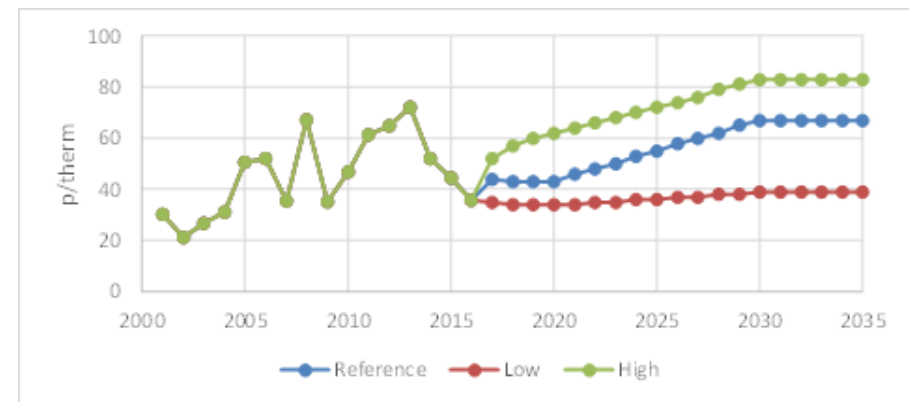
Negative emissions

- CO_2 can be absorbed from the environment (generally assumed to be from the atmosphere rather than the sea) using a range of processes including Direct Air Capture and Storage (DACS) and biomass. These can balance the GHG emissions of natural gas used to make hydrogen, or input to boilers or CHP, but there is uncertainty about the potential, impacts and costs of these processes.

- DACS is a machine whereby atmospheric CO_2 is absorbed with chemicals, then separated from the chemicals, purified and compressed and sent to long term geological storage. The low concentration of CO_2 of about 410 ppm in the air means that about 1 in 2500 'air molecules' is CO_2, so large absorber areas, and much energy and other inputs (chemicals, water etc) are required for DACS processes.

- The size of DACS and its inputs and waste have environmental impacts including water consumption.

- The cost in £/tCO2 of DACS depends on many factors including: the capital cost of the DACS, its capacity factor, the operational costs (e.g. water, chemicals) and the cost of energy (e.g. variable renewables, constant nuclear).

- The uncertainty in these factors, because there are no large scale plant currently operational and because local factors vary (such as electricity supply), means that DACS costs quoted range about 20 fold, from around 50 to 1000 £/tCO2. In the analysis below a figure of **300 £/tCO2** is assumed. DACS plant and the associated energy supply would be have to built in step with gas heating plant.

- Consequently, the cost of balancing the GHG emissions from natural gas use for hydrogen or direct combustion are uncertain.

Three natural gas (NG) heating options

All natural gas options need negative emissions (e.g. Direct Air Capture and Storage - DACS) to reach net zero

1. Steam methane reforming (SMR/CCS) + emission balanced with DACS

2. District heat (CHP/CCS +heat pumps) + DACS

3. Gas boiler + DACS

Energy Space Time
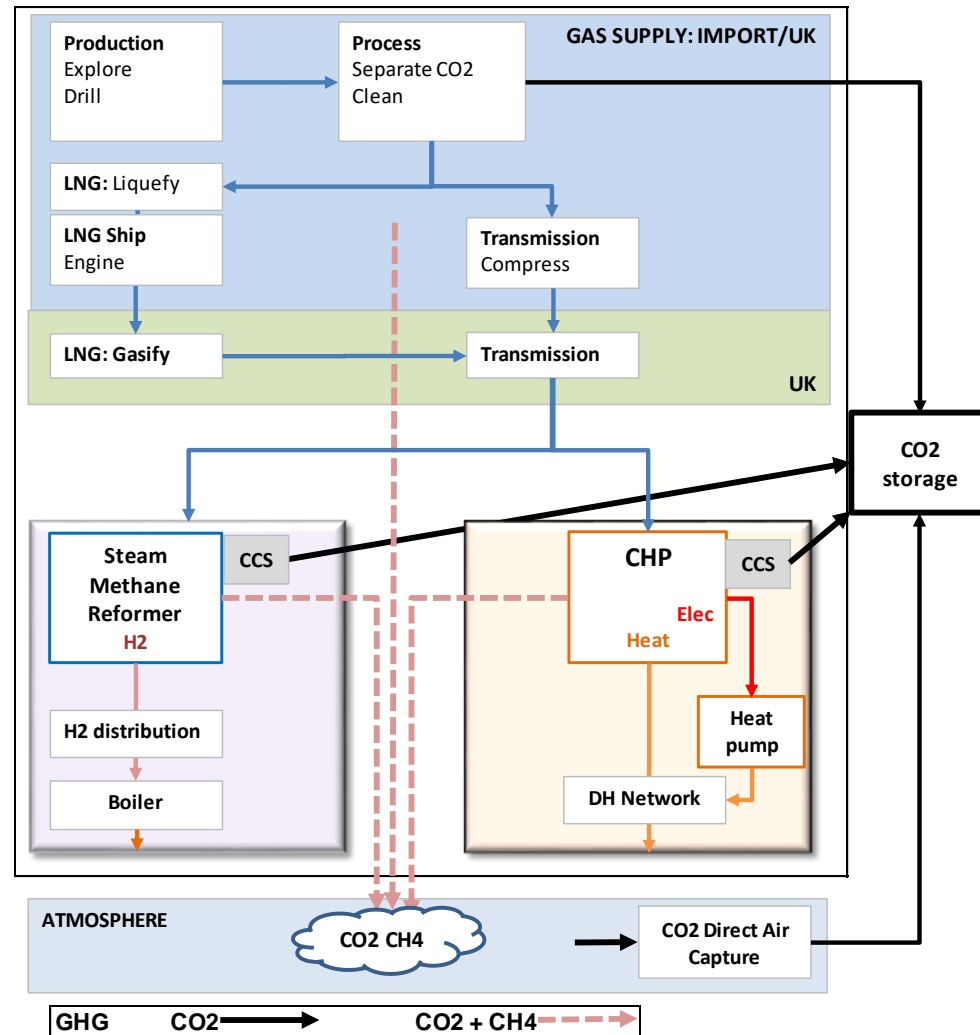
Natural Gas:
'Blue' hydrogen from steam methane reforming CCS

- Steam methane reforming (SMR) is one option for producing hydrogen from methane. There are two scale operational SMR CCS plant in the world.
  - Port Arthur: https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/956-2018-05-the-ccs-project-at-air-products-port-arthur-hydrogen-production-facility
  - Quest: https://open.alberta.ca/dataset/00bafb16-6e20-407b-9752-77acec295ff7/resource/c9d793d5-2381-4508-be37-6af329828c68/download/quest-2017-annual-summary-report.pdf

- SMR operational and cost data are limited because of commercial interest for operational plant, and small scale prototype and desk study data range widely.
- SMR with CCS may have an efficiency (natural gas to hydrogen HHV energy) in the range 70-80%.
- CCS can remove 80-90% of SMR CO2 emissions but not upstream CO2 and methane. For net zero, these emissions have to be balanced with atmospheric CCS such as with Direct Air Capture (DAC), with the costs of this added to hydrogen heat.
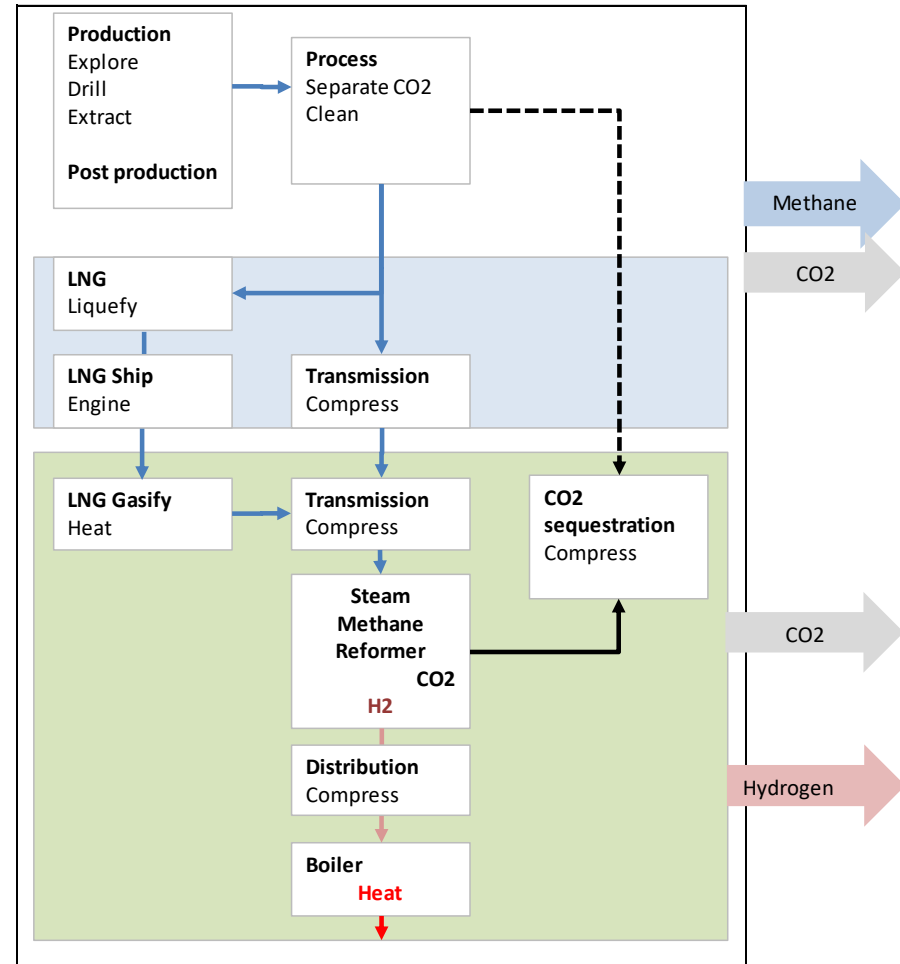
Natural Gas:
DH – Combined Heat and Power CCS + Heat pump

- This system is gas fuelled DH CHP with CCS producing heat and electricity assumed used in heat pumps.

- A CHP CCS example is Mongstad (https://ramboll.com/projects/re/mongstad_chp_plant) with 280 MWe (electrical efficiency 31%) and 350 MWth (thermal efficiency 39%) capacities and an overall efficiency of 70%.

- CHP electricity is assumed here to power DH HPs with COP 350% (the electricity could be used in consumer HPs, or for other demands)

- CHP and HP heat is delivered through the DH network with efficiency 93%

- The overall efficiency of gas to delivered heat is 137%.

- Assume 85% CO2 emission is captured by CCS, so DACS is still required for net zero; its costs are added to the heat cost.

- A possible transition is from gas fuelled CHP to other fuels such as hydrogen, ammonia, or bioenergy, and thereafter replacement by heat pumps using renewable electricity. This highlights the evolvability of DH.
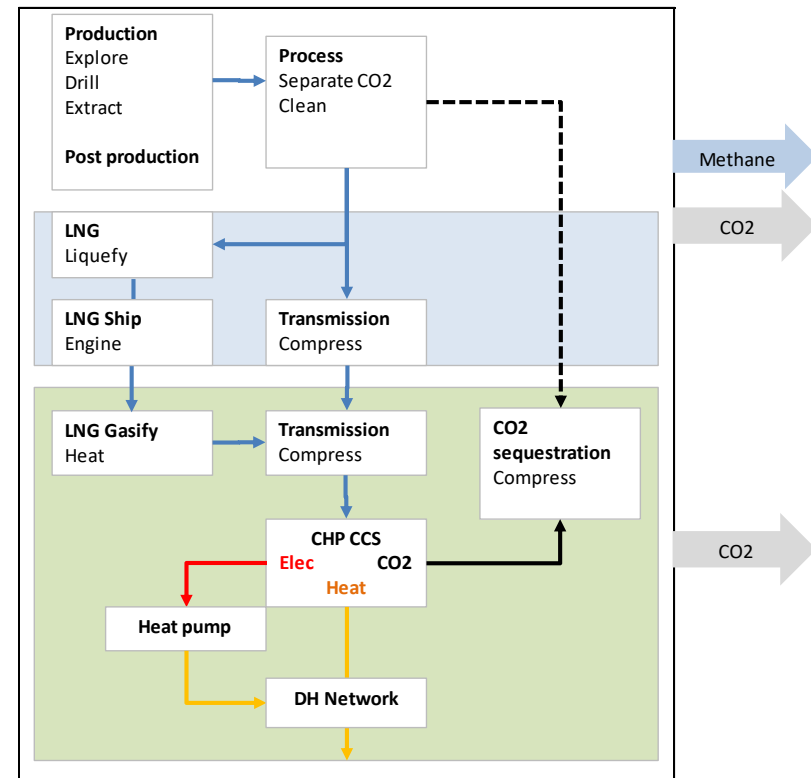
Natural gas options – preliminary estimates

For reference, natural gas can be also be used in consumer boilers but they have no CCS.

The simple calculation of natural gas options given at the right has been carried out with different assumptions. It is emphasised that there is great uncertainty in most assumptions: 'central', lower and higher assumptions for gas supply GHG CO2e/kWh, gas prices and DACS costs have been tested.

- **NG boiler** uses 25% less gas per kWhh than **H2 blue** but the CO2e emissions gCO2e/kWh are 129% higher, and so also the DAC balancing cost.

- **NG CHPCCS+HP** uses 53% less gas per kWhh than **H2 blue** and the CO2e emissions gCO2e/kWhh are 53% lower, and so also is the DAC balancing cost.

- The NG **H2**: **Boiler**: **DH CHP+HP** heat cost p/kWhh ratio is 100:91:78.

COMMON ASSUMPTIONS

Central	Gas gCO2e/kWh	50
	Gas p/kWh	3
	DACS £/tCO2	300
Interest rate	**5%** %/a	
Natural gas supply		
Gas cost	**3.0** p/kWh	
Upstream emission		
CH4 (GWP100)	**30** gCO2e/kWh	
CO2	**20** gCO2/kWh	
At H2 plant		
Gas CO2	**190** gCO2/kWh	
DACS	**300** £/tCO2	
	0.03 p/gCO2	

Sensitivity case: Central

			NG: H2 blue	NG: boiler	NG: DH CHPCCS+HP
CHP heat efficiency					39%
CHP ele eff					31%
DH HP eff					350%
DH network eff					93%
Boiler eff			90%	90%	
SMR eff			75%		
Eff overall			**68%**	**90%**	**137%**
CHP CCS					85%
SMR CCS			85%		
Boiler	Capital	£/kWth	170	150	
	Life	yrs	15	15	
	CapAnn	£/kW/a	16.4	14.5	
	CapFac	%	20%	20%	
	CapUnit	p/kWhh	1.0	0.9	
	O&M	p/kWhh	0.3	0.3	
	Total	**p/kWhh**	**1.4**	**1.2**	
			SMR		**CHP**
	Capital	£/kW	1000		1000
	Life	yrs	30		30
	CapAnn	£/kW/a	65		65
	CapFac	% capfac	50%		20%
	CapUnit	p/kWhh	2.2		**2.7**
	O&M	p/kWhh	0.7		0.8
	Total	**p/kWhh**	**2.9**		**3.5**
					HP
	Capital	£/kWth			300
	Life	yrs			25
	CapAnn	£/kW/a			12
	CapFac	%			20%
	CapUnit	p/kWhh			0.7
	O&M	p/kWhh			0.2
	Total	**p/kWhh**			**0.9**
System Cap+O&M			**4.2**	**1.2**	**4.4**
	Gas network	p/kWhh		0.6	
	DH network	p/kWhh			2.8
	DH store	p/kWhh			0.1
	H2 network	p/kWhh	1.8		
	H2 store	p/kWhh	0.4		
	NGas	p/kWhh	4.4	3.3	2.2
	NGas cost index	%	100%	75%	49%
	Total system	**p/kWhh**	**10.9**	**5.1**	**9.5**
	CO2e	p/kWhh	116	267	57
	CO2e cost index	%	100%	229%	49%
	DACS	**p/kWhh**	3.5	8.0	1.7
TOTAL COST		**p/kWhh**	**14.4**	**13.1**	**11.2**

Comparison sensitivities

- Sensitivity to the costs of renewable heating components has not been explored here. However the systems modelled have no fuel or DACS costs and the technologies are generally widespread today.

- Gas use is unchanged in the **natural gas NG** options as there are no variations in efficiency

- The costs of NG heat are sensitive to three variables: gas emission, prices and DACS costs – these are varied by +/- 33%.

- The comparative NG costs change significantly and the NG cost ranking is altered

- CHP+HP is least sensitive to the three variables as its higher efficiency means it uses less gas and has lower emission

Lower: gas CO2e/kWh, gas price and DACS costs
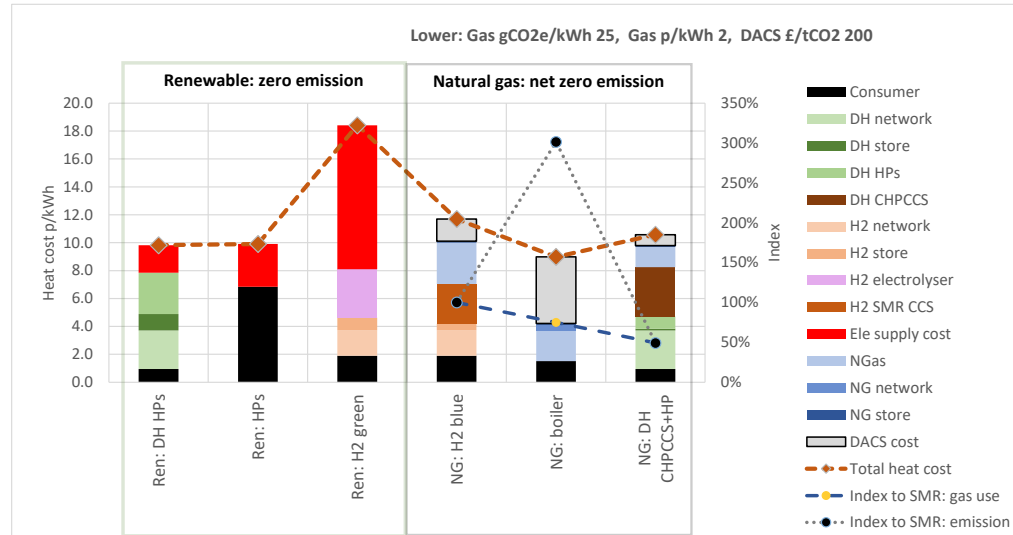
Higher: gas CO2e/kWh, gas price and DACS costs

Energy Space Time
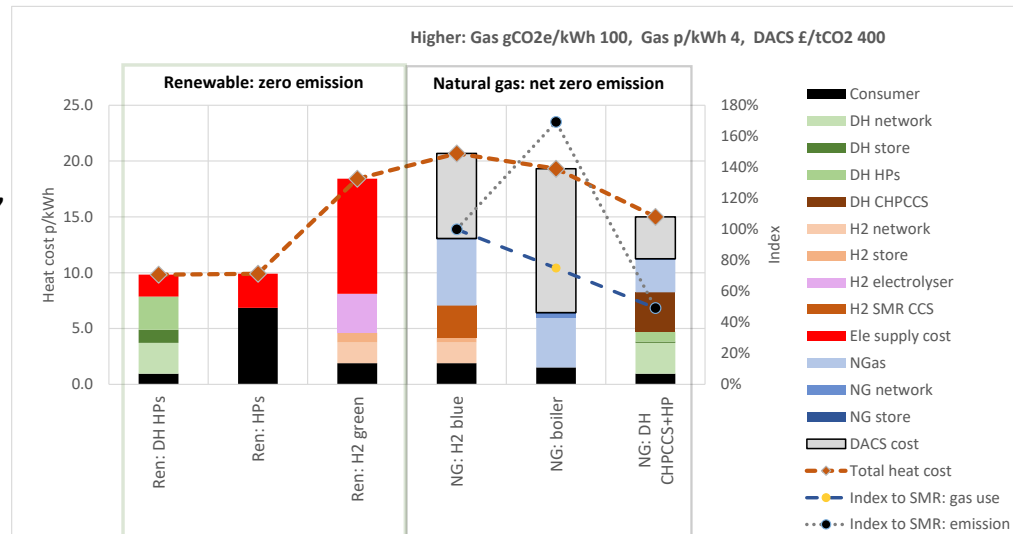
Hard to solve challenges

Aviation

Carbon based fuel best– but where does the carbon come from in a low carbon world (tragic irony!)? Kerosene synthesised from biomass, atmospheric CO_2 capture and electrolytic hydrogen? Some electric aviation…?

Technological, economic and environmental prospects of all-electric aircraft.
A Schaefer, 2018.
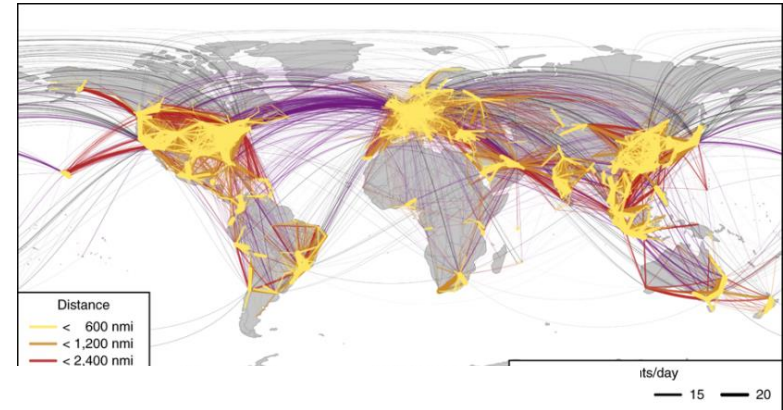
Dynamic system operation

Can autonomous competing agents deliver stable, minimum cost, equitable system operation?

How dumb is smart?

Do we need a Global Optimal Dispatcher (GOD)?

Energy Space Time
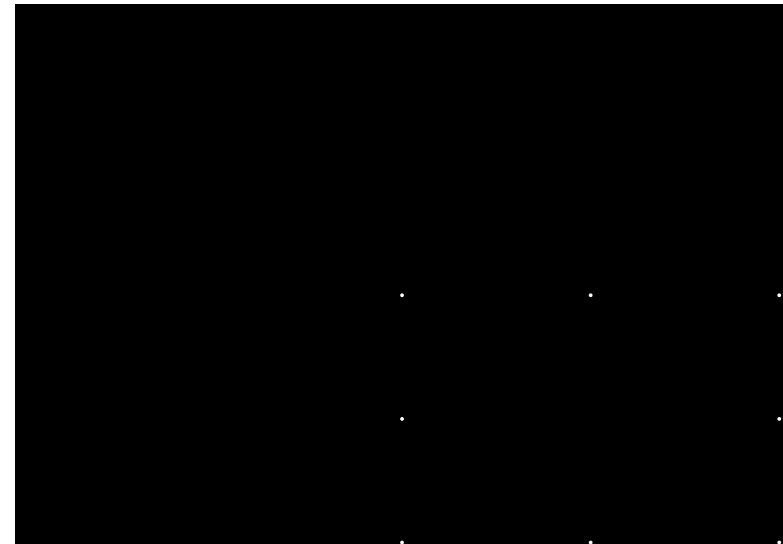
ESTIMO – illustrative results

NB: The results are to illustrate some of the functionality of ESTIMO using different scenarios and meteorology. These are not related to the heat scenarios.

Flows in countries differ at any universal time (UTC: Coordinated Universal Time) because of different:
- Local times and therefore activity
- Service demands
- Weather
- Energy mix at consumer, intermediate and primary stages
- Storage levels
- International electricity trade

Energy Space Time

District heat supply in DH scenario – 2010 meteorology

District heat can dynamically switch between:
Heat pumps - CHP - Boilers - Heat storage
and so help manage the wider energy system
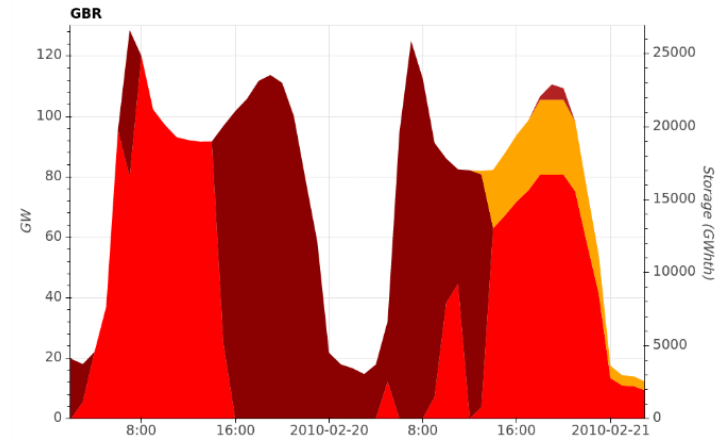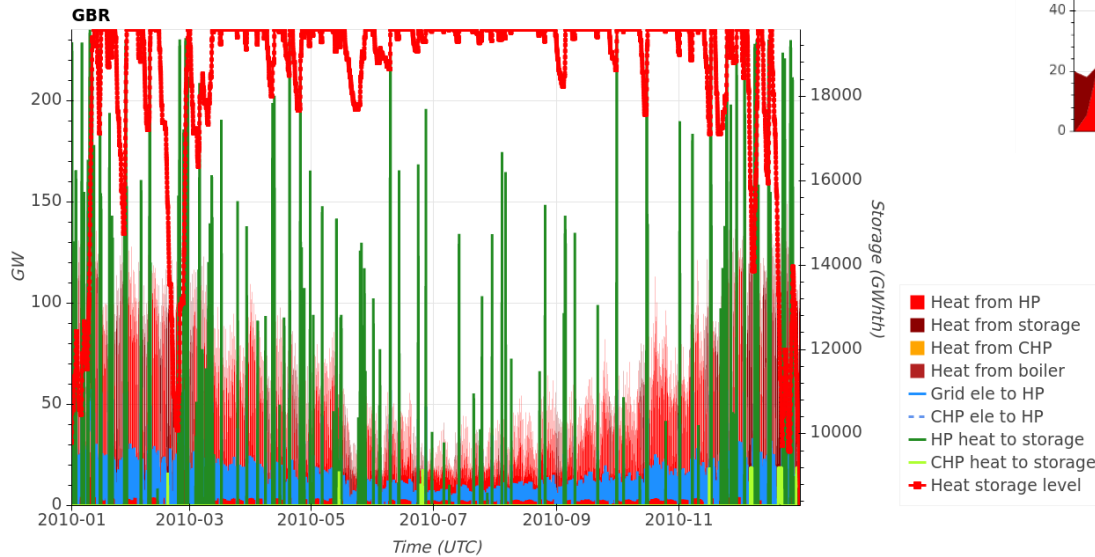
ESTIMO – weather impact on battery electric vehicles (2030)

Vehicles are buildings on wheels and need heating and cooling like buildings, which affects their total demands and system efficiencies. ESTIMO includes a model of the effect of weather on EV demand.

In case of extreme weather events – like low winds and low temperatures – renewable generation could be low for several days and might not be able to meet electricity demand. The plots on the right show how social and weather patterns heavily influence a future UK energy system in 2030.

During the 10 days in December shown by the plots, in a typical winter weather (as in 2004), EV batteries were fully charged (light blue area). During extreme weather (as in 2010), EV batteries would be left almost empty for several days in a row.

Typical weather (2004)
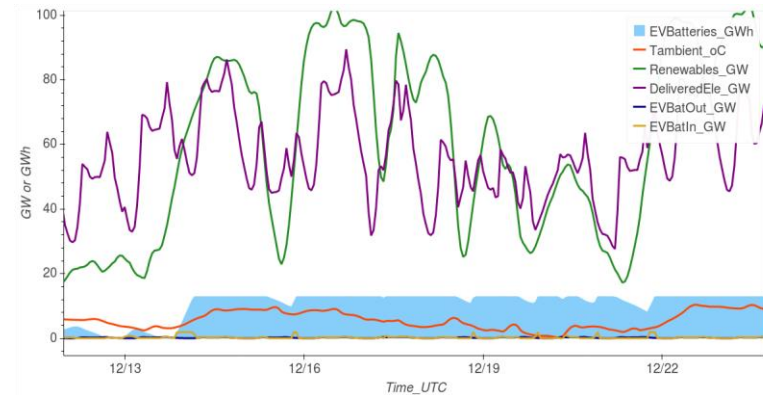
Extreme weather (2010)

Energy Space Time
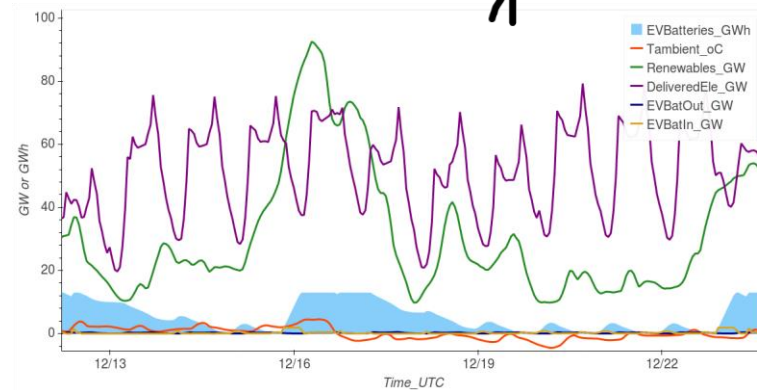
ESTIMO – district heating
(hourly simulation for one month)

Shows heat demand and heat pump, CHP, and boiler heat input varying with demand level and renewable surplus. District heat a valuable subsystem for managing larger system. Flows are different in GBR and FRA because of local time difference and weather.
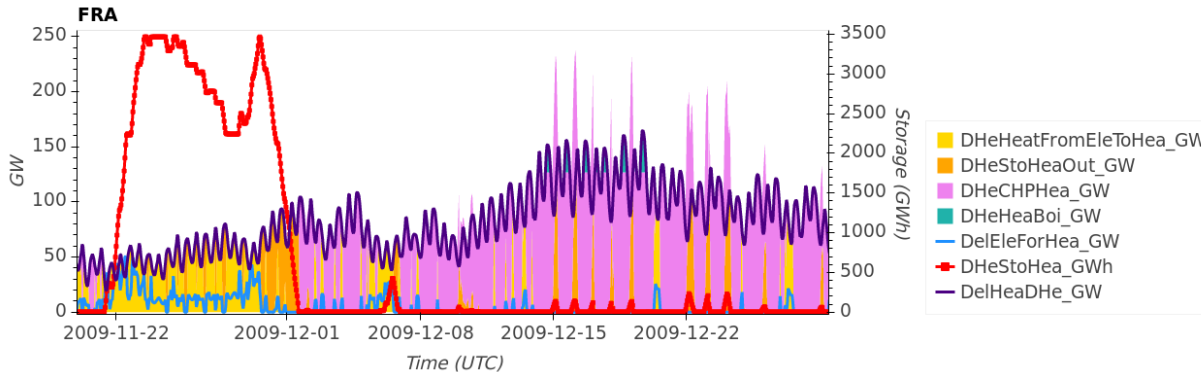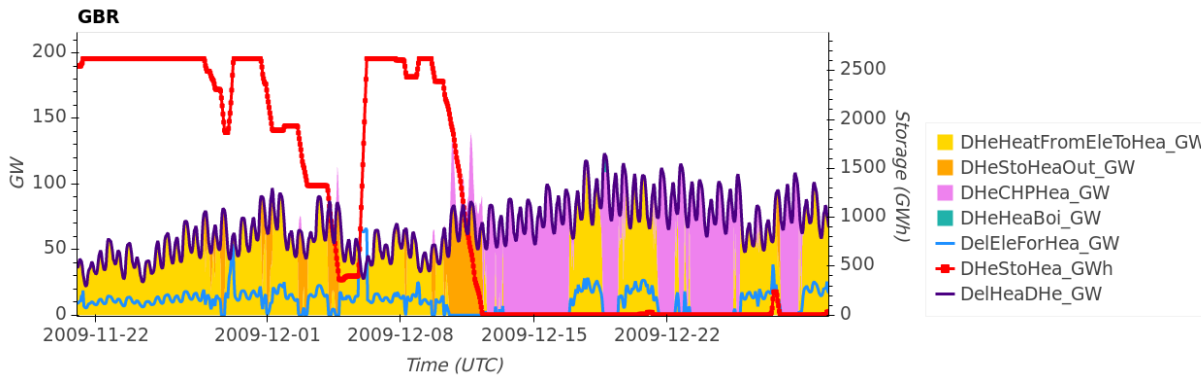
ESTIMO – district heating (annual sum)

Demand and heat pump, CHP, boiler heat input varying with demand level and renewable surplus. District heat is a valuable subsystem for managing larger system.

Flows are different in GBR and FRA because of weather.

Energy Space Time
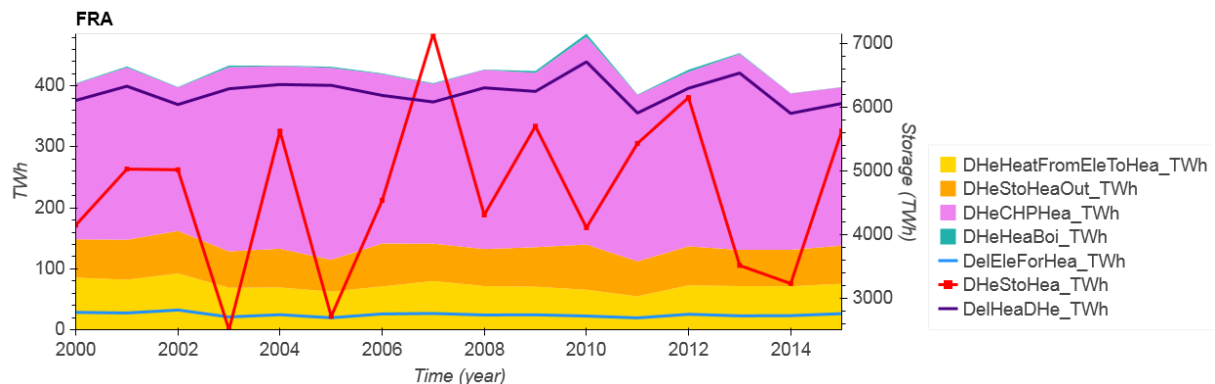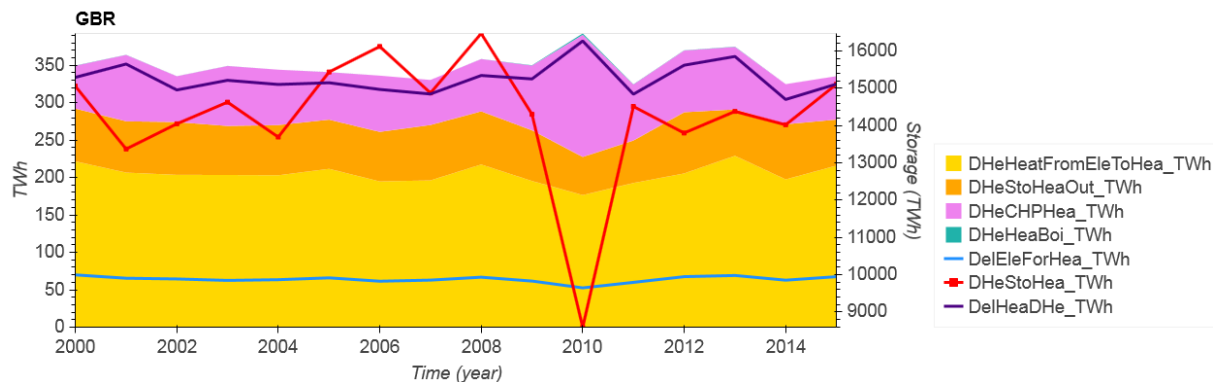
ESTIMO – electrofuels (hydrogen,ammonia) demand, production, storage

Electrofuels are for powering ships, and dispatchable electricity and heat supply. Flows are different in GBR and FRA because of local time difference and weather.
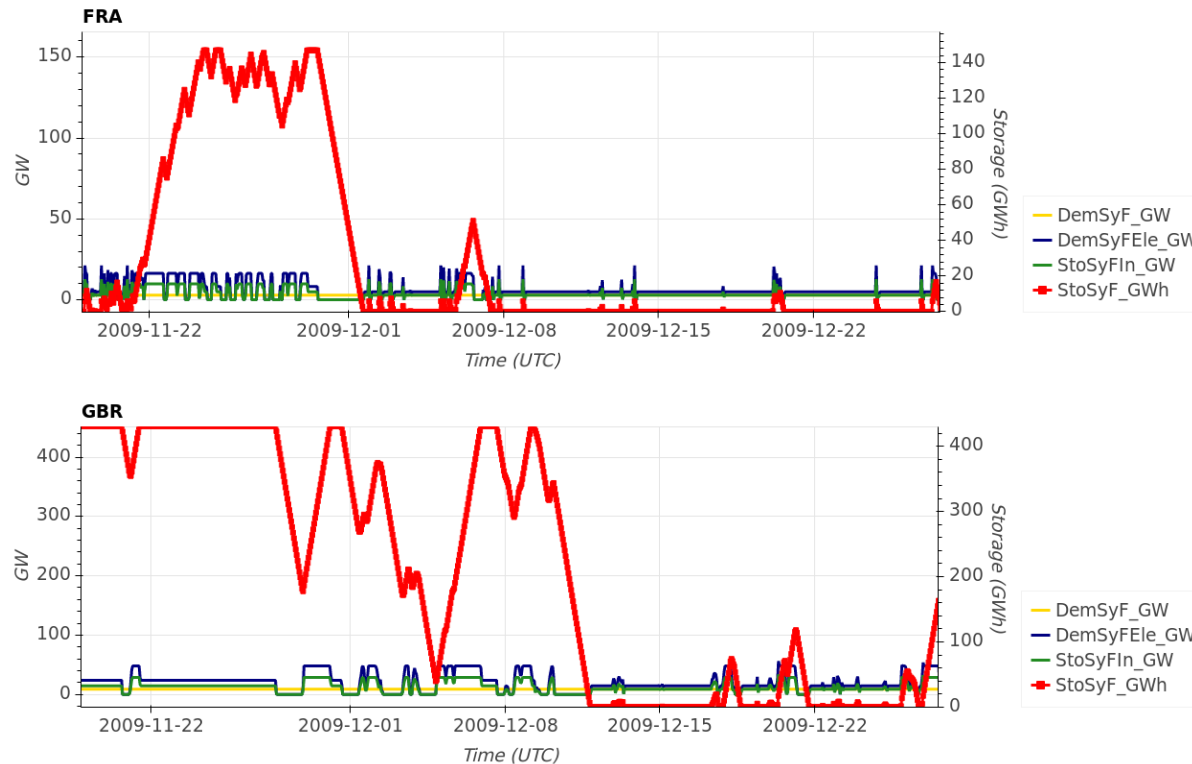
ESTIMO – weather and renewable generation

Prolonged periods of high demand and low renewables stress the UK energy system determining minimum storage needs. E.g. 2010 is a stress year with a period that is cold, so high heat load, and also low wind.

Energy Space Time
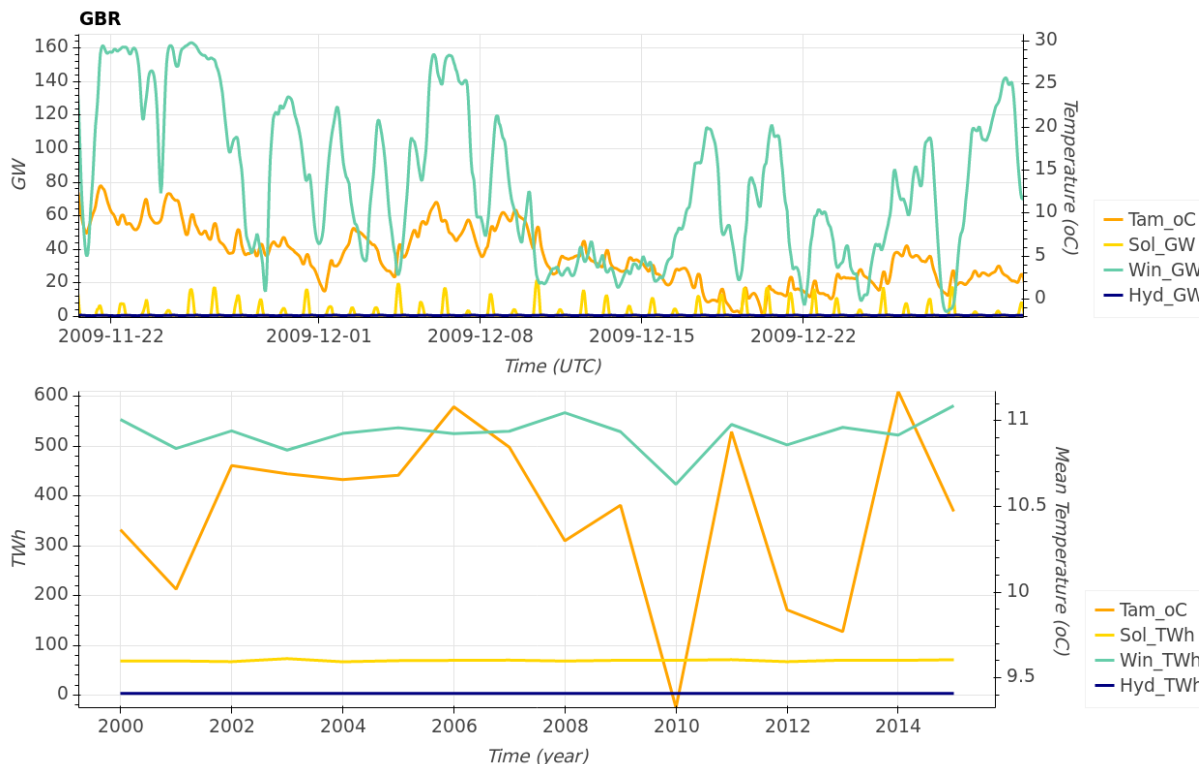
ESTIMO – heat supply
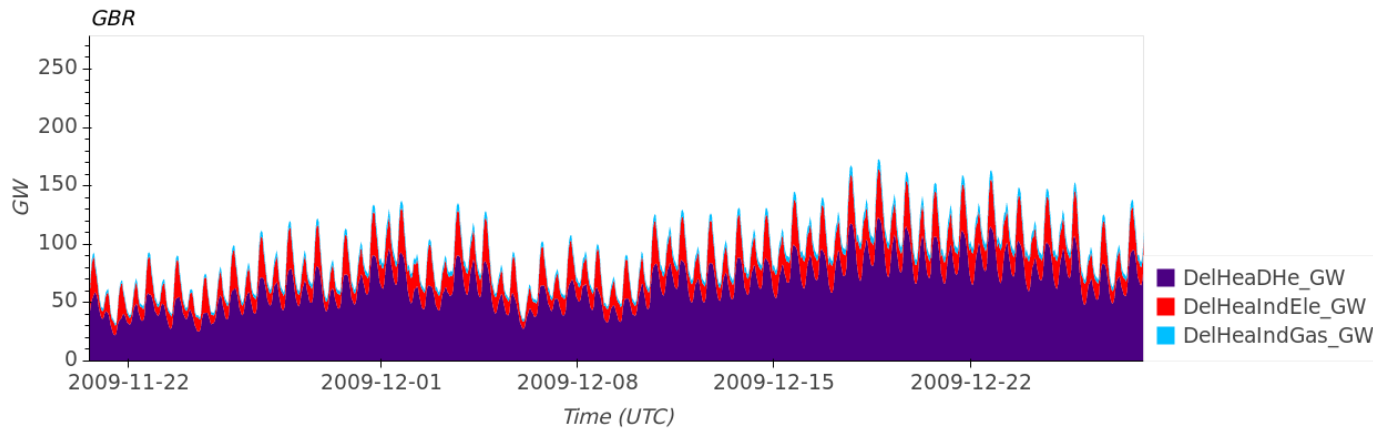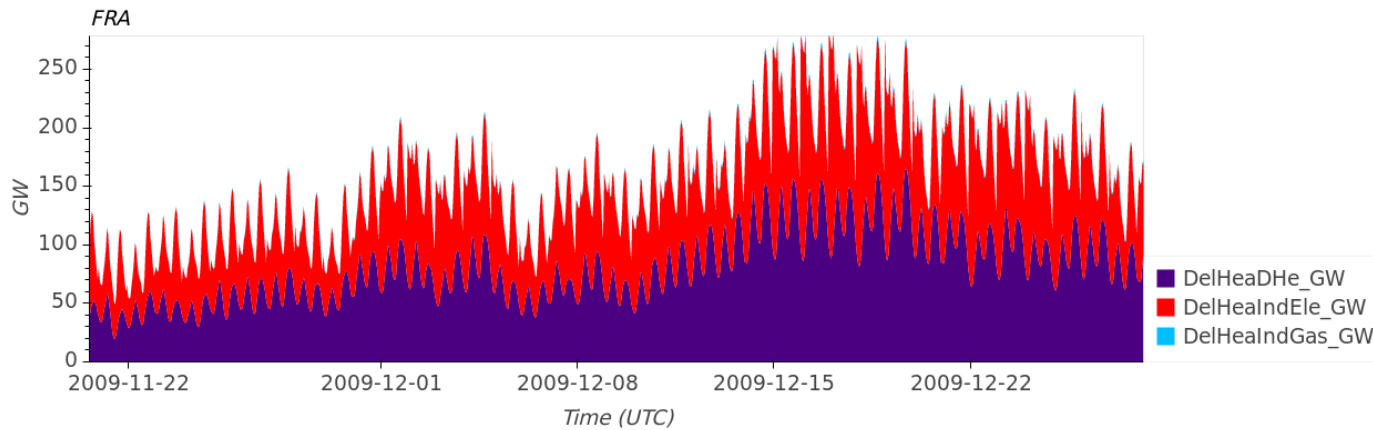
ESTIMO – gas

Natural gas is used if no other energy is available and is used in DH CHP and boilers, and in electricity only generators (PstGas).
[**NB**: in the zero emission scenarios no gas or other fossil fuel is used.]

ESTIMO: Energy Space Time Integrated Model Optimiser

International system
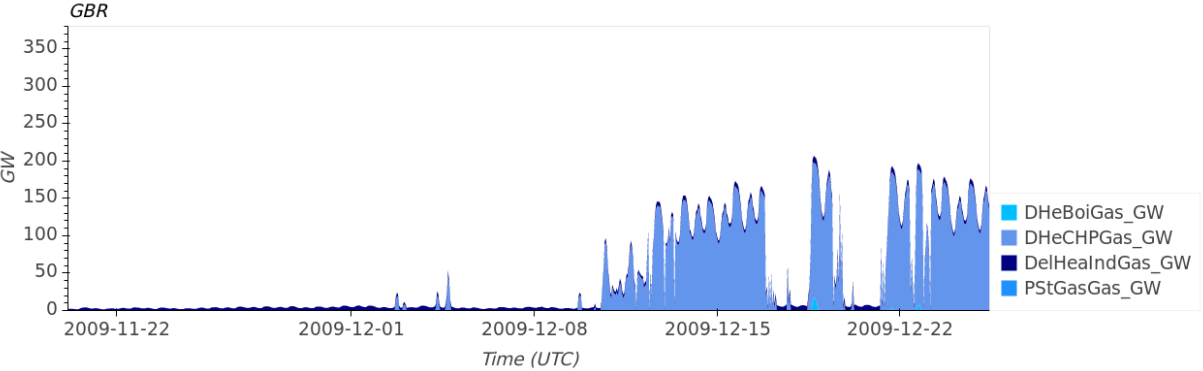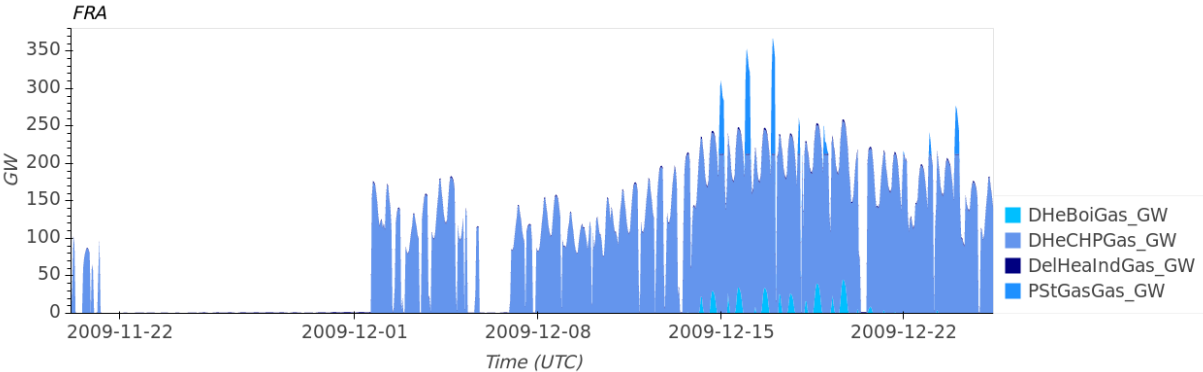
ESTIMO for zero emission system design

- Hourly simulation with up to 35 years' meteorology
- Demands using social patterns and weather
- Renewables, storage and interconnectors
- System economics
- UK + 4 European regions => 5 nodes
- Assessment of heat pumps, district heating and hydrogen
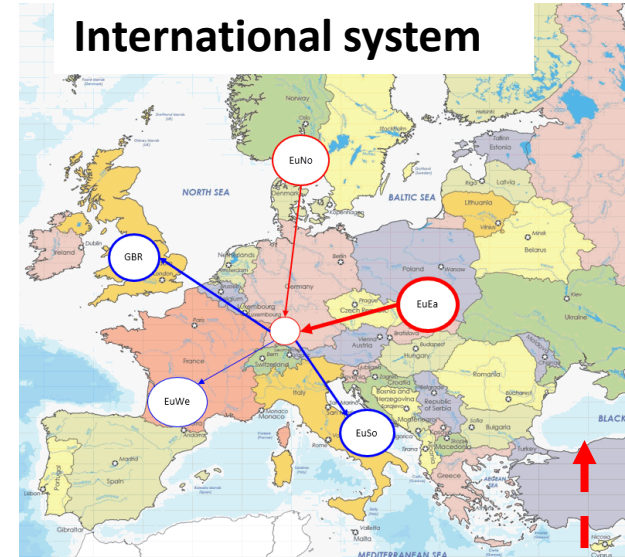
Energy demands
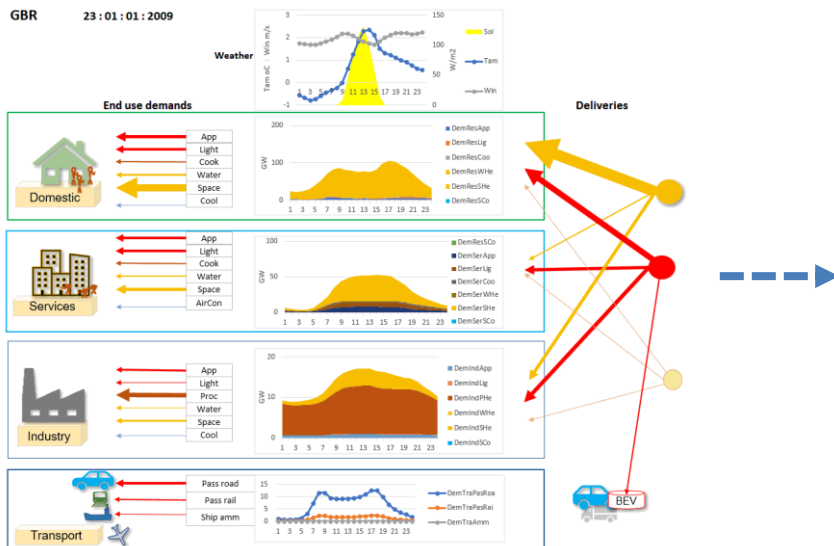
National systems
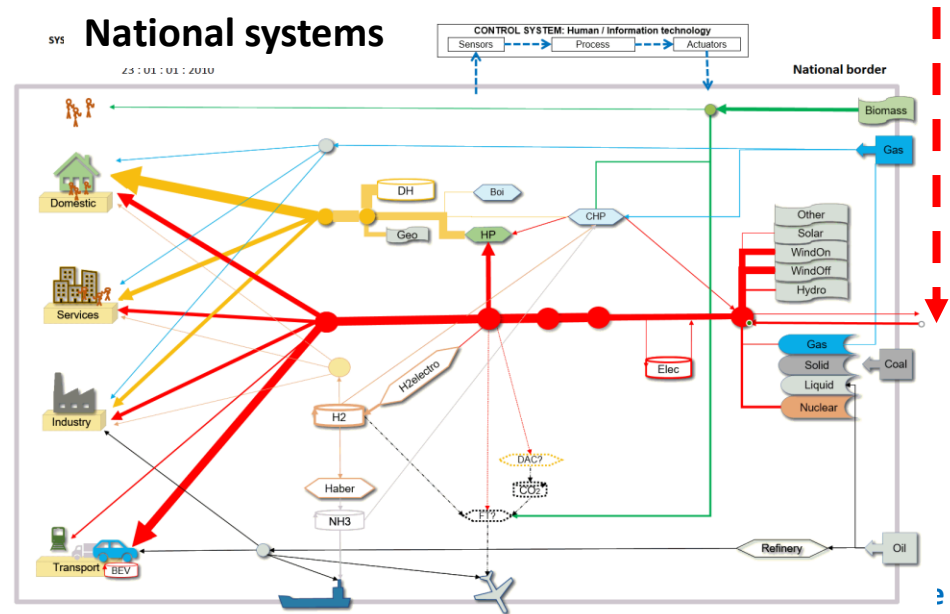
District heating integration with renewable electricity

Heat model

Heat demand

Electricity model

Consumer HP

Ele demand

Renewable

Flexible

Base load

Grid

Elec prices

DH model

DH HP

DH Heat

DH
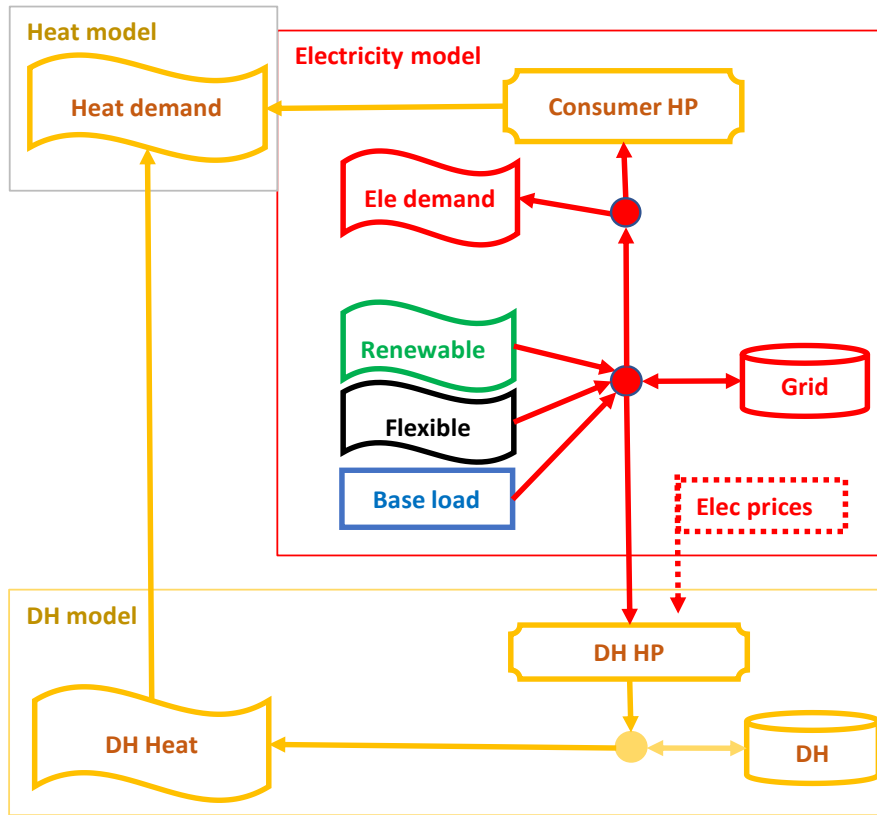
Electricity demand
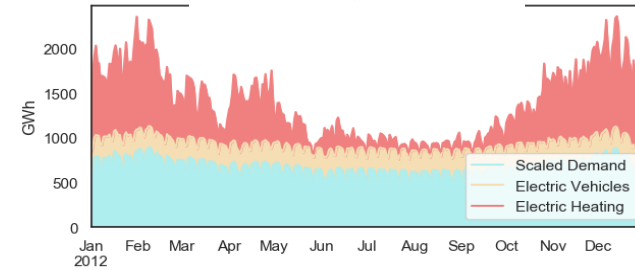
Generation
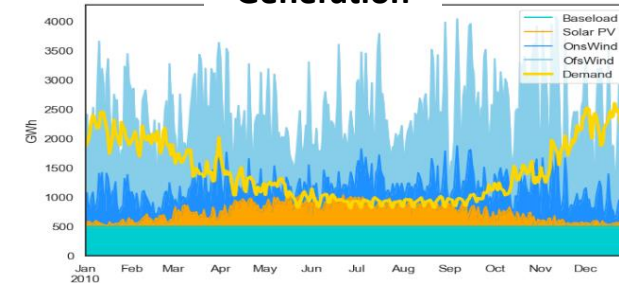
Price Duration Curve
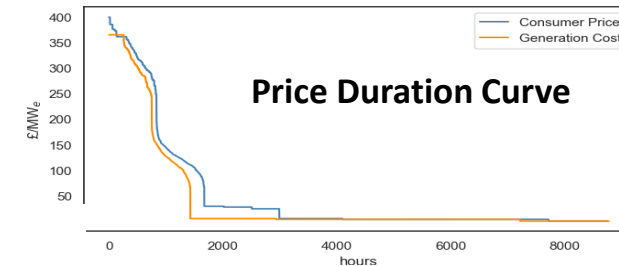
Daily mean cost
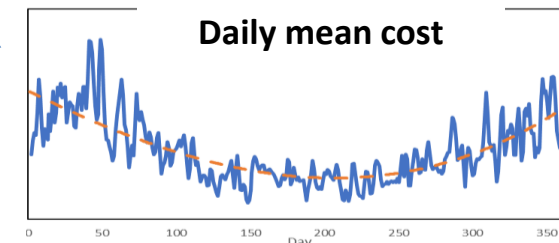
DH operation optimization using heat storage reduces:

- heat pump electricity cost by 60%

- grid storage need - 3.5 GWhth displaces 1 GWhe

- grid storage by about 40% with 10% DH UK heat share

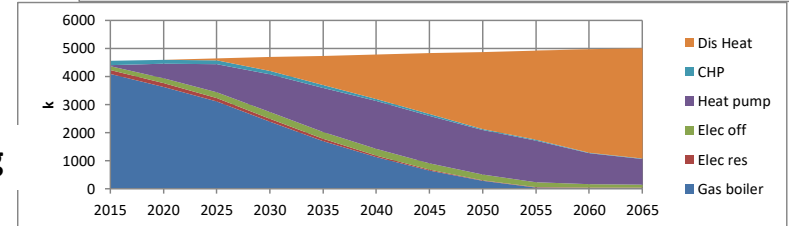- electricity system costs and DH costs relative to heat pumps

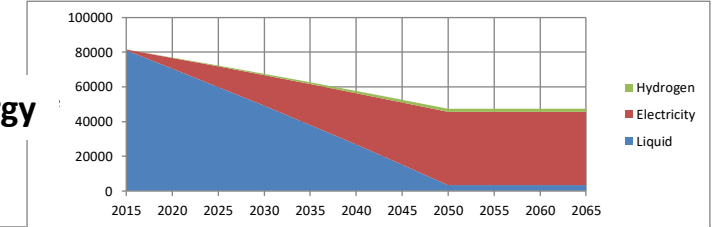# SEECity model

Long term scenarios:

- Energy demands of stationary and transport sectors
- Spatial energy demands
- Energy efficiency and switching to renewable electricity
- District heating algorithm
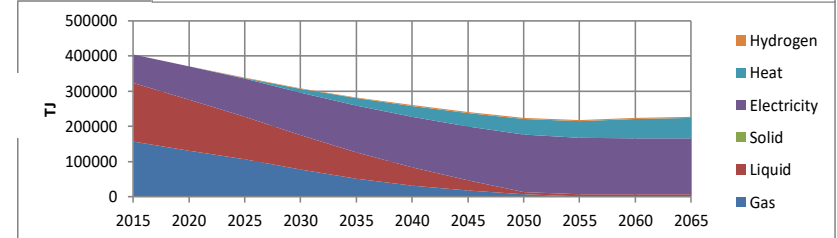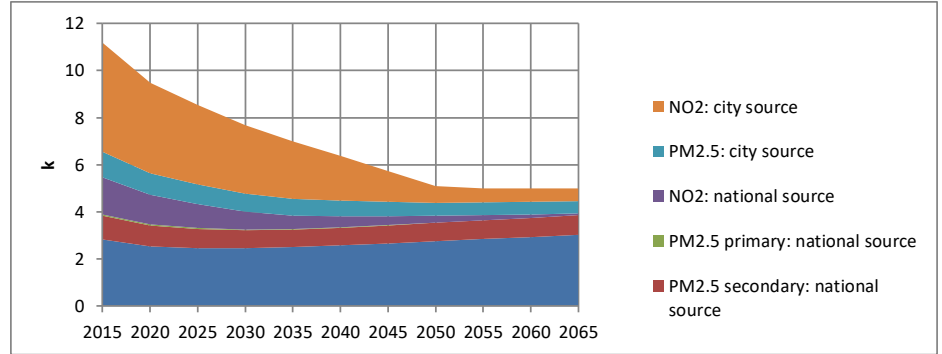- Economics
- CO2, and air pollution and health

Heat load

District heating

Services
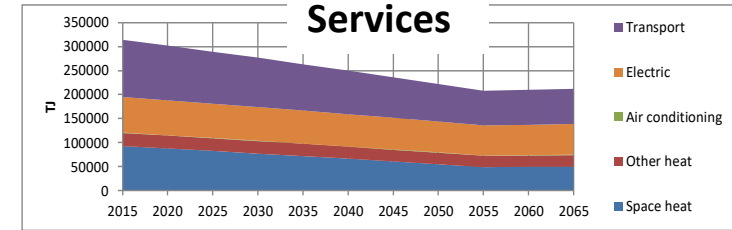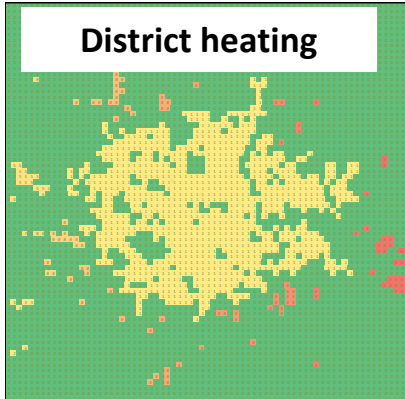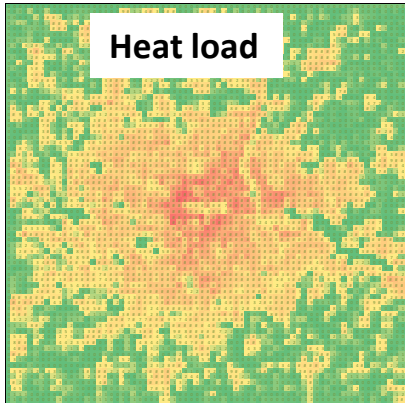
Heating

Transport energy

Electrification

Health: premature deaths by pollutant and source

Plans

Engage with BEIS, CCC, NG, OFGEM, DfT…
- Heating and cooling options
- Electricity system and market pricing
- Electric vehicle integration

Refine, extend and apply models
- Cooling – individual and district cooling
- Aviation fuelling, Direct Air Capture, Fischer Tropsch
- Develop real time electricity market algorithm
- Extend beyond Europe

Energy Space Time

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.

Siddiqui, S., Barrett, M. and Macadam, J. (2021) 'A high resolution spatiotemporal urban heat load model for gb', *Energies*, 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', *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.

Energy Space Time