UCL

# Meeting UK heat demands in zero emission renewable energy systems using storage and interconnectors

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December 2020

Run presentation to see animations

# Structure

Design overview

Model

System

Demand

Heating systems

System results

Gas systems

Comparison of systems

# 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

# Design overview

# Design procedure

**A. Demand assumptions for each European country**

**B. Collate 35 years' historical meteorology and renewables for each European country**

**C. Aggregate to multi-regional scope – e.g. UK + 4 NSEW European regions**

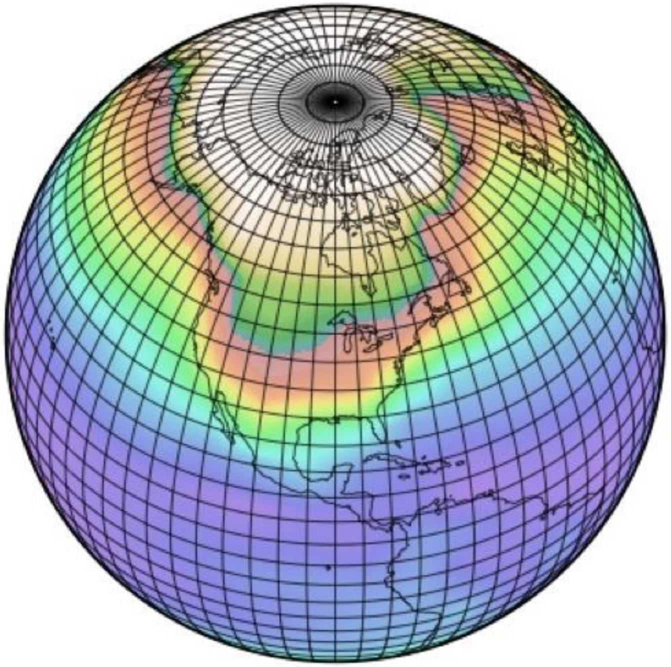
**D. Technology screening**

**Iterate**

1. Design system using manual and ancillary optimisation
2. Simulate hourly operation of system
3. Calculate costs

# Meteorology

- Decades of MERRA global hourly data at 0.5 degree Lat/Lon resolution available
- **Data collated for each European country** – 35 years 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

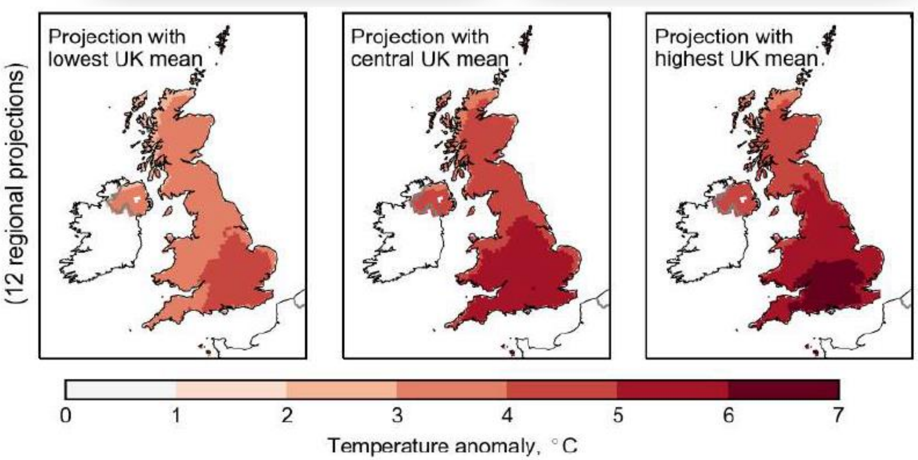


This data collation and modelling by Dr Ed Sharp

# UK climate projection for late 21$^{st}$ century

**UKCP18 National Climate Projections. MetOffice, 2018**

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




**Consequences for comfort, heating and cooling and renewables?**

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

# Designing low emission energy systems for a changed climate

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

**Scales**

- Building to city to national to international

**Demands**

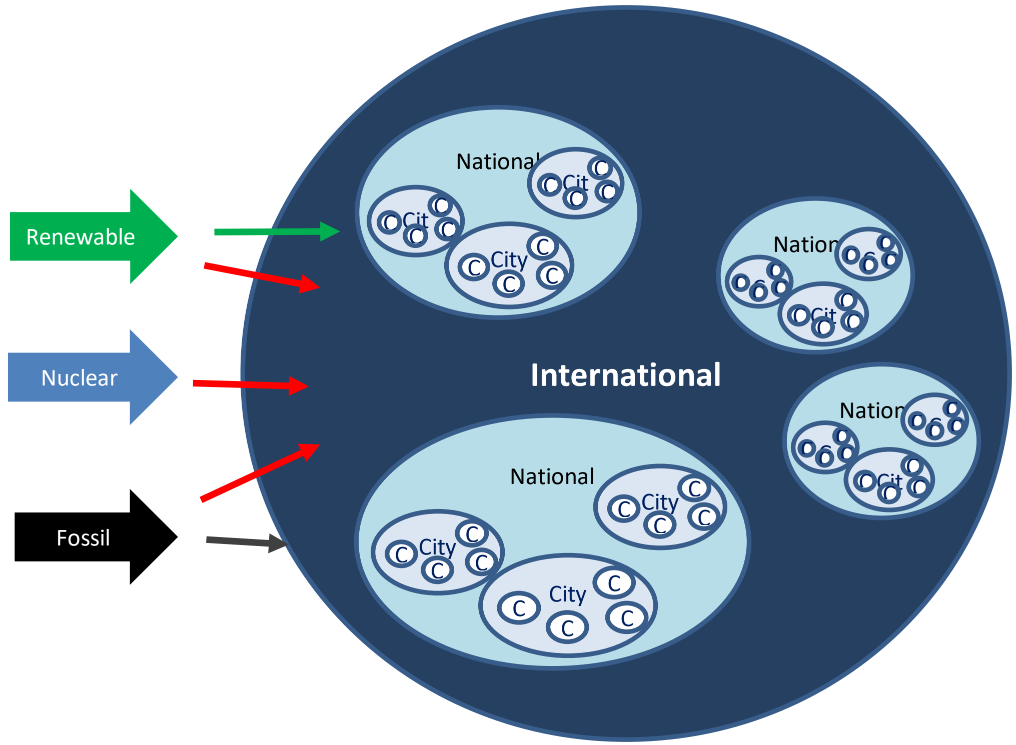
- Heat, cool, power, electricity…
- Domestic, services, industry, transport

**Energy sources**

- Renewable
- Nuclear
- Fossil

**Vectors**

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



# 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 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 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 |

# 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. Ammonia during production, storage and use in ships
- Industry, agriculture, waste processes
- Biomass – cultivation, processing and use
- Indoor air pollution - indoor combustion appliances

**Other impacts**

- Heat pump fluids – can be zero GWP
- Hydrogen from electrolysis – water, chemicals
- Direct Air Capture – chemicals, water
- 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

# 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? |

# 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

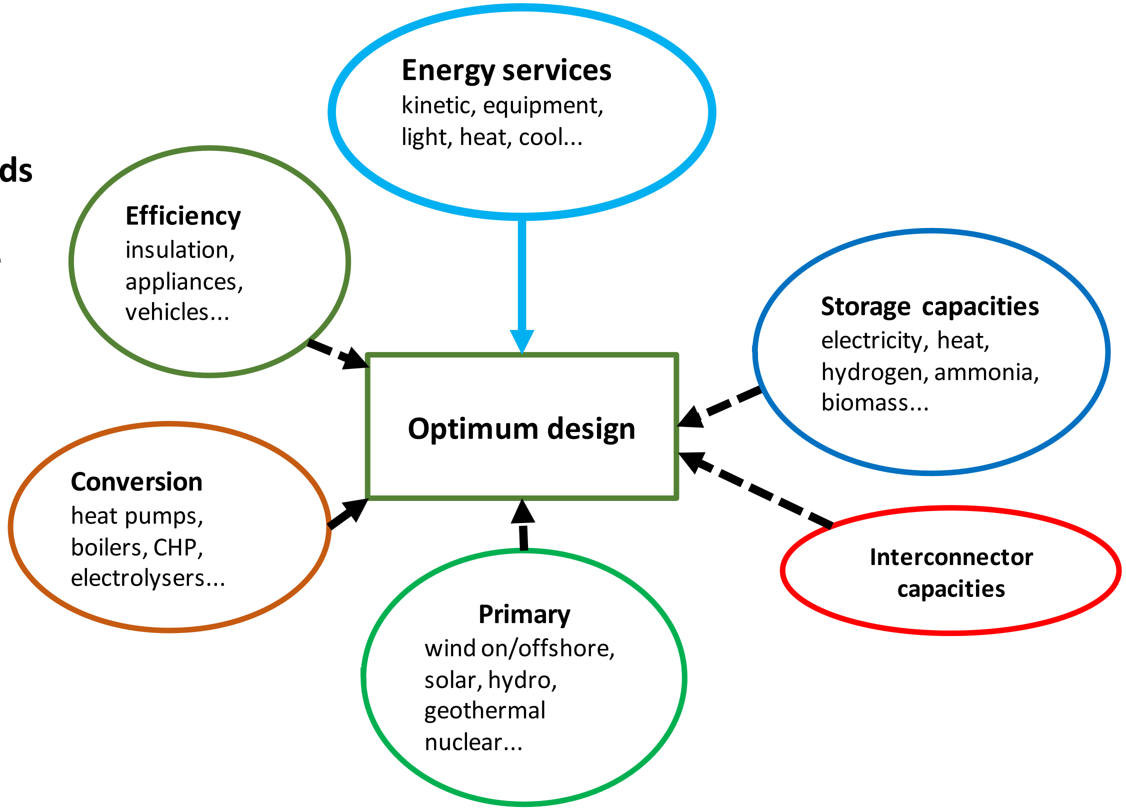
- **Forests, soil etc.**
- **BECCS** Biomass combusted and CO2 or char buried/sequestered

**DAC** Direct air capture of CO2 from atmosphere – unproven, costly, chemical inputs, water use, but best?

# 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

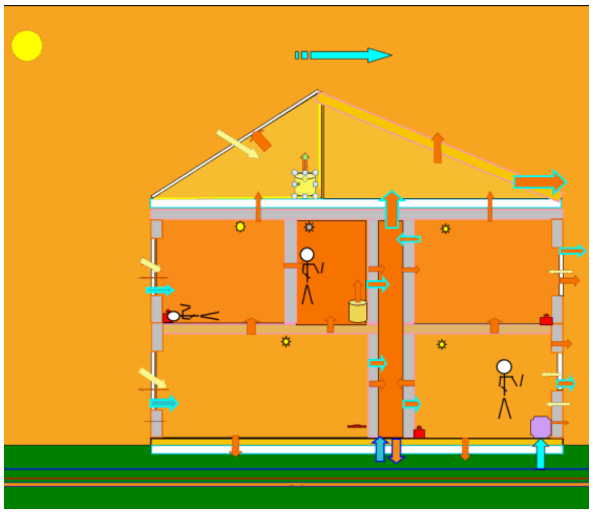


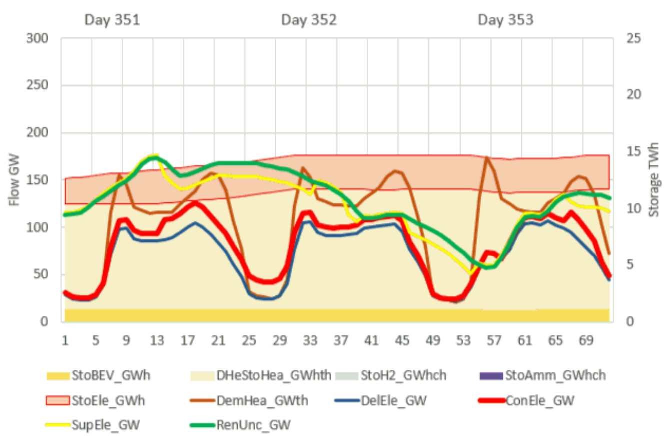
# Some modelling questions

1. How will hourly demands and renewables vary?
2. Which generation, storage and transmission technologies will be included?
3. What temporal and spatial resolutions are required for accuracy?
4. How will the system be controlled hour by hour to best use renewables with storage and interconnectors?

# Model

# Varying demands and generation - storage, transmission



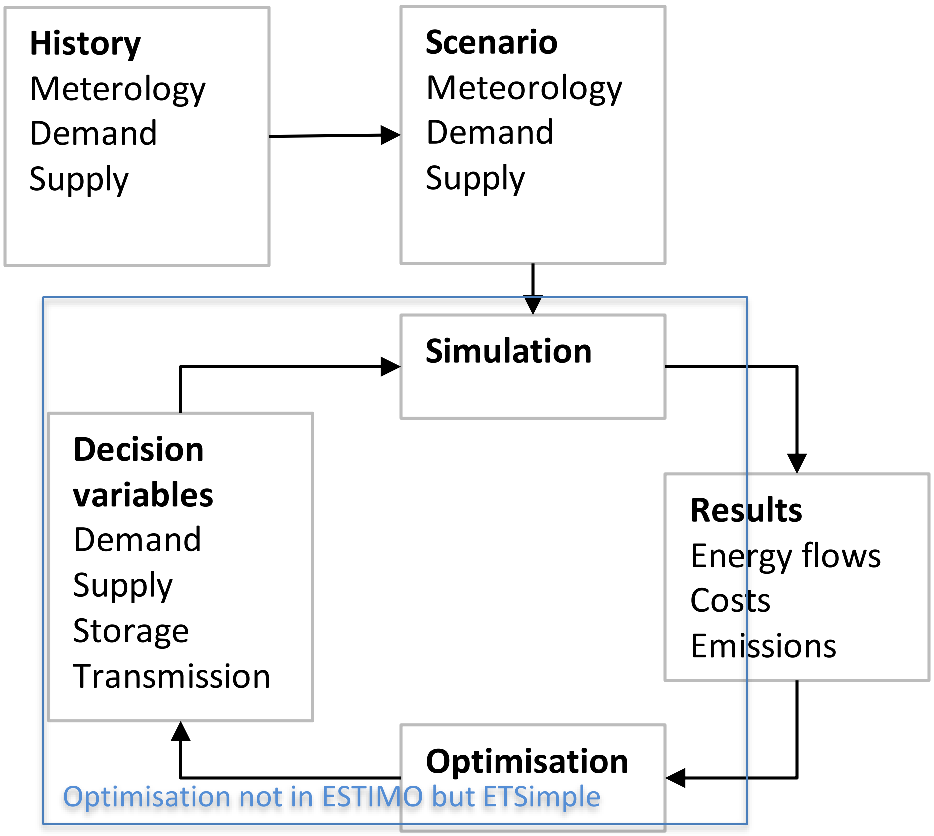


# ESTIMO – Energy Space Time Integrated Model Optimiser

**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



# 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

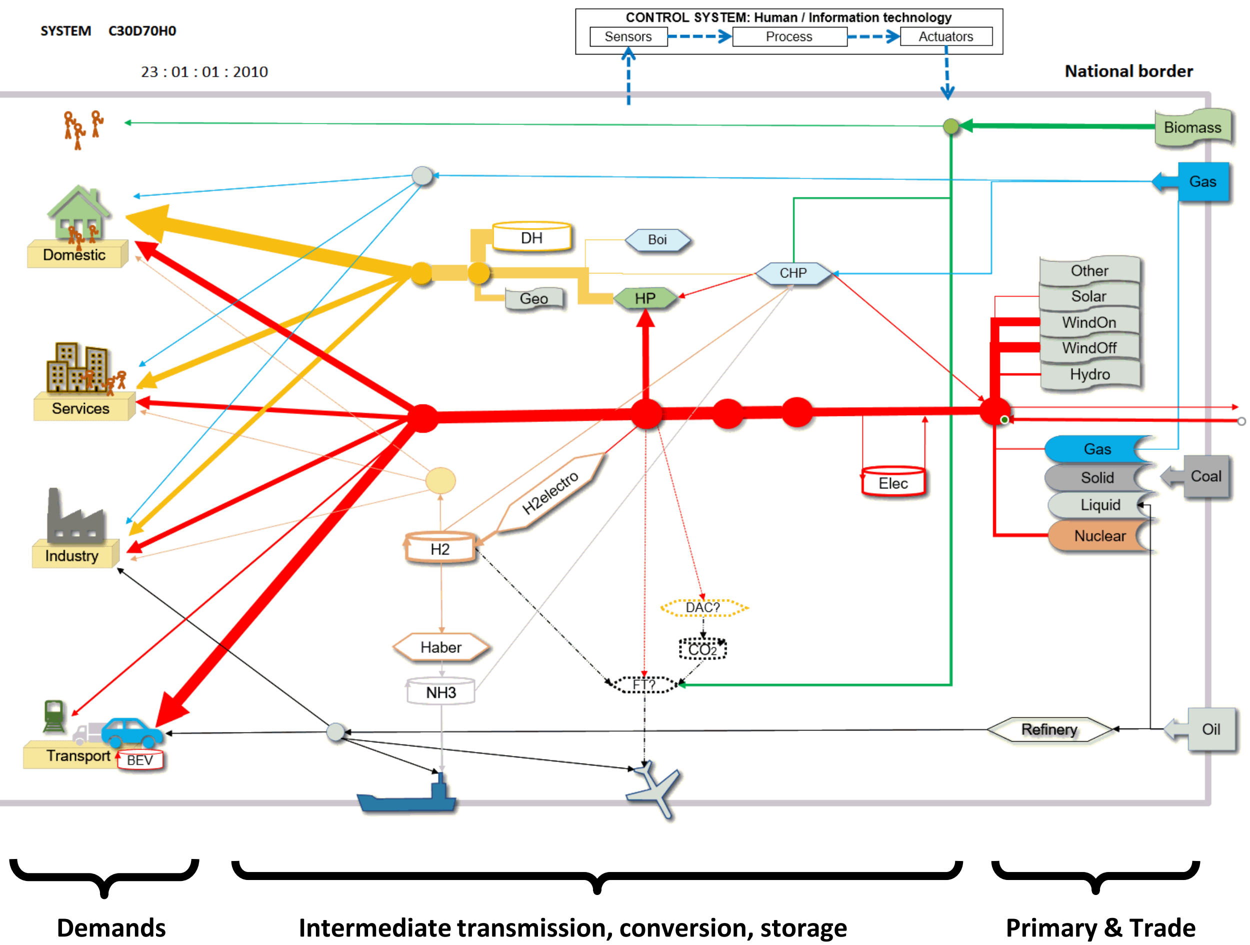
# A national energy system

**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



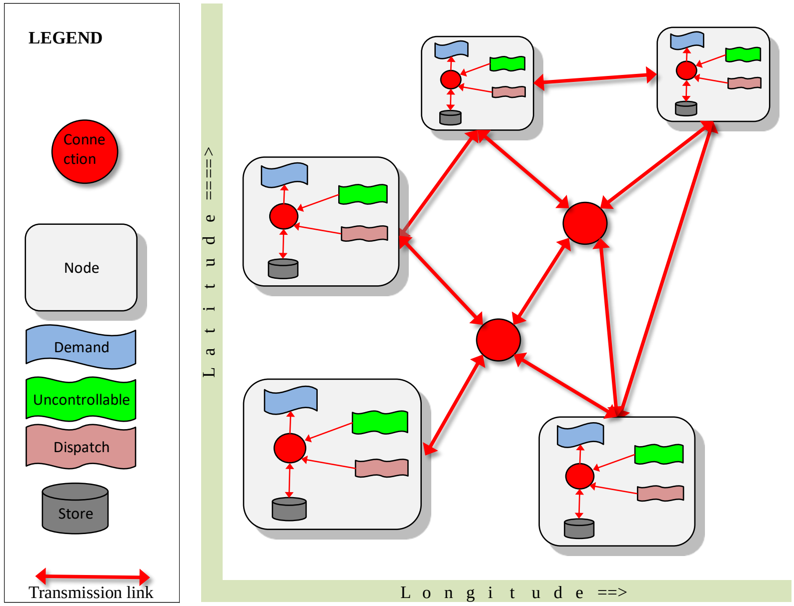



Energy Space Time

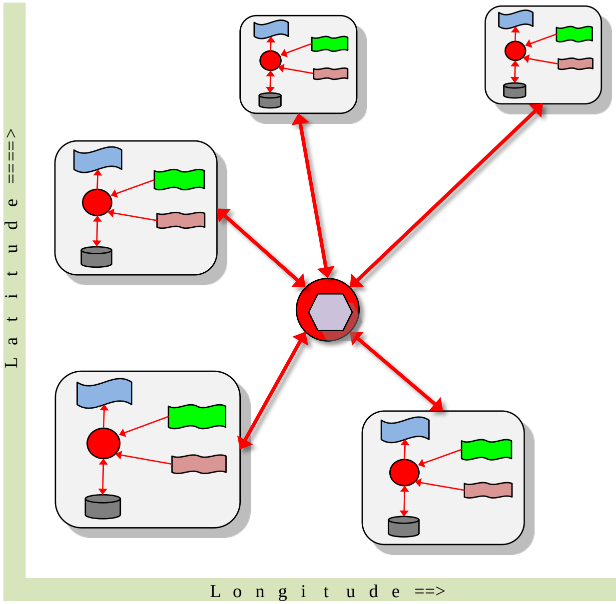
# ESTIMO – interconnector network topology

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



# 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

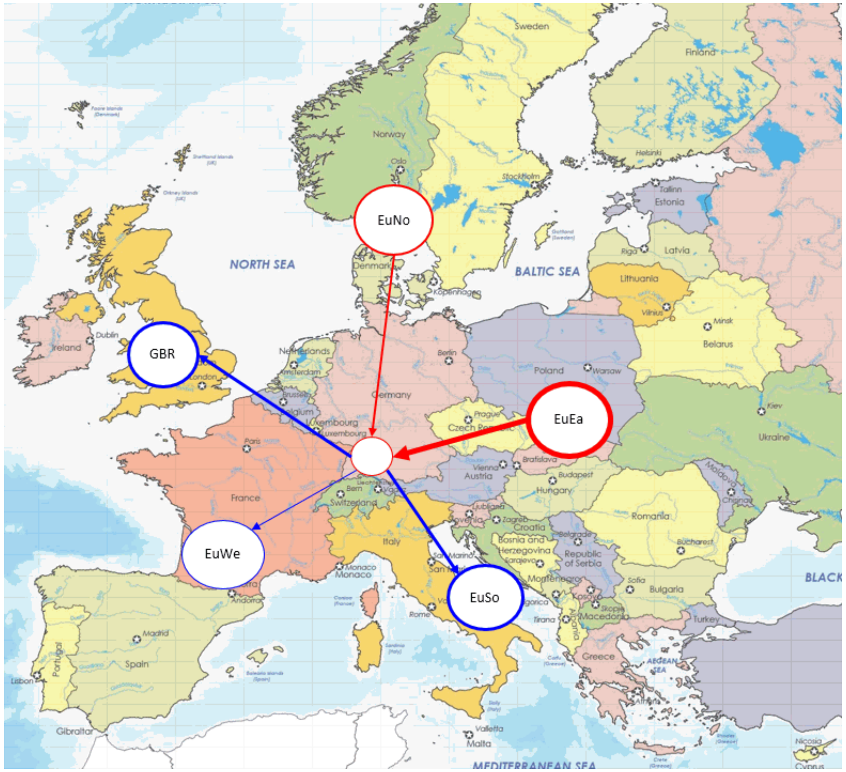
# Interconnector trade

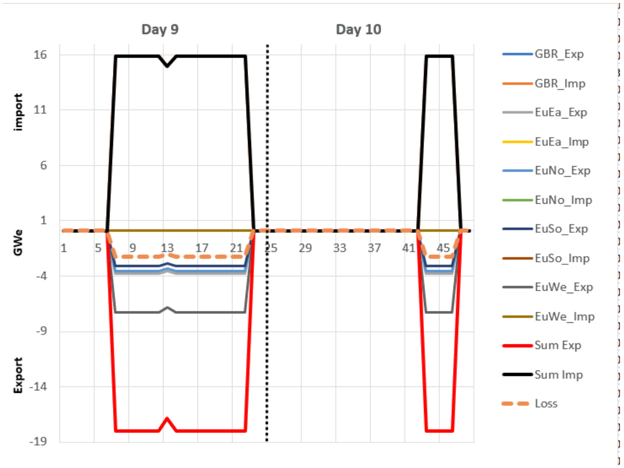
**ESTIMO concurrently simulates:**

**Energy systems at each node with different simultaneous:**

- Demands because of local weather and time zone differences
- Renewable supply because of local meteorology

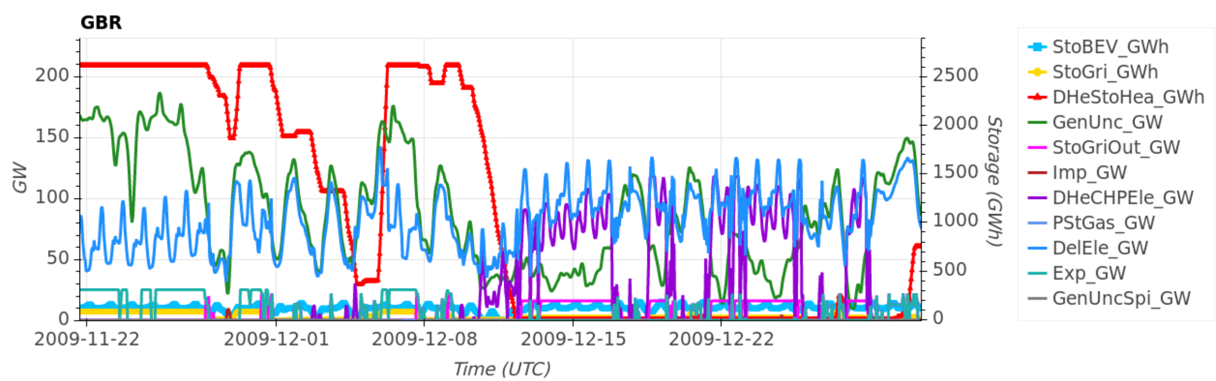
**Interconnector transmission** trade of renewable surpluses and deficits at different nodes, this can greatly reduce storage need.

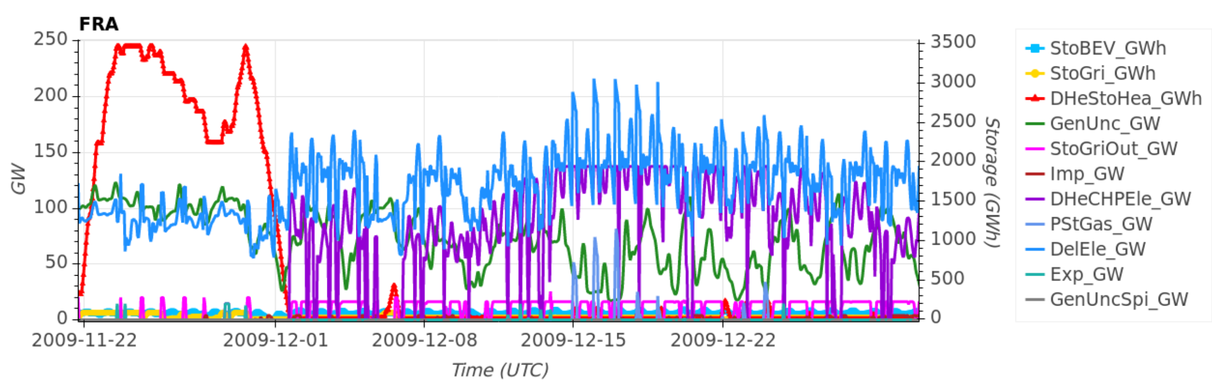


# ESTIMO– electricity system integration (simulation hourly for one month)

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



# 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.

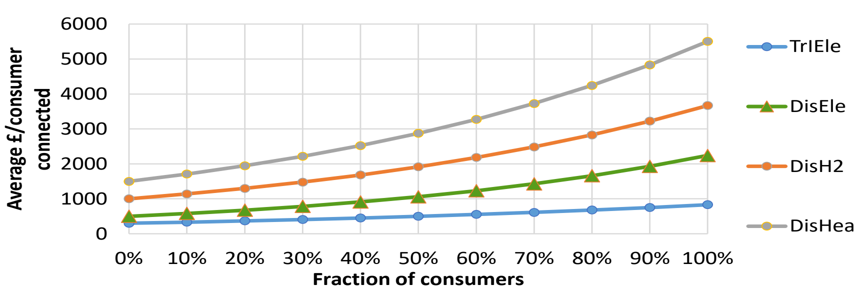
* https://ens.dk/en/our-services/projections-and-models/technology-data

## Conversion and storage costs

Heat pump efficiencies are fractions of Carnot efficiency

| Technology | Unit | Tech Size | Effi-ciency | Capital Projection Index | £/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 |
| Solar PV | kWe | 10000000 | | 100% | 7000 | 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

# Demands

# 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 – 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 Di are modelled simply: Di(h) = U(h) (Average annual demand) Watts

**Weather dependent** demands Dw are primarily driven by ambient temperature (Ta 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 (Ti oC), specific heat loss (SHL) of the building or vehicle, and incidental gains (I) from people, appliances and solar radiation: Dw(h) = U(h) [SHL (Ti-Ta) – I] Watts. This enables the exploration of varying internal temperatures and efficiency (insulation etc.), as well as past and future climates.

If Dw>0 then there is a space heat load, if Dw<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.

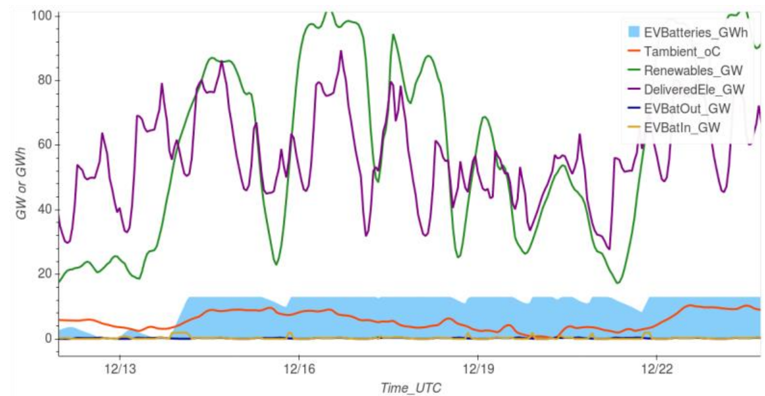
# ESTIMO – weather impact on battery electric vehicles (2030)

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.

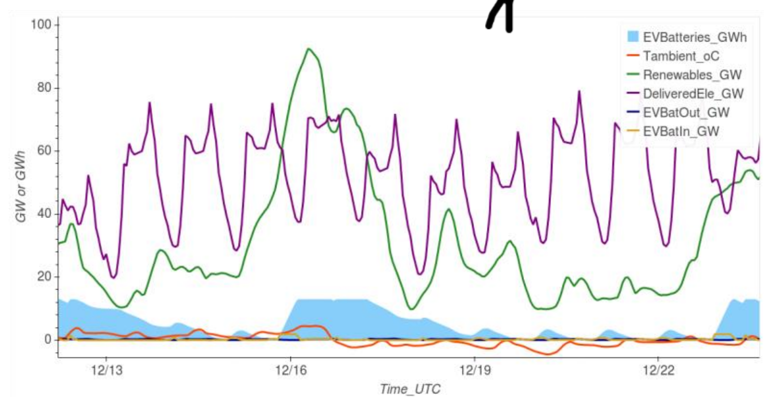
In case of extreme weather events – like low winds and low temperatures – renewable generation could be low for several days and might not be able to meet electricity demand. The plots on the right show how social and weather patterns heavily influence a future UK energy system in 2030.

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)**



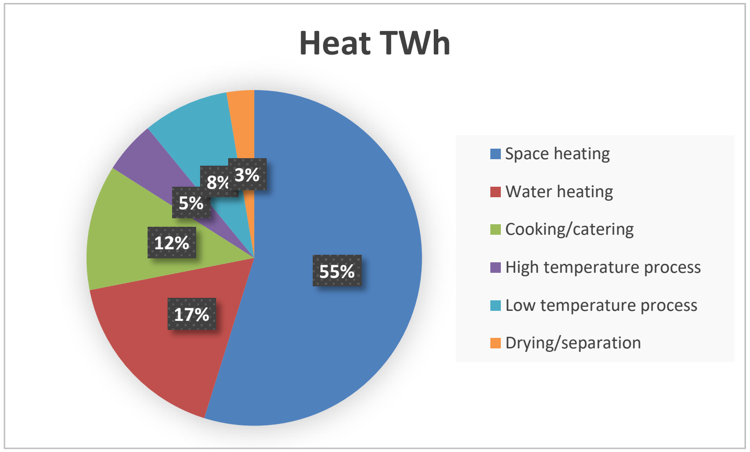
# Heat demand and emissions

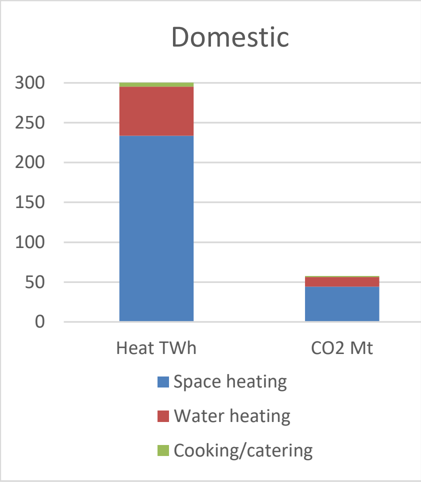
We can estimate heat **emitted** from boilers etc. But this is not service, as **not all emitted heat is useful**. We want comfort not heated buildings.

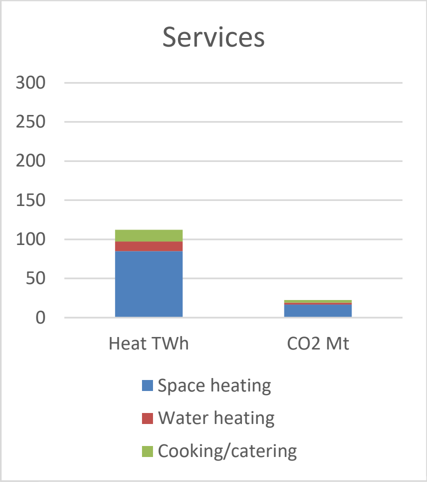
**Heat accounts for about half of UK energy CO2 emissions.**

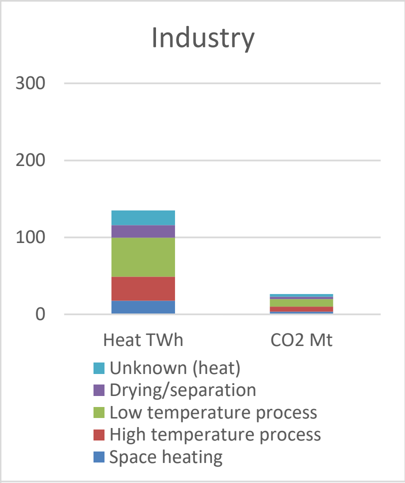
**Future heat demand** will be affected by population and economic growth, efficiency (insulation) and climate change.

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



# Heat 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 <u>emitted</u> 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 CO2 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%** |

# Annual: heat and cooling demands

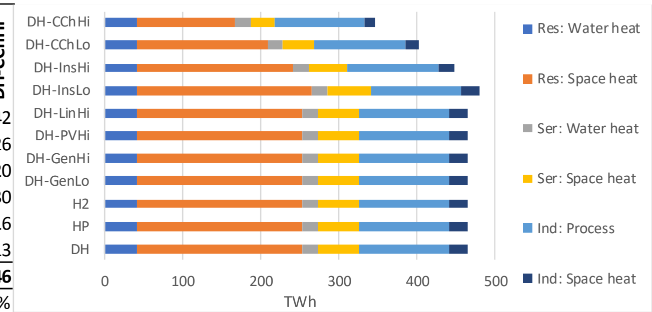
**Total heat demand** in the core scenarios is 464 TWh, similar to today's demand. This falls to 402 and 346 TWh in the climate change scenarios of +2 oC and +4 oC respectively.

**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

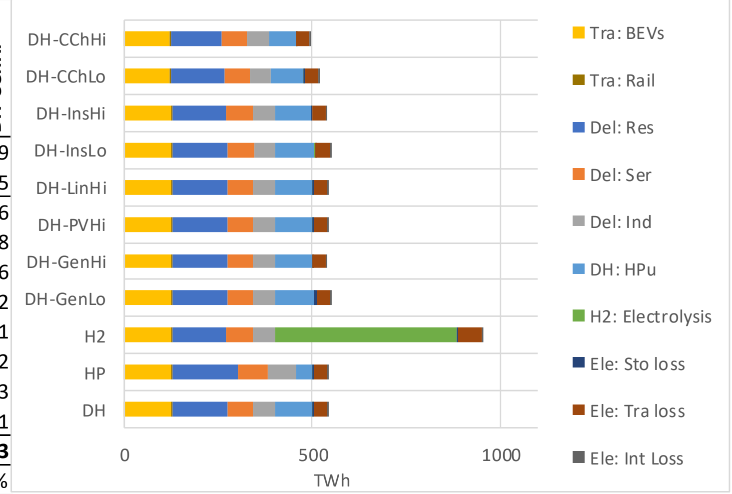
**Electricity consumption** includes that by:

- **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% |



# Heat demand variation

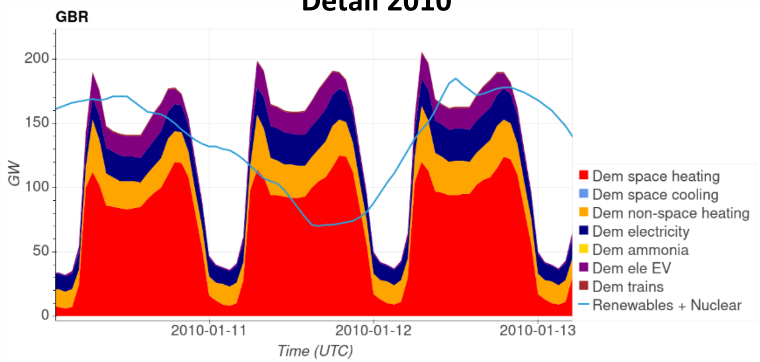
**Variation driven by:**

- Social activities
- Meteorology

**Stationary:**

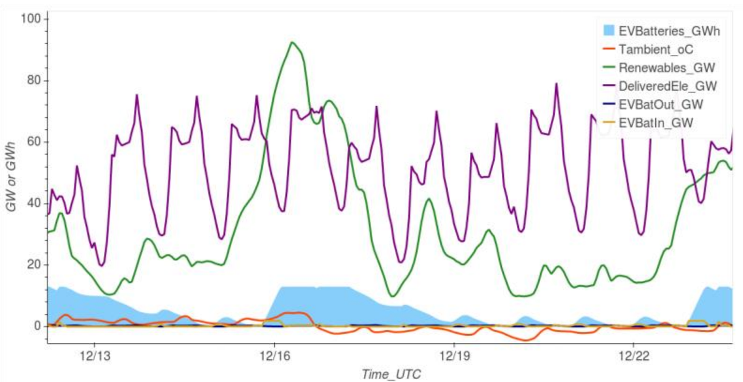
- Buildings
- Industry

**Detail 2010**

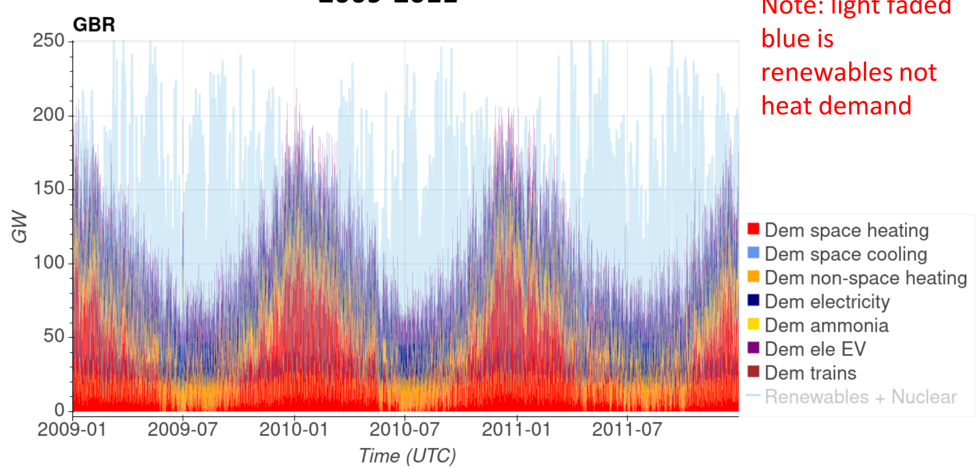



**Electric vehicles:**

- Buildings on wheels need heating/cooling!




**2009-2011**



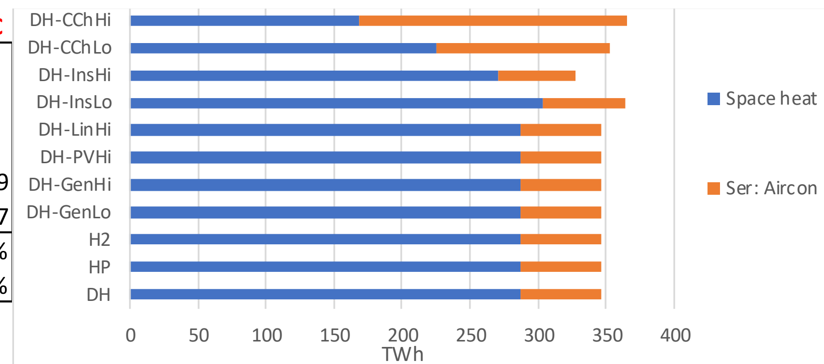

Note: light faded blue is renewables not heat demand

# 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.

| | | | | | | | | | | +2 oC | +4 oC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **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% |




Note: these are heat/cool demands, not electricity

# Heating Systems

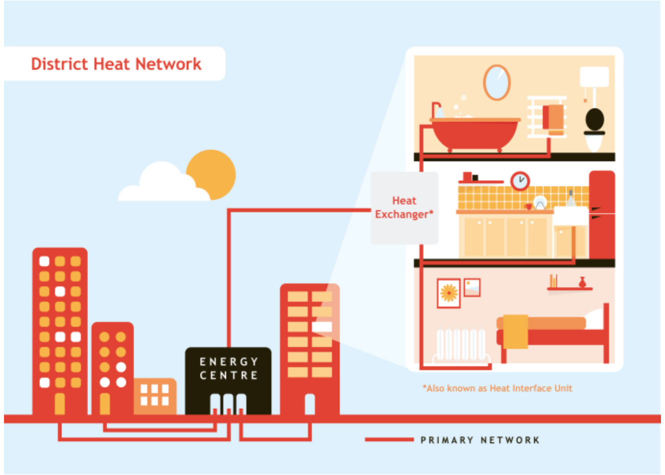
# Heating technologies using zero emission electricity

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

# 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?

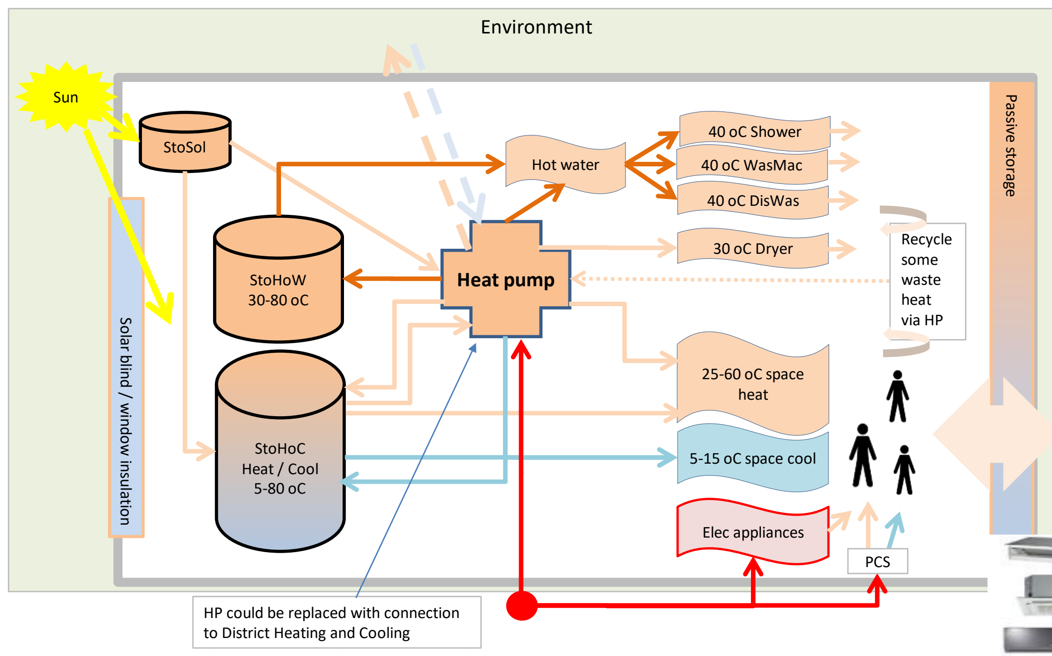
**A reversible electric heat pump** provides:

- 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)**?




**Split reversible air conditioner/heater heat pump?**

- Flexible, multi-function, spatiotemporal control.
- Hot water and heat storage in some systems.
- Millions installed

# Consumer heat and cool supply simulation – peak design conditions

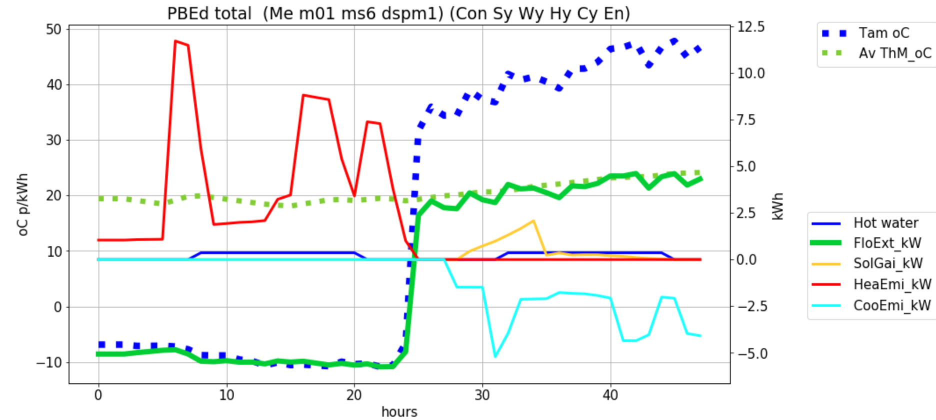
Human health requires air temperature around 16-26 °C. Climate change will mean UK summers 1-5 °C hotter, but still cold spells.

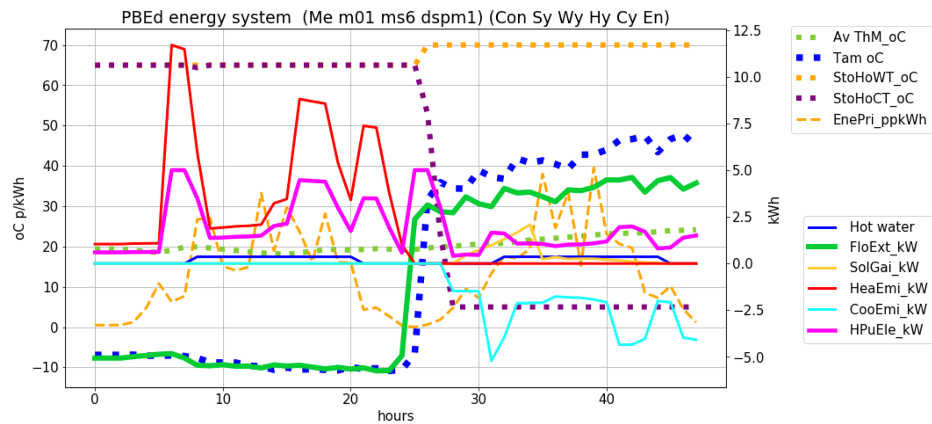
**A reversible heat pump can provide comfort in extreme cold and hot conditions**

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 =>**

Winter (extreme) | Summer (extreme)



# District heat – a flexible, multi heat source system

**District heating has a major system balancing** role using:

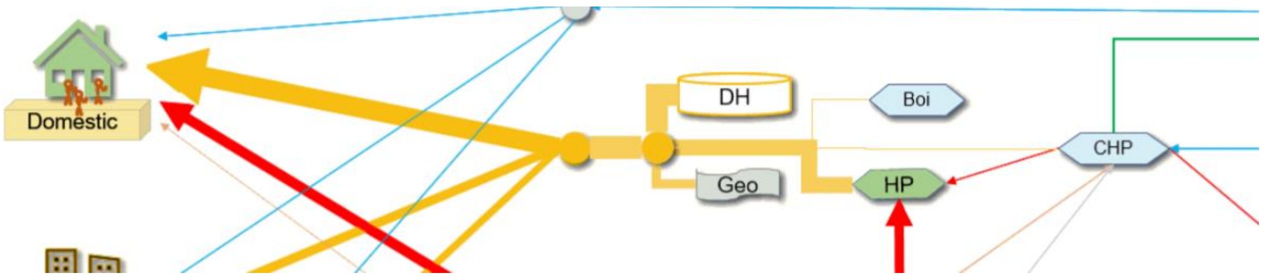
- low cost heat **storage**
- **multiple heat sources** (heat pumps, CHP, boilers)

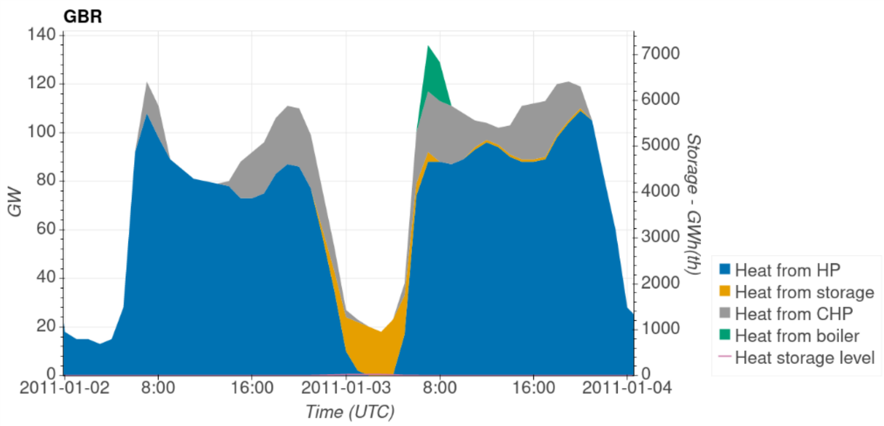
These may be adjusted to conditions of renewable surplus or deficit.

**Surplus**: run HPs

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

**District cooling** is also an option



# Systems performance

# 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 (°C) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | +2 | +4 |

# Primary renewable capacities and annual production

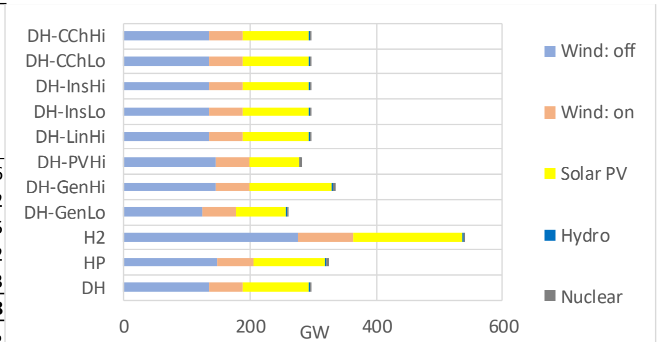
**Hydrogen** requires about 80% more primary capacity than DH and HP

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

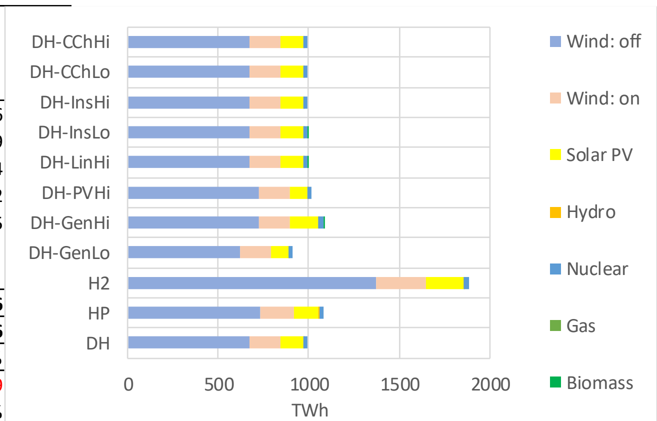
**Decreasing spillage** would require more **storage**, **interconnector** or other capacity such as electroysers.

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%** |



# Hourly flows and storage 2009-2011

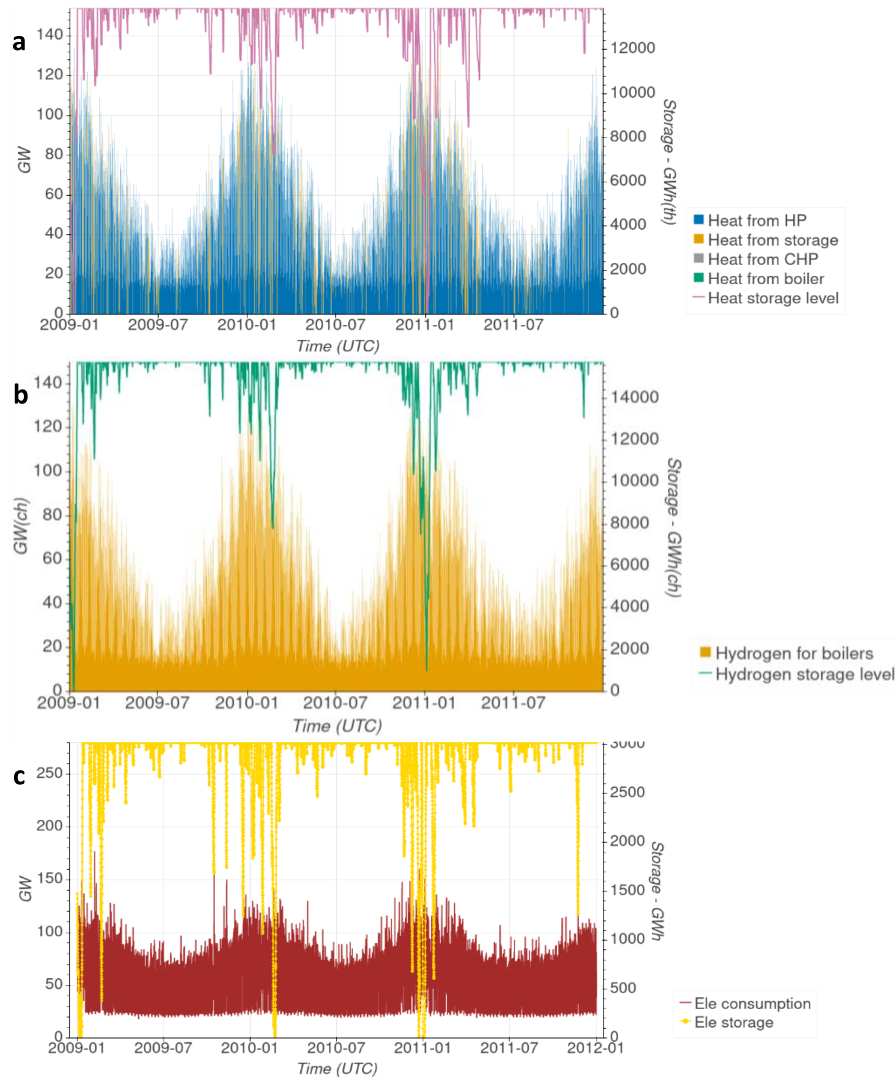
a: **Hourly heat storage** level (right axis) and delivered heat from heat pumps, heat storage, CHPs, boilers (left axis).

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**



# District heat

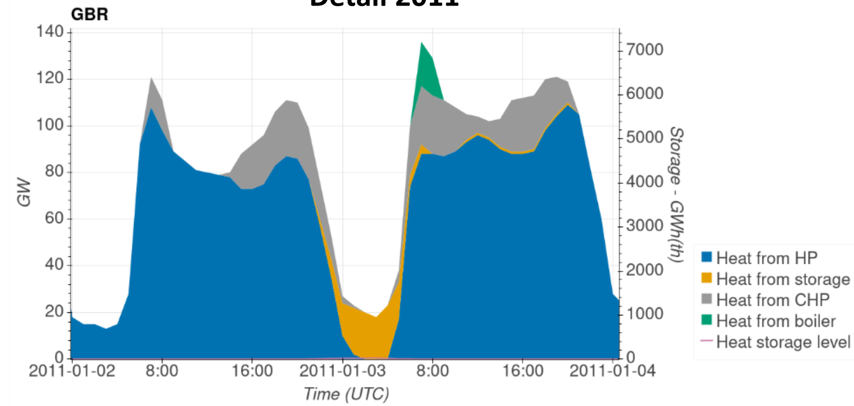
**Scenario: DH core**

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.

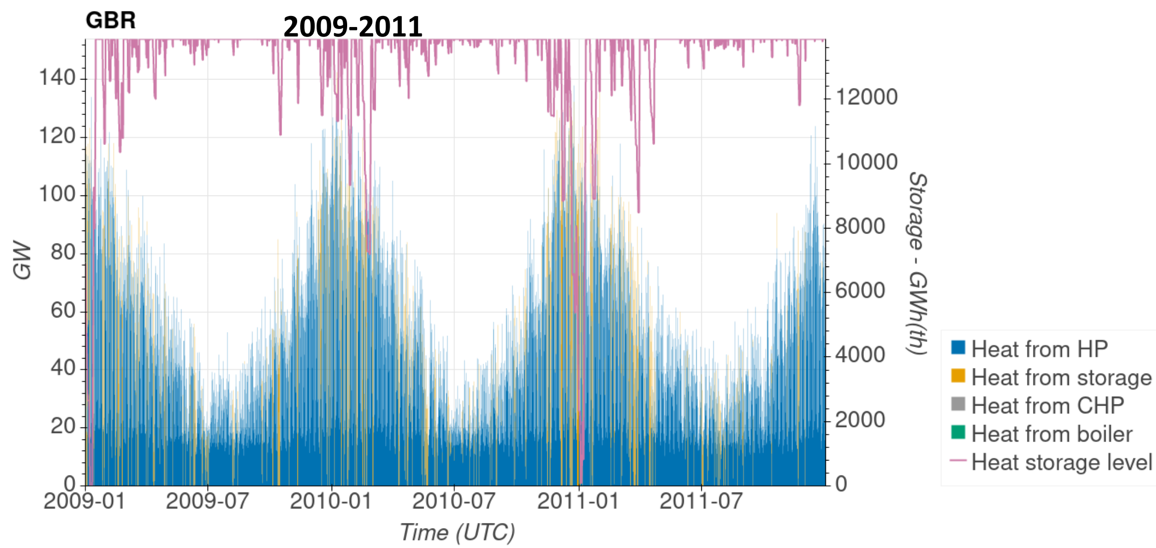
**Surplus**: run HPs

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

**Detail 2011**



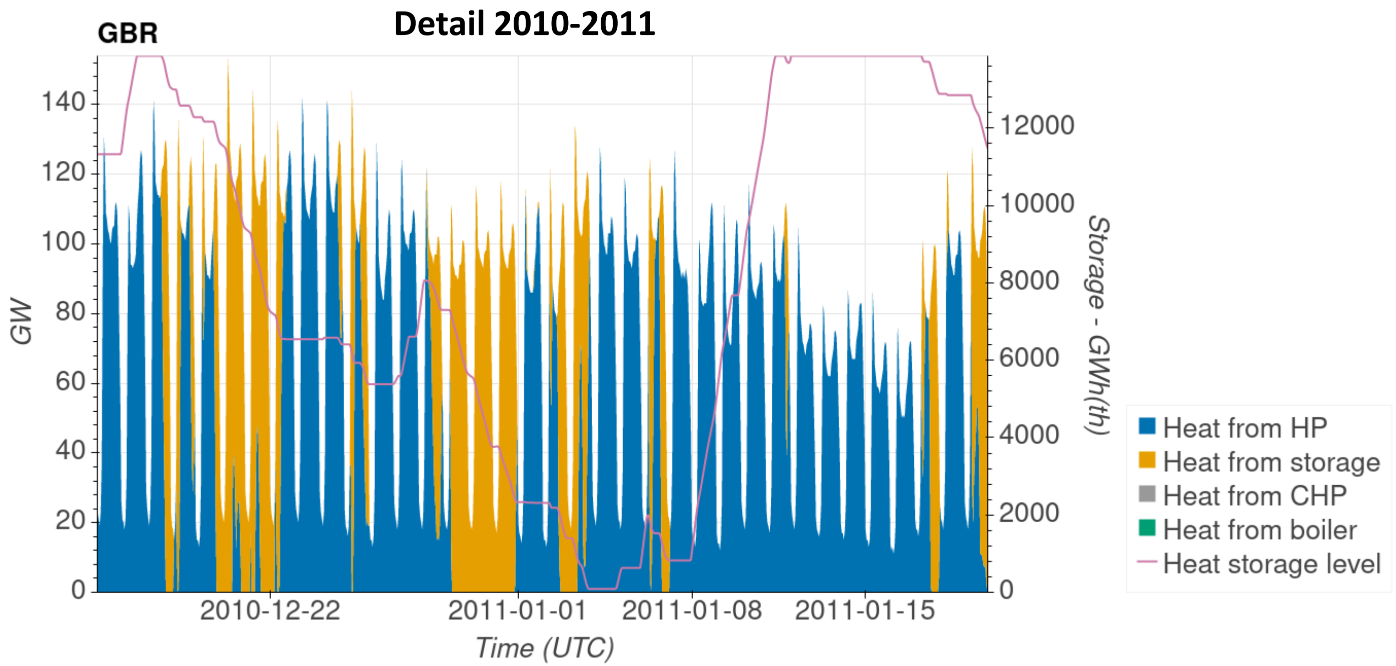

**2009-2011**



# District heat – low storage period

Scenario: DH core

Illustration of dynamically changing heat supply mix.

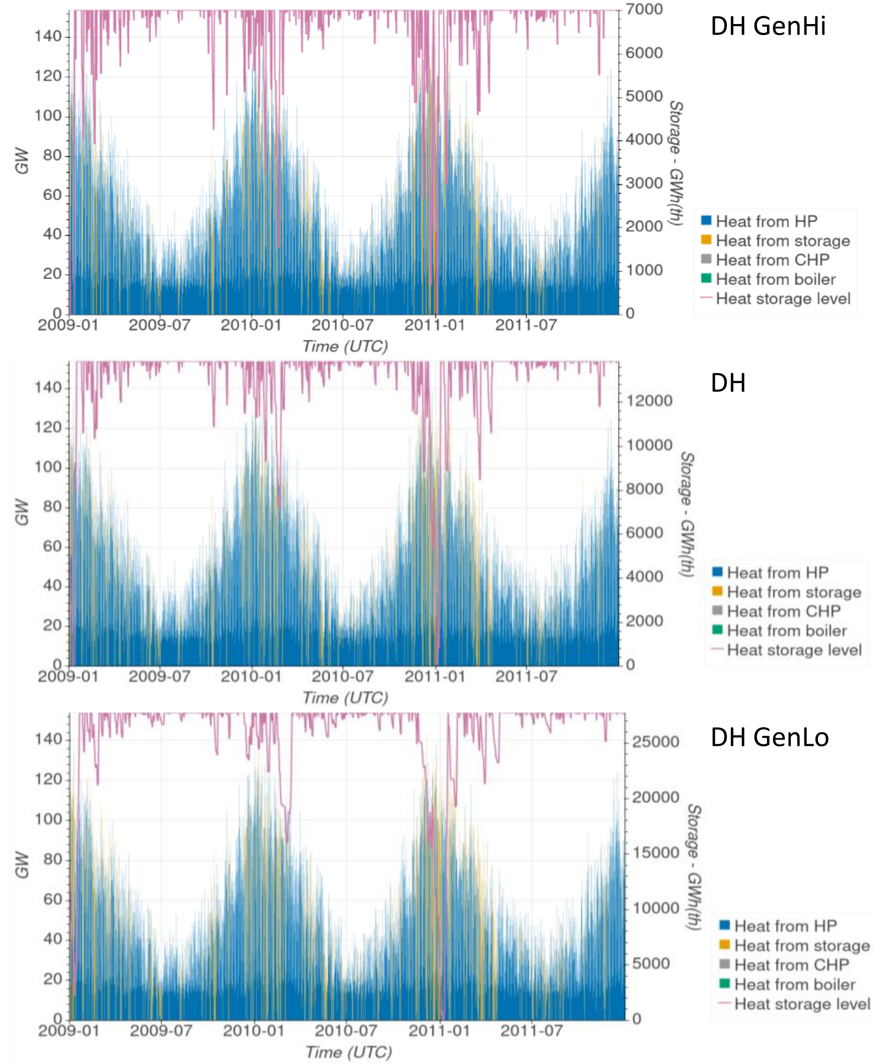


# District heat – storage in scenarios

**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.

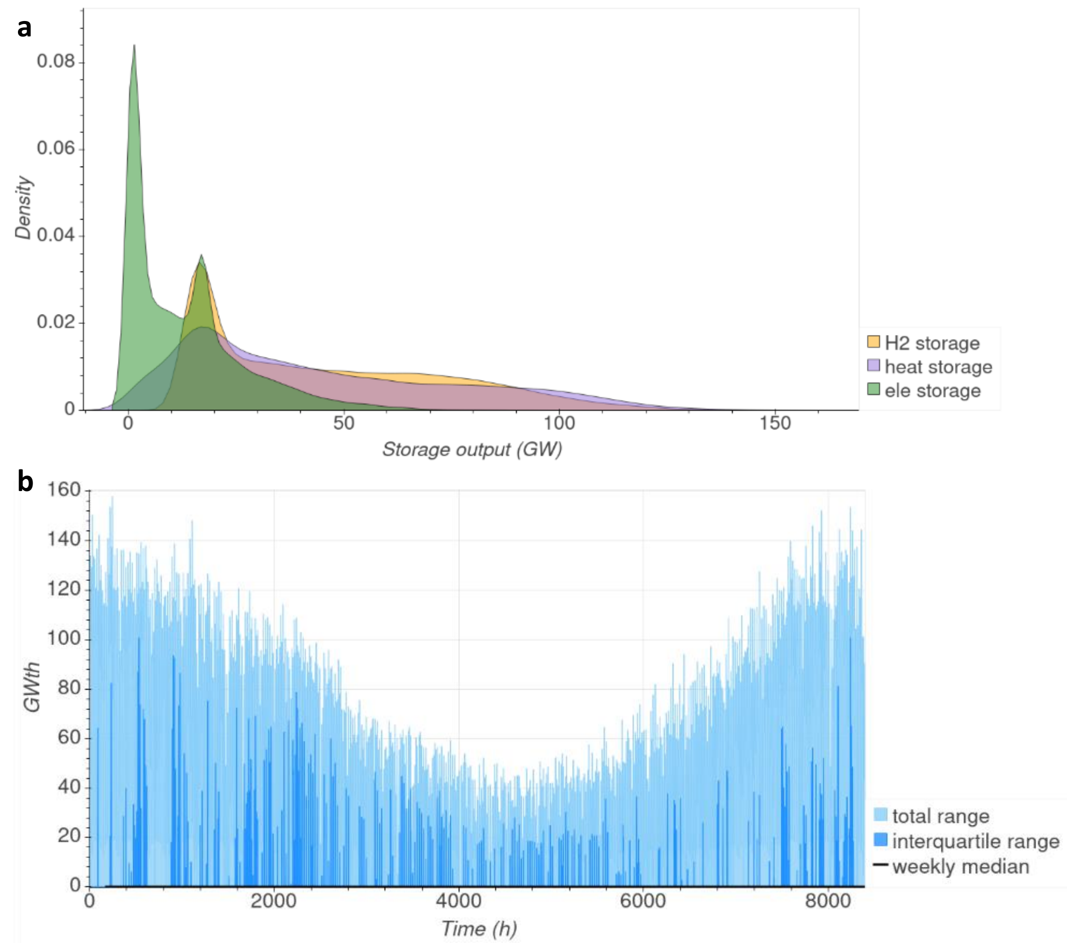


# Storage over 35 years

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.

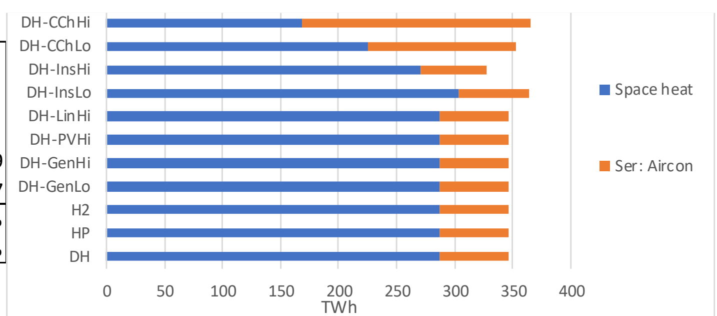


# Commentary: climate change

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

| | | | | | | | | | | +2 oC | +4 oC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **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% |



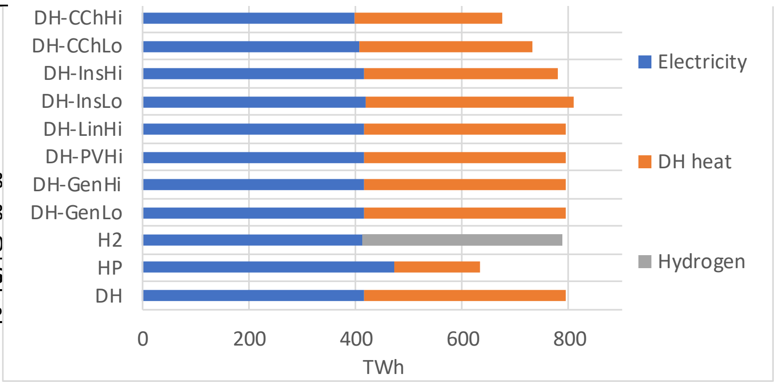

Note: these are heat/cool demands, not electricity

# 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% |



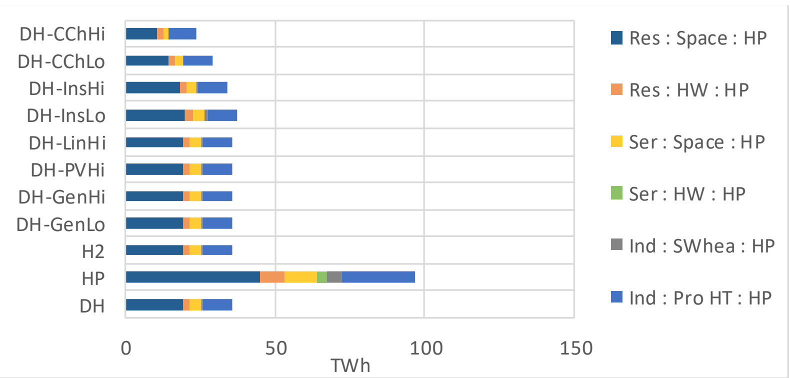
# Annual: electricity delivered for heat

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% |



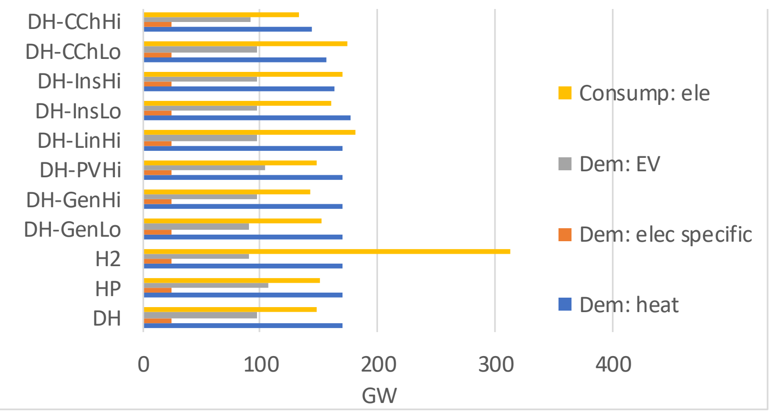
# Peak flows

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 |





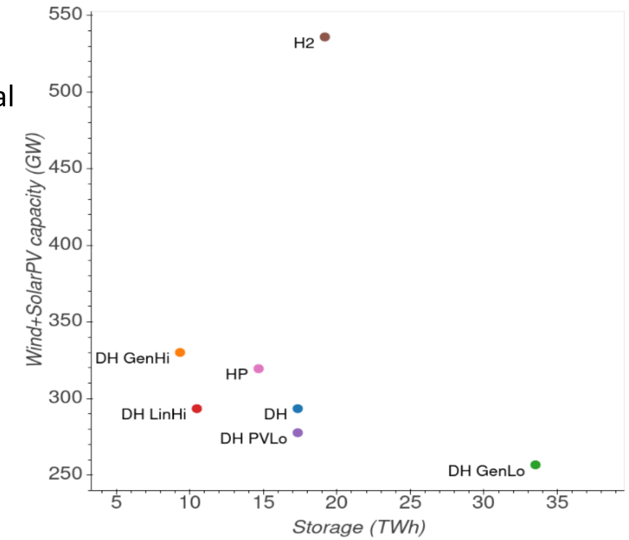

Energy Space Time

# Storage

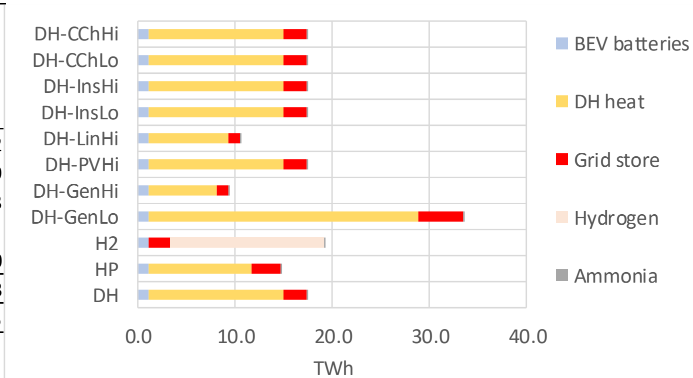
The amounts and types of storage varies with heat share, renewable capacities and interconnectors.

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% |

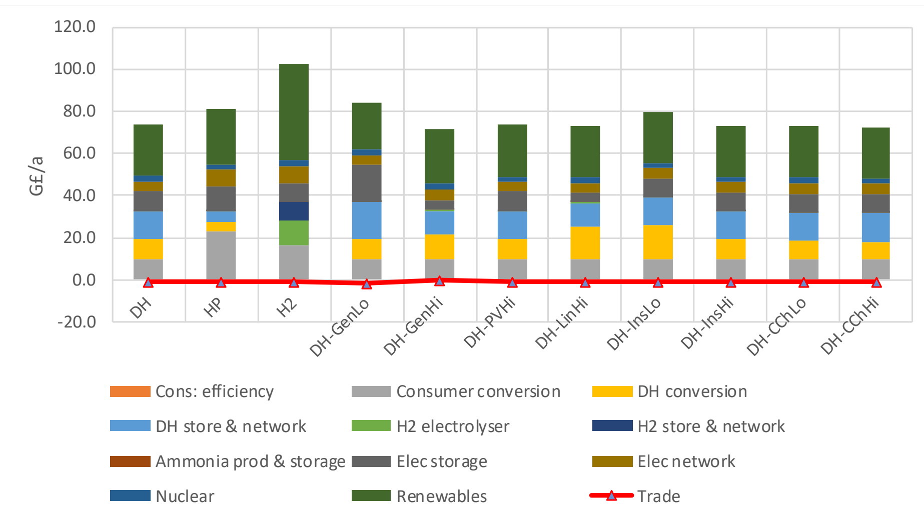


# Costs: disaggregated

**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

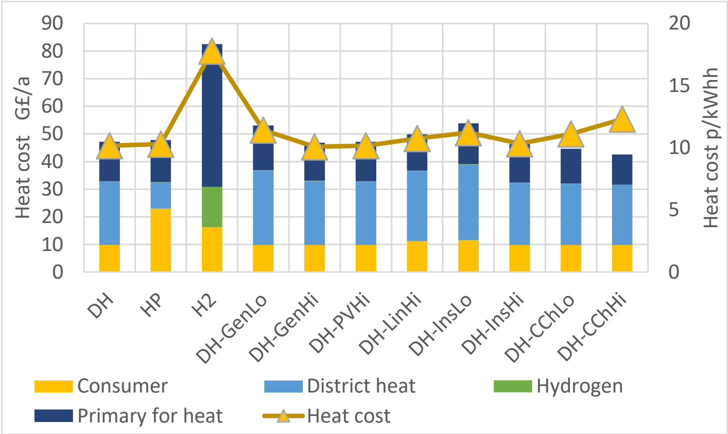
# Costs of heat and electricity

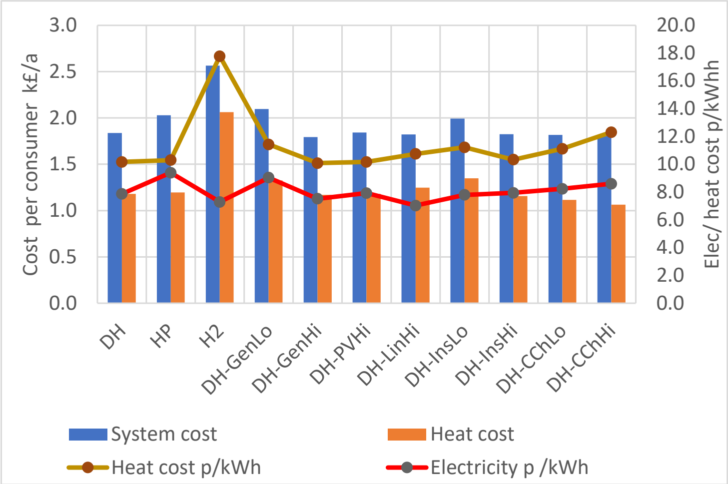
Energy systems are interconnected systems with some components serving multiple demands. Estimation is needed to separate out the cost of heat, but note that these are for 70:30 mixed DH/HP/H2 systems:

- 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.



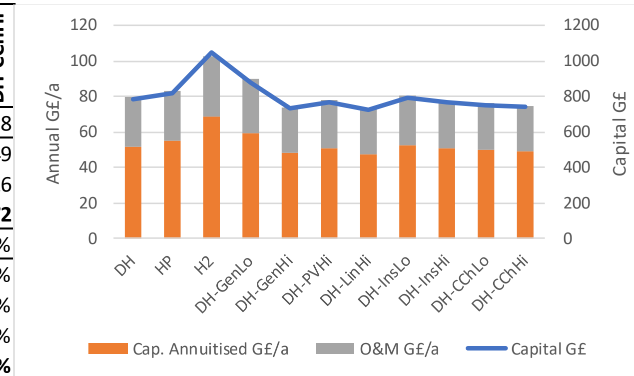



# Costs: whole system and electricity subsystem

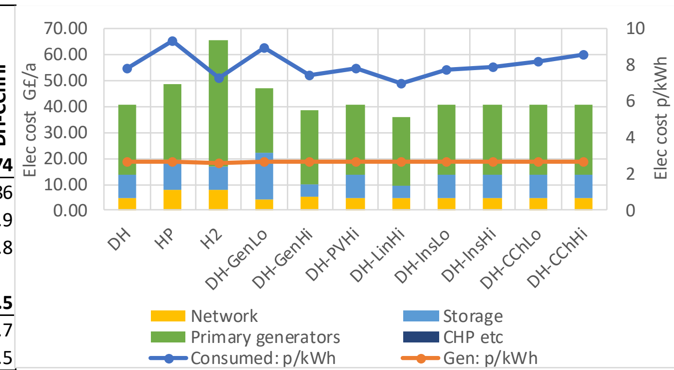
**Capital costs** are annuitized using technology unit costs (£/kW, £/kWh), life (yrs) and interest rate 5%/a.

**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 |

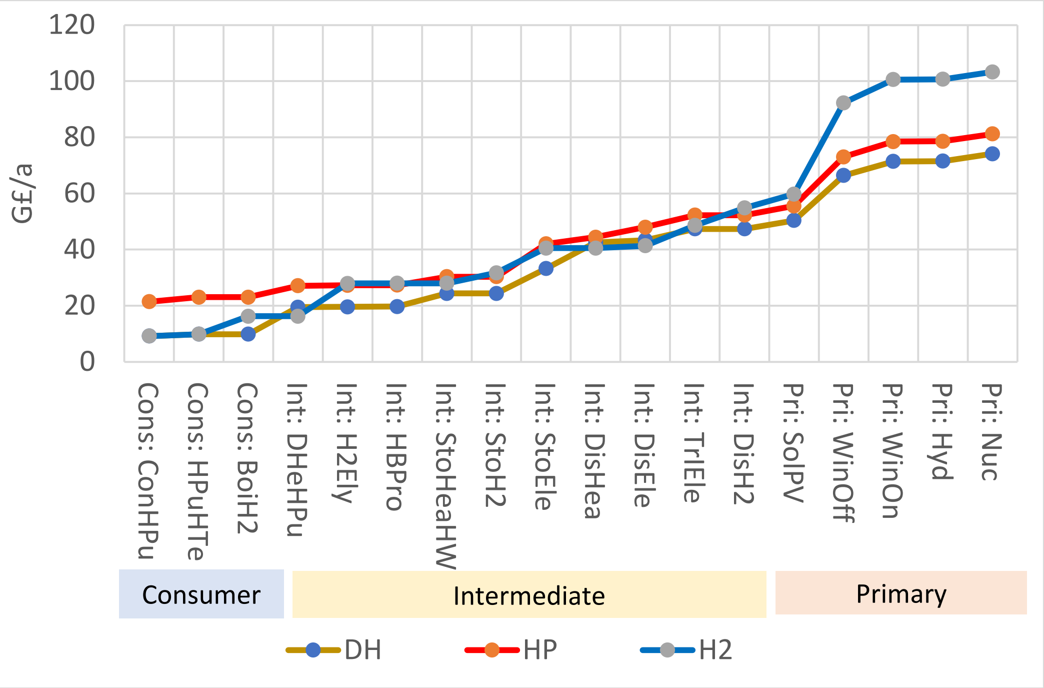


# Costs cumulated across the system

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.



# Heating systems comparison

# 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.

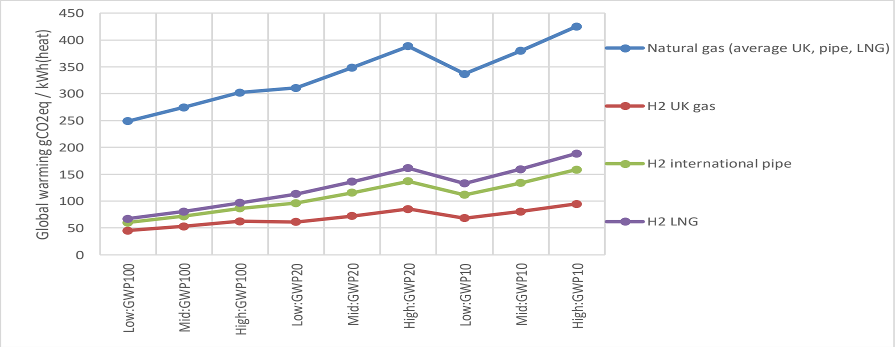
- The production and transport in the supply of natural gas results in $CO_2$ arising from the energy used in these processes, and methane emissions from leakage. These upstream GHG emissions cannot be captured by **NG plant**.

- 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).

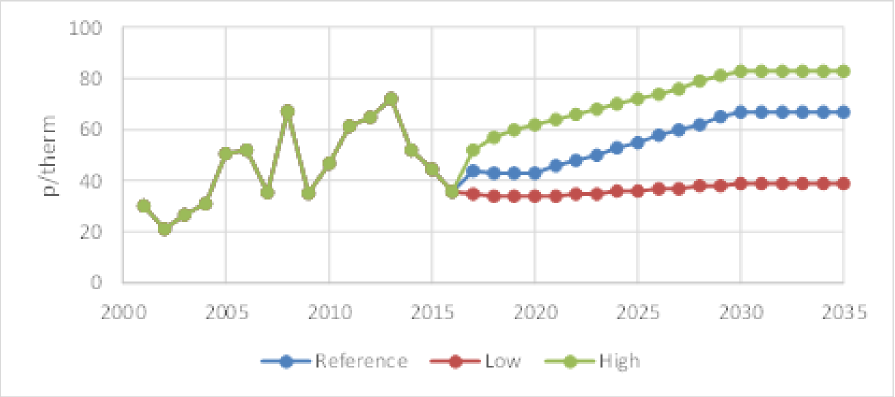
# Natural gas supply

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



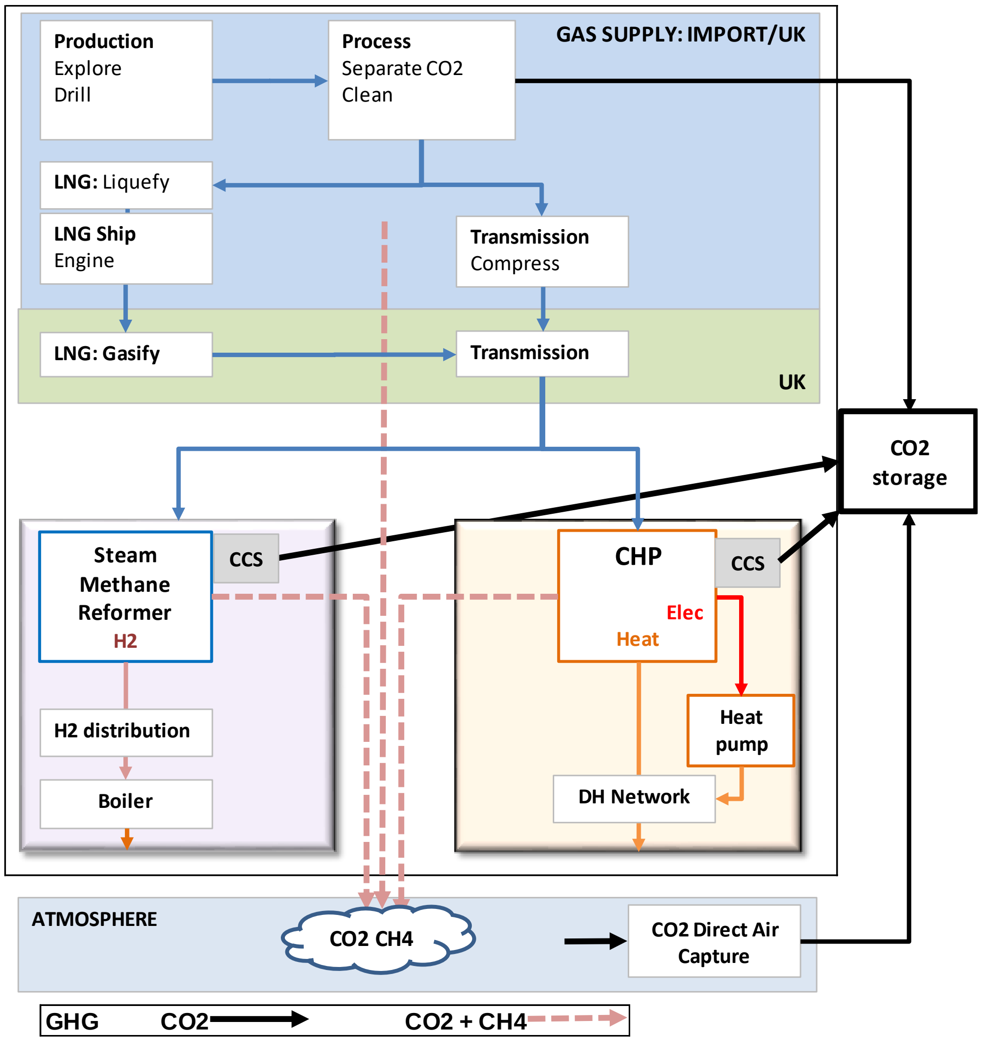
# Negative emissions

- $CO_2$ 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 £/t$CO_2$ 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 £/t$CO_2$. In the analysis below a figure of **300 £/t$CO_2$** 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

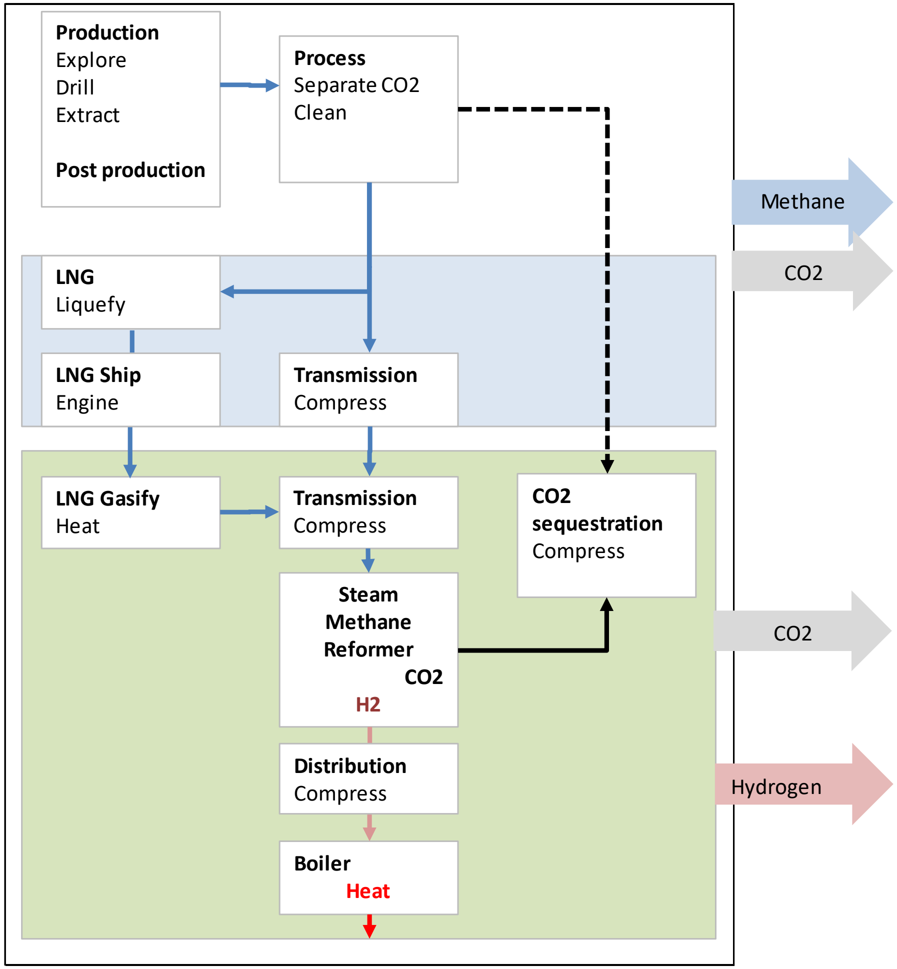


# Natural Gas:
# 'Blue' hydrogen from steam methane reforming CCS

- 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

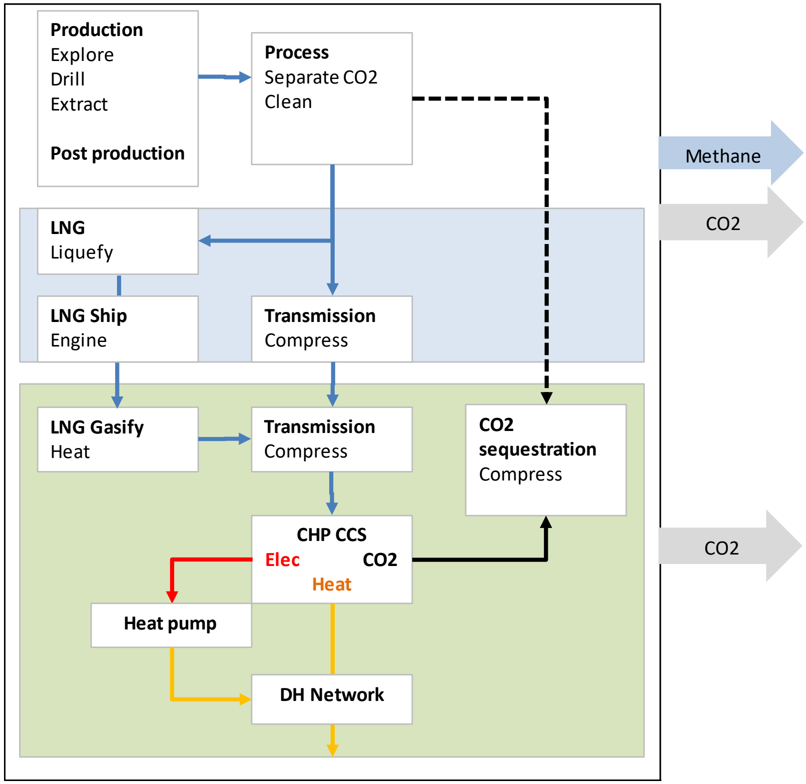
- SMR operational and cost data are limited because of commercial interest for operational plant, and small scale prototype and desk study data range widely.
- SMR with CCS may have an efficiency (natural gas to hydrogen HHV energy) in the range 70-80%.
- CCS can remove 80-90% of SMR CO2 emissions but 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.

Analysis: 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/



# 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](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.

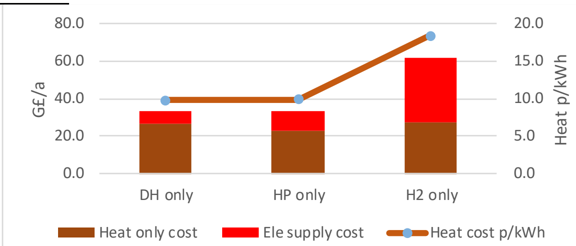
| COMMON ASSUMPTIONS | | |
|---|---|---|
| **Central** | Gas gCO2e/kWh 50 | |
| | Gas p/kWh 3 | |
| | DACS £/tCO2 300 | |
| **Interest rate** | 5% | %/a |
| **Natural gas supply** | | |
| Gas cost | 3.0 | p/kWh |
| **Upstream emission** | | |
| CH4 (GWP100) | 30 | gCO2e/kWh |
| CO2 | 20 | gCO2/kWh |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

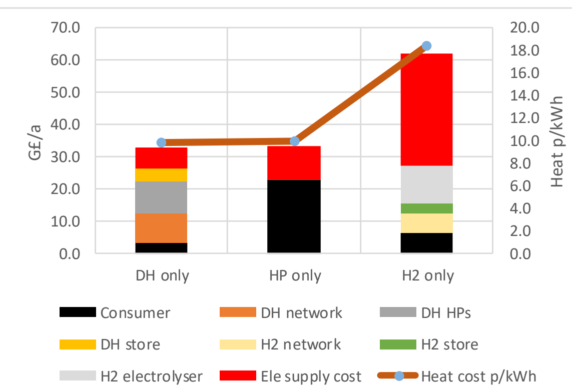
| **Sensitivity case: Central** | | | **NG: H2 blue** | **NG: boiler** | **NG: DH CHPCCS+HP** |
|---|---|---|---|---|---|
| CHP heat efficiency | | | | | 39% |
| CHP ele eff | | | | | 31% |
| DH HP eff | | | | | 350% |
| DH network eff | | | | | 93% |
| Boiler eff | | | 90% | 90% | |
| SMR eff | | | 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** |

# 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%** |



# Renewable and natural gas heating costs and emissions

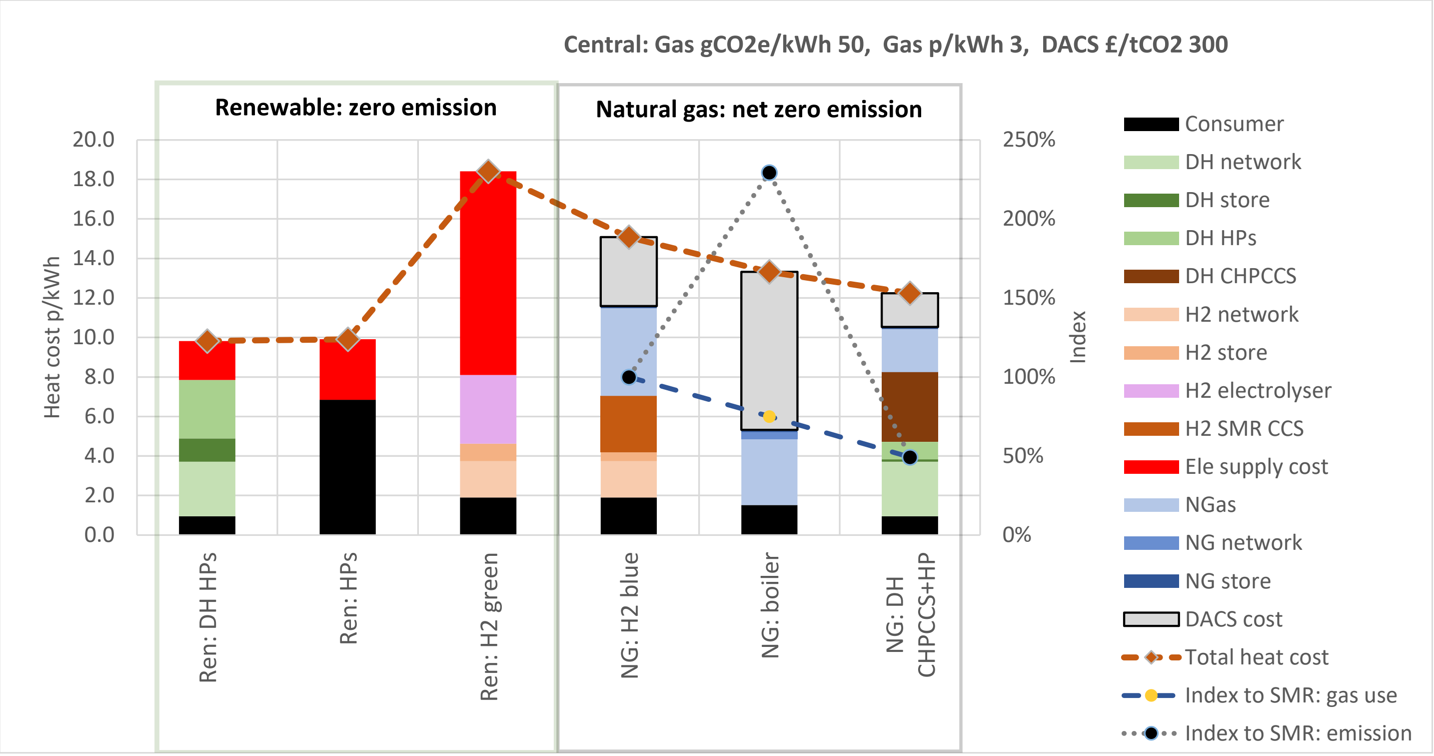
**Systems**

- **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:**

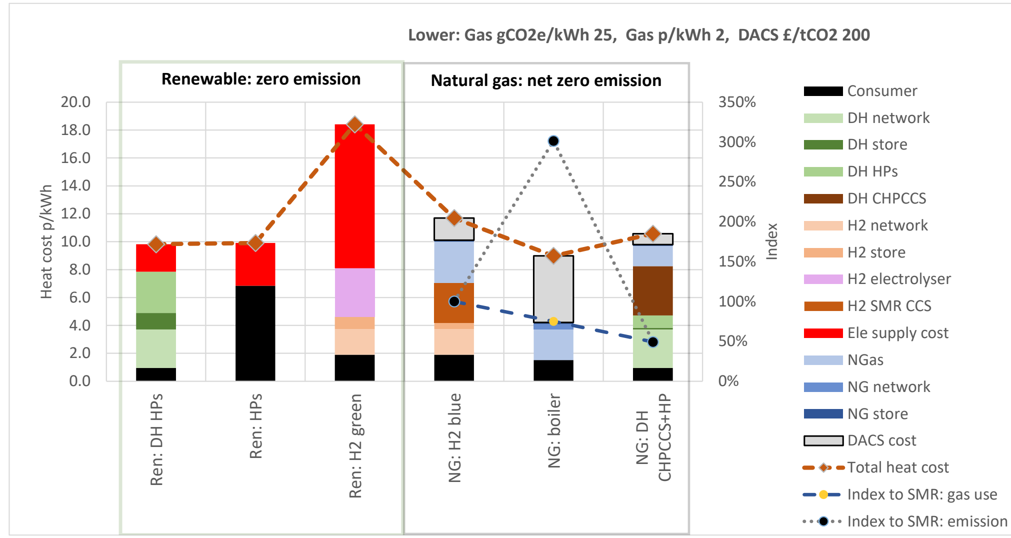
- future gas prices
- upstream gas emissions
- technologies: DACS, SMRCCS, CHPCCS



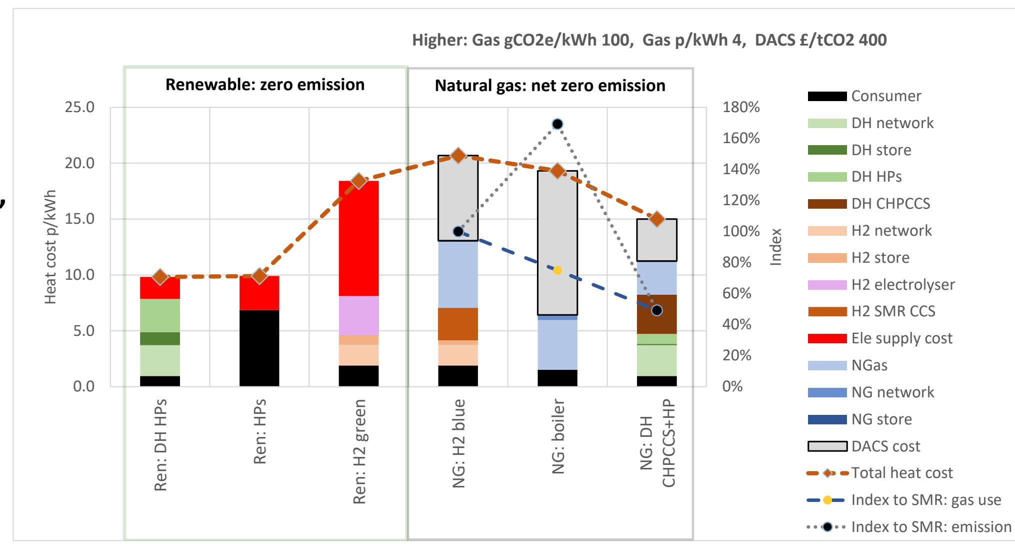
# Comparison sensitivities

- 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 $CO_2e$/kWh, gas price and DACS costs**




**Higher: gas $CO_2e$/kWh, gas price and DACS costs**



# 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** |

# 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 |

# Miscellaneous

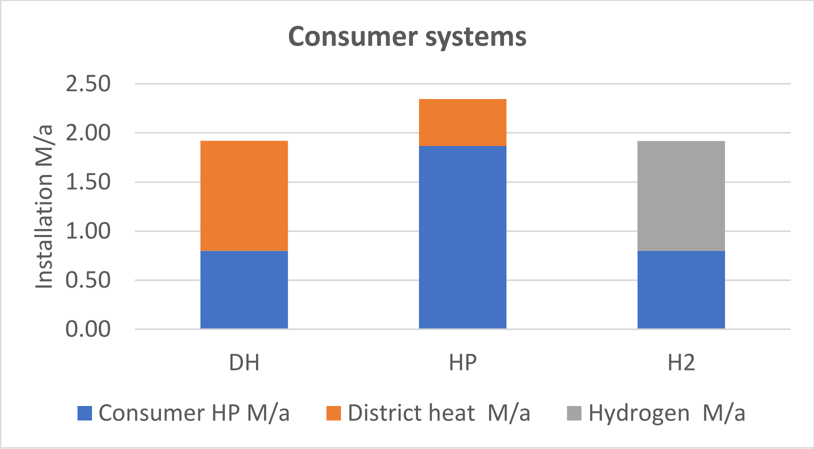
# Indicative implementation rates

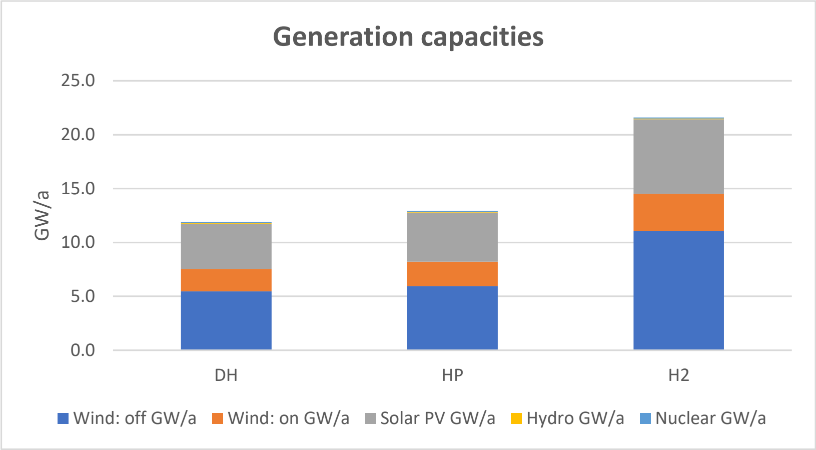
The **possible development path** from the current system to a zero emission system has not been analysed here.

**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 maintain 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.



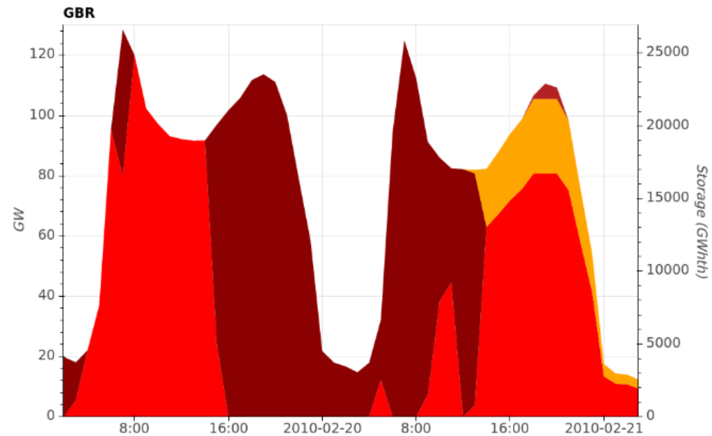



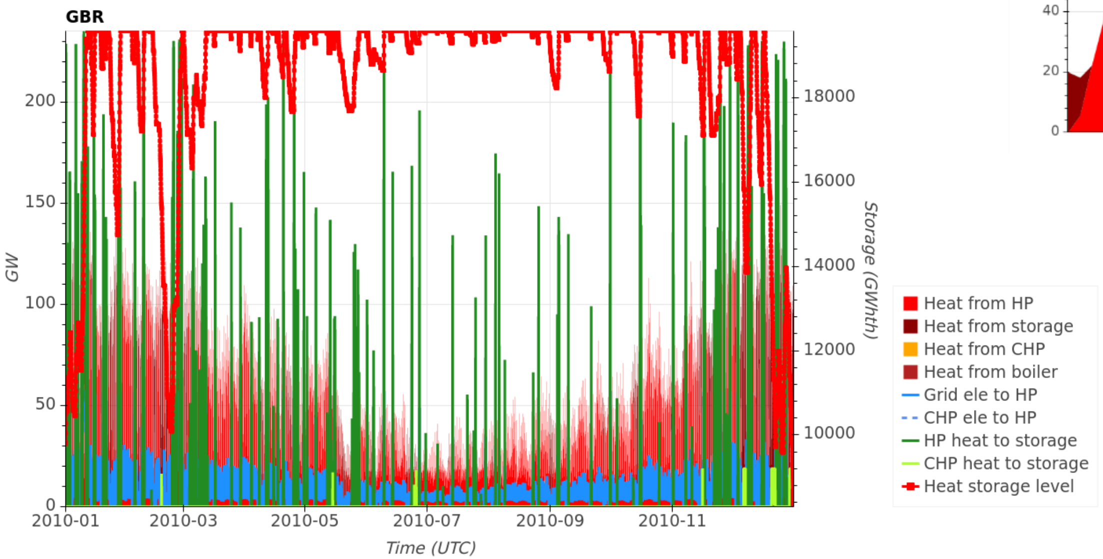
# Security and resilience of zero emission systems

- **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.

# 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**

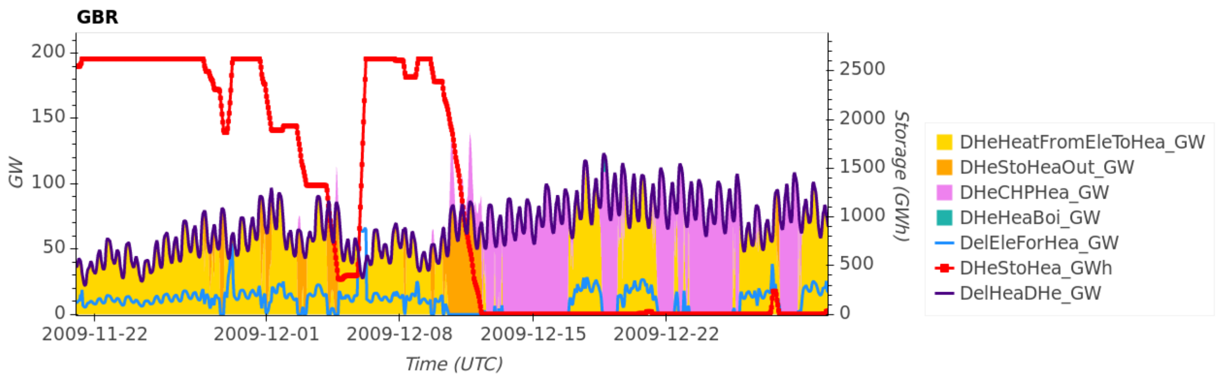


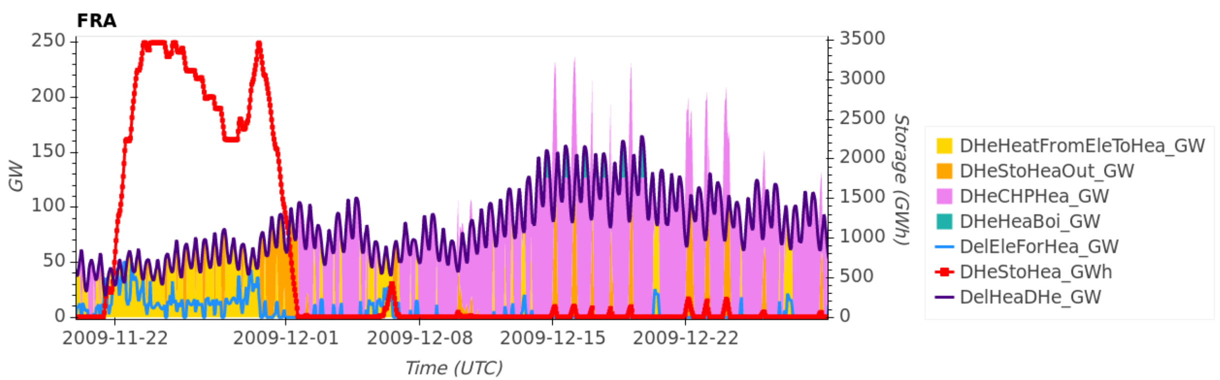



# ESTIMO – district heating

## (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.

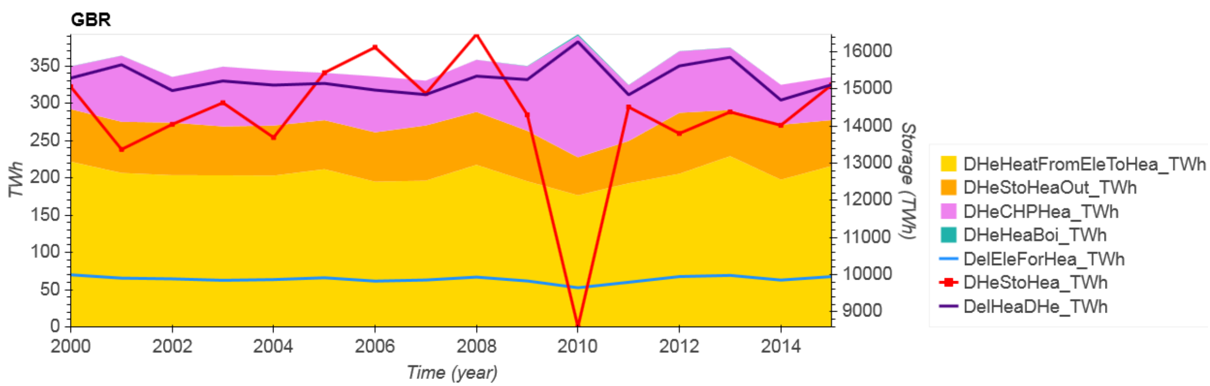


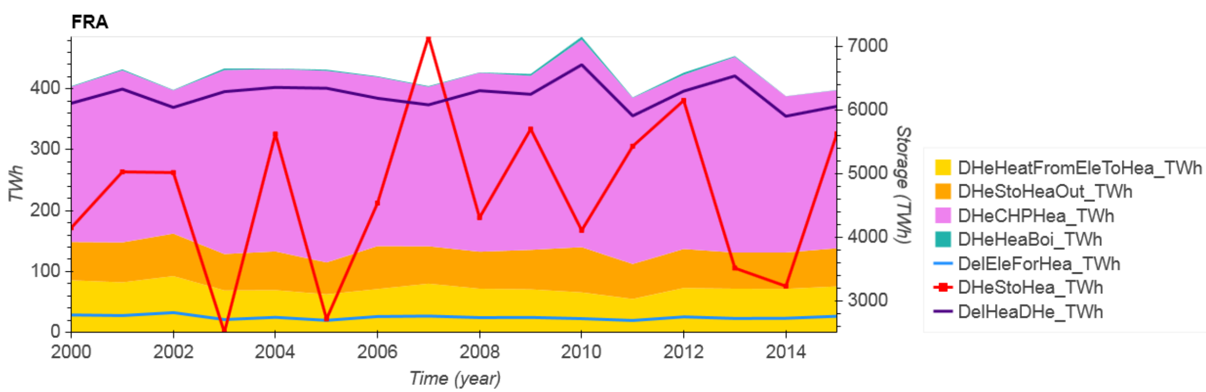



# ESTIMO – district heating (annual sum)

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.



# Primary supply illustration

**Wind and solar have no integral storage**

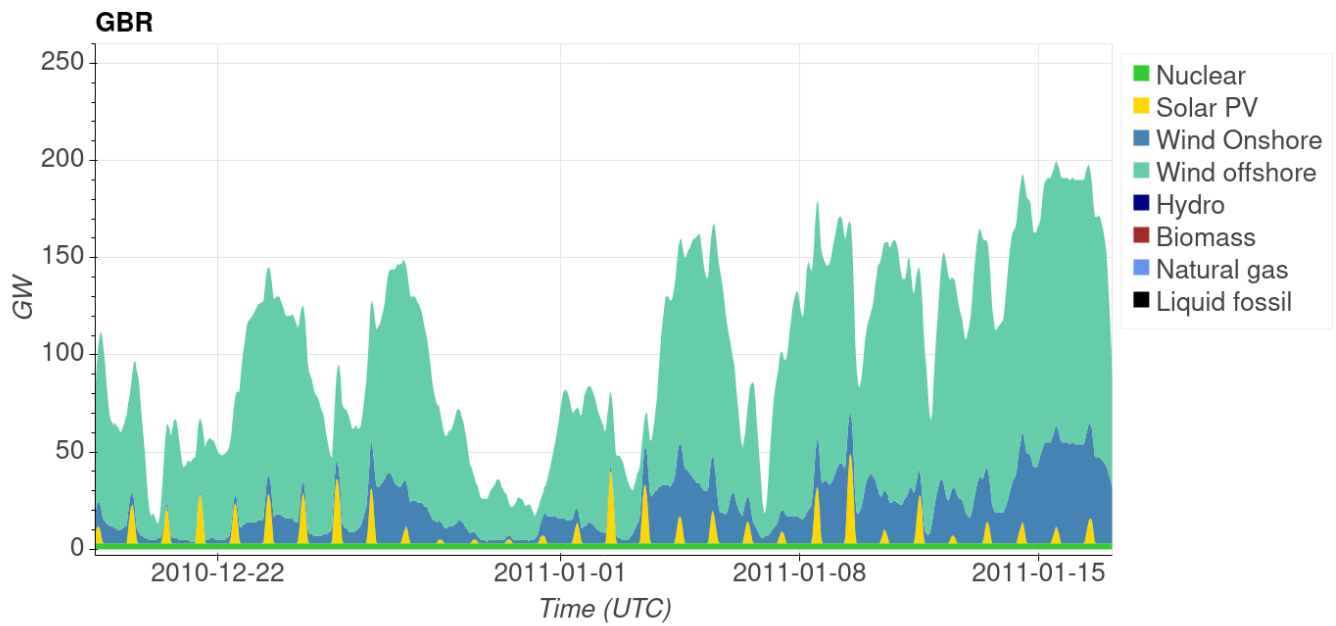
**Wind** varies, generally more in the winter than summer

**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**



# 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.

# 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

**Commentaries**

**Illustrative results for other scenarios and countries**

# Commentaries

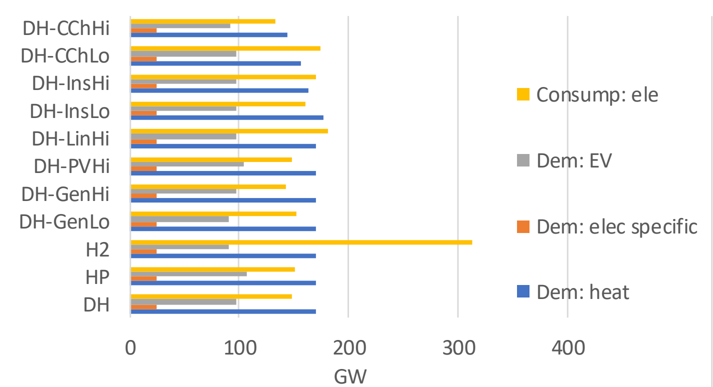
# Commentary: electricity network

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 |



# 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.

# 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.

# 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 a simple model (ETSimpleMo) 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.

# 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.

# 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.

# 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 maintain 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 |

# More Results

# 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.**

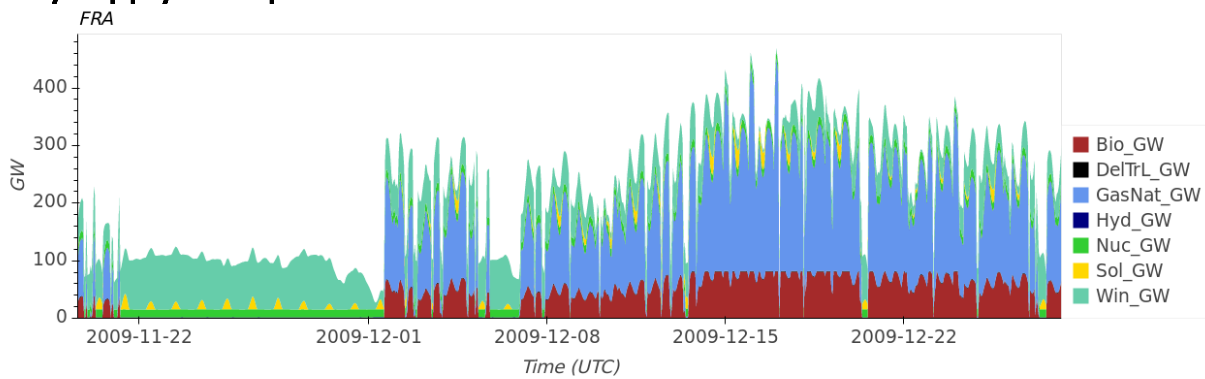
**Flows in countries differ at any universal time (UTC: Coordinated Universal Time) because of different:**

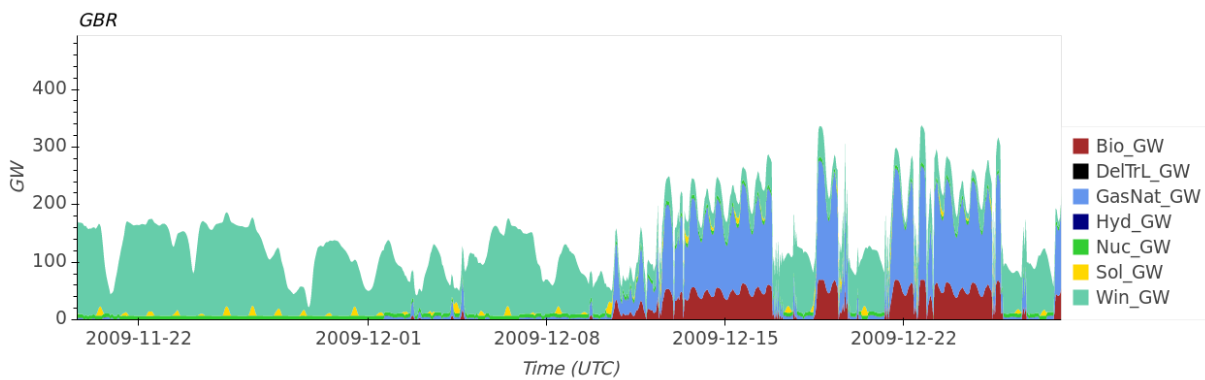
- Local times and therefore activity
- Service demands
- Weather
- Energy mix at consumer, intermediate and primary stages
- Storage levels
- International electricity trade

# 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**



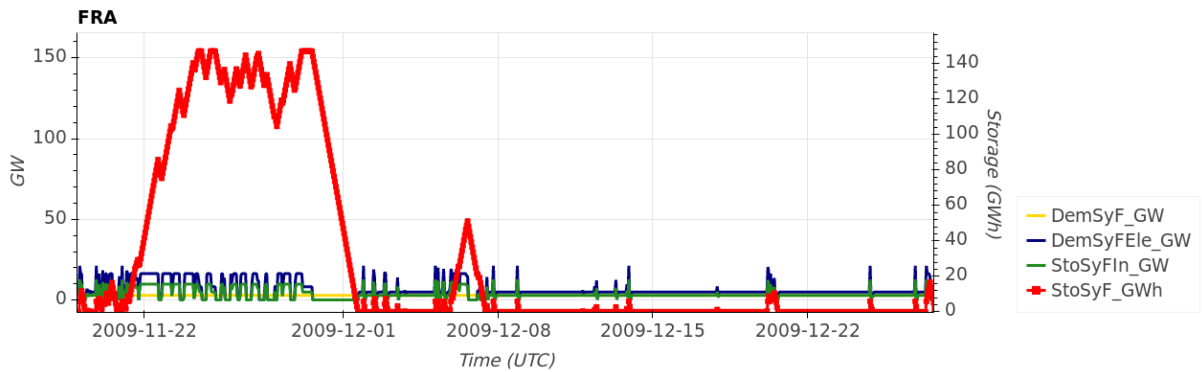



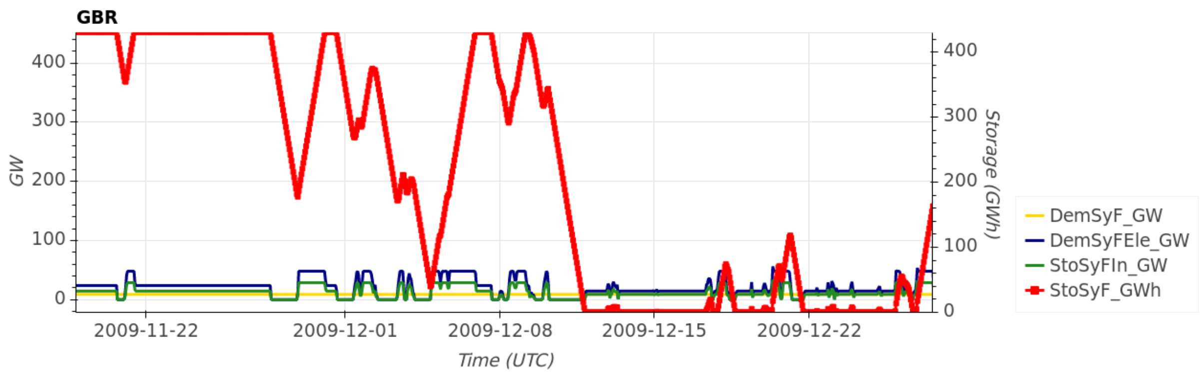

DelTrL: fossil liquid fuels (petrol, diesel etc.) for transport

Bio: generic biomass

# ESTIMO – electrofuels (hydrogen,ammonia) demand, production, storage

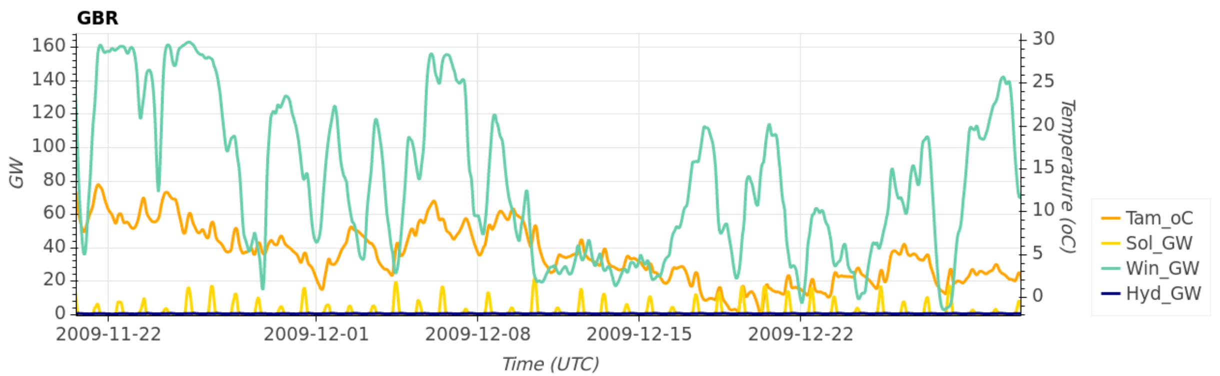
Electrofuels are for powering ships, and dispatchable electricity and heat supply. Flows are different in GBR and FRA because of local time difference  and weather.

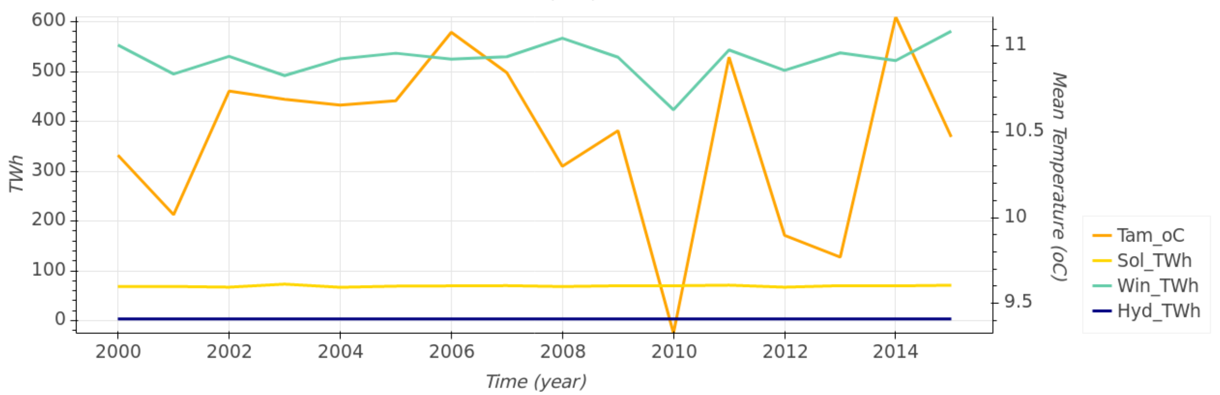


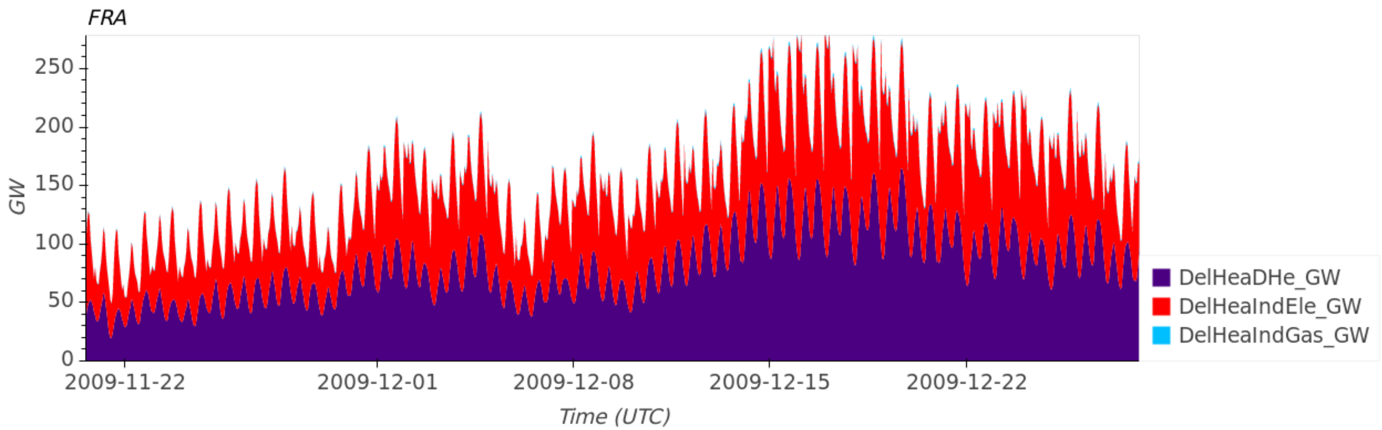
# ESTIMO – weather and renewable generation

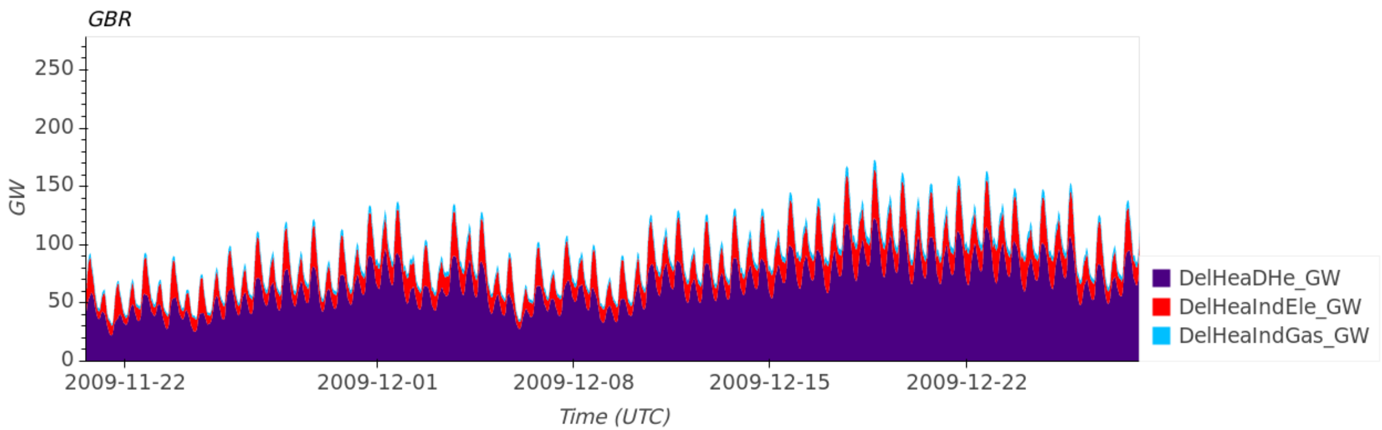
Prolonged periods of high demand and low renewables stress the UK energy system determining minimum storage needs. E.g. 2010 is a stress year with a period that is cold, so high heat load, and also low wind.



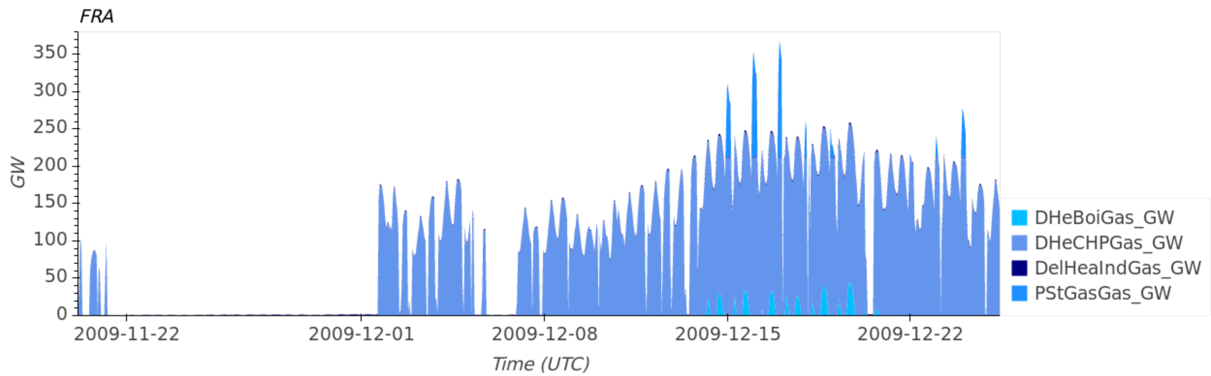
# ESTIMO – heat supply

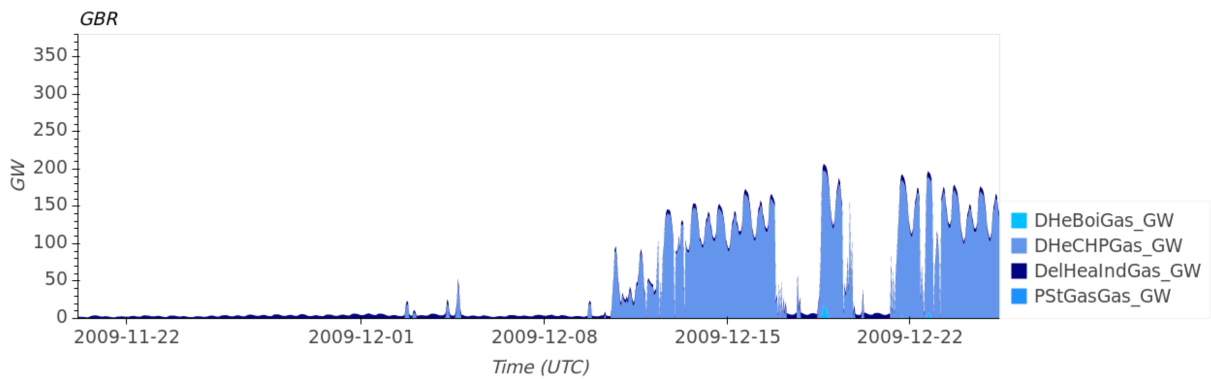


# ESTIMO – gas

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.]



# Next steps

# Hard to solve challenges

**Aviation**

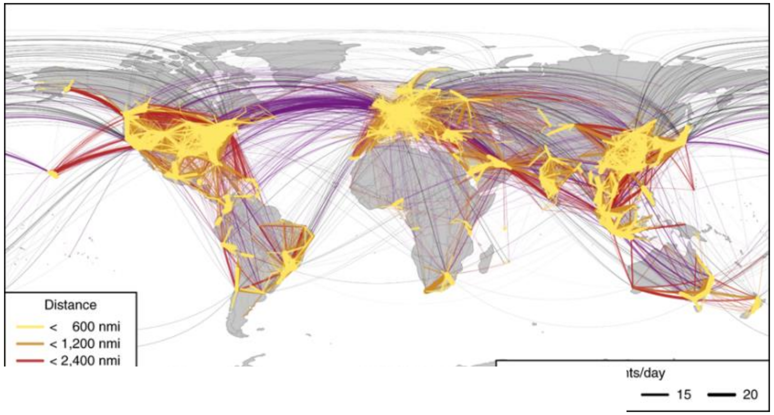
Carbon based fuel best– but where does the carbon come from in a low carbon world (tragic irony!)?

Kerosene synthesised from biomass, atmospheric CO2 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)?

# 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**

# 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.

# The authors

The first version of **ESTIMO** 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.

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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/

**Some questions:**
**How will hourly demands and renewables vary?**
**Which generation and storage technologies will be included?**
**What temporal and spatial resolutions are required for accuracy?**
**How will the system be controlled hour by hour?**

| | |
|---|---|
| Type: | Bottom-up, technology-rich cost optimisation |
| Purpose: | Decarbonisation pathways, technology assessment, European policy |
| Spatial scale: | 11-region EU model |
| Temporal scale: | 3 seasons (summer, intermediate, winter), 2 intra-day (day, night) |