Turning up the heat on decarbonisation – findings from the LoT-NET programme

Dr Ángeles Rivero Pacho
Dr Roger Moss

School of Engineering - University of Warwick

WARWICK
THE UNIVERSITY OF WARWICK

LoT-NET

Low Temperature Heat Recovery and Distribution Network Technologies

Institutions and organisations

WARWICK
THE UNIVERSITY OF WARWICK

Loughborough University

EST 1892 LSBU

Ulster University

WARWICK
THE UNIVERSITY OF WARWICK

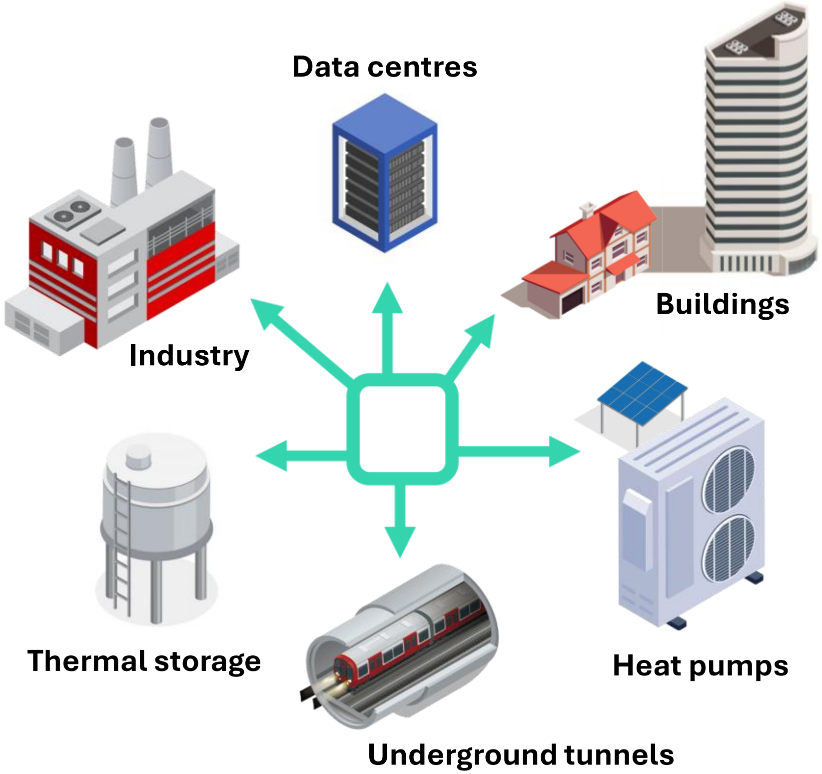
- 6-year research project
- Funded by an EPSRC program grant
- Collaboration between four university teams
- Guided by an industrial advisory panel

sirach

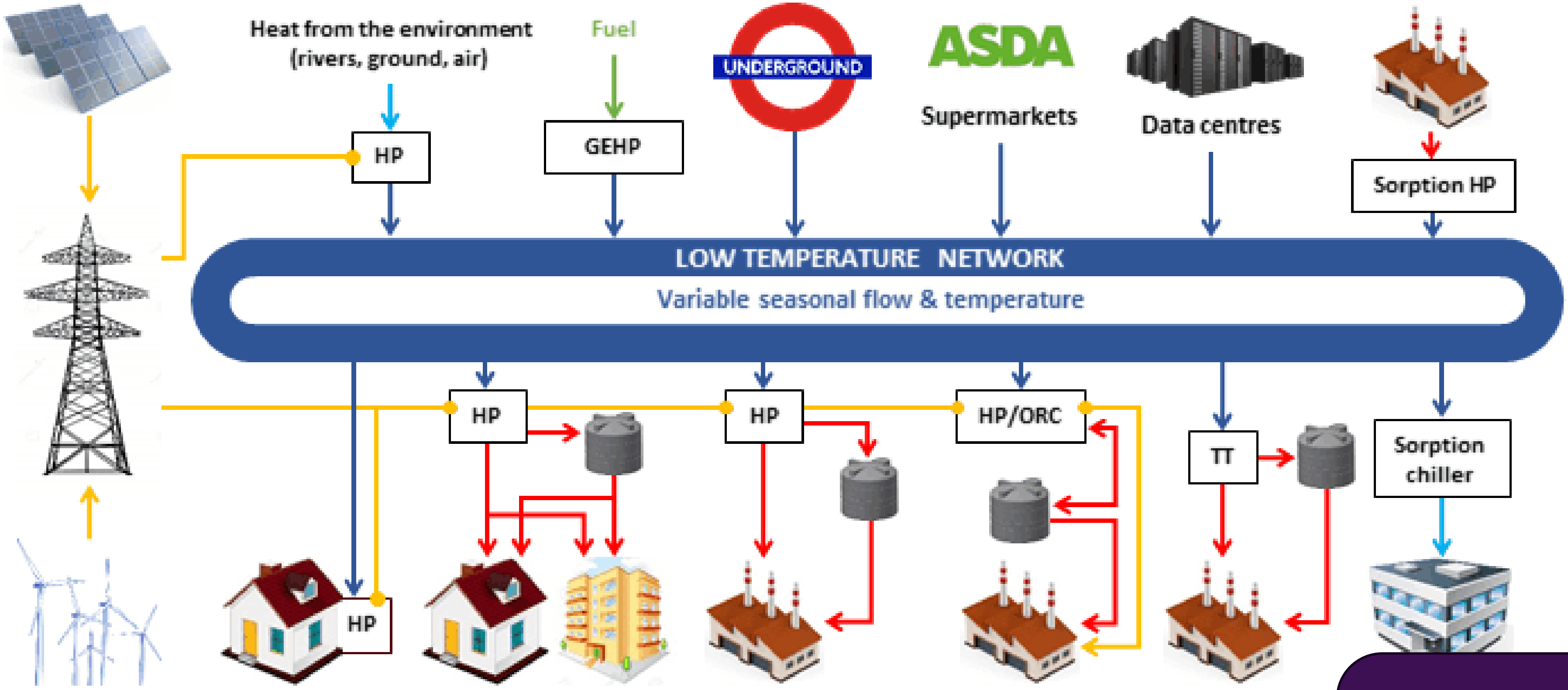
IOR.org.uk
REFRIGERATION AIR CONDITIONING HEAT PUMPS

Basic principles

1) Heating can only be decarbonised via low-carbon electricity powering heat pumps
2) For good heat pump efficiency, we must minimise the temperature lift
    - Look for "warm" heat sources
3) Renewable energy is intermittent
    - Use thermal storage
4) Heat sources and storage are typically far from the buildings needing heat
    - Use a heat network to link buildings to sources, storage and heat pumps



Original proposal – how would everything link into one big system?



This then morphed into a number of individual case studies

LoT-NET

Loughborough University

EST 1892 LSBU

Ulster University

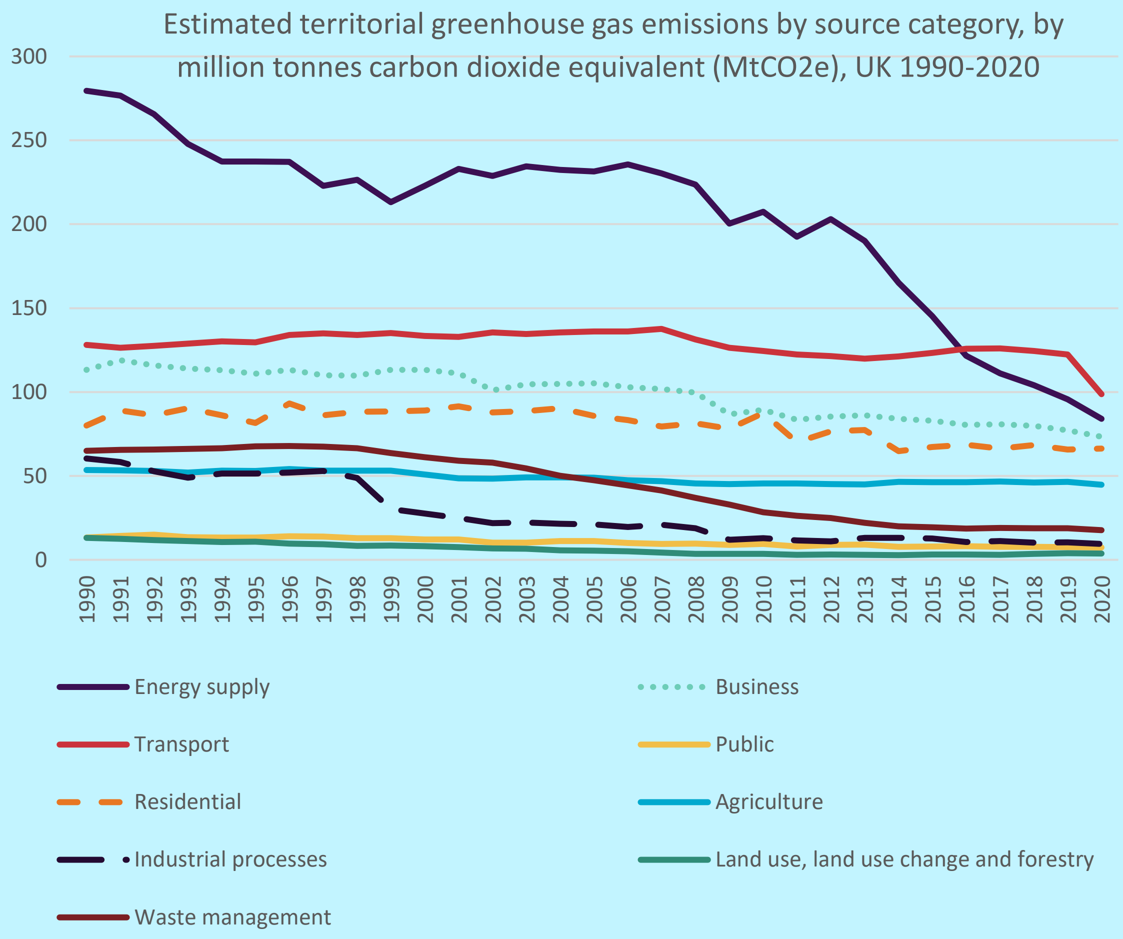
WARWICK
THE UNIVERSITY OF WARWICK

- Thermal storage
- Recoverable heat sources
- High temperature heat pumps
- Heat network case study

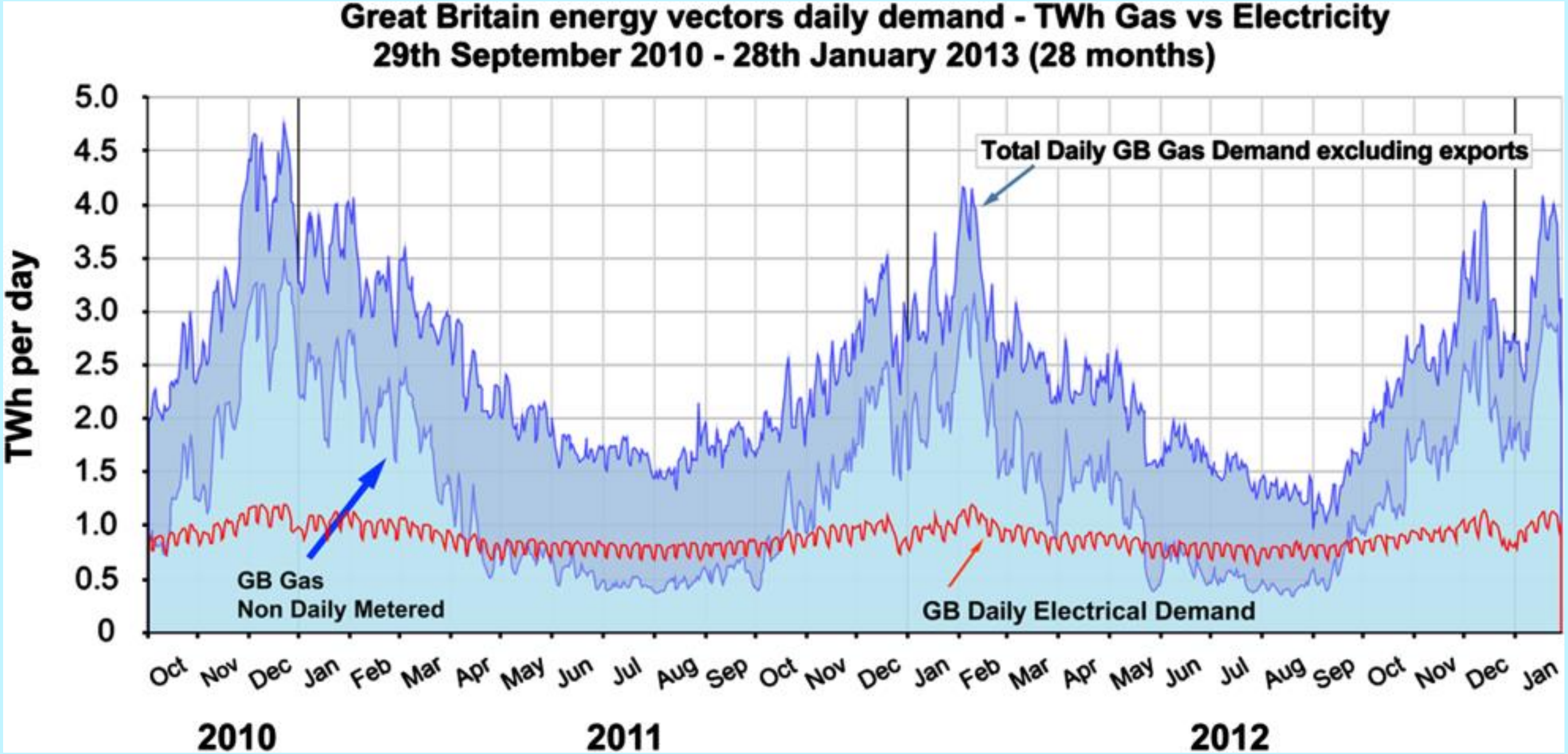
Thermal Energy Storage in the UK Energy System

Work by Prof. Phil Eames' team, Loughborough University

Domestic emissions not falling fast enough



Heat Demand



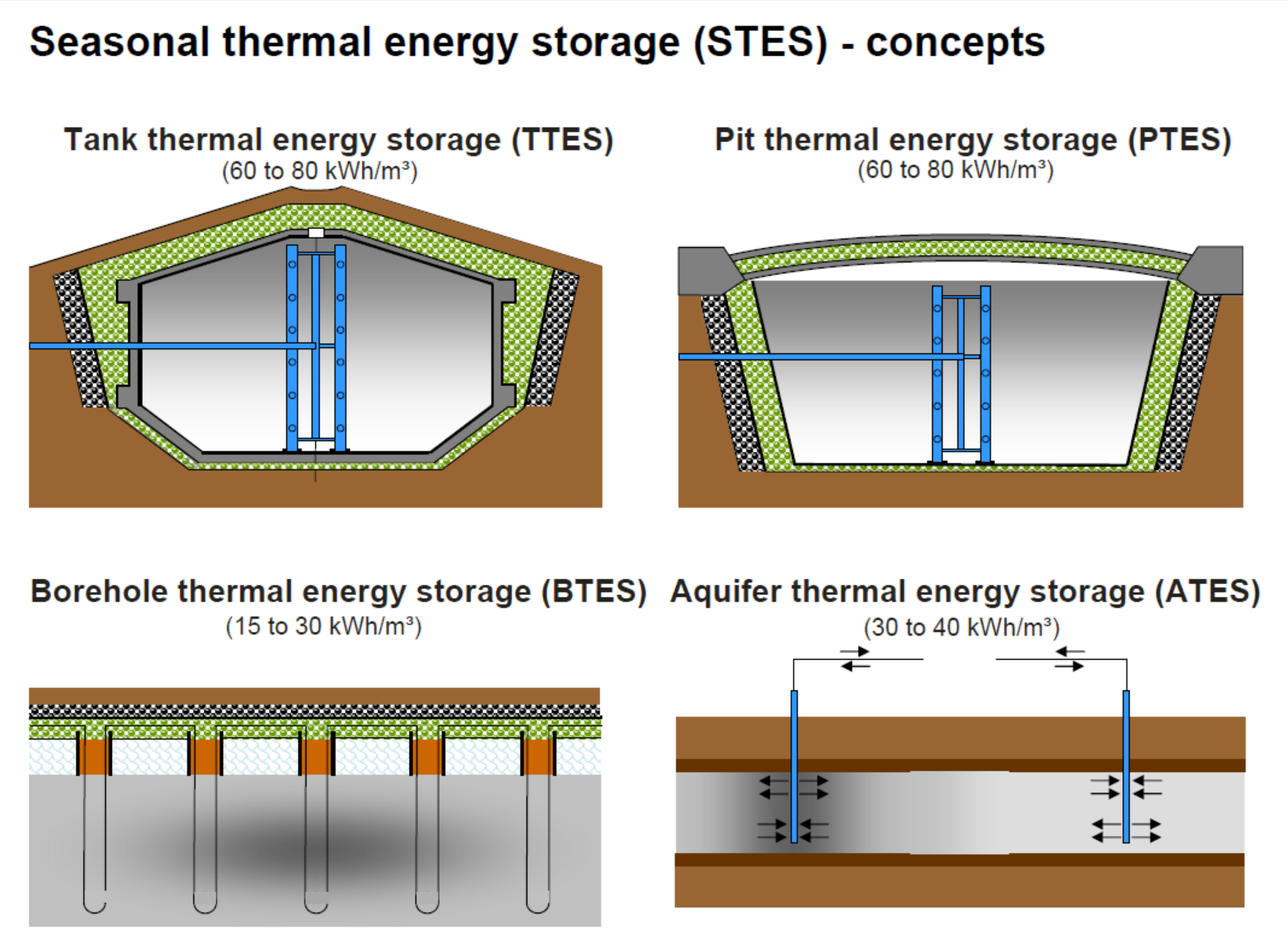
Winter peak demand for low grade heat can peak at about 300GW;
electricity demand peaks at 60 GW.

Even with COP=5, if everyone had a heat pump the peak electricity demand would double.

Wilson, I. G., Rennie, A. J., Ding, Y., Eames, P. C., Hall, P. J., & Kelly, N. J. (2013). Historical daily gas and electrical energy flows through Great Britain's transmission networks and the decarbonisation of domestic heat. *Energy Policy*, *61*, 301-305.

LoT-NET

Loughborough University



Seasonal thermal energy storage (STES) - concepts

Tank thermal energy storage (TTES)
(60 to 80 kWh/m³)

Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)

Borehole thermal energy storage (BTES)
(15 to 30 kWh/m³)

Aquifer thermal energy storage (ATES)
(30 to 40 kWh/m³)

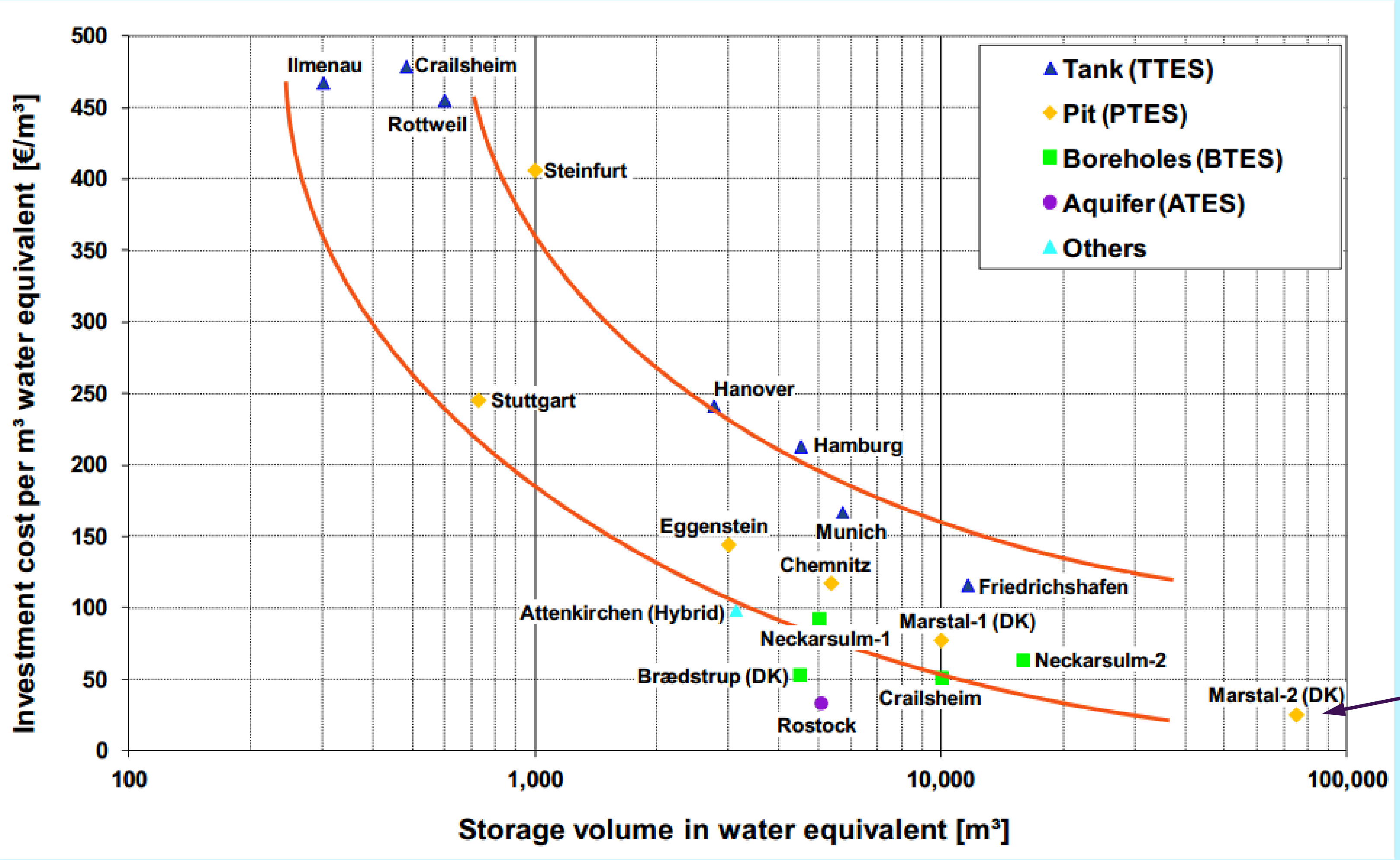
Stores would be heated using high temperature heat pumps and (possibly) solar thermal collectors.

Thermal storage can:

- benefit from electricity cost variations
- maximise use of low/zero emissions generation
- reduce/manage peak electricity demand
- allow ASHP operation in daytime to improve COP

Mangold, D. Seasonal Heat Storage – Pilot Projects and Experiences in Germany. *Solites.* [Online] http://www.solites.de.

Cost per m^3 for large thermal water tanks.



Specific storage costs of demonstration plants (cost figures without VAT) Schmidt T, Miedaner O, *Solar District Heating Guidelines, Storage*. Solar District Heating, 2012.

Pit storage 60-80kWh/m^3

Investment cost (Marstel-2) 30€ /m^3

Investment cost ≈ 0.5€/kWh

Thermal storage for *annual domestic heat requirement*

Stores of volumes up to **2,000,000 m^3** have been proposed in Austria.

- Land area 0.1km2 (20m depth) or 0.067km2 (30 m depth).
- 60°C operating temperature; assume perfect thermal stratification
- Storage capacity 140 GWh
- Equivalent to total annual heat load for 12000 dwellings (if current UK housing quality).

UK has 28 million houses each using 8MWh heat (average) annually = 224 TWh

- ➢ One could store all this heat in 1600 of these 140GWh stores (e.g. 16km × 10km × 20m)

Coventry has about 144,000 houses.

- ➢ Coventry would need 12 stores to store its entire annual heat demand (e.g. 1200m × 1000m ground area)

This is a good way to use PV-generated electricity that peaks at lunch time!

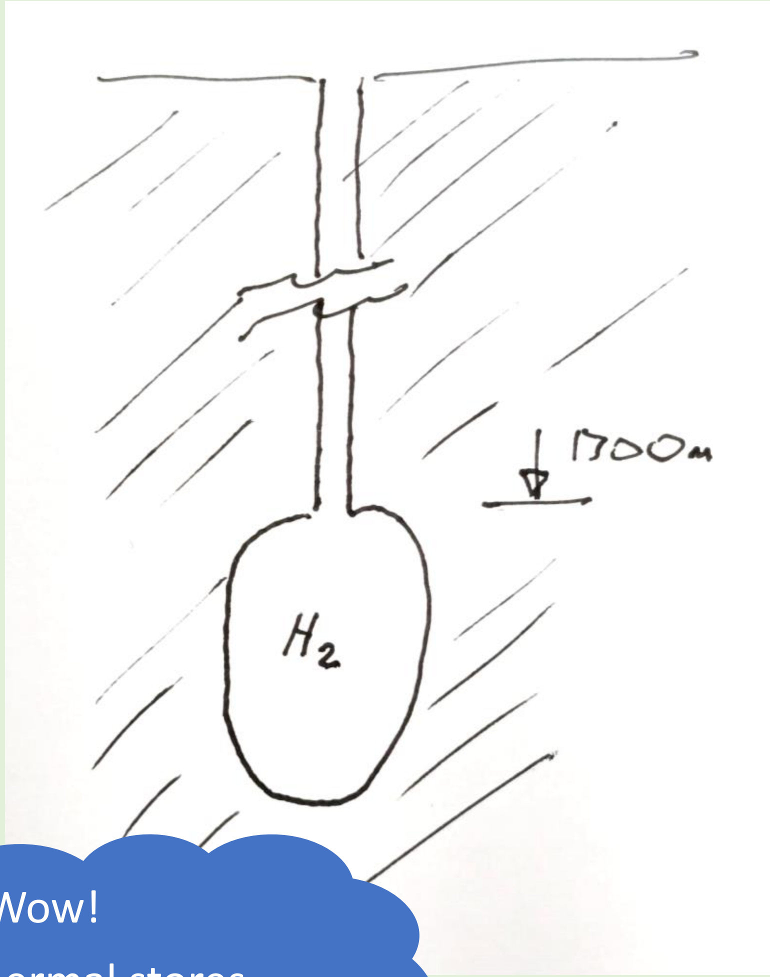
Renewable energy: what do we do when there is no wind?.

The Royal Society has proposed 850 salt caverns to store 123TWh of hydrogen for use in low-wind years.

Capacity (each) 300,000m^3
Average diameter 62m.
Height 100m
Cavern top: 1700m below ground

Overall:
30% excess generation capacity required
89GW electrolyser capacity

550 million tons of salt to be dissolved out, using 2.5 km^3 of sea water (equivalent to 1.25 years of flow down the Thames)



Wow!

Could thermal stores reduce the demand for salt caverns?

How much thermal storage to avoid running heat pumps during a very cold and windless week in Winter with *no renewable electricity supply?*

Assume we might eventually get enough wind turbines to run heat pumps in "normal" weather.

Imagine a week with no wind…

Peak winter heat demand is approximately 3 × the weekly average (8 MWh/26 weeks)

12% of the annual capacity would store enough heat for this week

- 185 of these stores for the whole UK
- Coventry would need:
  - One 140GWh store to provide heat for a week
  - (cf. 12 stores to provide the annual heating)

So obvious!
Why haven't we done it already?

- Need **district heating networks**

Waste (“recoverable”) heat availability and capture

Work by:
Prof. Graeme Maidment
Dr Henrique Lagoeiro
Dr Catarina Marques
at
London South Bank University.

- Underground Railways
- Data Centres
- Mine water
- Supermarkets & Cold stores
- Substations
- Wastewater
- Crematoria

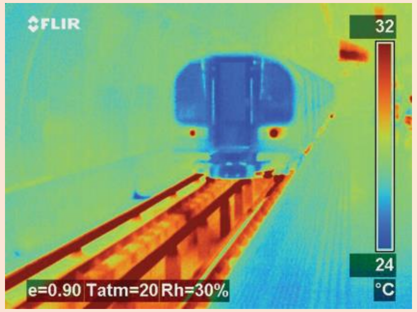
Waste heat - The big questions

- How large?
- Where are they?
- How to capture?
- What is the benefit?
- How do they compare?

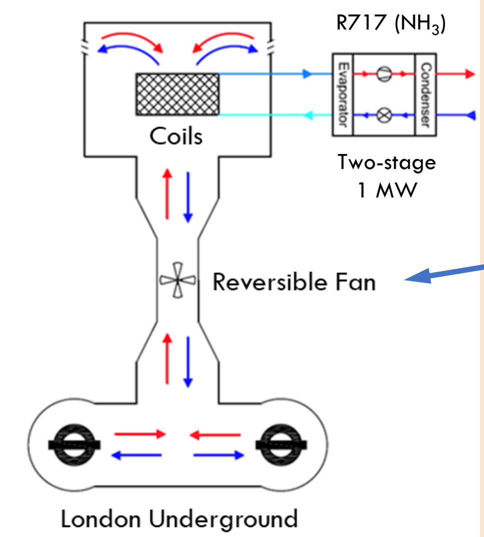
Waste heat source	Number of heat sources > 250kW	Waste heat recovery site/medium	Waste heat temperature(s) (°C)	Total thermal energy (heat) output (GWh year^{-1})
Data centres	264	IT server exhaust air	30 to 40°C	16200
		Chilled water heat rejection	10 to 20°C	
Electricity substations	1336	Transformer cooling system	40 to 70°C	4000
Wastewater	985	Final WWTP effluent	12 to 23°C Average 17.6°C	22514
Mine water	18584	Water	12 to 40°C	519644
Supermarkets	3653	Condenser heat rejection	21 to 27°C	7800
		Desuperheater	53°C	
Cold stores	195	Condenser heat rejection	15 to 30°C	3600
		Desuperheater	60 to 90°C	
Underground railway tunnels	65	Ventilation shaft air	11.5°C to 28°C	290
Cremations	269	Combustion exhaust gases	800 to 1000°C	165

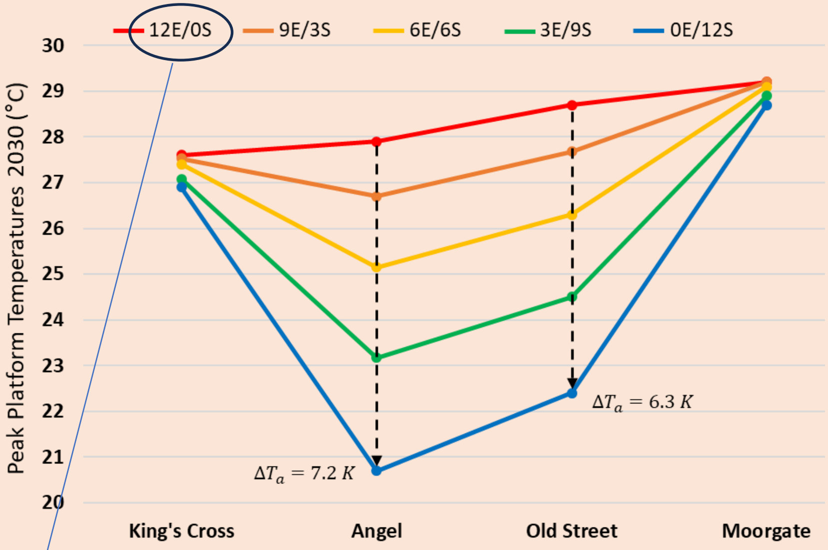
UNDERGROUND RAILWAYS

Integration of heating and cooling via district-scale heat pumps



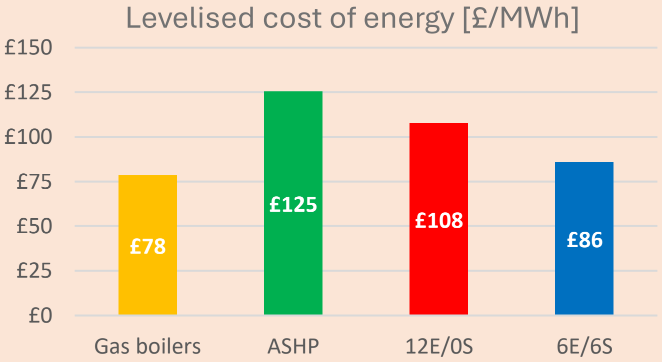
Temperatures up to 40°C have been recorded

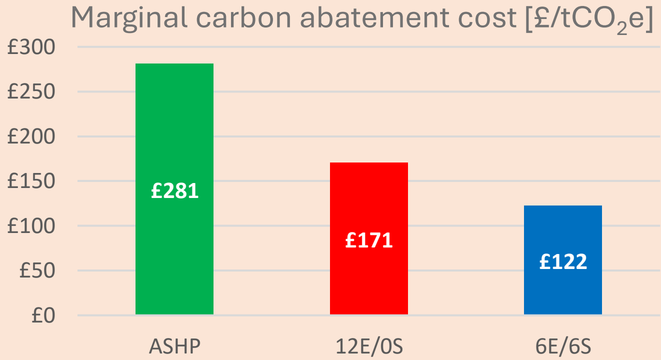




Extract vs Supply:
- Cooling potential?
- Cost of heat?

Bunhill 2 energy centre, Islington.
Taking warm air from Northern Line tunnels



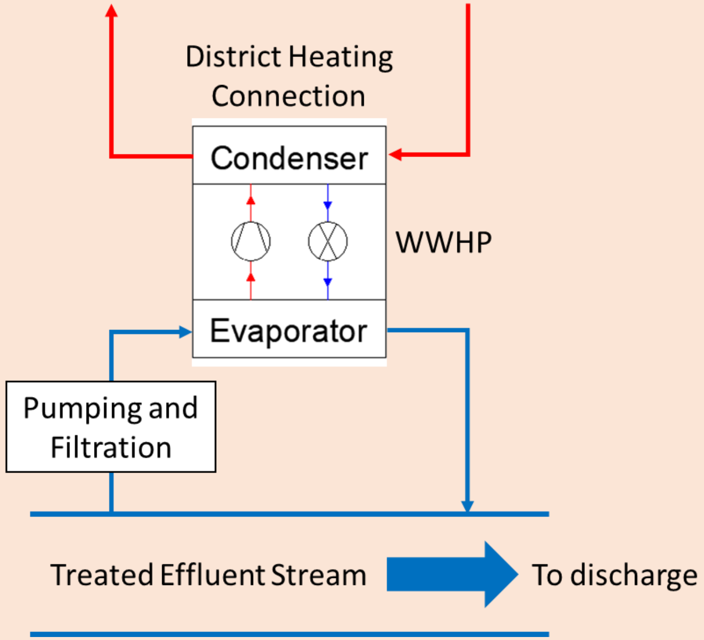


https://ior.org.uk/public/downloads/-IRQA/Waste%20heat%20from%20the%20London%20Underground.pdf

WASTEWATER TREATMENT PLANTS

A large and stable heat source, suitable for meeting base-loads

- 1,876 WWTPs in the UK serving agglomerations > 2,000 people
- Typical effluent temperatures from 13 to 22°C (average 15°C during winter)
- 22.5 TWh per annum (2.5GW average) could be extracted with effluent ΔT of 5 K i.e. evaporator ≈ 8 - 17 °C
  - 64% of this is in urban areas.



District Heating Connection

Condenser

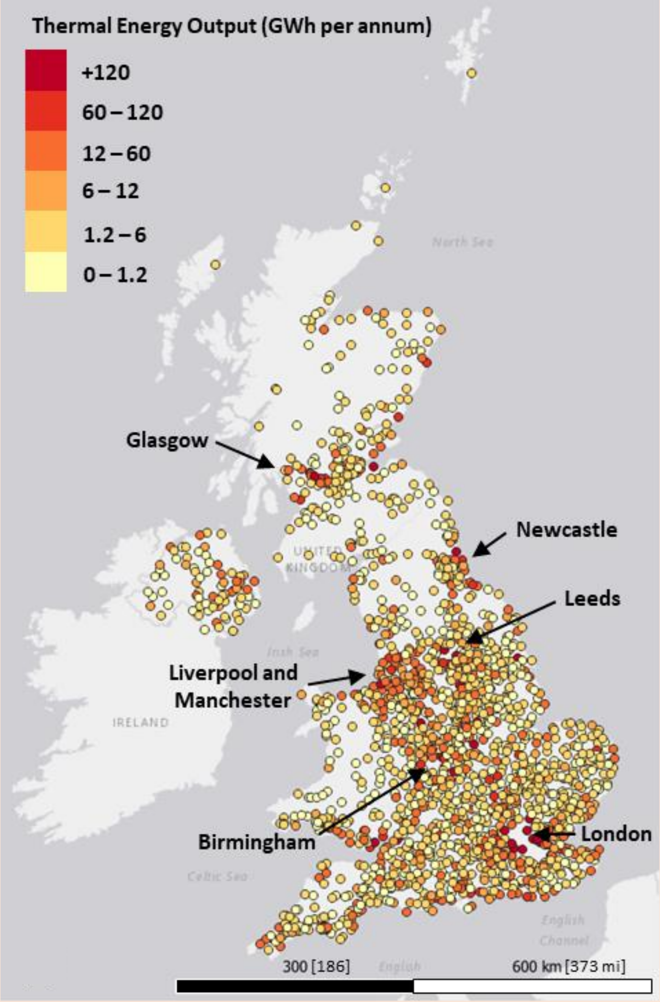
WWHP

Evaporator

Pumping and Filtration

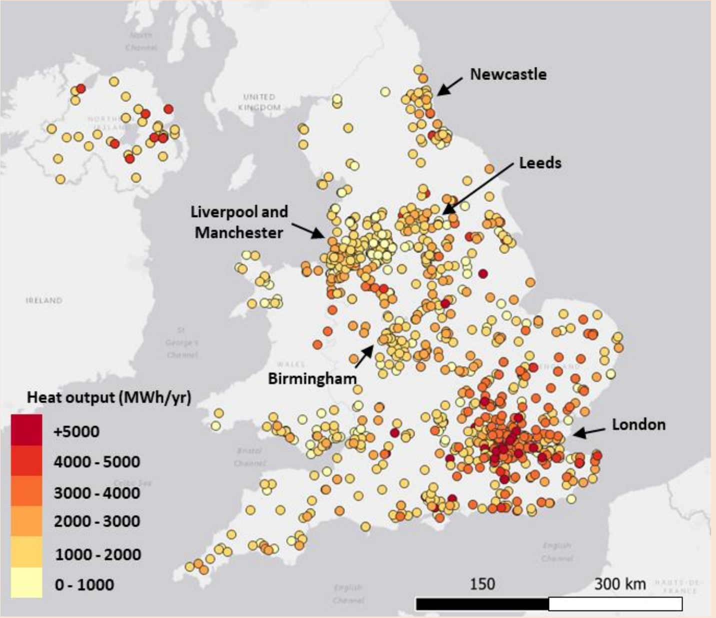
Treated Effluent Stream

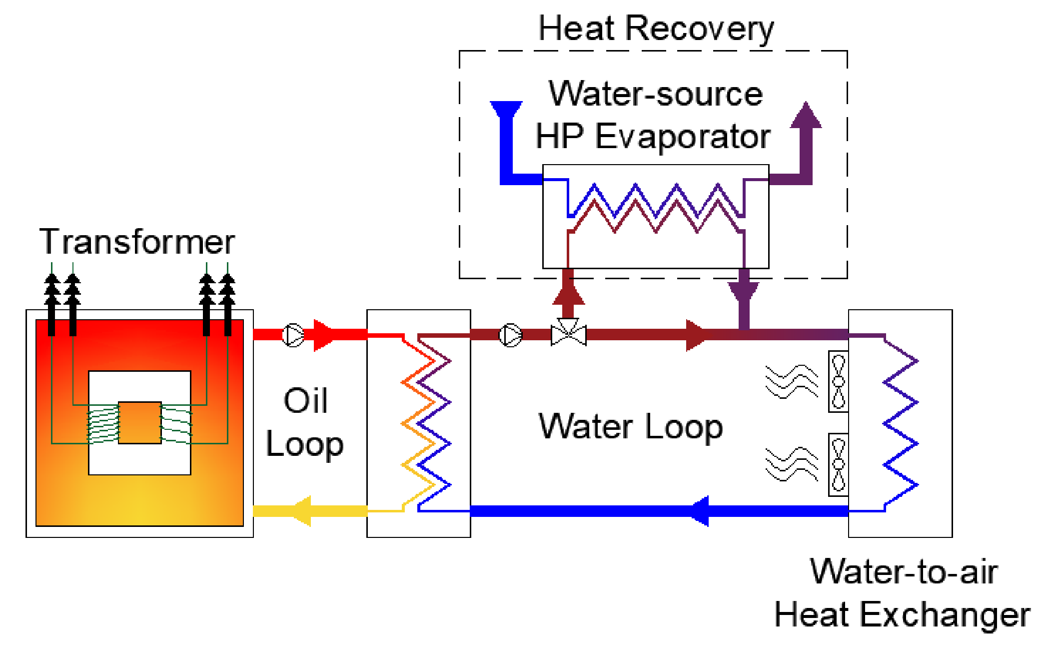
To discharge



ELECTRICAL TRANSFORMERS

- 1.4% of grid electricity is lost as heat in transformers
- 40 – 70 °C

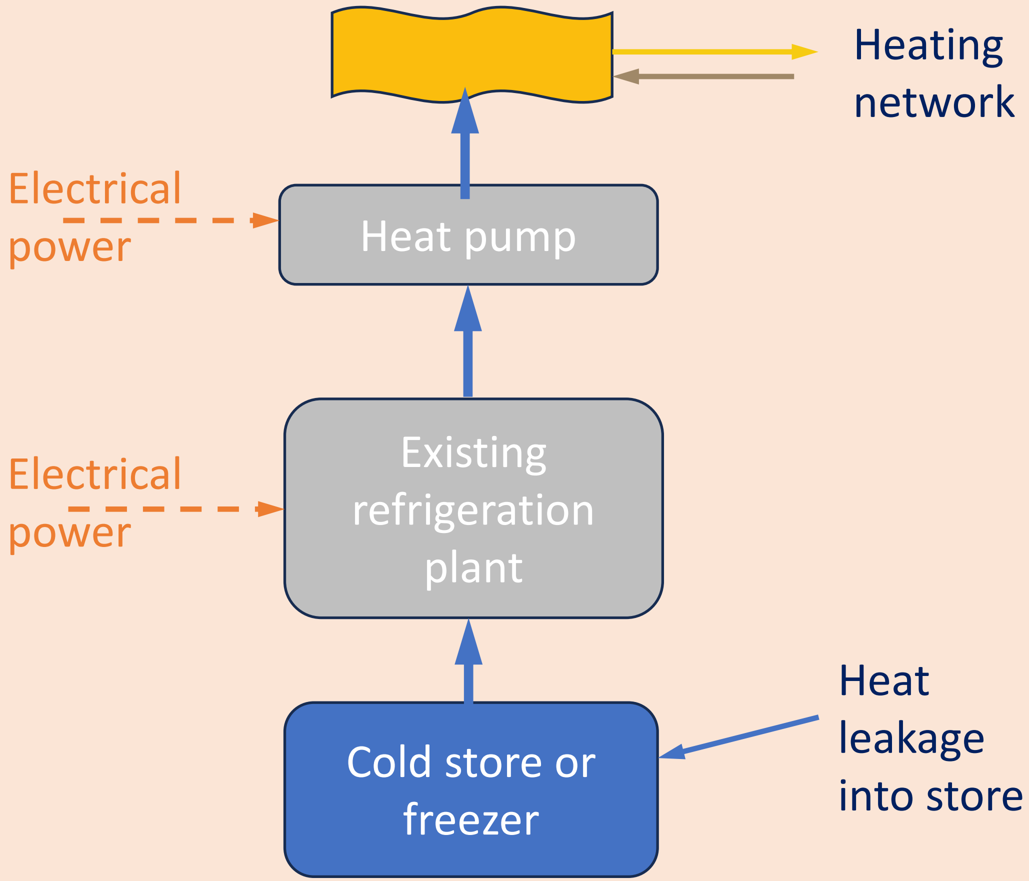




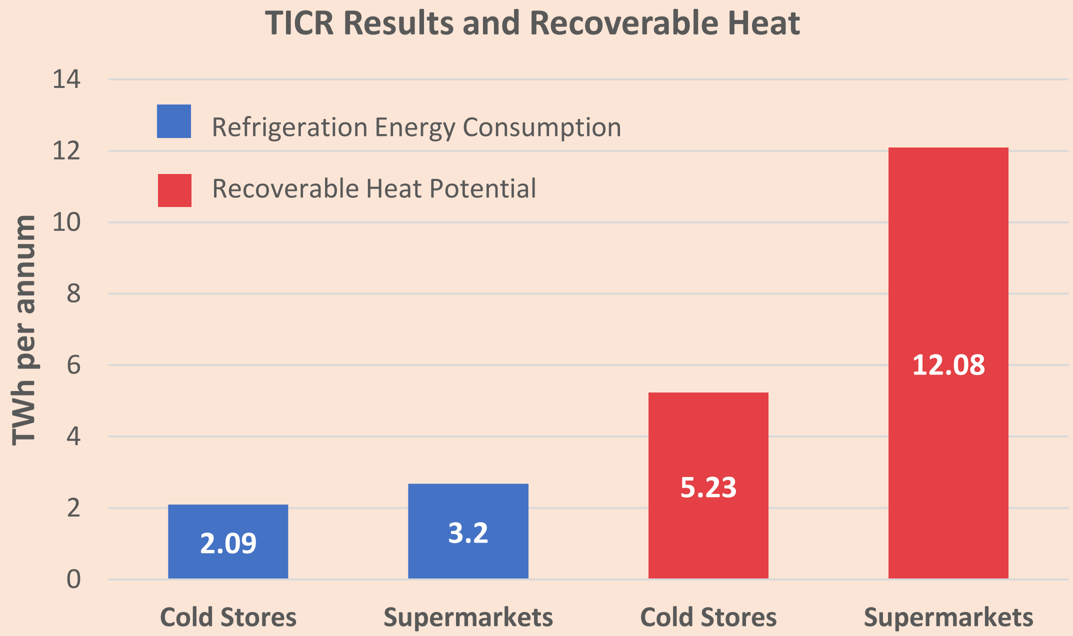
Country	Number of sites >60MVA	Recoverable heat (TWh)
England	1,181	3.52
Wales	78	0.18
Northern Ireland	77	0.30
Scotland*	55	0.32
Total	**1,391**	**4.32 (58% urban)**

*Obtained from an investigation by Sinclair & Unkaya (2020)

COLD STORES AND SUPERMARKETS



- Data gathered for 7,400 supermarkets and 607 cold stores (but there are more!)
- Recoverable heat calculated from annual energy use assuming SCOP = 1.5 for cold stores and 3.52 for supermarkets

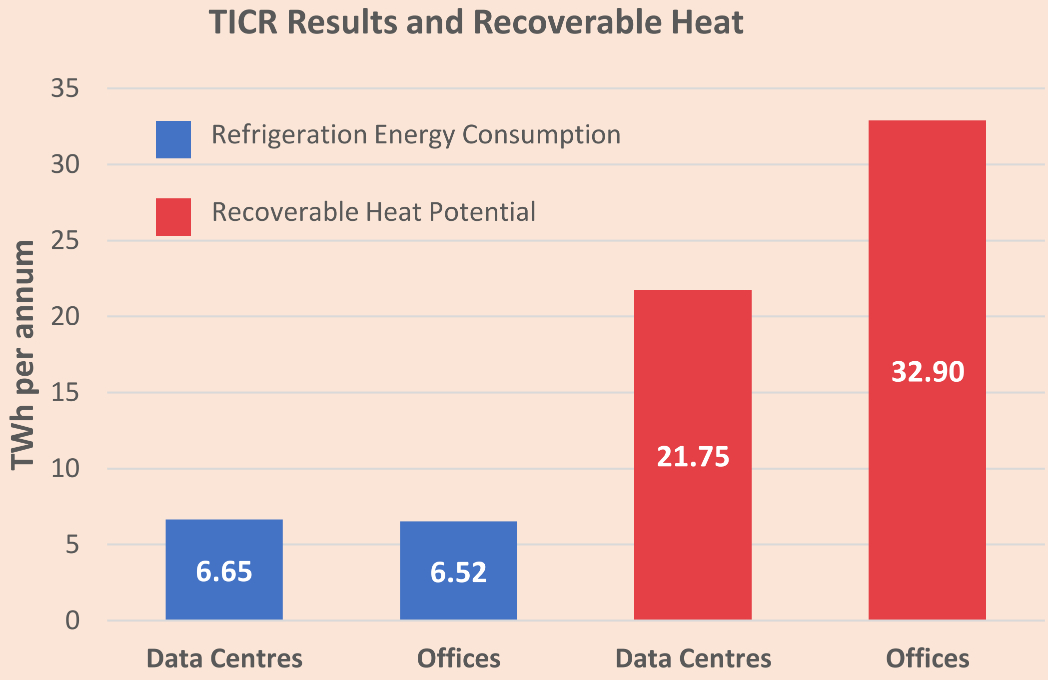


LoT-NET

EST 1892 LSBU

DATA CENTRES

- Data gathered for 521 data centres and 1584 office server rooms
- This could maintain the temperatures in an ambient-loop heat network (a virtual borehole for transmitting heat to heat pumps).



MINE WATER as a heat store

CIBSE JOURNAL

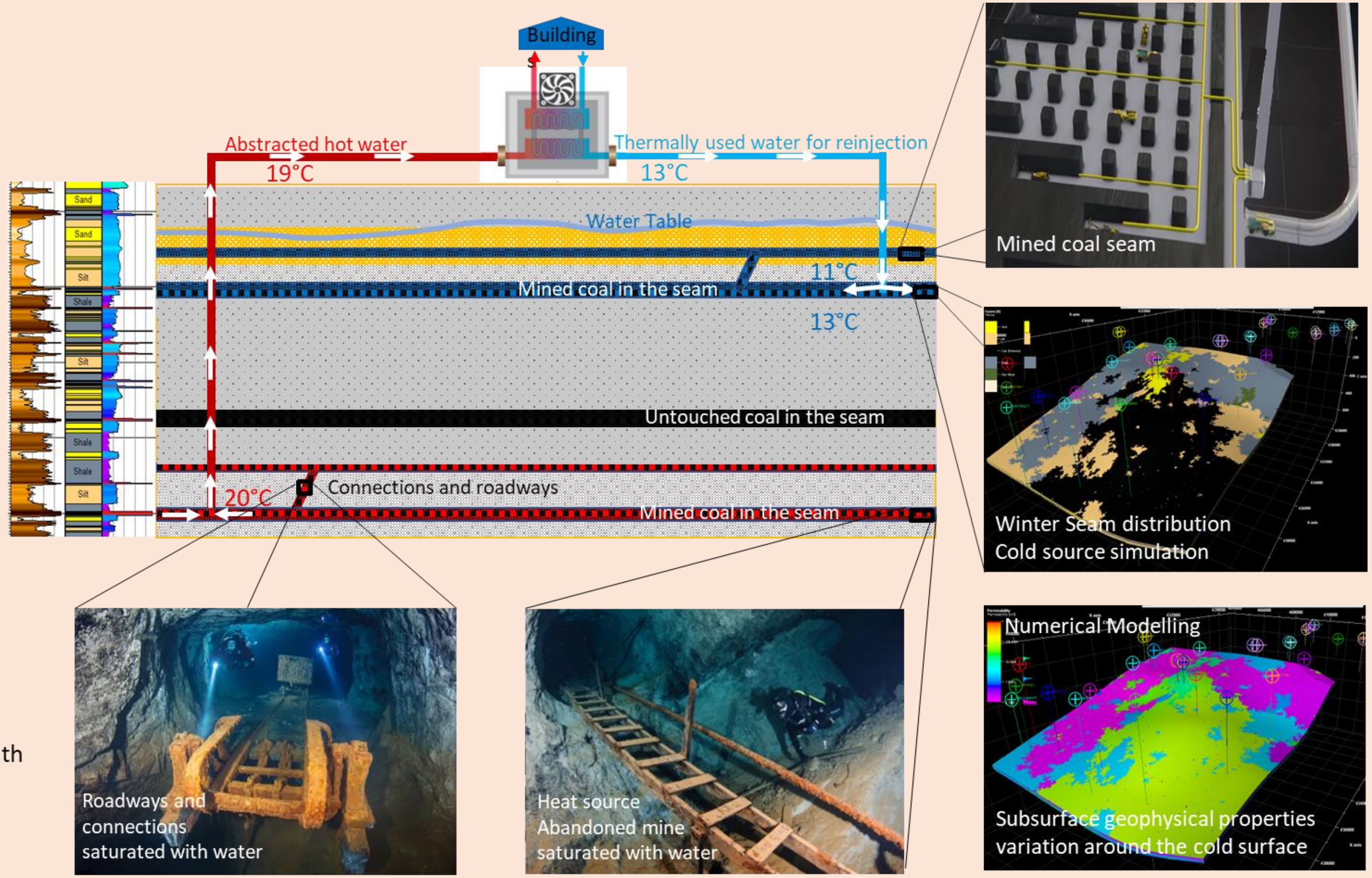
Minewater study wins symposium prize

The presentation of a case study on the integration of minewater into smart cooling and heating network systems has been voted the 'Most significant contribution to the art and science of building services engineering' at the annual CIBSE ASHRAE Technical Symposium.

- 23,000 abandoned coal mines in the UK beneath 25% of UK buildings

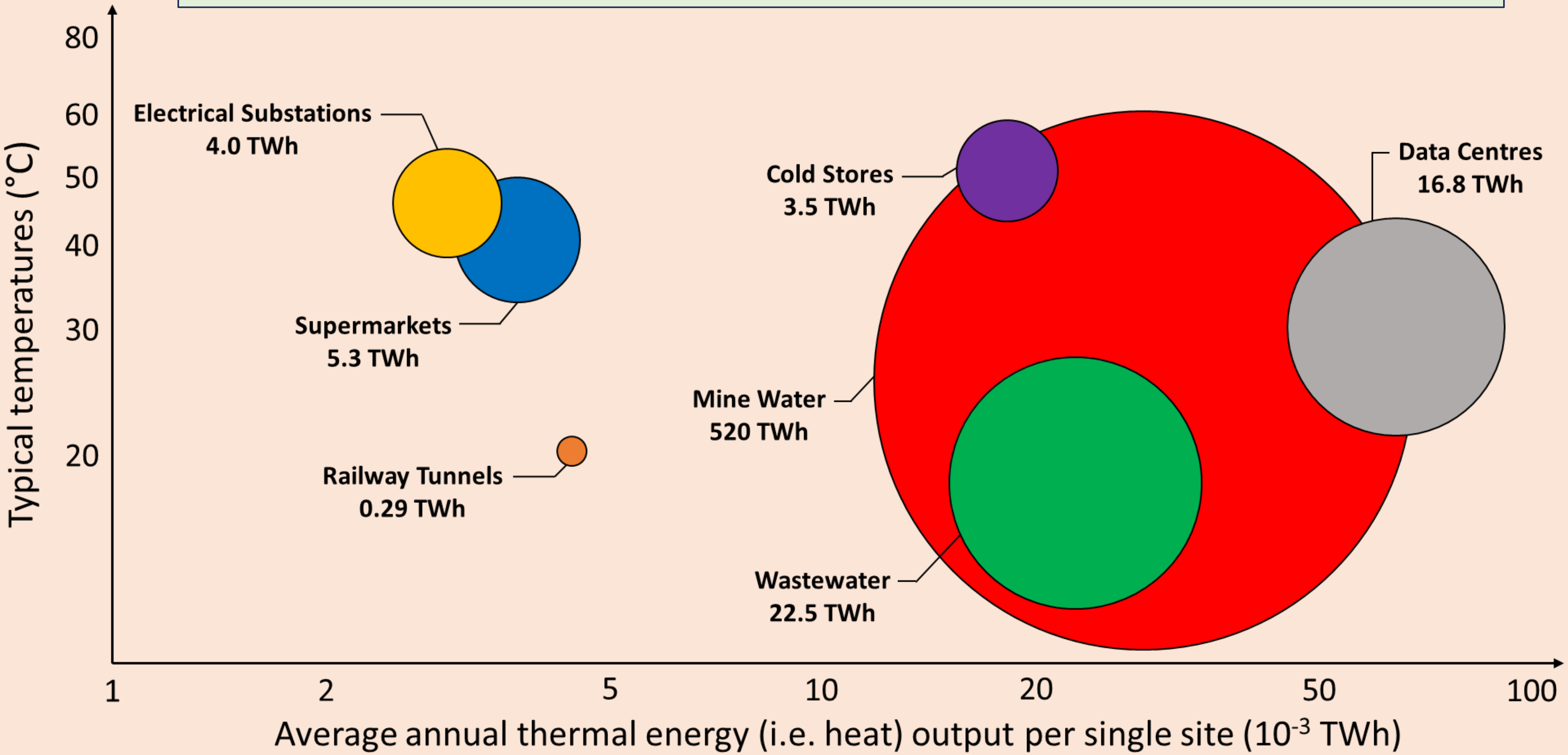
Integration of waste heat and mine water:

- Saving 7MW of waste heat.
- Heating nearly 2000 buildings.
- Inter-seasonal heat storage.
- Economically efficient.



Summary: LOW-GRADE RECOVERABLE HEAT

- There are widespread opportunities for efficient heat capture and reuse across the UK
- Use these to charge **thermal stores** using **low lift**, **high COP** heat pumps.



53 TWh

released annually from low-grade heat sources

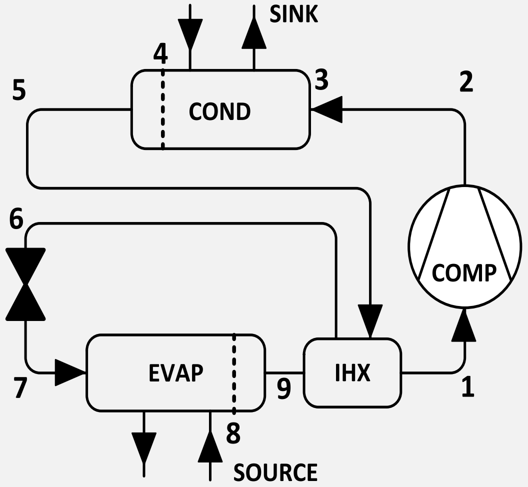
65%

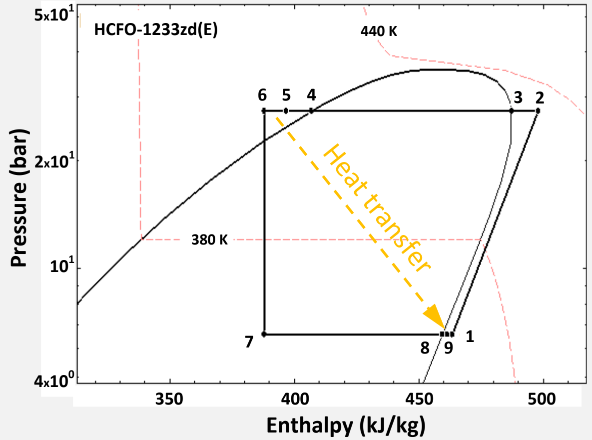
of the projected increase in annual heat demand for district heating in 2050

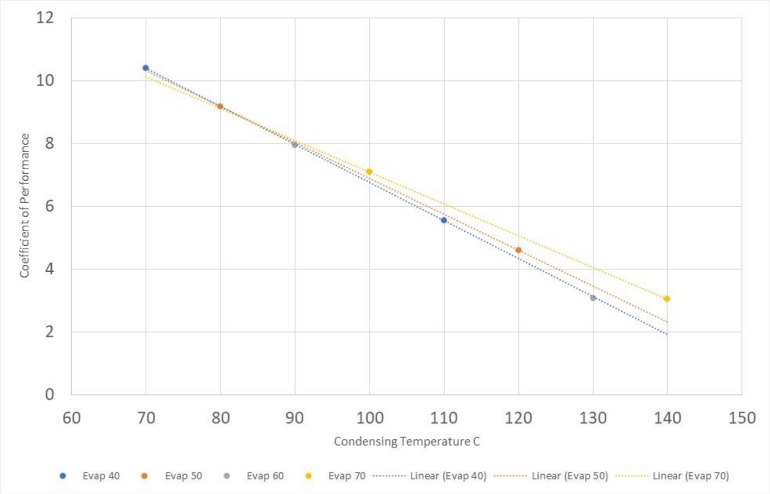
Ulster University

Work by Neil Hewitt's team on vapour compression heat pumps

WP3.1 Low temperature lift, high COP Vapour Compression Heat Pump

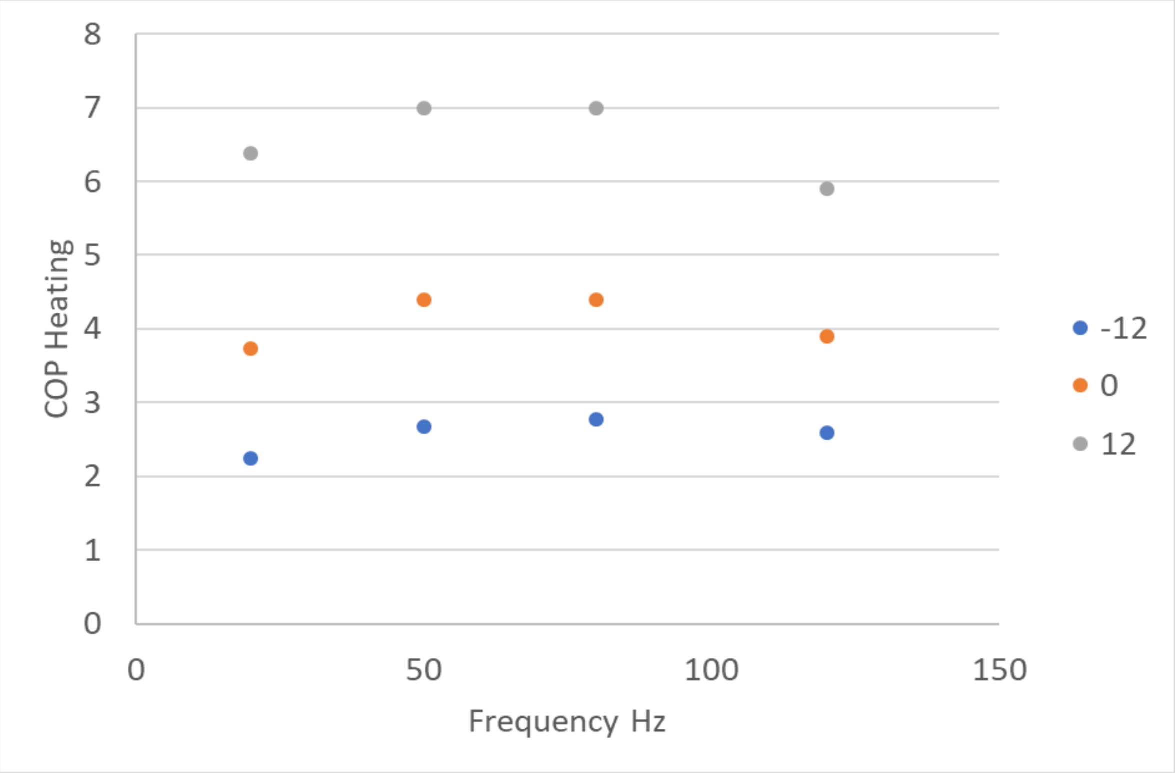






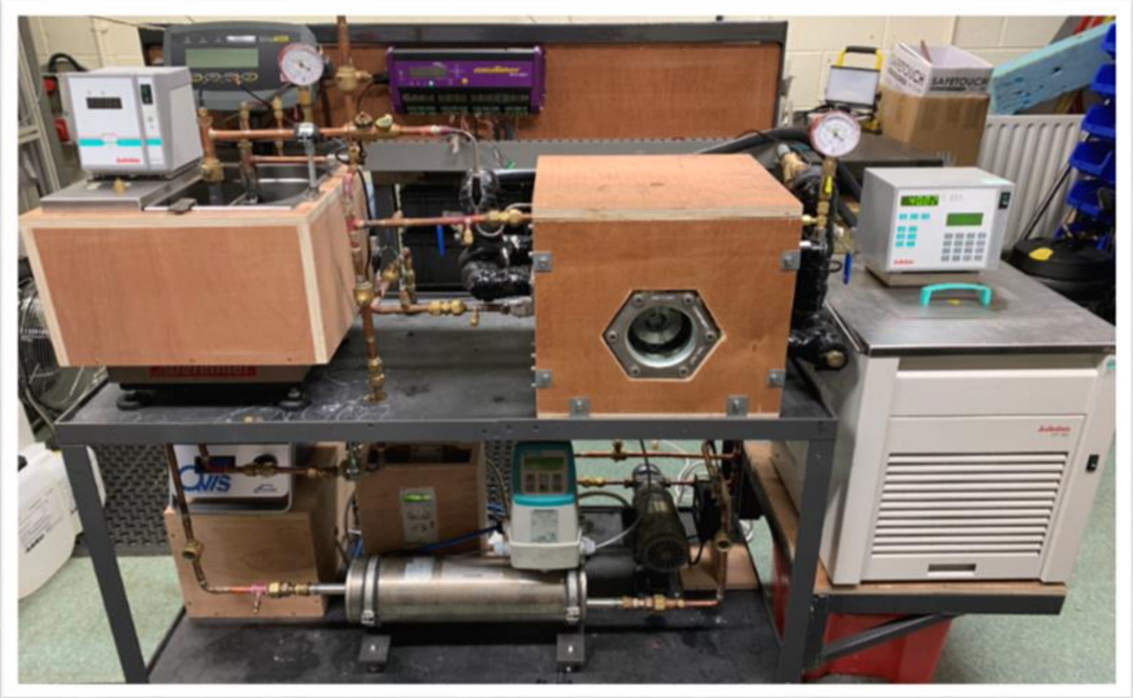
Work Package 3.2 – Vapour Compression Heat Pump for Demand Side Management

- **Variable Speed Drive** Compressor tested across a range of inlet and outlet temperatures
- Peak in performance at 50Hz-60Hz representing design condition
- Loss in performance becomes more pronounced at lower temperature lifts
- Work was carried out using R410a
- Replacement of R410a by R466A provided 5% greater performance
- R466A GWP of 733 compared to R410A of 2,088



Domestic Demand-Side Response: The Challenge for Heat Pumps in a Future UK—Decarbonised Heating Market. NJ Hewitt, N Shah, D Cotter, C Wilson, K Le, R Byrne, P MacArtain (2020) Renewable Energy and Sustainable Buildings, 735-745

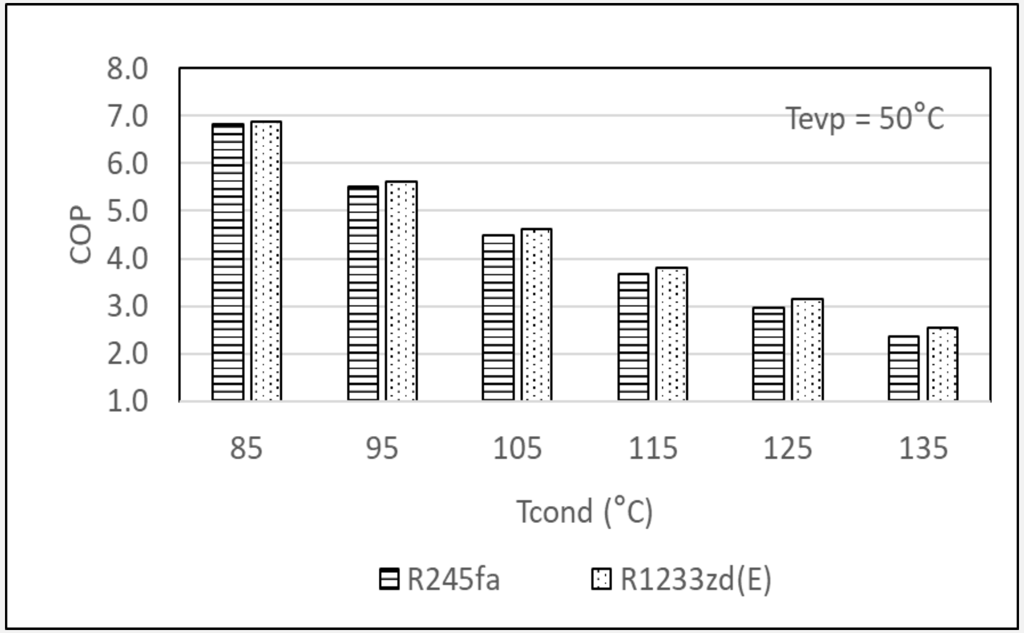
WP 3.3 – High Temperature Vapour Compression Heat Pump for Industrial Process Heating



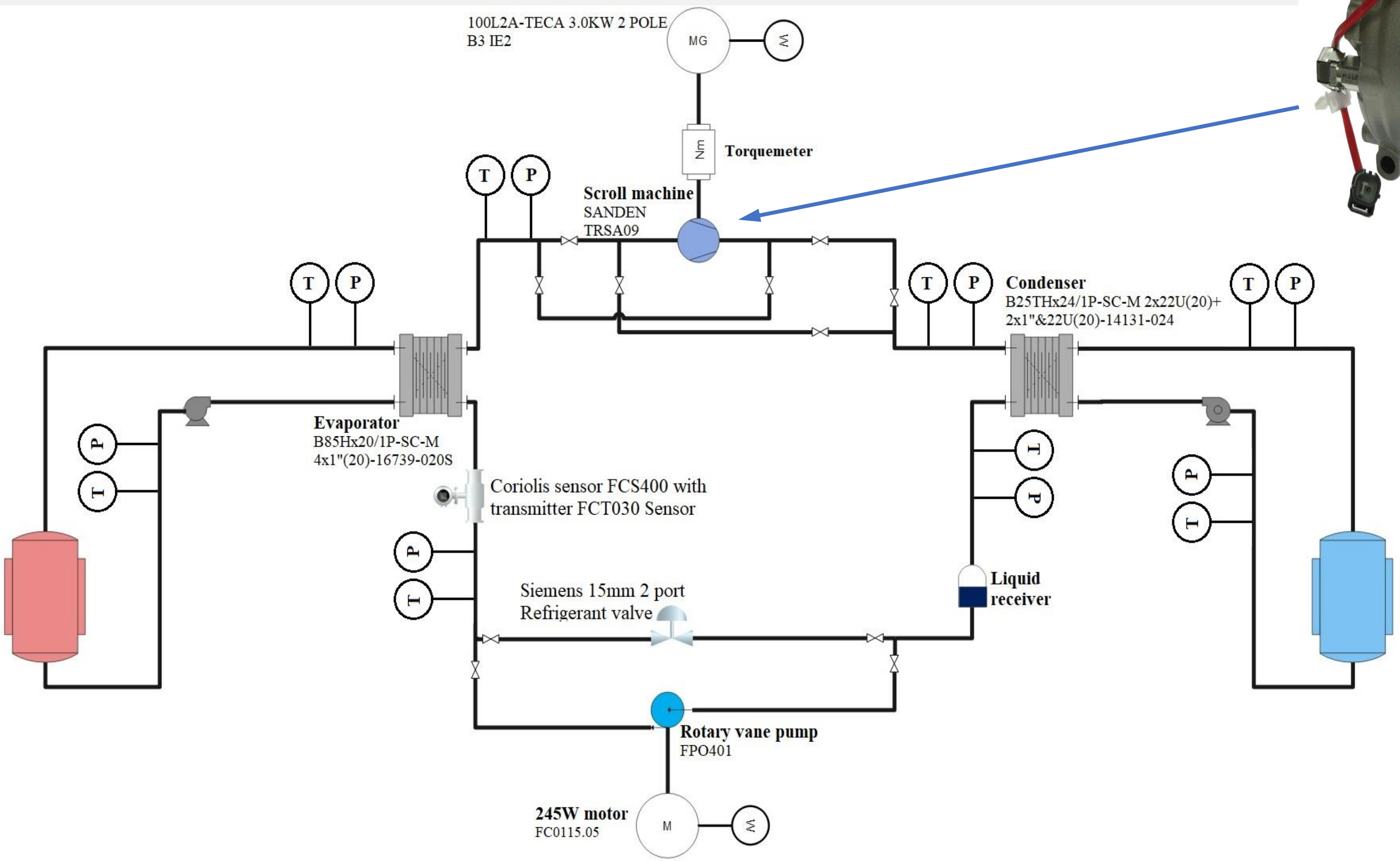
Temperatures up to 140°C can be delivered using R1233zd(E) as a replacement for R245fa

Compressor lubricants tested for solubility, miscibility and viscosity

R1233zd(E) performed better than the baseline R245fa.



WP3.4 – Combined Vapour Compression Heat Pump/ Organic Rankine Cycle for Heat or Electricity

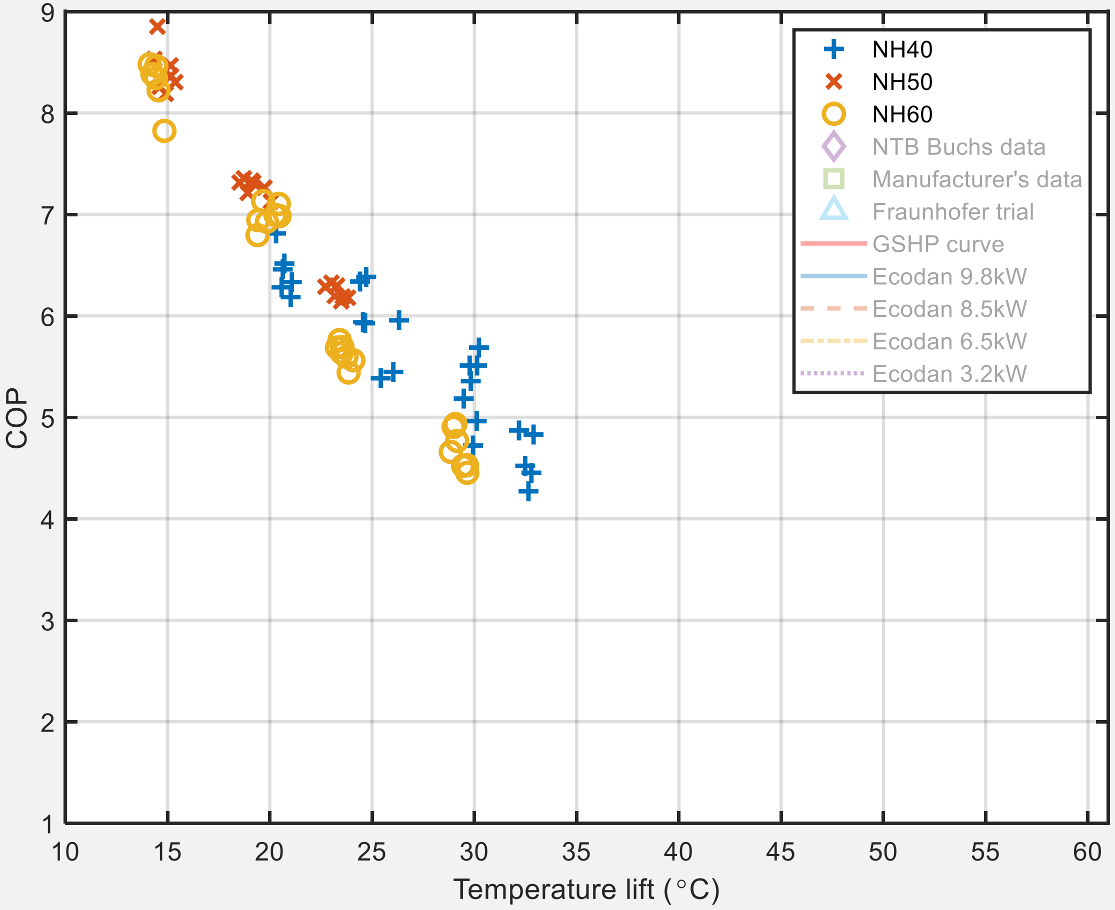


Using an automotive air-con scroll compressor/expander instead of an expansion valve!

LoT-NET

Ulster University

High COP heat pumps



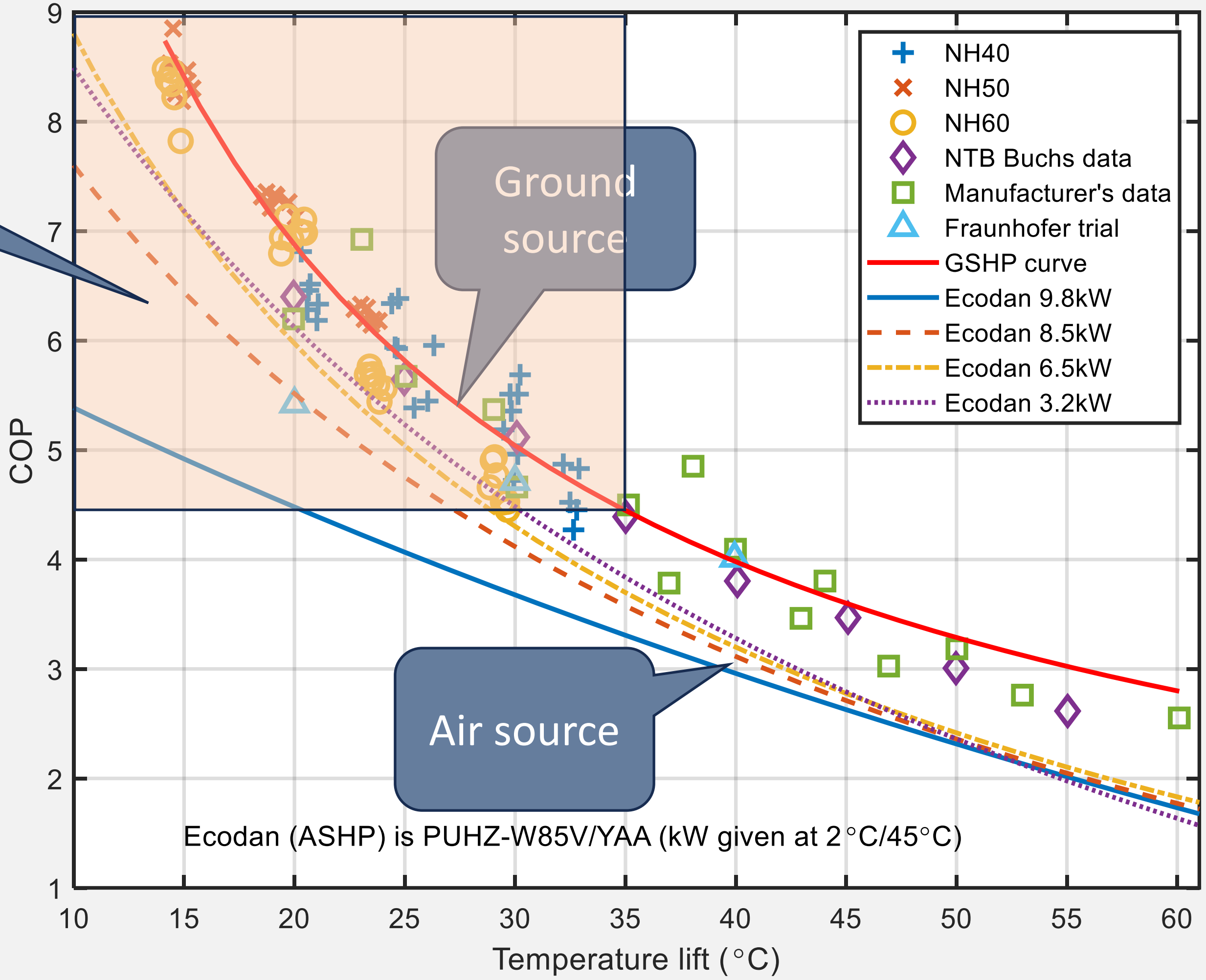
High temperature heat pump data from the University of Ulster.

- Source temperatures 40, 50 & 60°C (delivery range 62 to 94 °C).
- Temperature lift has been rescaled as if delivering heat at 45 °C

➢ The same technology could be used to give COP in the range 6-9 for low-temperature heat pumps.

Heat pump COP increases if less temperature lift is required.

Desired operational area



Ground source

Air source

Ecodan (ASHP) is PUHZ-W85V/YAA (kW given at 2°C/45°C)

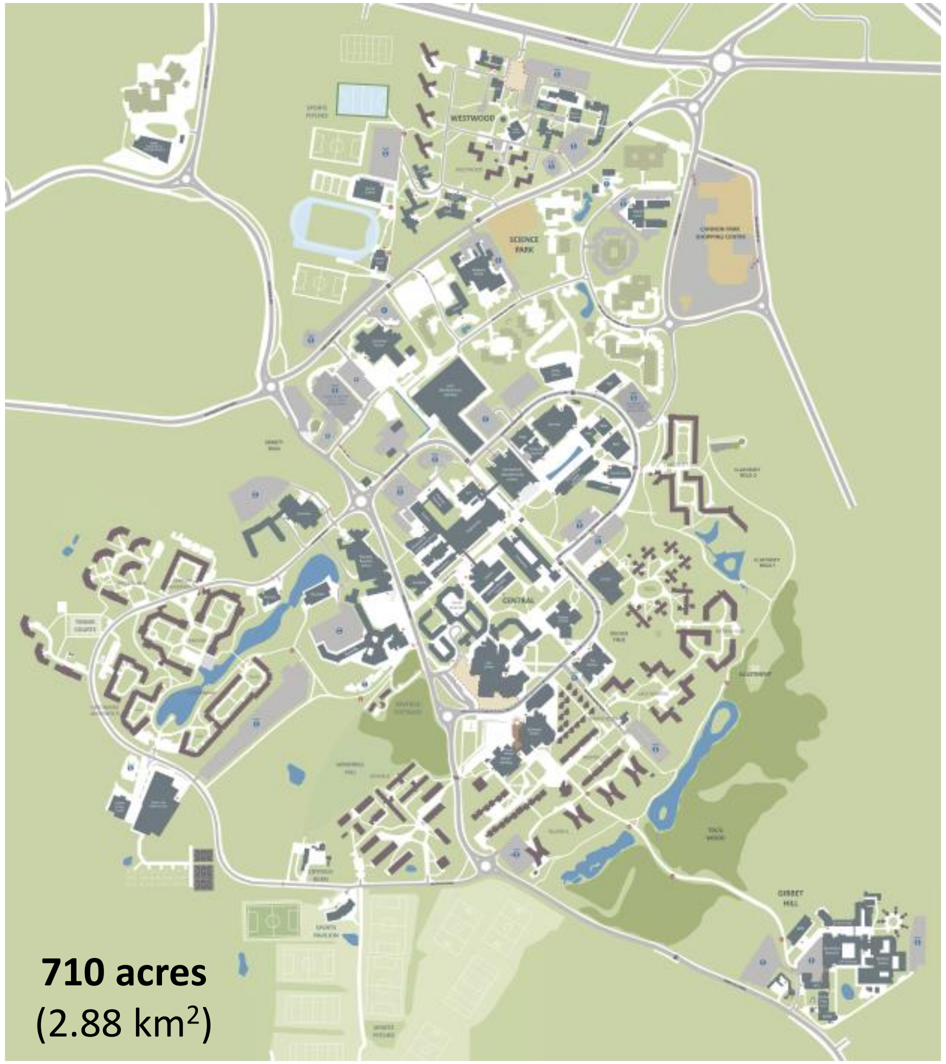
What might a low temperature heat network look like?

- Source 11°C
    - Energy centre heat pumps with 14 °C lift
- Low temperature network 25°C
    - Heat pumps in each building with 20 °C lift
- Building heating circuits at 45 °C
- *Overall temperature lift 34 °C* (+ heat exchangers' ΔT)
- Some rooms should be kept slightly cool (e.g.16 °C) and have a temperature boost button for users to push *if required*.

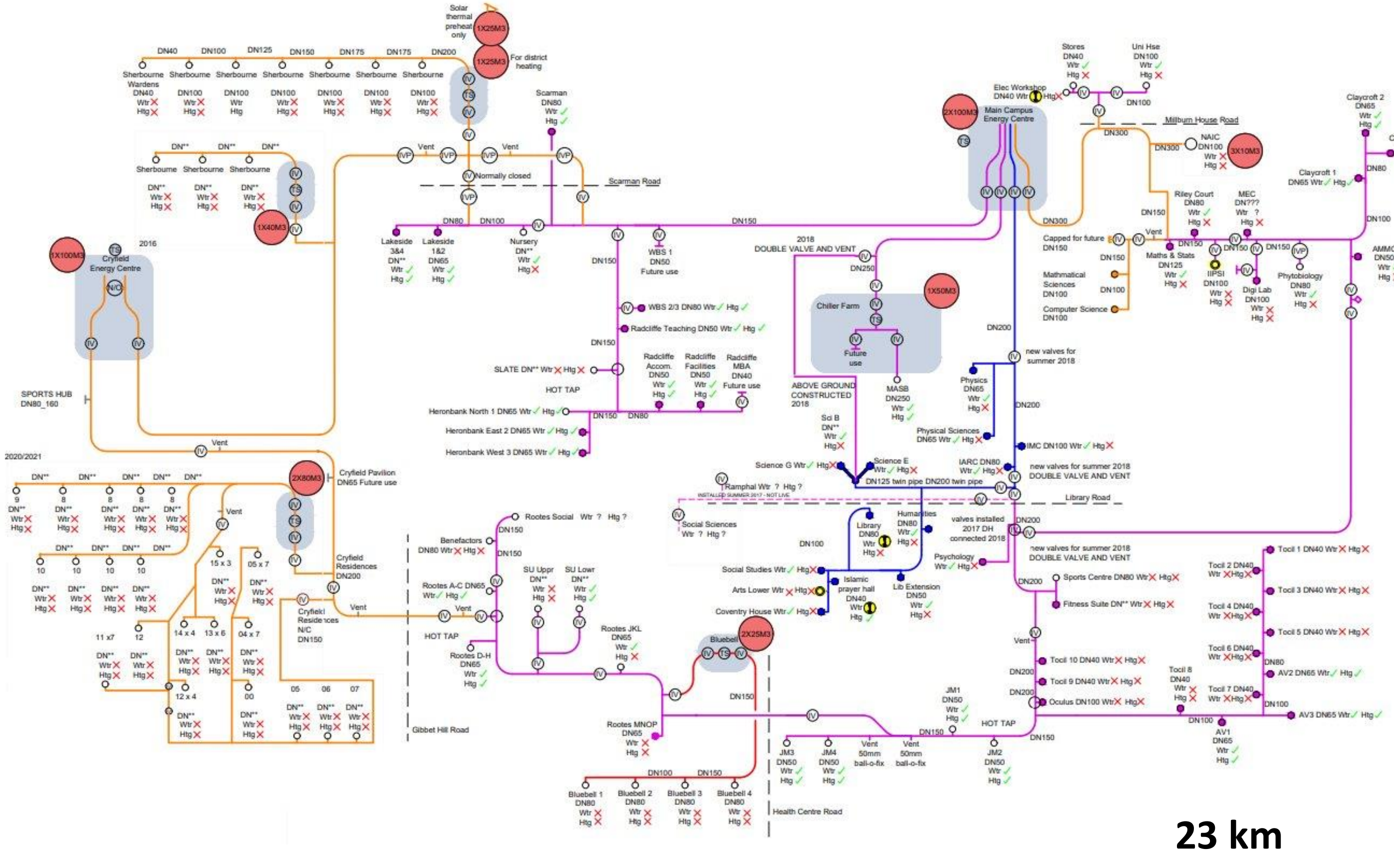
University of Warwick

WARWICK
THE UNIVERSITY OF WARWICK

Warwick case study background

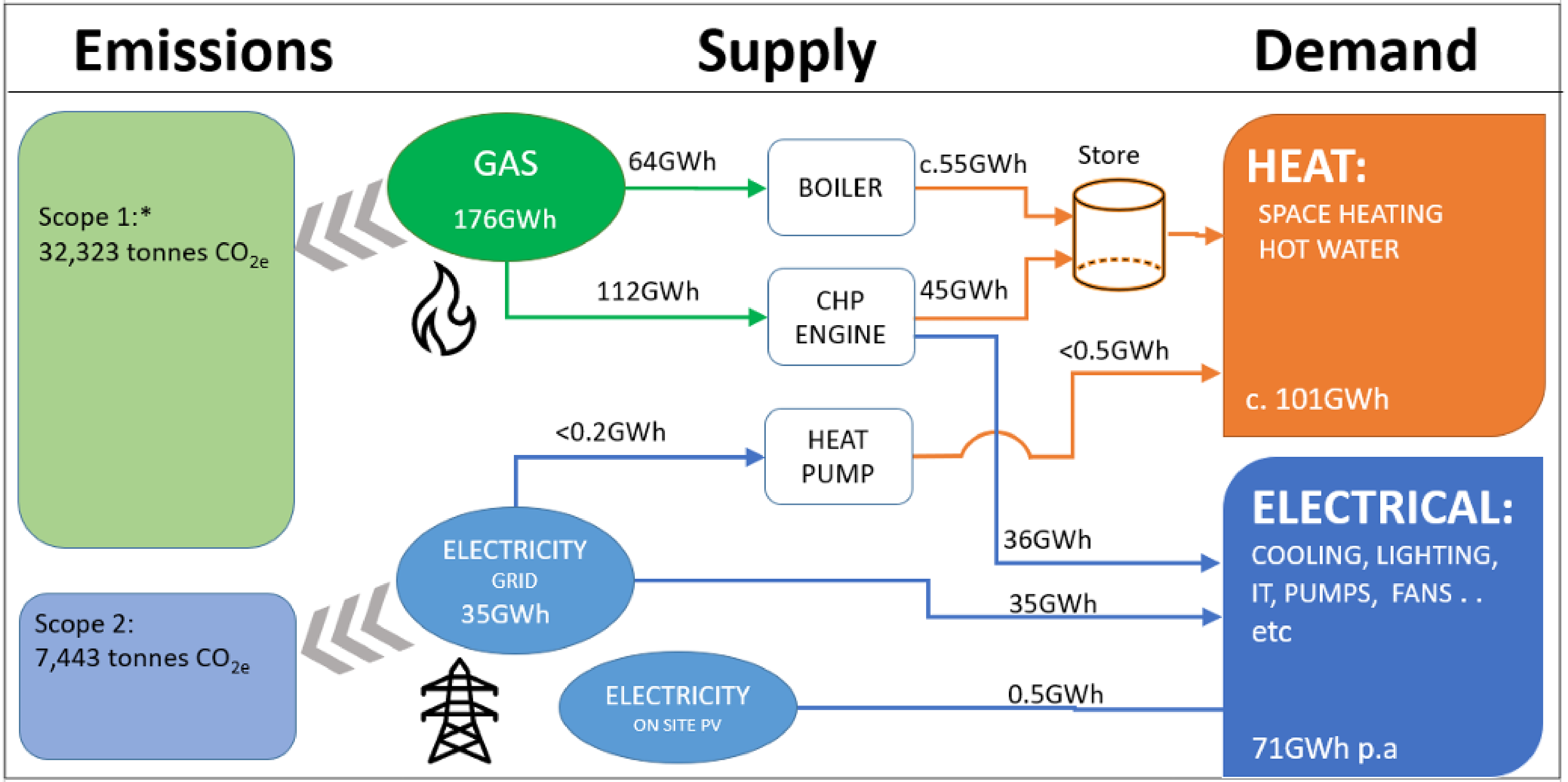


710 acres
(2.88 km^2)

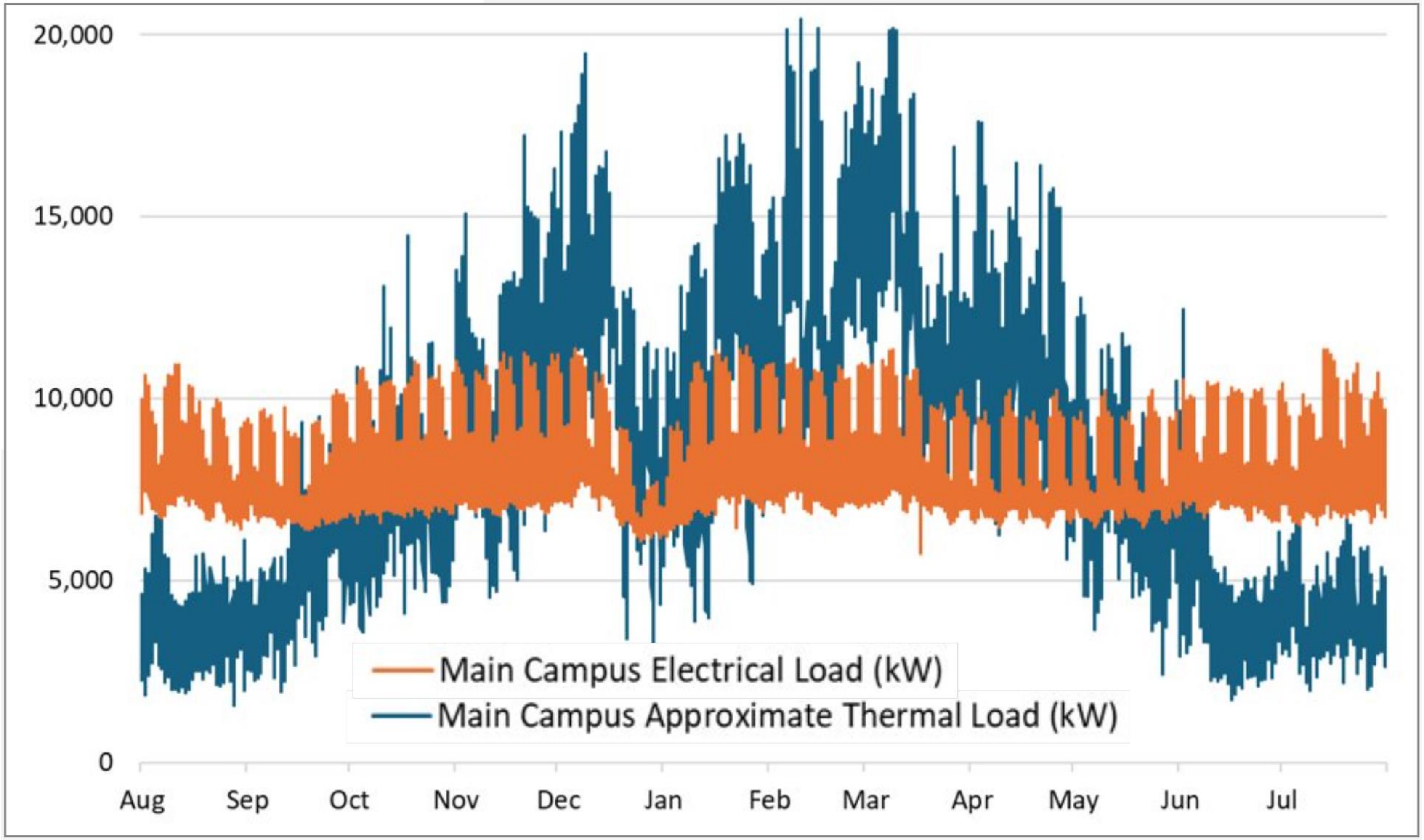


23 km

Background: campus emissions



Campus annual energy consumption profile



71 GWh electricity

101 GWh heat

University policy on carbon emissions

The university declared a “Climate Emergency” in 2019

Targets:

- Scope 1 & 2 Net Zero by 2030
  - Eliminate gas use in CHP engines
  - Reduce demand
  - Use electricity for heating (assuming GB grid is decarbonised)
  - Roof-top PV

- Scope 3 Net Zero by 2050

University of Warwick provost

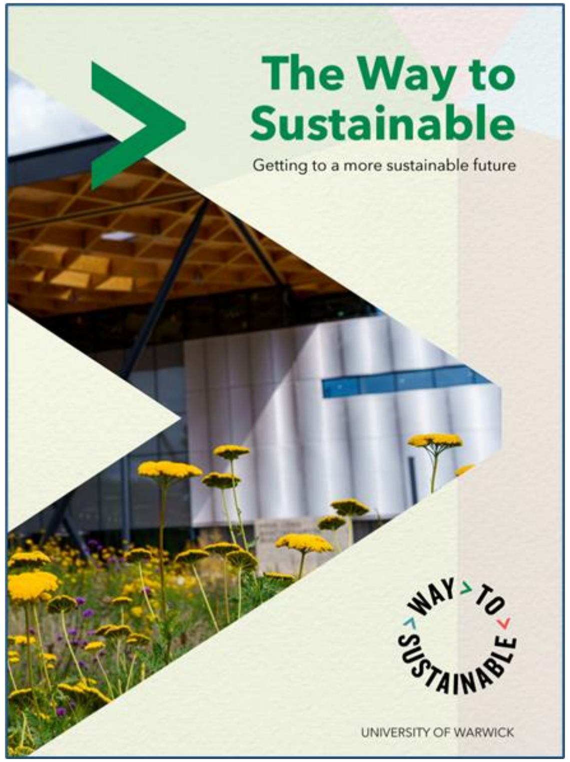
Moving to a decarbonised system

Guiding principles:

1. **Reduce** the heating requirement
    - Building fabric improvements & improvements in monitoring and control
2. **Decarbonise** the heat source
    - Heat pumps or direct electric heating?
3. Use **thermal storage**
    - Run heat pumps when electricity is lowest in carbon emissions
4. Use **recoverable heat**
    - Reduces the heat pump lift to raise the COP
5. Use **Smart** monitoring and control systems to deliver only the heat that is really needed

Reducing heat losses: the "Warwick Standard"

New build and retro-fit must be at least 20% better than the minimum Building Regulations standard.

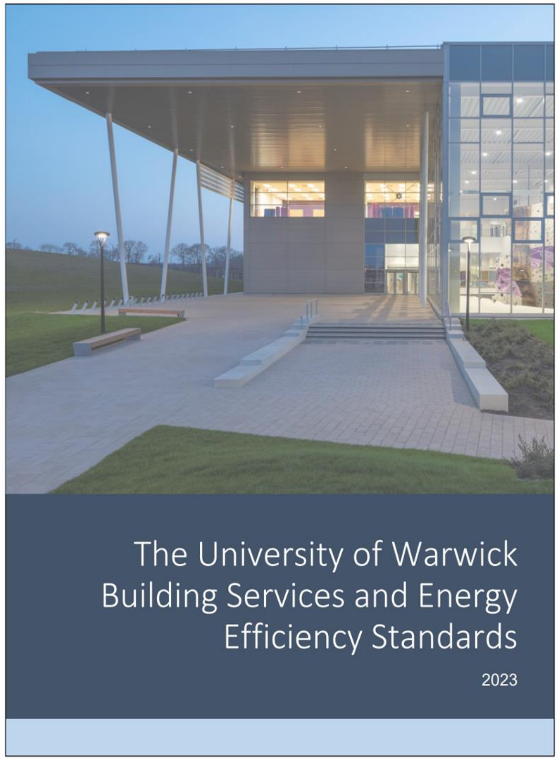


The Way to Sustainable

Getting to a more sustainable future

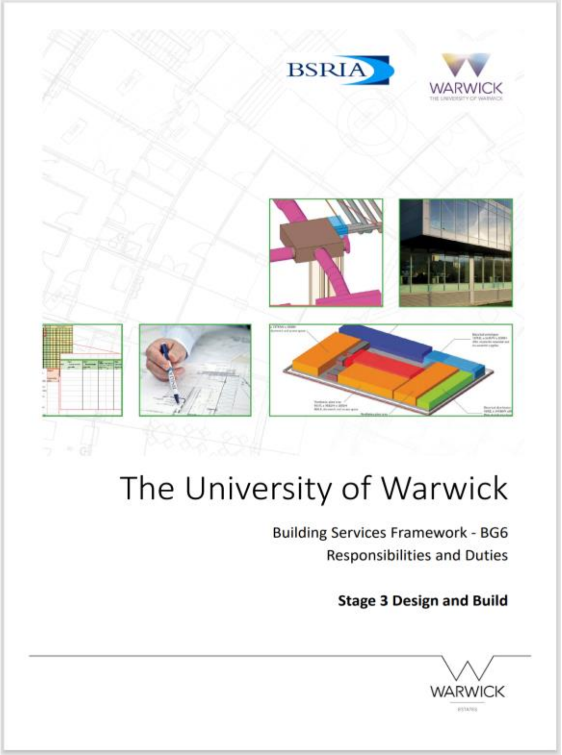
WAY TO SUSTAINABLE

UNIVERSITY OF WARWICK



The University of Warwick
Building Services and Energy
Efficiency Standards

2023



BSRIA

WARWICK

The University of Warwick

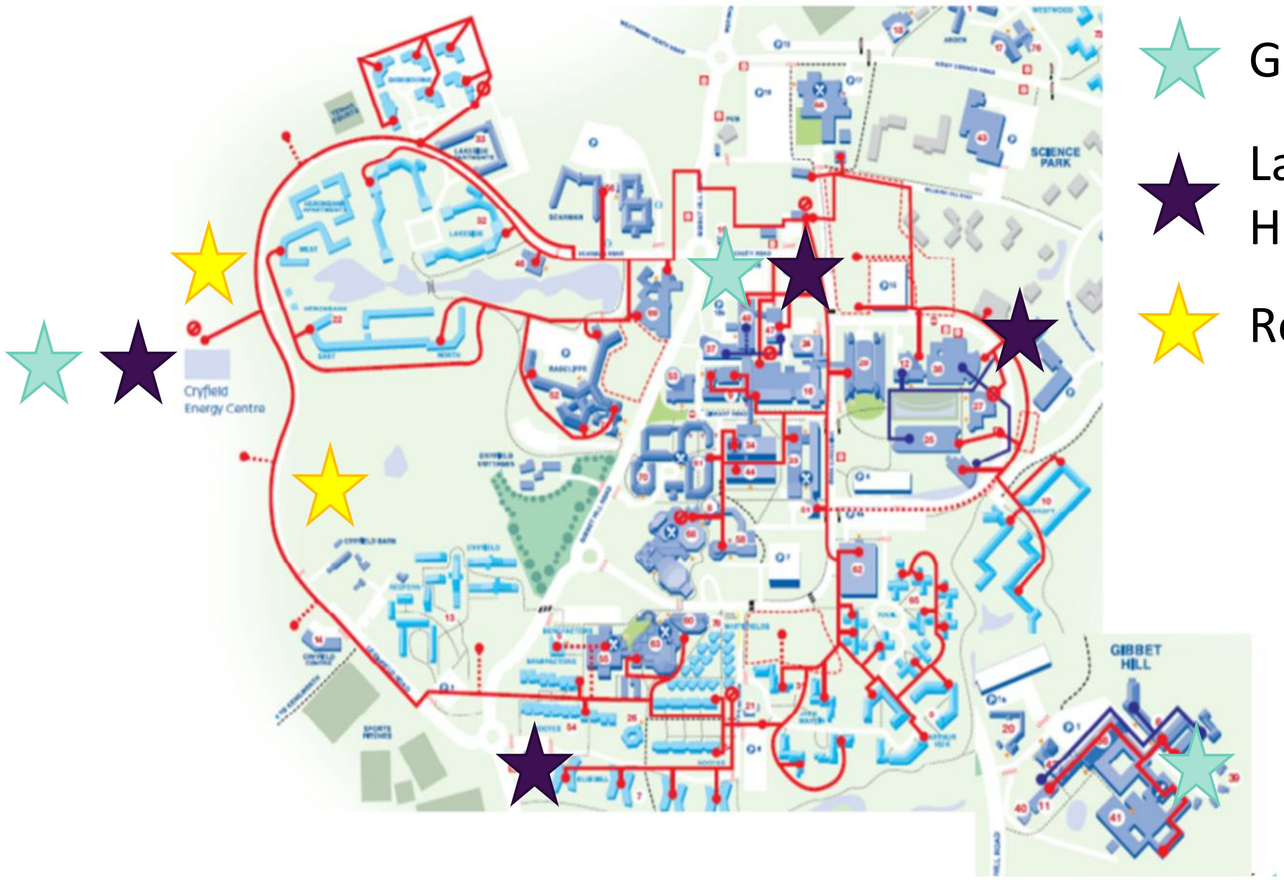
Building Services Framework - BG6
Responsibilities and Duties

Stage 3 Design and Build

WARWICK

→ Provides clarity for all stakeholders

Role of the heating network



★ Gas burning CHP (decommissioned)

★ Large Scale Decarbonised Heat Centres

★ Roof-top Solar (PV)

The district heating network allows a variety of heat systems to be installed:

- Heat pumps
- Boreholes
- Thermal stores
- Chillers

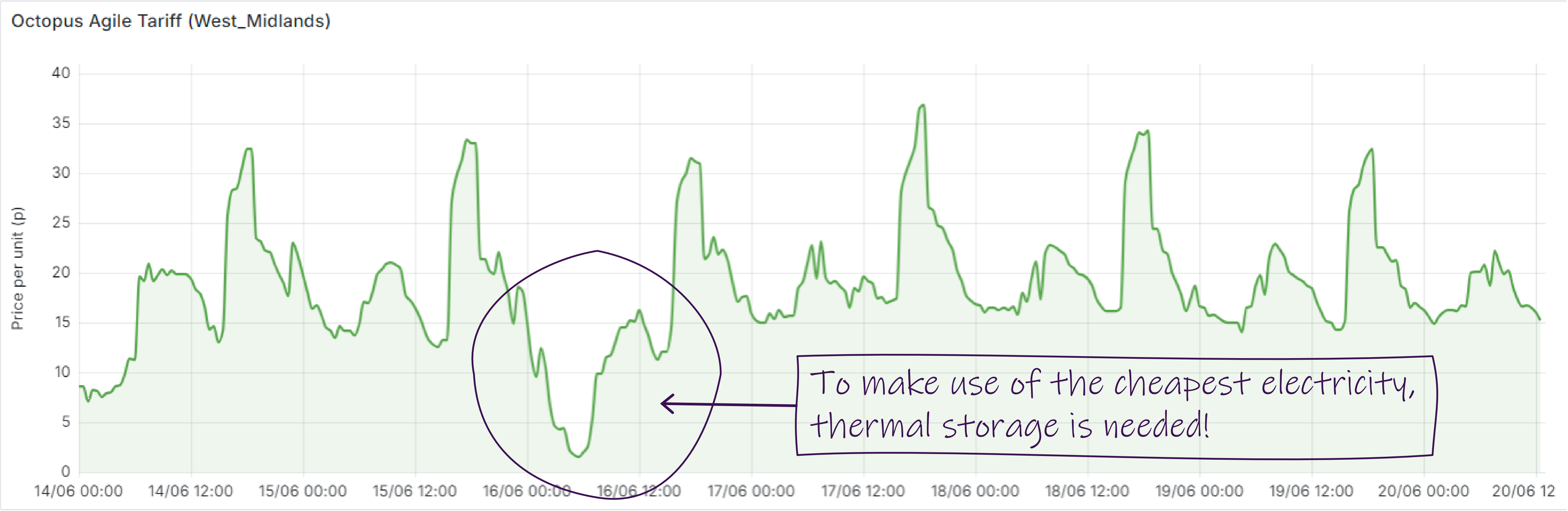
Advantages of the heating network

If heat pumps were installed locally in each building:

- ASHP would be noisy, unsightly, and with limited COP
- Not usually enough land nearby for a borehole array
- No room for large thermal stores in each building

Diversity, helps to balance the grid if HPs can be run when there is surplus renewable electricity

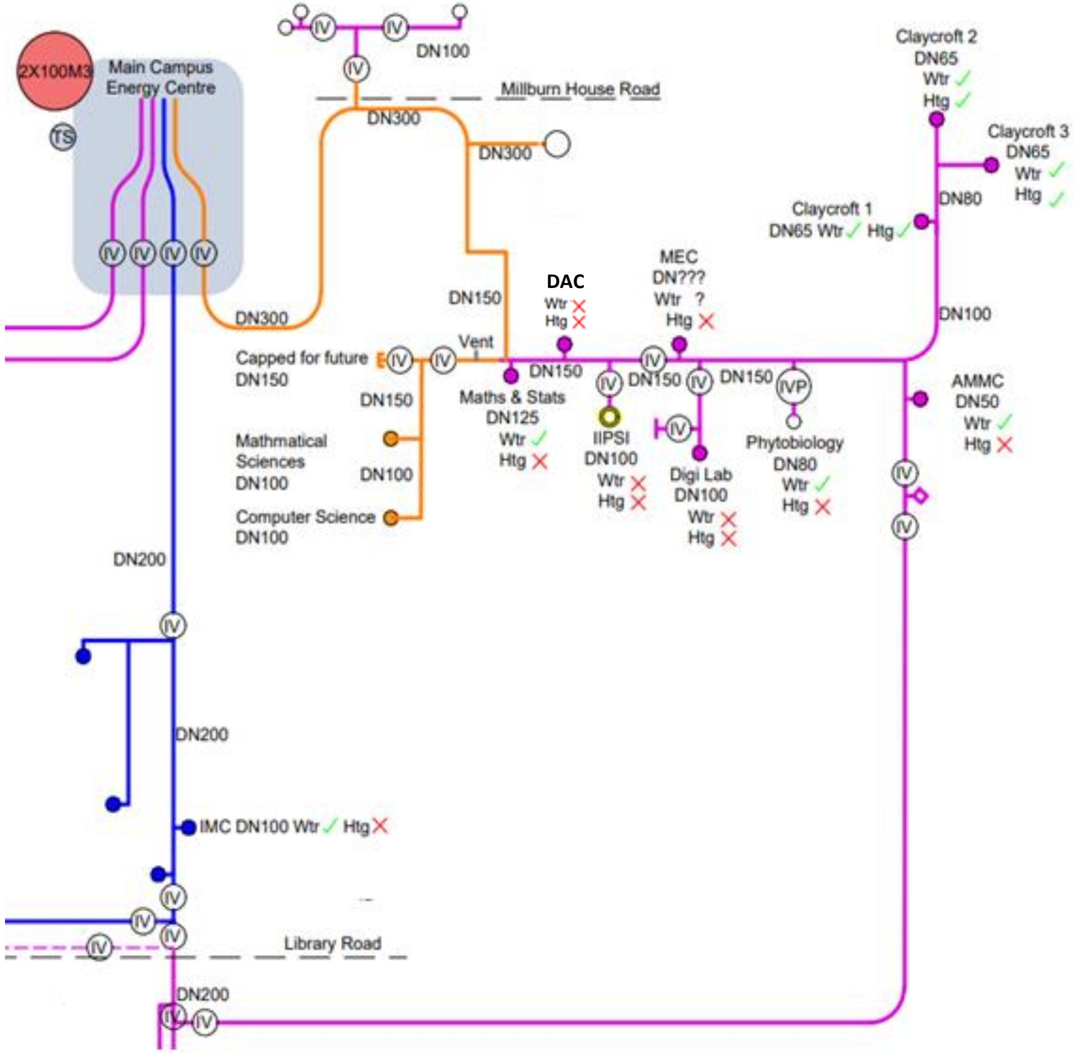
Half hour pricing for the last 7 days



To make use of the cheapest electricity, thermal storage is needed!

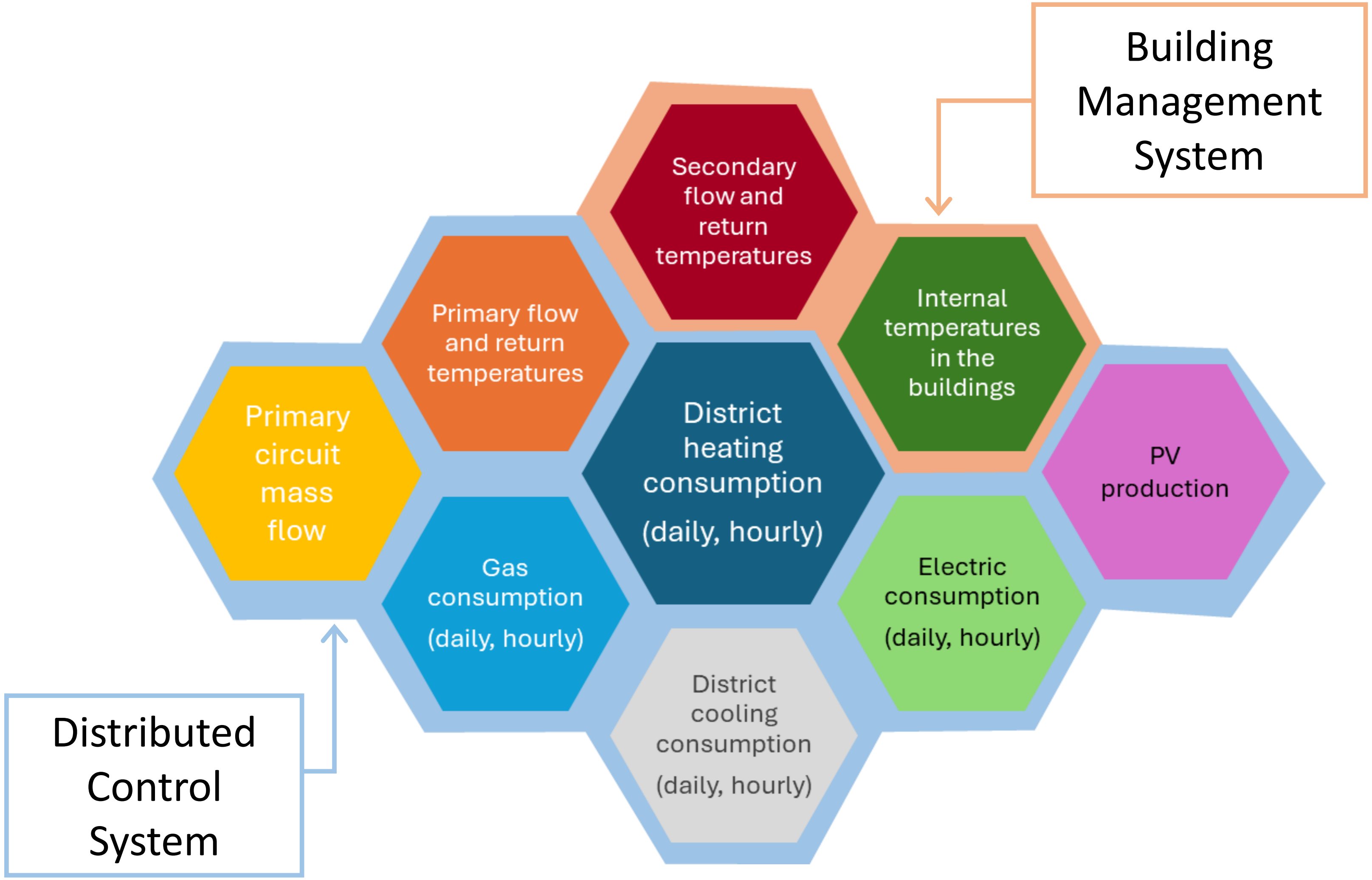
https://energy-stats.uk/octopus-agile-west-midlands/

Warwick case study background - SmSq



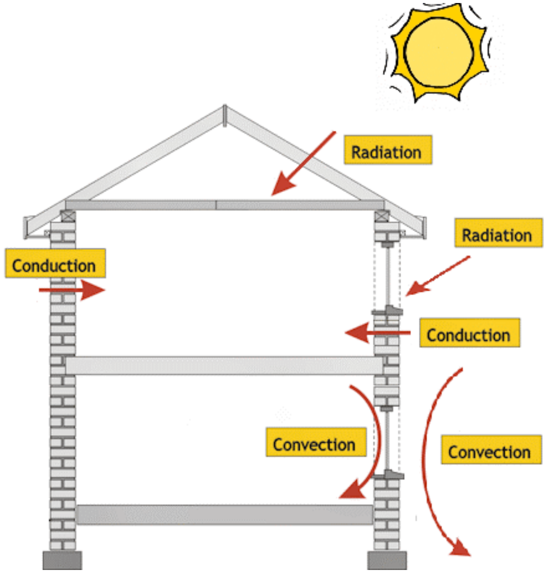
Residential Non-residential Car Park

The need for comprehensive data



- Accurate and reliable internal temperatures are needed
- Accurate and reliable secondary circuit temperature is needed
- BMS data was difficult to access as contractors managed it
- Ultimately the need for DCS and BMS integration

Building properties

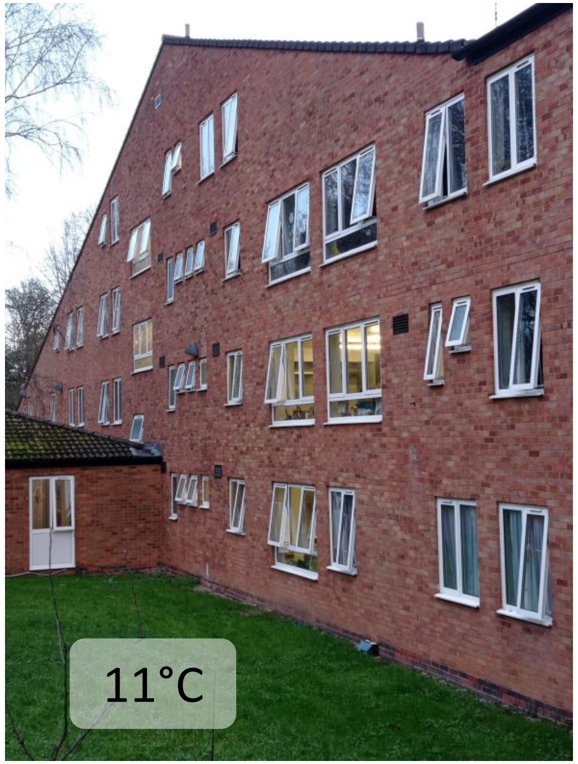


Thermal transmittance

Thermal mass

Solar gain

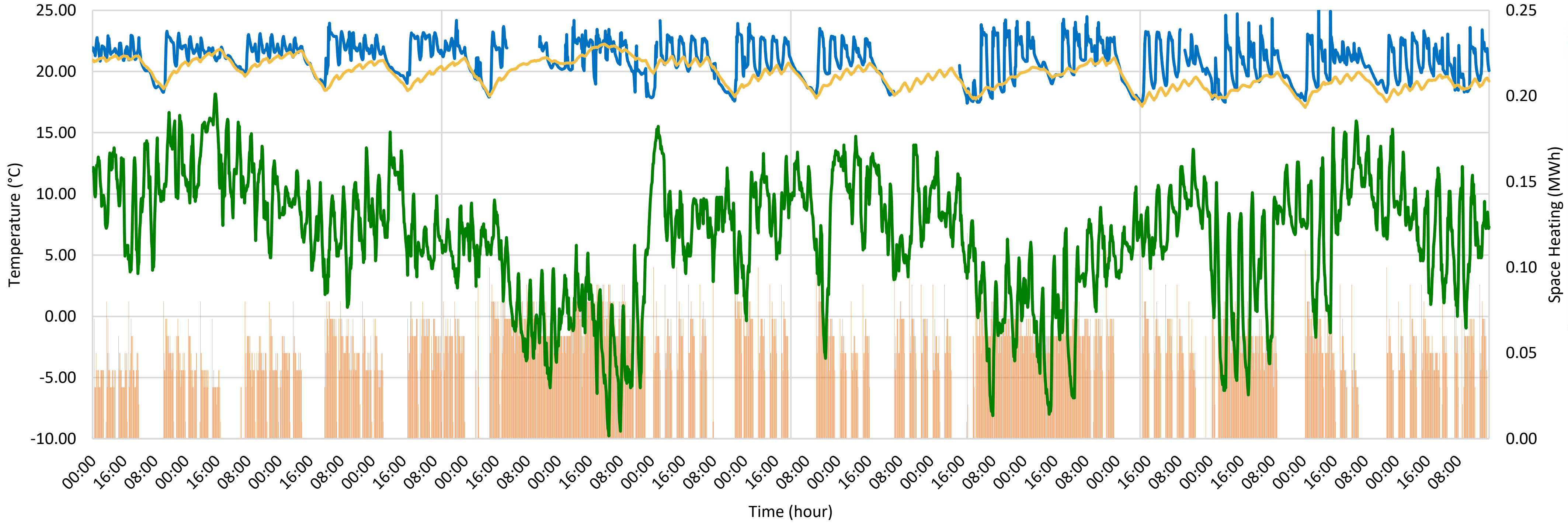
But...



"Human factor"

Building temperature modelling

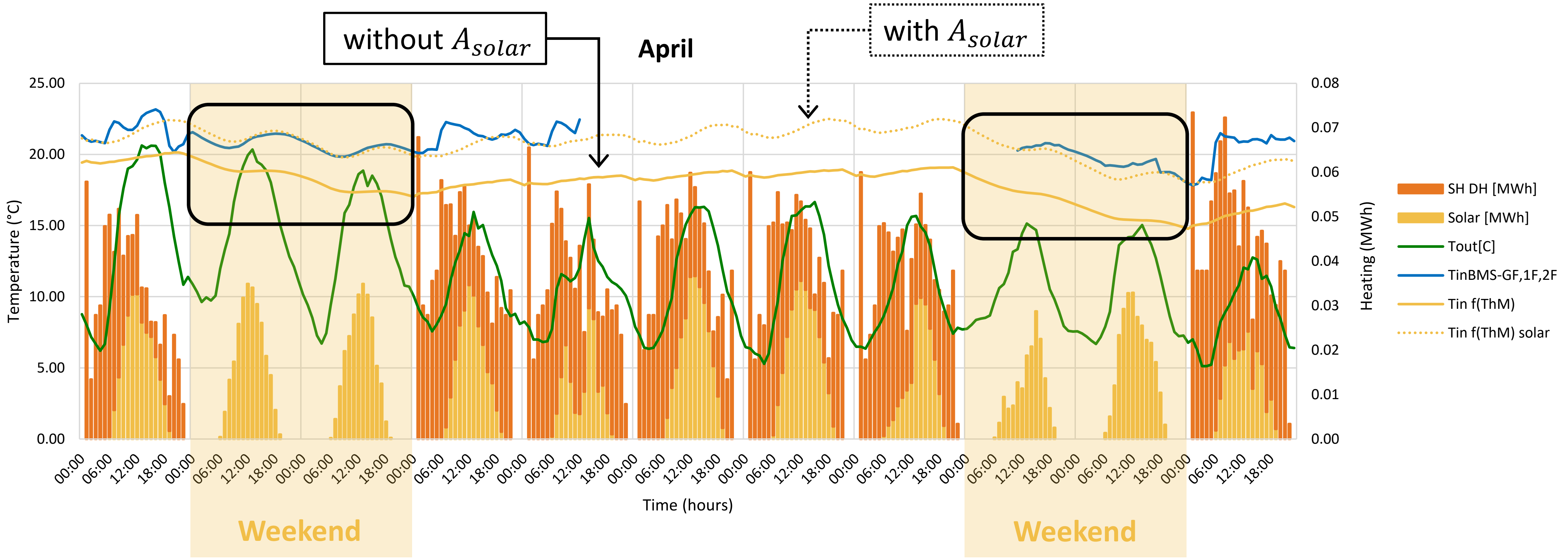
Thermal transmittance + *Thermal mass*



Good match!

Building temperature modelling

Thermal transmittance + *Thermal mass* + *Solar gain*

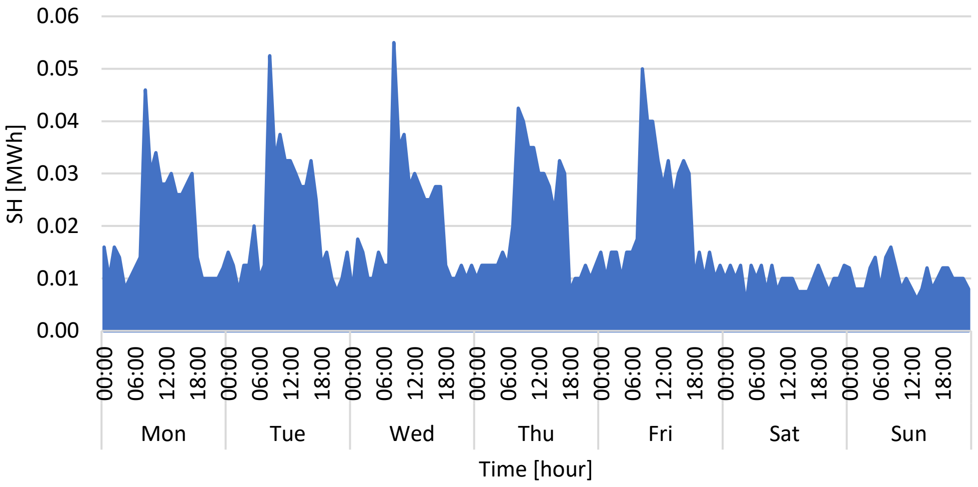


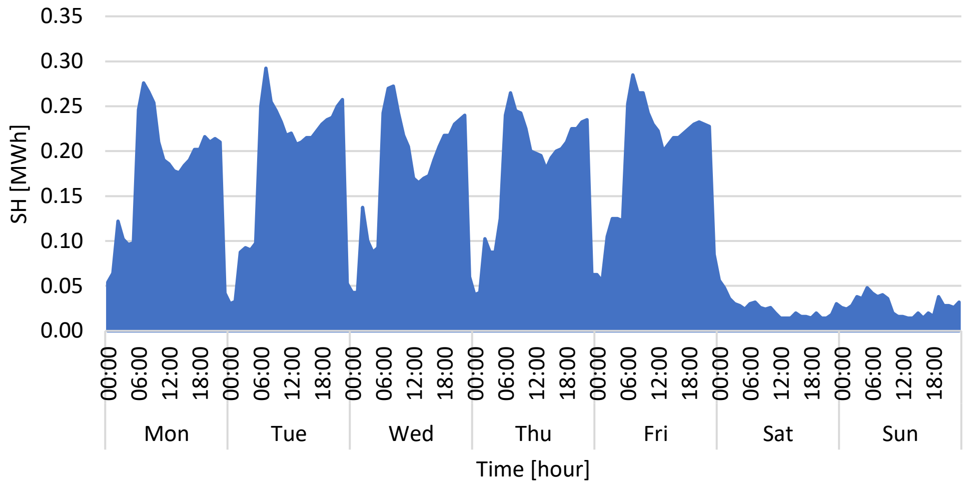
without A_{solar}

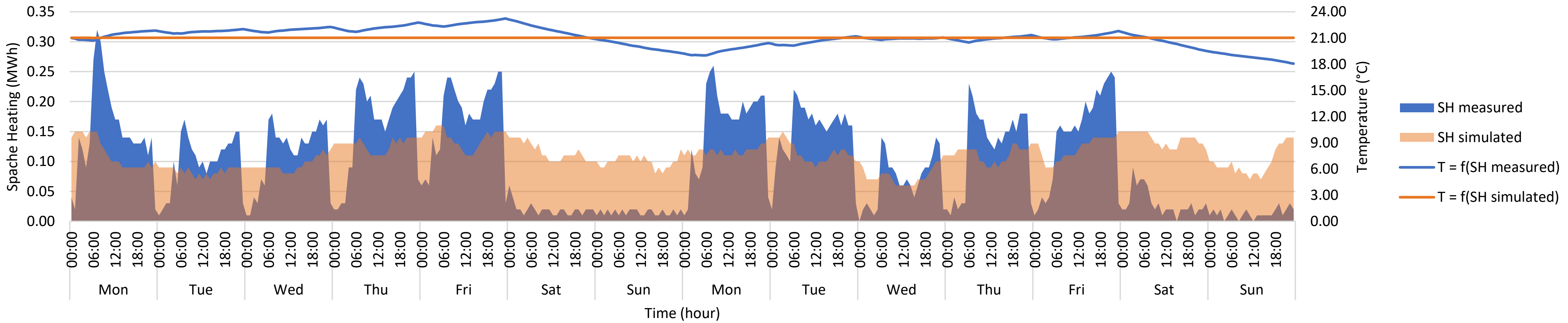
with A_{solar}

April

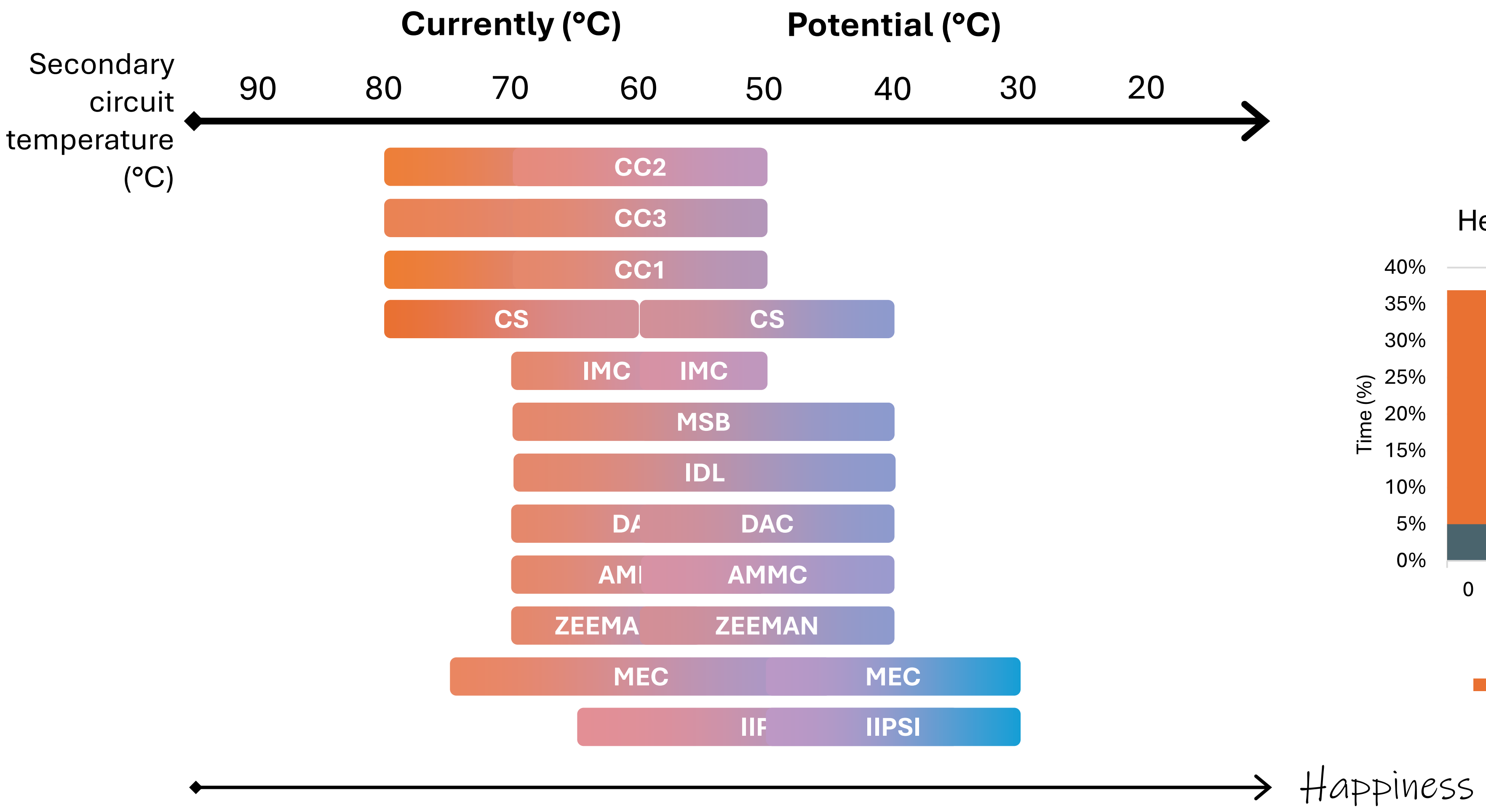
Building thermal behaviour modelling

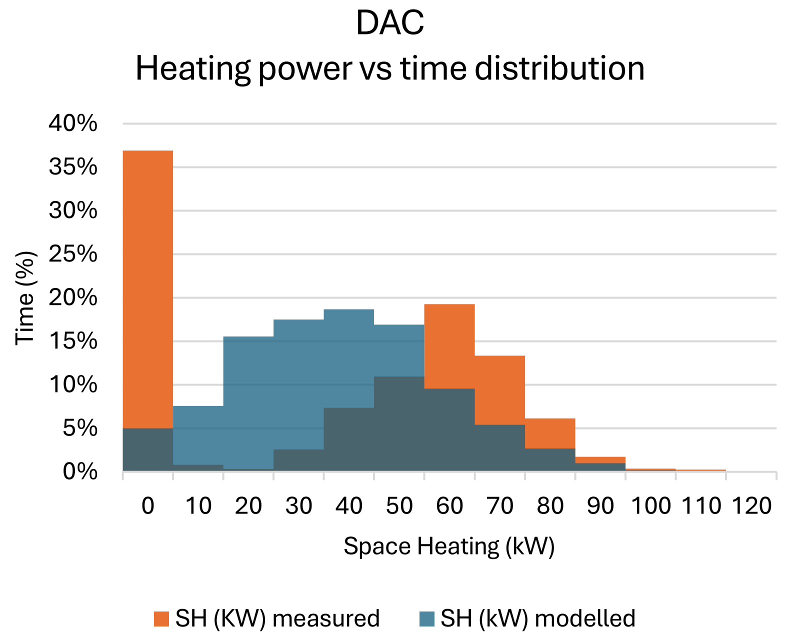




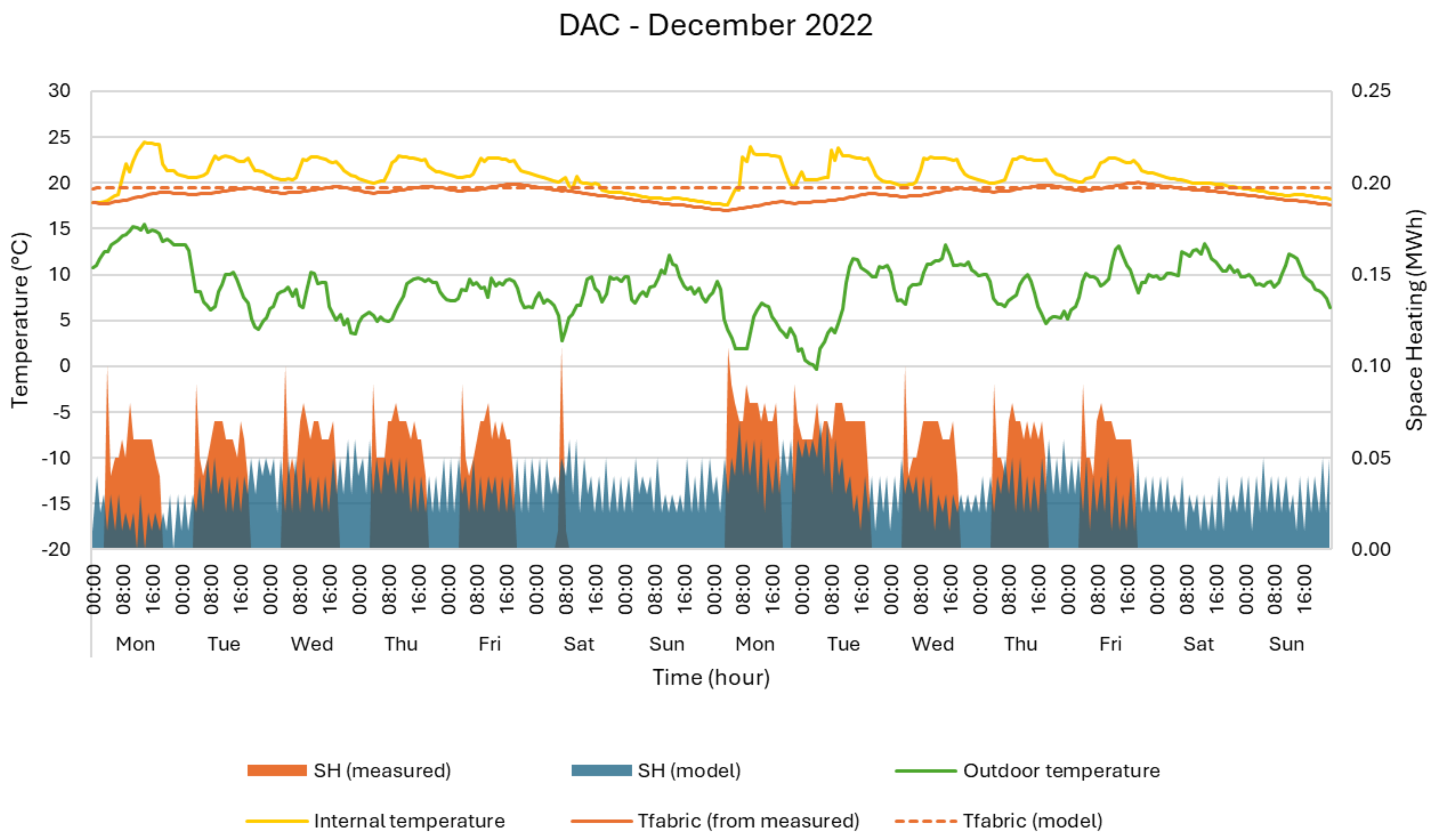


Reducing temperature in the district heating network





Building thermal behaviour modelling



Measured maximum Space Heating power: 0.11 MW

Low temperature network maximum Space Heating power: 0.07 MW

↓36%

Measured total Space Heating energy: 10.18 MWh

Low temperature network total Space Heating energy: 11.03 MWh

↑8%

When heat is electrified with Heat Pumps:

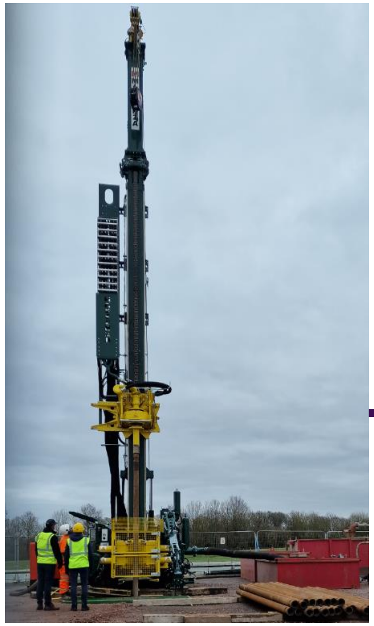
Current Space Heating profile COP: 1.72	**Lower temperature network Space Heating profile COP:** 3.15

Current temperature network Electrical energy consumption: 6.08 MWh

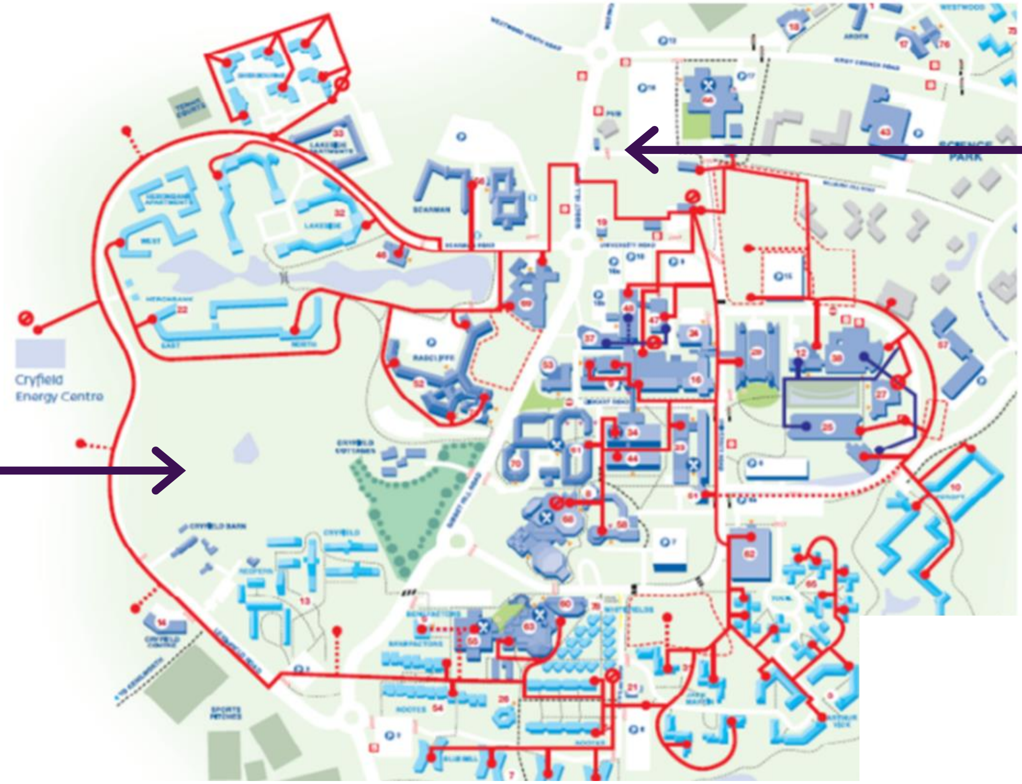
Lower temperature network Electrical energy consumption: 3.82 MWh

↓37%

Boreholes to investigate potential for GSHP



Cryfield Rig



Kirby Corner Rig

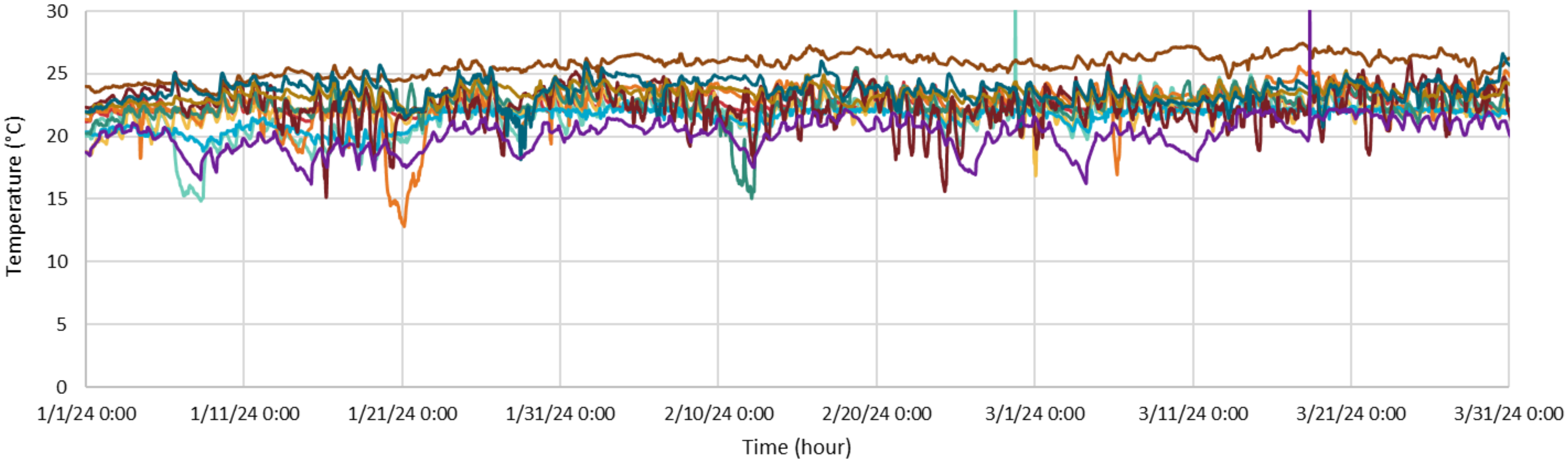
Monitor and control in buildings

"**Out of control**" buildings:
Rooms with BMS-connected thermostats typically at a suitable temperature, but:

- Other rooms too hot or cold
- Significant electricity wastage from circulating pumps, etc.
- Excessive use of heating and cooling

"**In control**" buildings:

- The desired room temperatures are achieved
- Energy use is understood and energy-saving measures can be applied

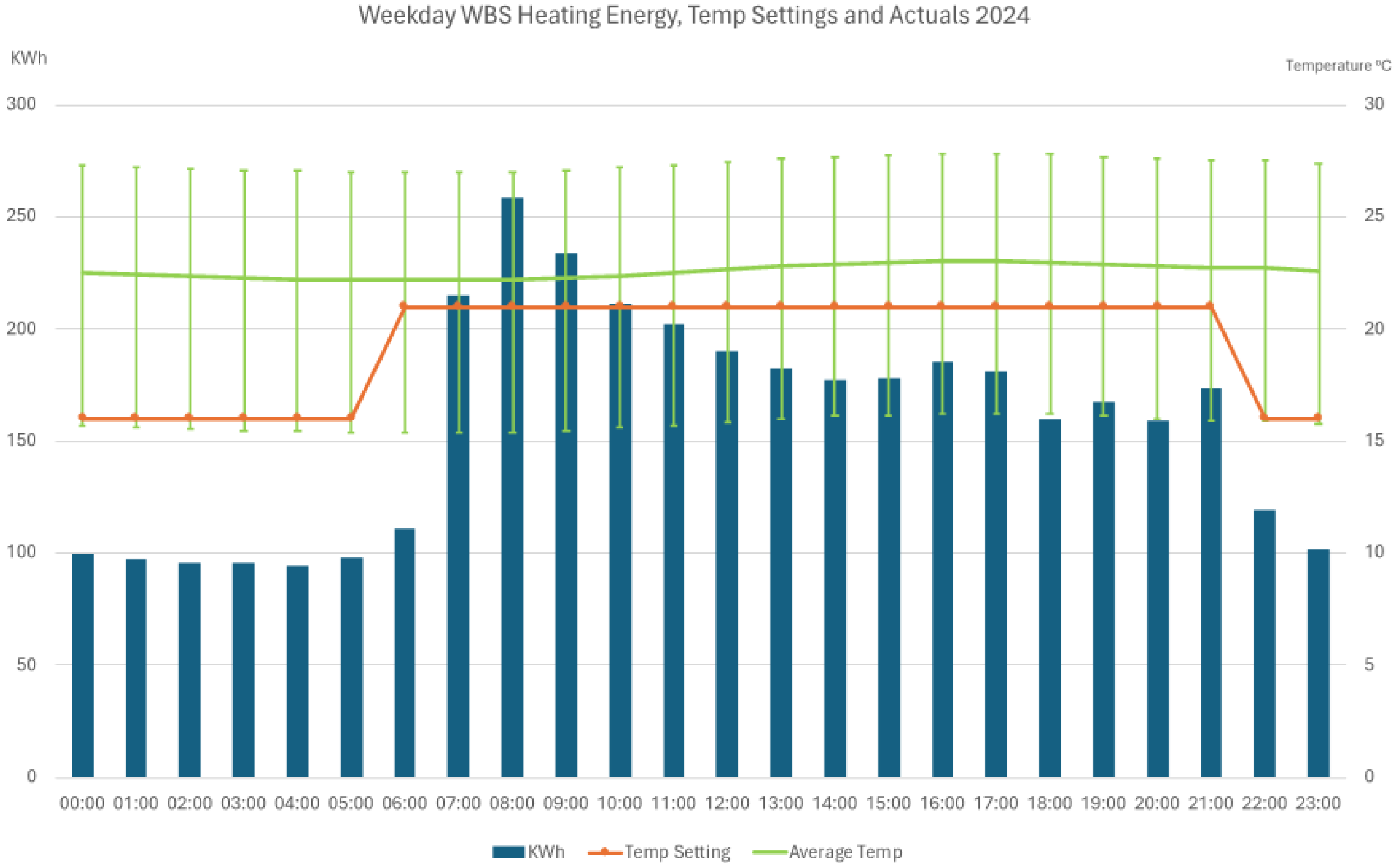


At an instant in time:

- Set temperature 21°C
- Hottest room 28°C
- Building average 23°C
- Coldest room 14°C
- 1 room was cooling to 19 °C whilst heating to 21°C!
- No opportunity to save energy by reducing overall temperature without some rooms getting even colder

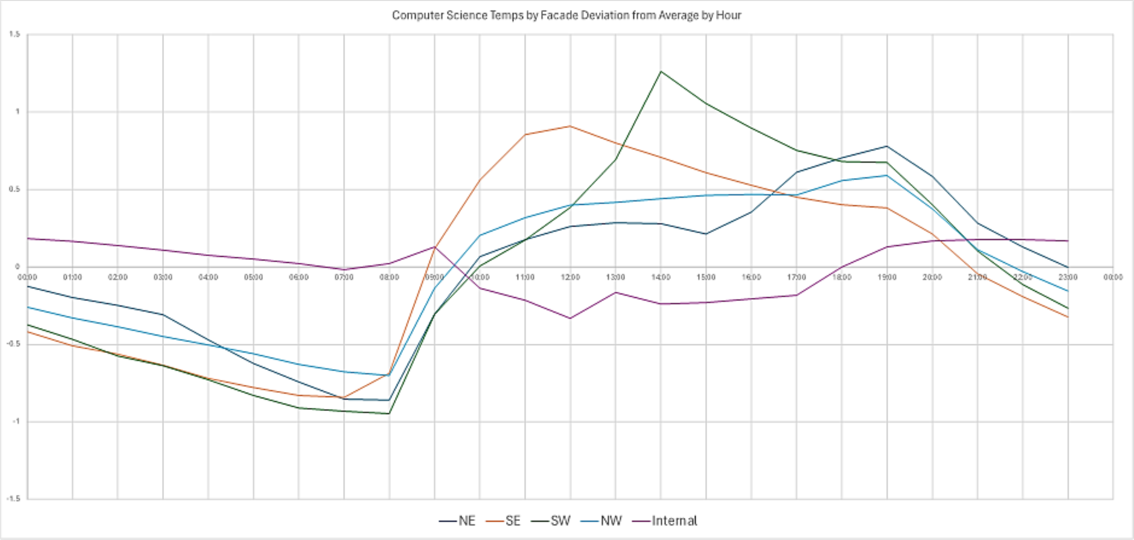
LoT-NET

Monitor and control in buildings

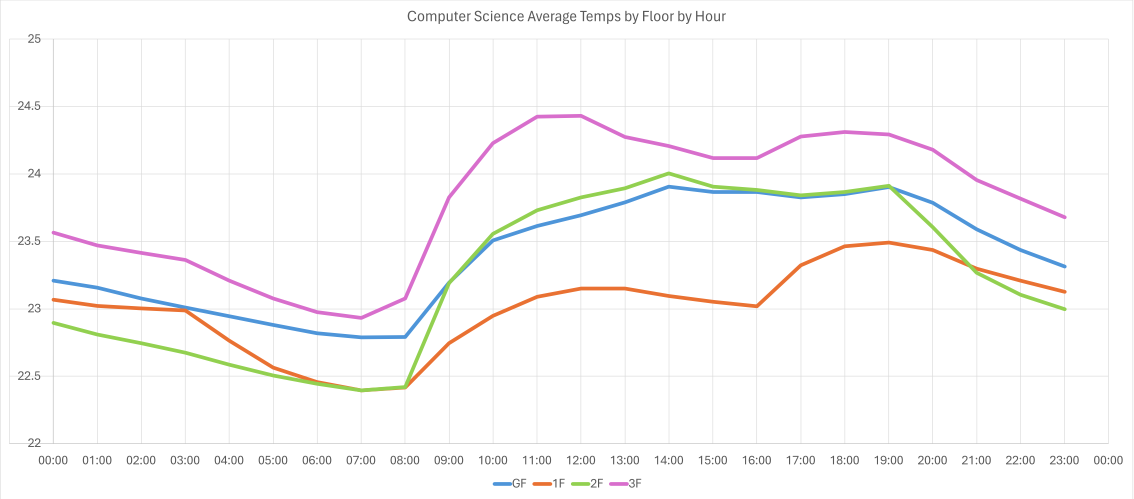


- System is set to deliver min. of 16°C at night and 21°C in the day
- Our sensors show an avg. temp of 22-23°C over the whole day
- Our sensors show max. temp ranges between 16 and 27 °C for 90% of time
- Older buildings need standards for retrofit monitoring and control

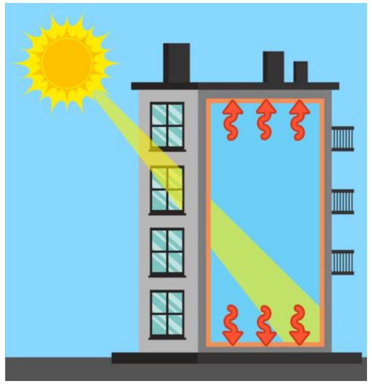
Designing BMSs that work even when the sun shines



Computer Science Temps by Facade Deviation from Average by Hour



Computer Science Average Temps by Floor by Hour



A typical building has 4 façades (N, S, E, W or similar)

- Each absorbs sunlight at different times of day (if at all).

Hot air rises within the building, making the upper floors hotter - the top floor may not need heating.

A building with 3 floors would need 3*4 = 12 heating zones to maintain comfort in all areas.

The core of the building has no heat loss to outdoors and may not need heating.

Summary

- Very large thermal stores can help manage electricity demand
- Must be combined with district heating networks and heat pumps
- Heat networks can also link recoverable heat sources to the heat pumps
- COP up to 8.8 has been achieved by low temperature rise heat pumps; delivery up to 90°C also possible.
- Before planning a large installation, building management systems must operate effectively so that energy use data is dependable (avoid oversizing). Use localised sensing and control to achieve a uniform building temperature; schedule heating to use cheap/low carbon electricity.

And finally:

1. See the LoT-NET website for technical papers and briefing notes
2. Warwick Thermal Energy (aka STET, Sustainable Thermal Energy Technologies) are looking for research partnerships in boreholes, heat pumps, heat networks, and thermal stores – either fundamental research or installation details. Talk to us!

Any questions?