ZERO Institute

# Innovations for zero-carbon heating and cooling:

*the path to net-zero buildings by 2050.*


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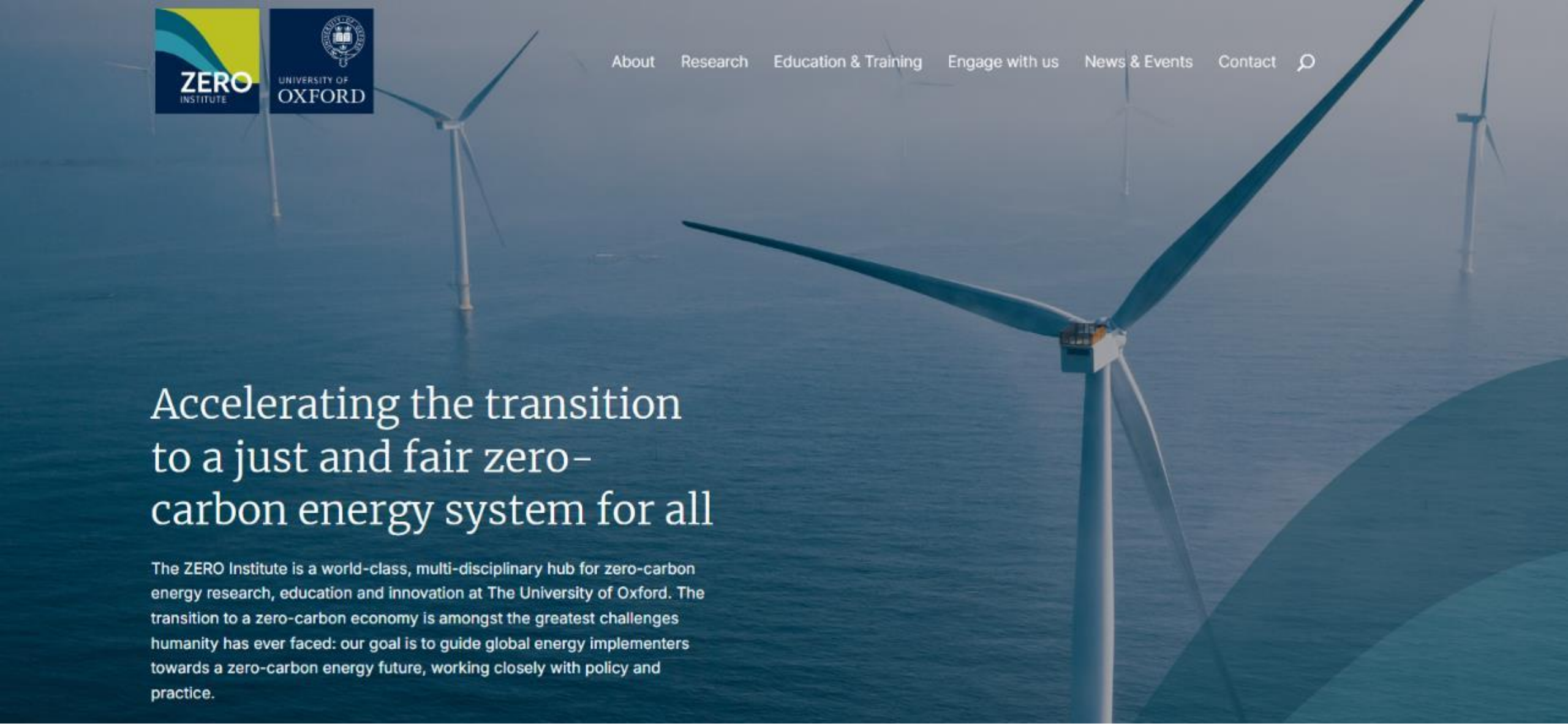
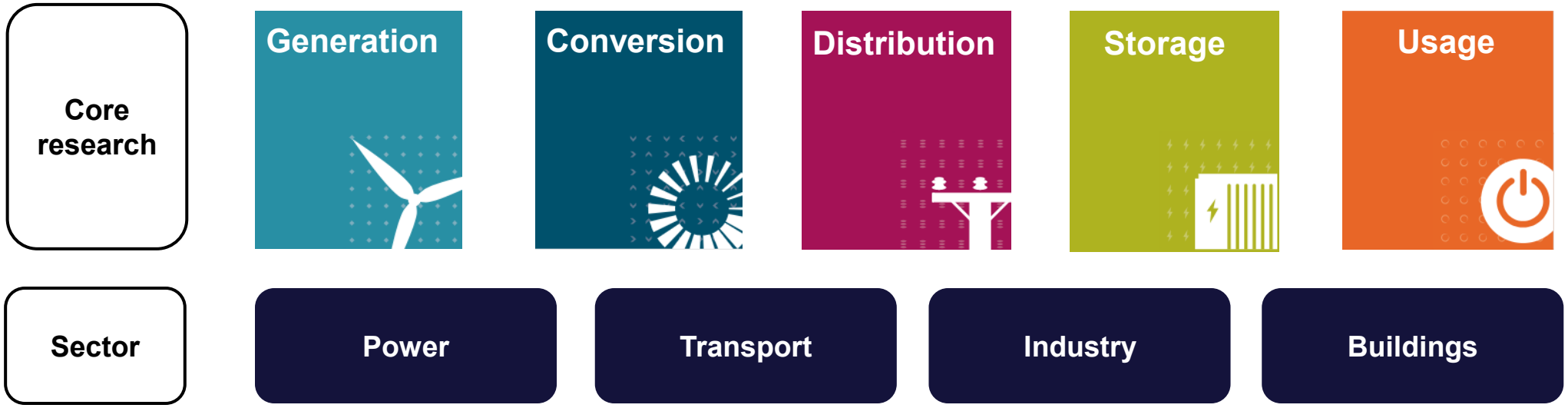
*+ contributions from Scot Wheeler, Zeynep Tekler, Amr Suliman, Jessica Ibanes, Juan Arcenegui, and many others!*




**The ZERO INSTITUTE at Oxford**
**https://zero.ox.ac.uk/**

www.zero.ox.ac.uk | @ZERO_Oxford

# ZERO Institute at Oxford




Global target: **Net ZERO by 2050**

All energy sectors need to have net-zero emissions by 2050

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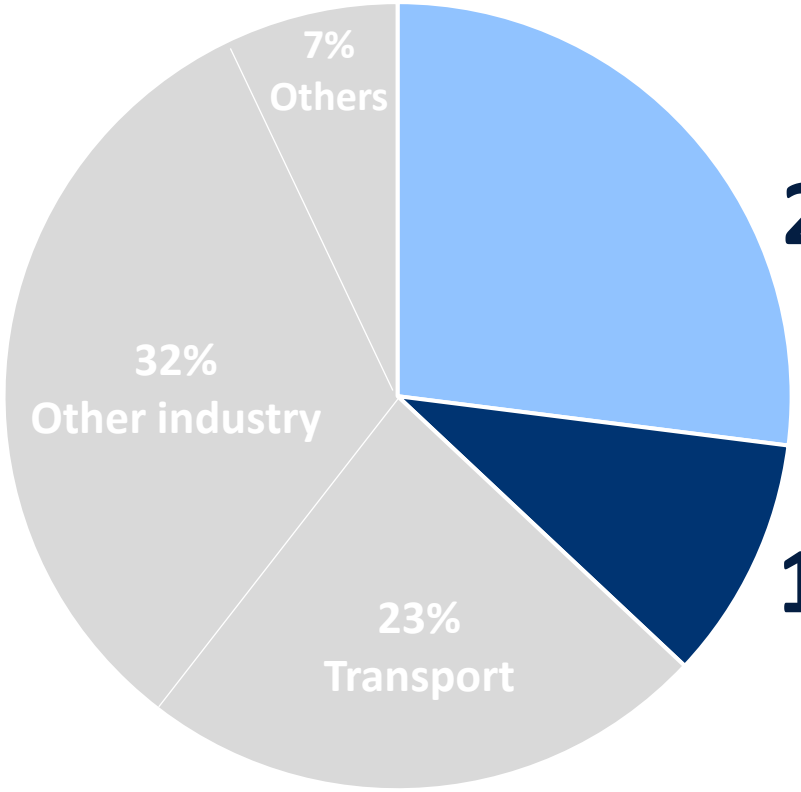
# CO2 emissions in the building sector




## 27% - Building operations

**Operational carbon**

## 10% - Materials and construction

**Embodied carbon**

UNEP (2024). Global Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. https://doi.org/10.59117/20.500.11822/45095

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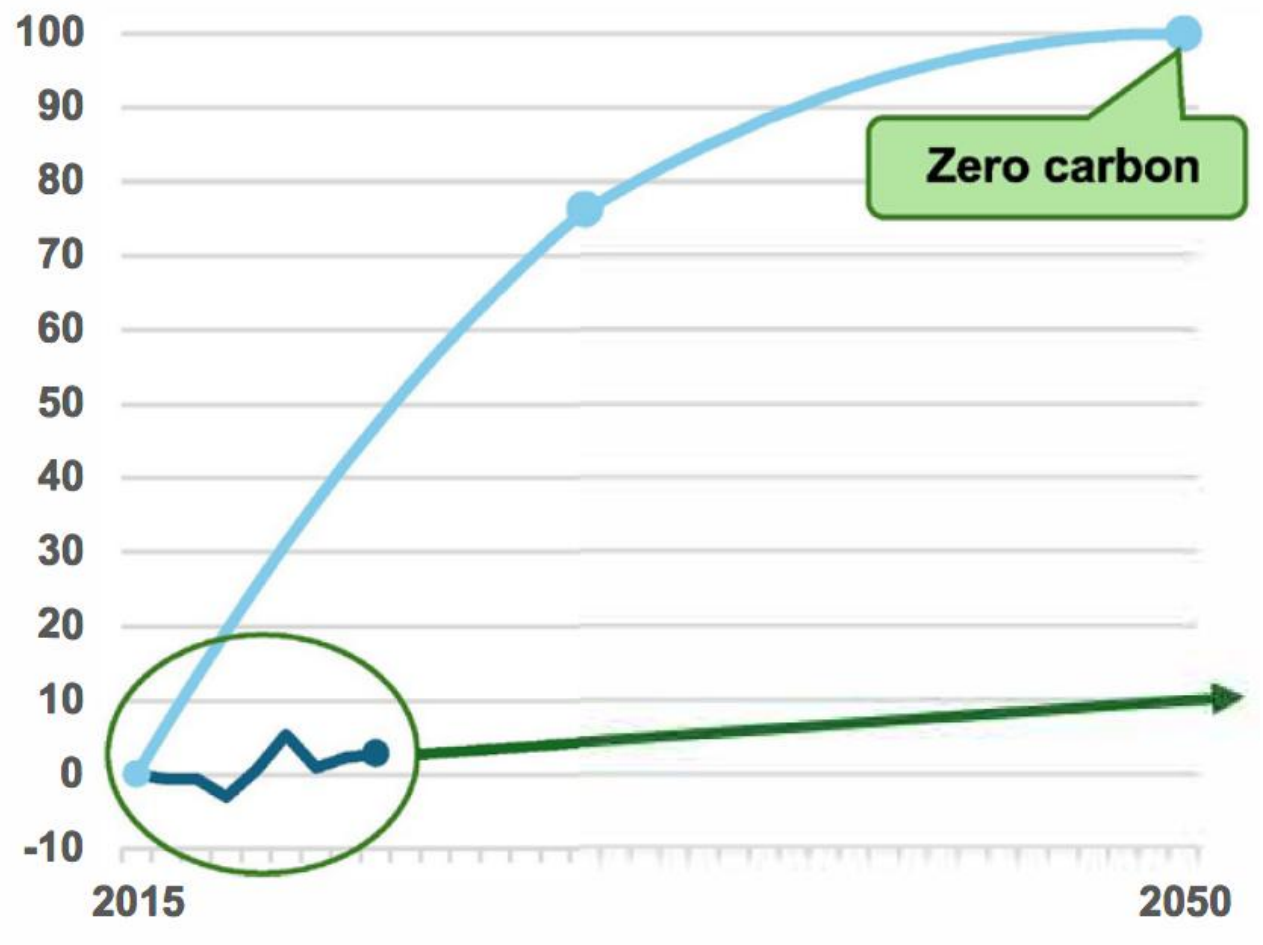
# The decarbonisation path




Source: BPIE

Will things improve next year?

UNEP (2025). Global Status Report for Buildings and Construction 2024/25.

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# Content

1. What is a net-zero building?
2. The role of building services engineering and academia
3. Limits of current Best Practices in the building sector
4. Four key innovations in Heating and Cooling

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# What is a net-zero building?

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# A net-zero building…

Is it just about installing photovoltaic panels?

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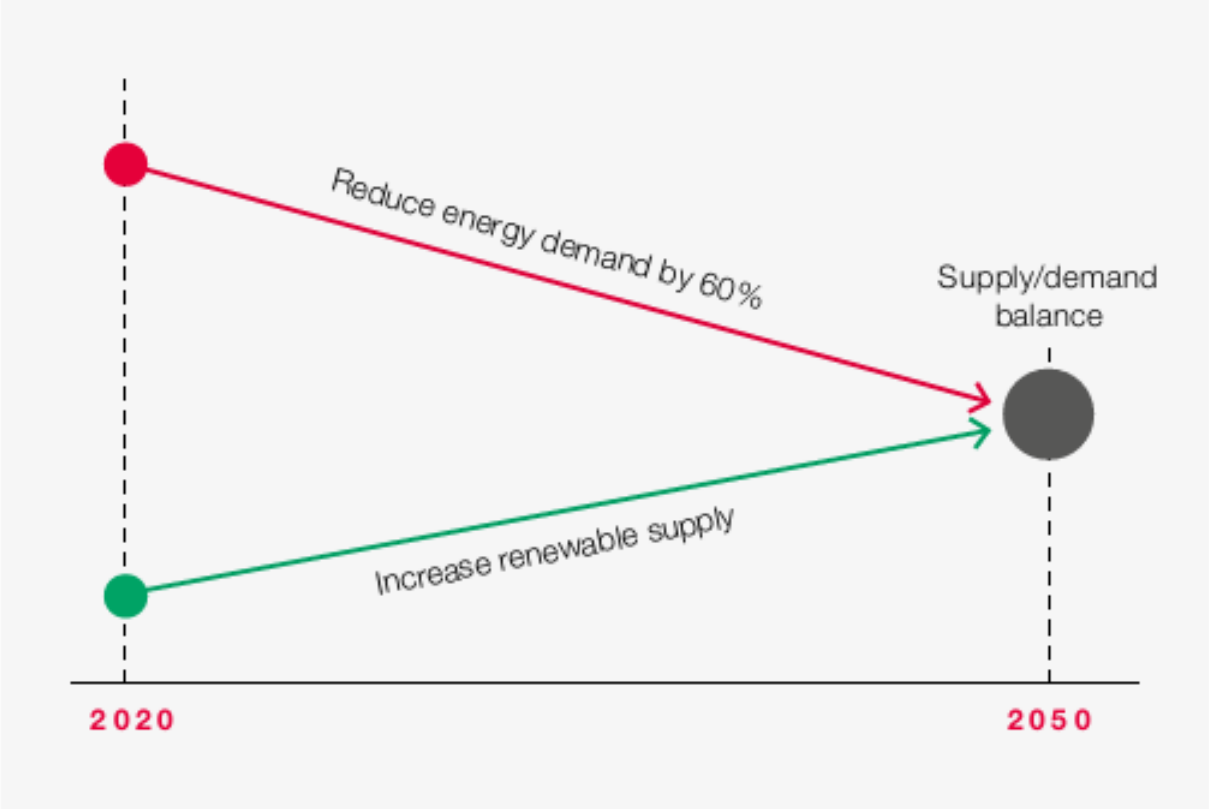
# A net-zero building…




*UK Green Building Council (GBC):*

## Energy demand VS Renewable supply

A reduction in buildings' energy demand of 60% will be necessary by 2050 for demand to be matched by available renewable supply

S. Hill, A. Dalzell, M. Allwood, Net Zero Carbon Buildings: Three Steps to Take Now, Arup, 2019.

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# Definitions of net-zero buildings

| Institutions | Terms: |
| --- | --- |
| UKGBC (Green Building Council) - 2019 | Net Zero Carbon Buildings Framework |
| International Energy Agency (IEA) -2021 | *Zero-carbon-ready building code* |
| European Union (EPBD, EU) - 2024 | *Zero-emission buildings (ZEBs)*<br>*Nearly-zero energy buildings (nZEBs) – previous term (EPBD 2010)* |
| UK NZCBS Standard – 2024 (pilot) | *Net Zero Carbon Buildings* |

# Metrics (what and when?)

Transitioning to Zero-Carbon Buildings, Buildings and Cities. (2022). https://www.buildingsandcities.org/insights/commentaries/zero-carbon-buildings.html
UK NZCBS Standard. https://www.nzcbuildings.co.uk/pilotversion

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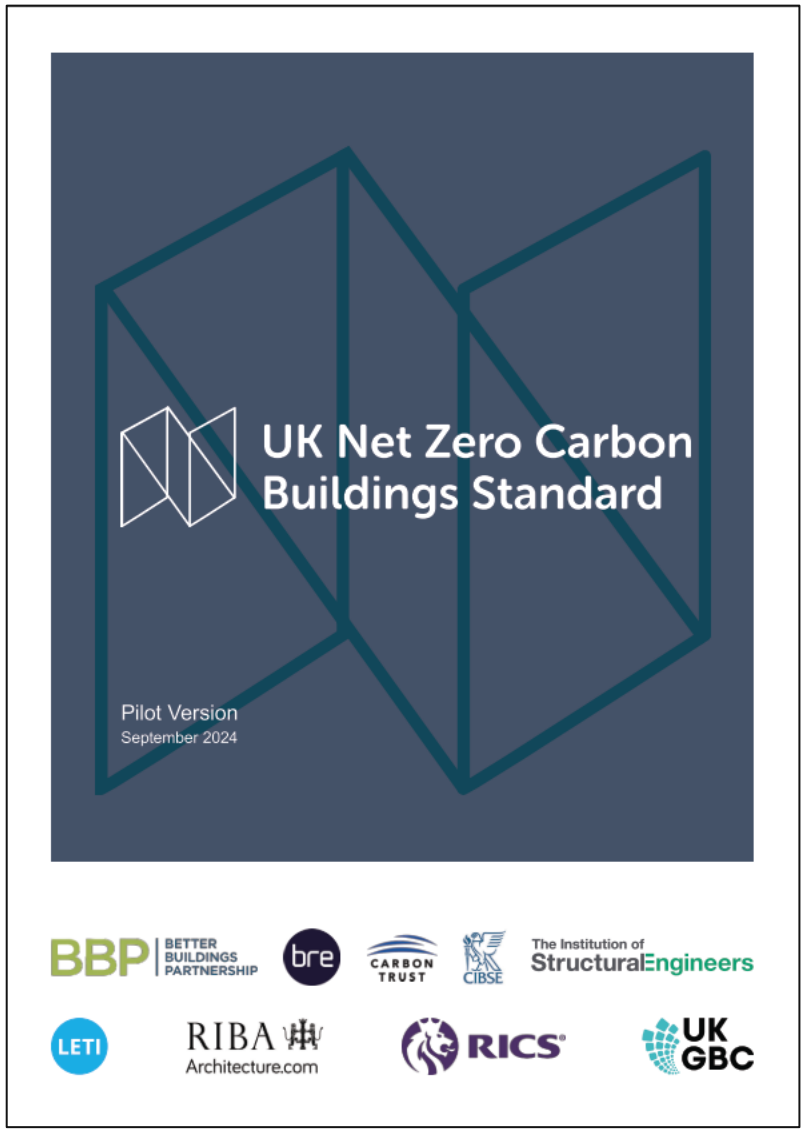


# Definition of a net-zero building UK context

BBP BETTER BUILDINGS PARTNERSHIP bre CARBON TRUST CIBSE The Institution of StructuralEngineers

LETI RIBA Architecture.com RICS UK GBC

UK GBC, UK Net Zero Carbon Buildings Standard, 2024. https://www.nzcbuildings.co.uk/pilotversion

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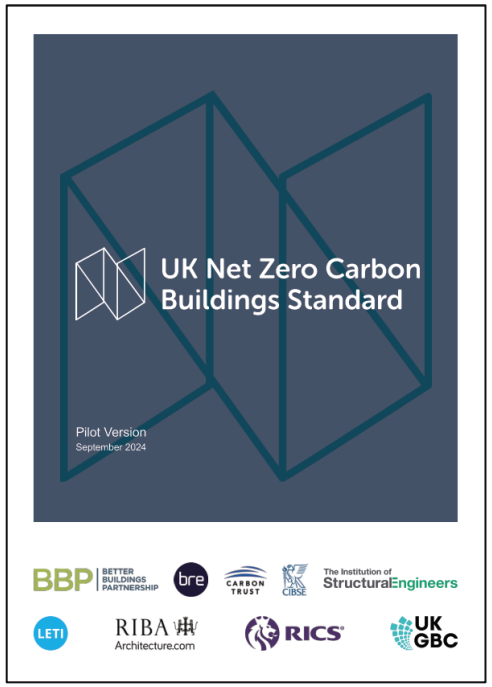
# The Standard's Requirements




**Limits are set for:**

- Upfront Carbon
- Operational Energy
- Fossil Fuel Free
- District Heating and Cooling Networks
- Refrigerants
- Heating Delivered

**Targets are set for:**

- On-site Renewable Electricity Generation

**There is an optional reporting requirement for:**

- Offsetting

**There are reporting requirements for:**

- Life Cycle Embodied Carbon
- Operational Water Use
- Electricity Demand
- Heating and Cooling delivered to the building

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# What is the role of building services engineering and academia in achieving net-zero?

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# Portfolio of technologies

*From district scale to building scale*


**Primary source**

- Wind
- Solar
- Geothermal
- Sky/Cold Universe
- Fuel
  - Gaseous, Liquid, Solid
  - Biomass

- Small wind turbines
- Photovoltaic modules
- Electric energy generator
- Combined heat and power
- Boilers
- Solar thermal collectors
- Radiative cooling systems

- Organic Rankine cycle
- Kalina cycles
- Electrical boiler/heater/radiator
- Heat Pump
- Sorption chillers
- Desiccant processes
- Evaporative systems

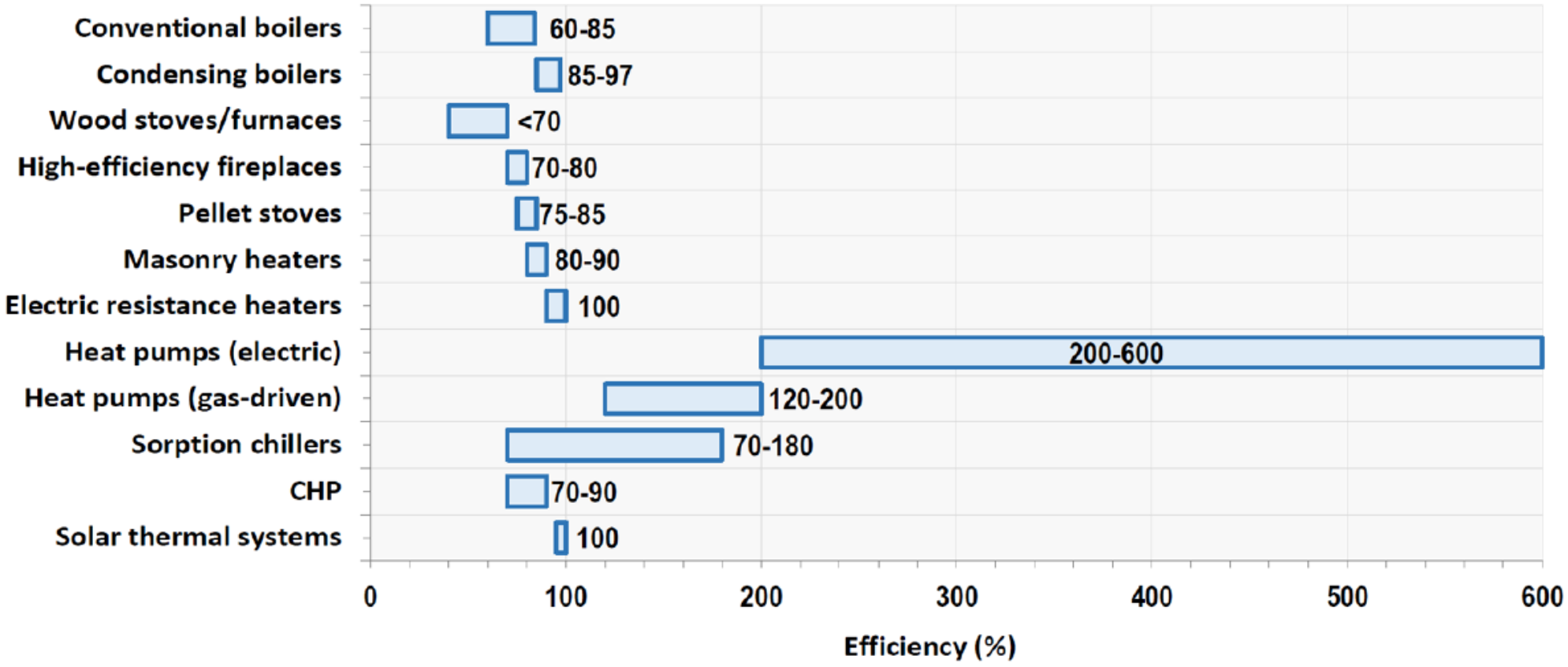
- Electric storage
- Thermal storage

- Electricity distribution
- Hydronic distribution
  - District network
  - Building scale
- Air distribution

- Electricity
  - Lighting
  - Ventilation
  - Cooking
  - ICT
  - Electrical appliances
- Heat
  - Space heating
  - Domestic Hot water
- Cool
  - Space cooling
  - Refrigeration

# Efficiency

## Typical efficiencies of heating and cooling technologies




International Energy Agency, Transition to Sustainable Buildings. Strategies and Opportunities to 2050, OECD/IEA, 2013. https://doi.org/10.1787/9789264202955-en

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# Our role as an academic institution…

## New Teaching Curriculum

- Undergraduate programmes
- MSc programmes
- DPhil programme
- Executive Education

## Educational resources

- Educational publications
- Educational software/tools
- Online courses

## University Competition on net ZERO


**Upcoming event at ZERO Institute:**
Friday, 21st November - The Future of Datacentres
5pm at Somerville College

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# Our role as an academic institution….

- **CIBSE 2025 Award** in Learning and Development
- **ASHRAE 2025 Award** for Zero Carbon Education
- **2025 MPLS Teaching Award**


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# Our role as an academic institution….

**First prize in the European ASHRAE 2025 student competition on Net Zero Data Centres**


**Rasing Start Award** in the 2025 ASHRAE Student Competition - Building EQ category


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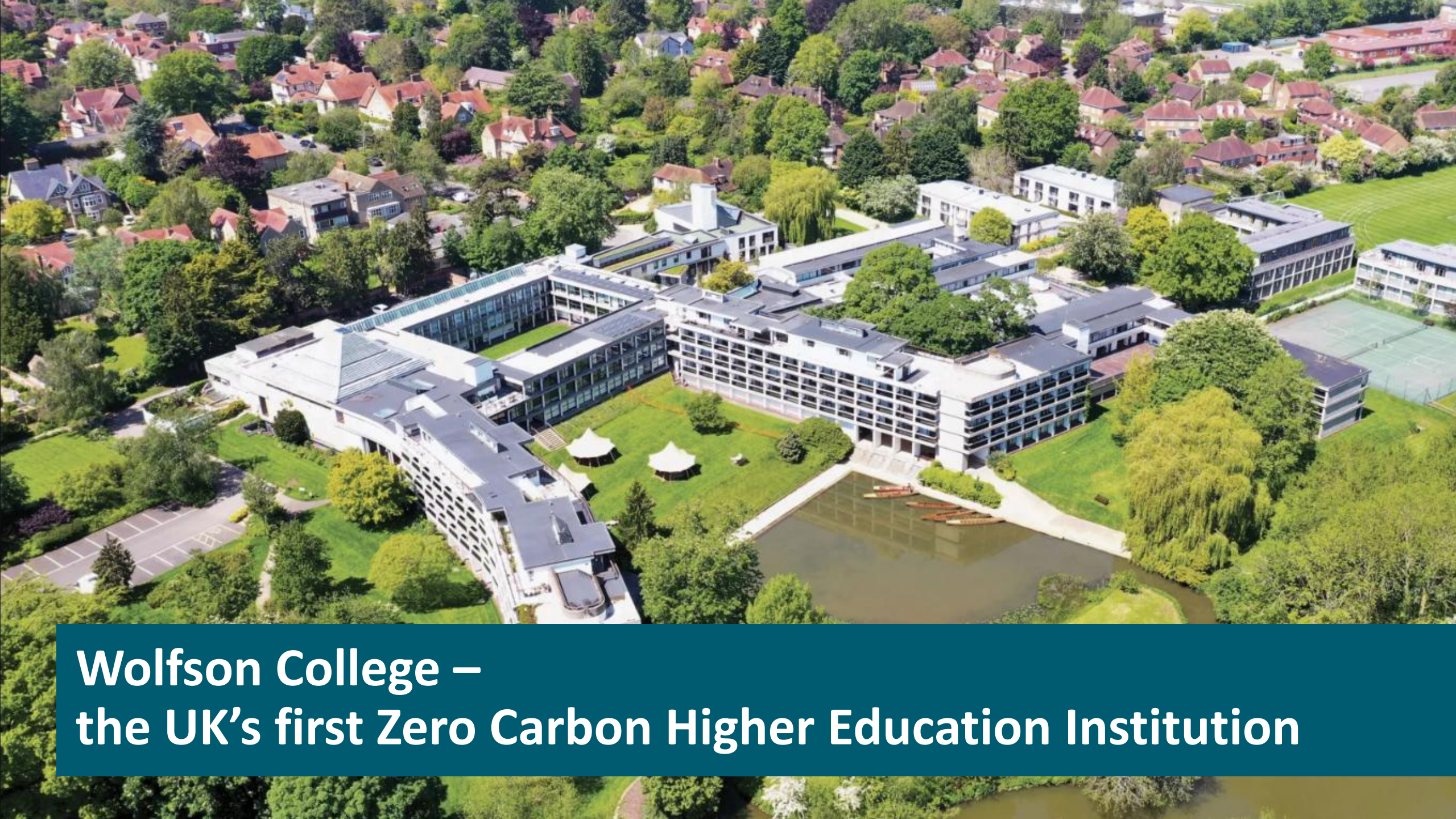
# Are the best practices in the building sector enough?



# Wolfson College – the UK's first Zero Carbon Higher Education Institution

# Best practices in the UK

**Sample of best practices in the UK Building sector**

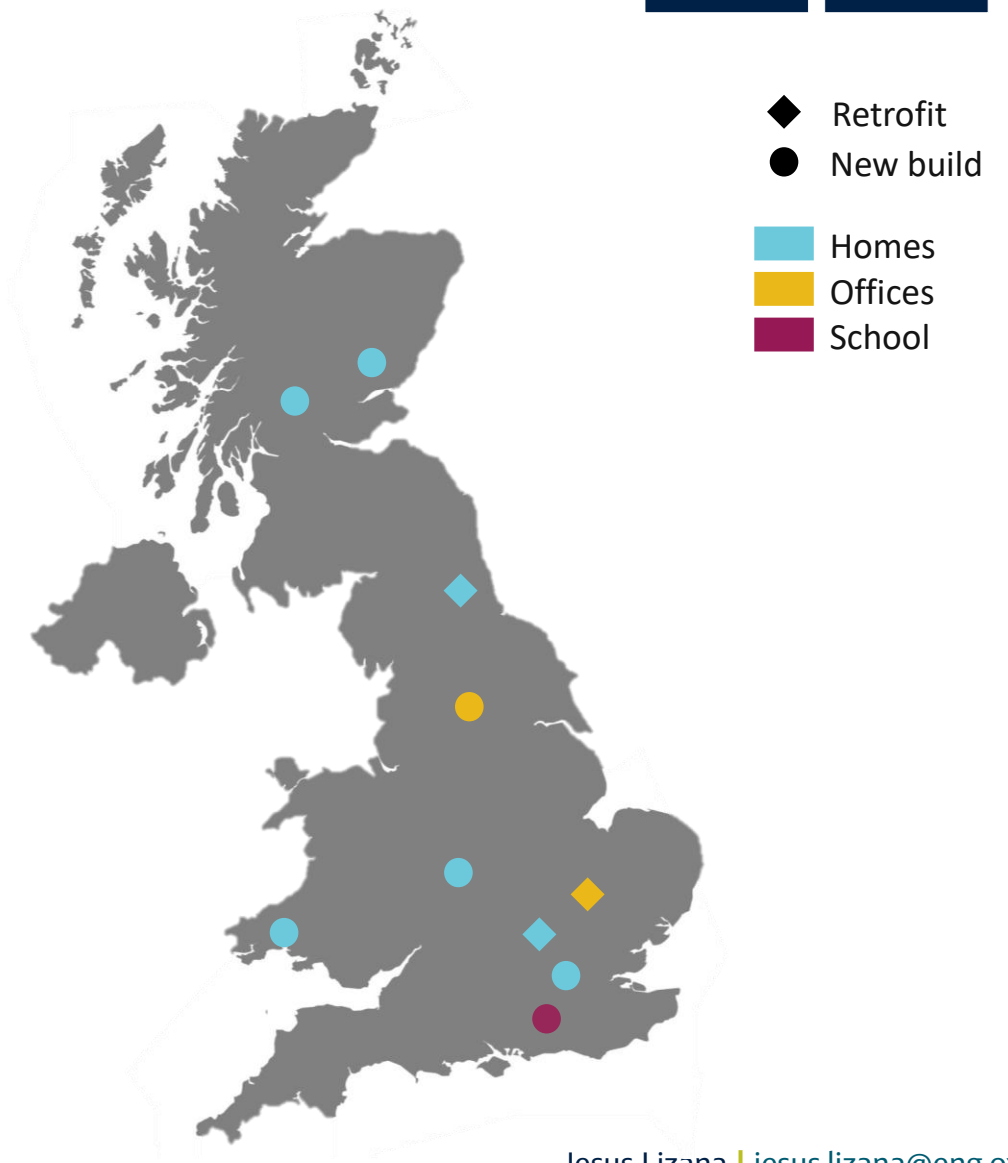
Recognition or award (e.g., CIBSE, BREEAM, Passive House, LEED) from 2021 onwards

↓

Data availability:
- Upfront embodied carbon
- Final energy demand

↓

**10 selected case studies in the UK vs. UK Net Zero Carbon Buildings Standard's targets by 2035 & 2050**




*Reference: Ibanes et al. (2025)*

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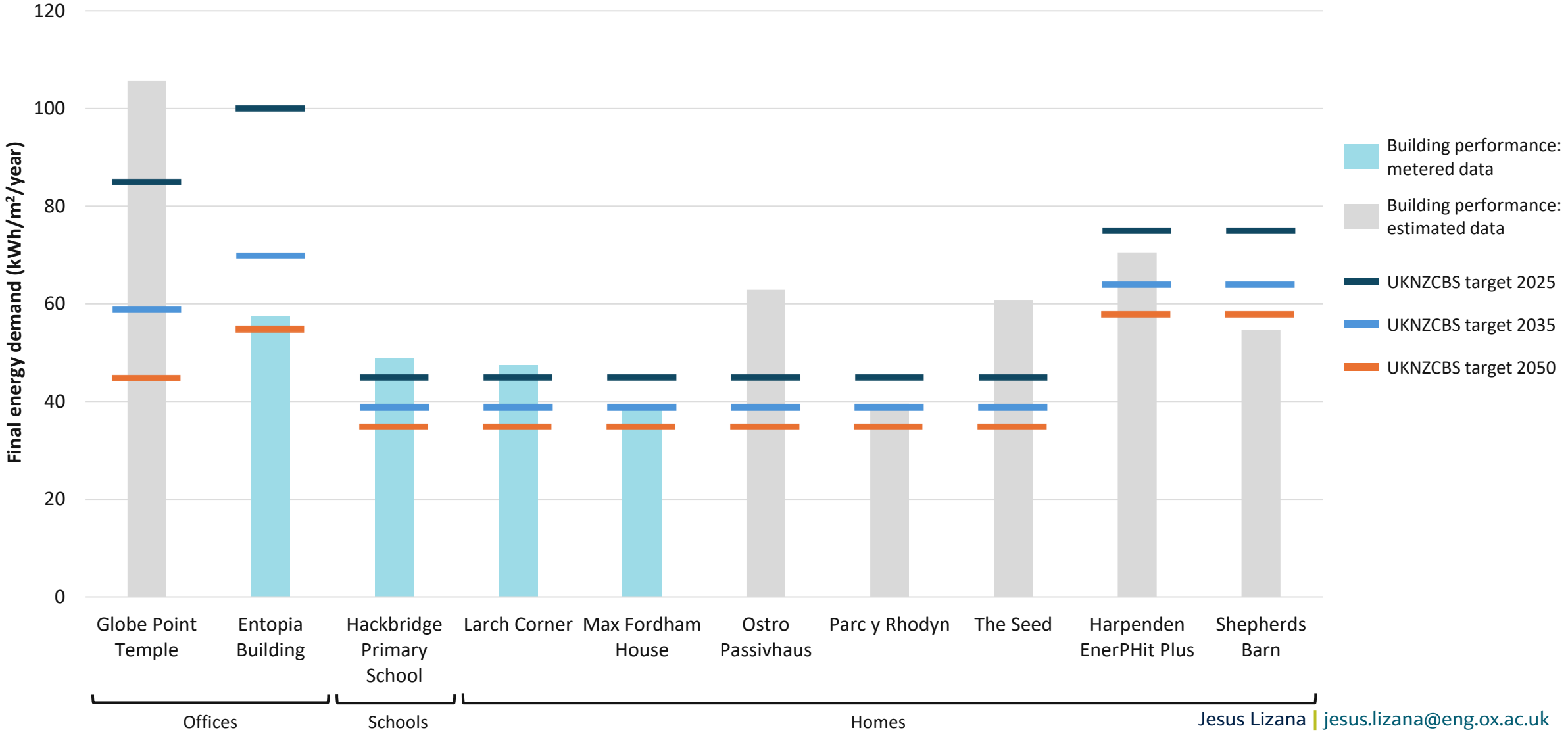
# Final energy demand vs. UK net zero targets

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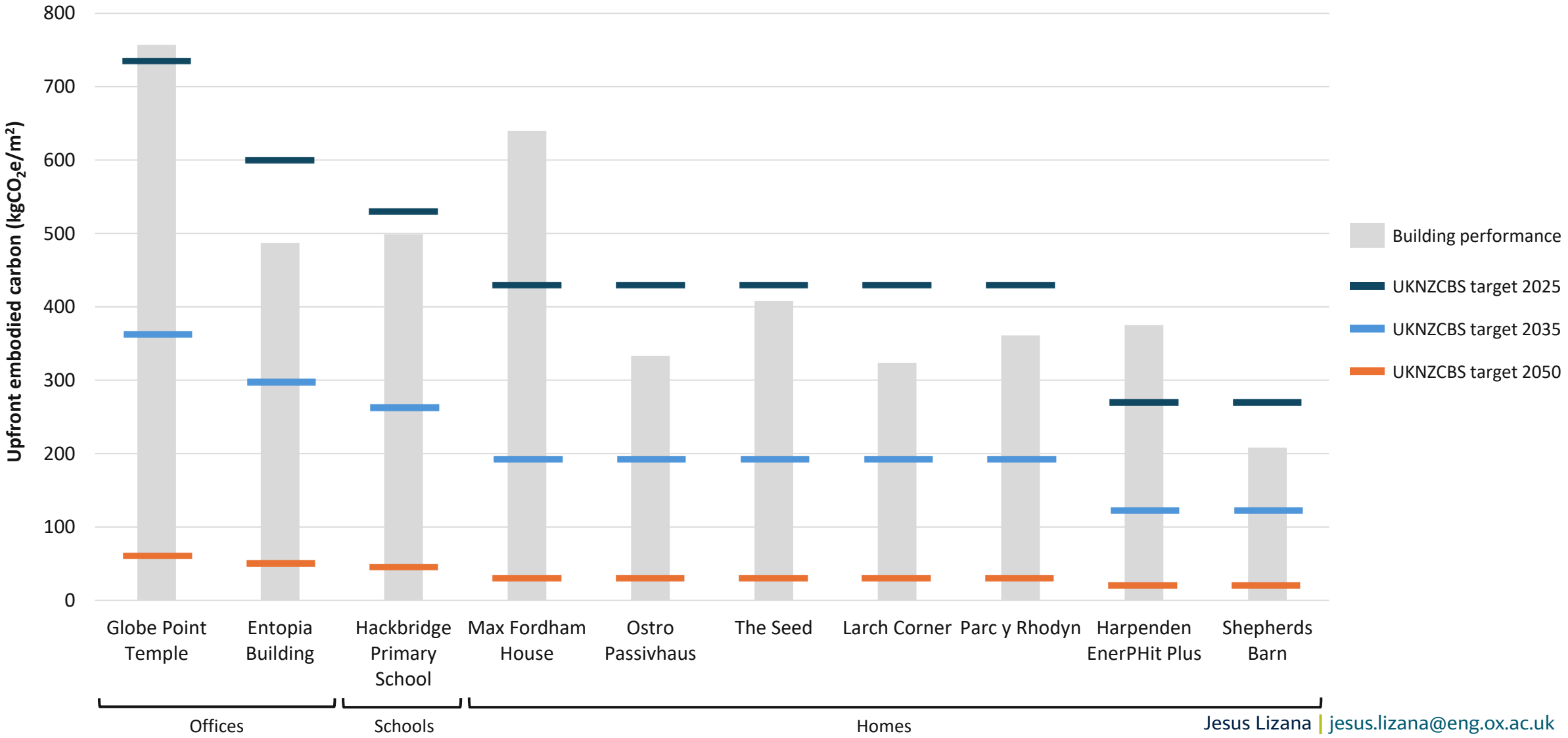
# Upfront embodied carbon vs. UK net zero targets

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# Best practices alone will NOT get us to Net Zero in the building sector

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# Zero-Carbon Heating and Cooling

**Leading research – Enabling collaborations in Oxford and abroad - With global impact**

in heating and cooling — standing on the shoulders of giants — in science, policy, and practice

**HEATING** ← → **COOLING**

| climate change **MITIGATION** | climate **RISK** | climate **ADAPTATION** |
|---|---|---|
| Heating decarbonisation - net-zero targets | Climate-related hazards – exposure - vulnerability | Mitigation of rising cooling needs - Resilience |

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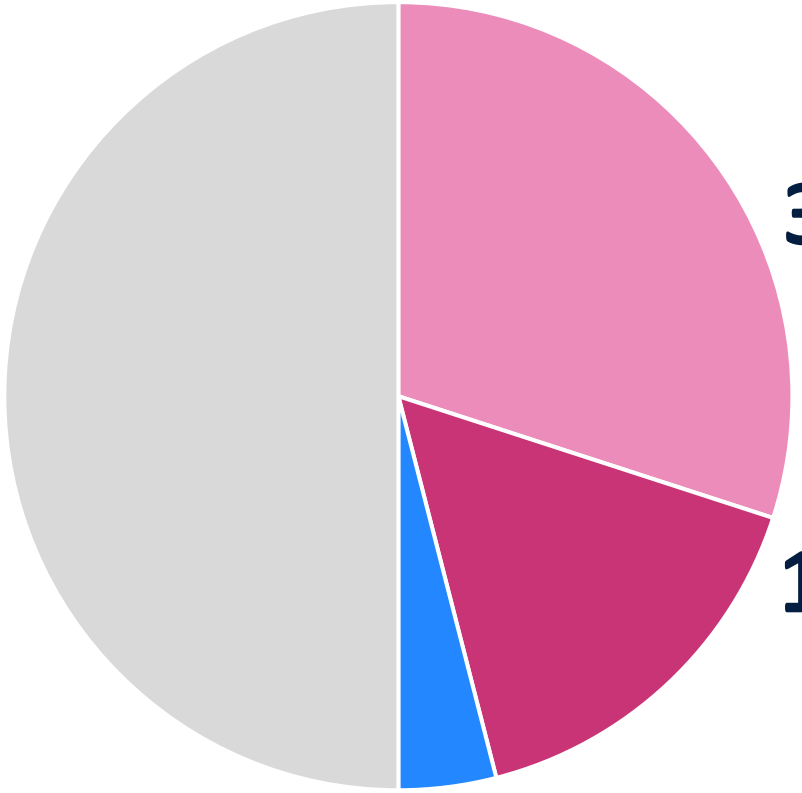
# Final energy consumption in Europe



**30% - Space and water hating**

**Building sector**

**16% - Medium-to-high temp heating**

**Industry sector**

**4% - Cooling**

**Agriculture, building, and industry sectors**

Source: European Union, Policy Support for Heating and Cooling Decarbonisation-Roadmap, 2022. https://doi.org/10.2833/977806.

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# Global research/global impact

**International institutions:**

**United Kingdom**
University of Oxford (England)
The University of Edinburgh (Scotland)
Cranfield University (England)
University of Bristol (England)
University of Gibraltar
Centre for Net Zero, Octopus Energy Group
KrakenFlex, Octopus Energy Group
**Spain**
Universidad de Sevilla
ICMS, CSIC
Polytechnic University of Madrid
CIEMAT
University of Granada
Universidad Rey Juan Carlos
**Norway**
Arctic University of Norway
**France**
University of La Rochelle
**Portugal**
Universidade de Lisboa
Instituto Politecnico de Lisboa
University of Porto
**Italy**
Politecnico di Torino (Italy)
**Belgium**
Hasselt University (Belgium)
**Germany**
Technical University of Berlin
Technical University of Munich

**Organisations:**
(R&I projects, research, consultancy, etc.)

**United Kingdom**
DESNZ – UK-GOV
CIBSE
University College London (UCL)
Oxfordshire county council
Oxford City Council
Third Generation Environmentalism (E3G)
**Spain**
Universidad de Cantabria
J. Terrados - Architecture
Living kits – Architecture
Sosteco – IoT
**Morocco**
Ctrl-Z - Architecture
**Denmark**
Tomorrow
Royal Danish Academy
**Portugal**
EDIGREEN
Instituto de Soldadura e Qualidade
Associaçao Bandeira Azul da Europa
**Israel**
Israel Institute of Technology
**Saudi Arabia**
Falcon Co. LTD – Architecture
**India**
UNEP – Cool coalition
CEPT university
**Vietnam**
Hanoi University of Science and Technology
**Australia**
University of New South Wales
**USA**
Stanford University
Rocky Mountain Institute (RMI)
Smart Surface Coalition (SSC)
WRI
**El Salvador**
Hábitat para la Humanidad

- **Working with >20 international academic institutions**
- **Collaborations with >45 organisations**
  (R&I projects, research & consultancy)

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# Innovations for heating decarbonisation

## 1 ) Hybrid indoor design conditions

*Projects resCOOL (MSCA - EU) – resilient cooling*

## 2 ) Optimal sizing and control of heating systems

*Project openBES (EPSRC) – open Building Energy Simulation software*

## 3 ) A better auxiliary system for heating systems

*Project ThermoReact – low-temperature TCES reactions*

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# Thermal comfort is not only temperature

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# 1) Hybrid indoor design conditions


Factors affecting human thermal comfort

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# 1ºC ≈ 5-10%

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# Psychrometric chart

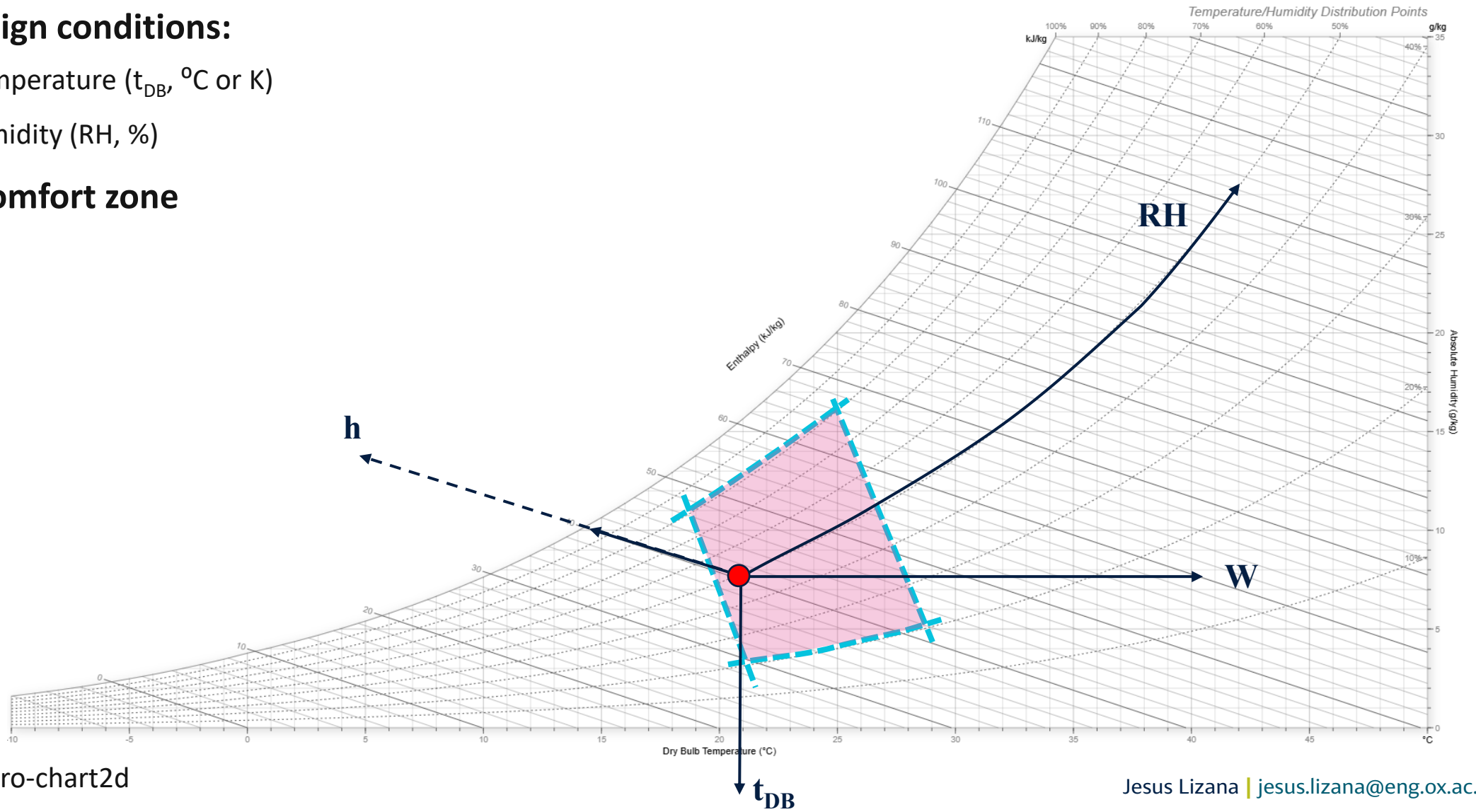
## Indoor design conditions:

- Dry-bulb temperature ($t_{DB}$, $^{o}$C or K)

- Relative humidity (RH, %)

## Thermal comfort zone

-ASHRAE-55




Source: psychro-chart2d

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# Psychrometric chart

## Indoor design conditions:

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- Relative humidity (RH, %)

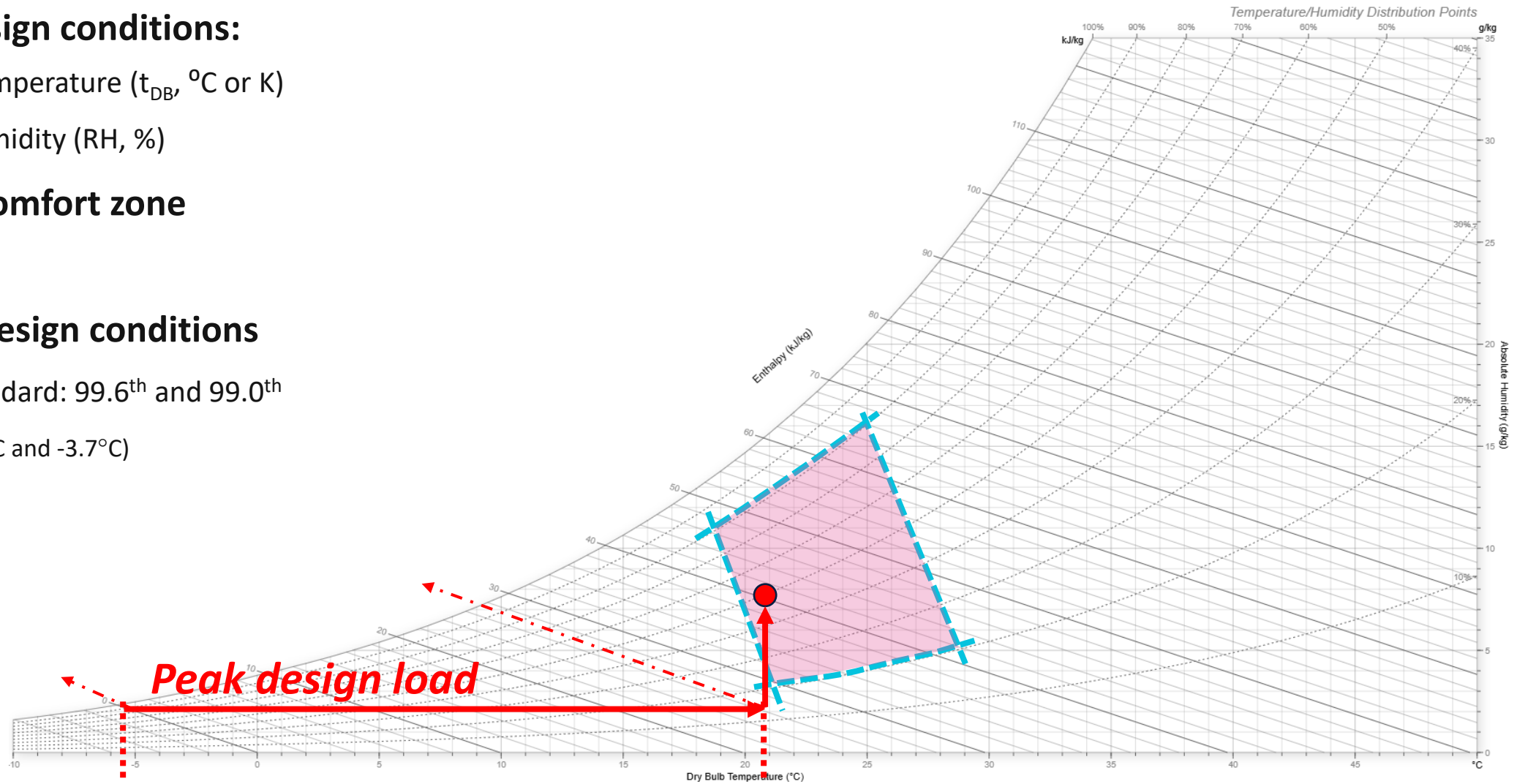
## Thermal comfort zone

-ASHRAE-55

## Outdoor design conditions

-ASHRAE standard: 99.6$^{th}$ and 99.0$^{th}$

In Oxford (-5.5°C and -3.7°C)




Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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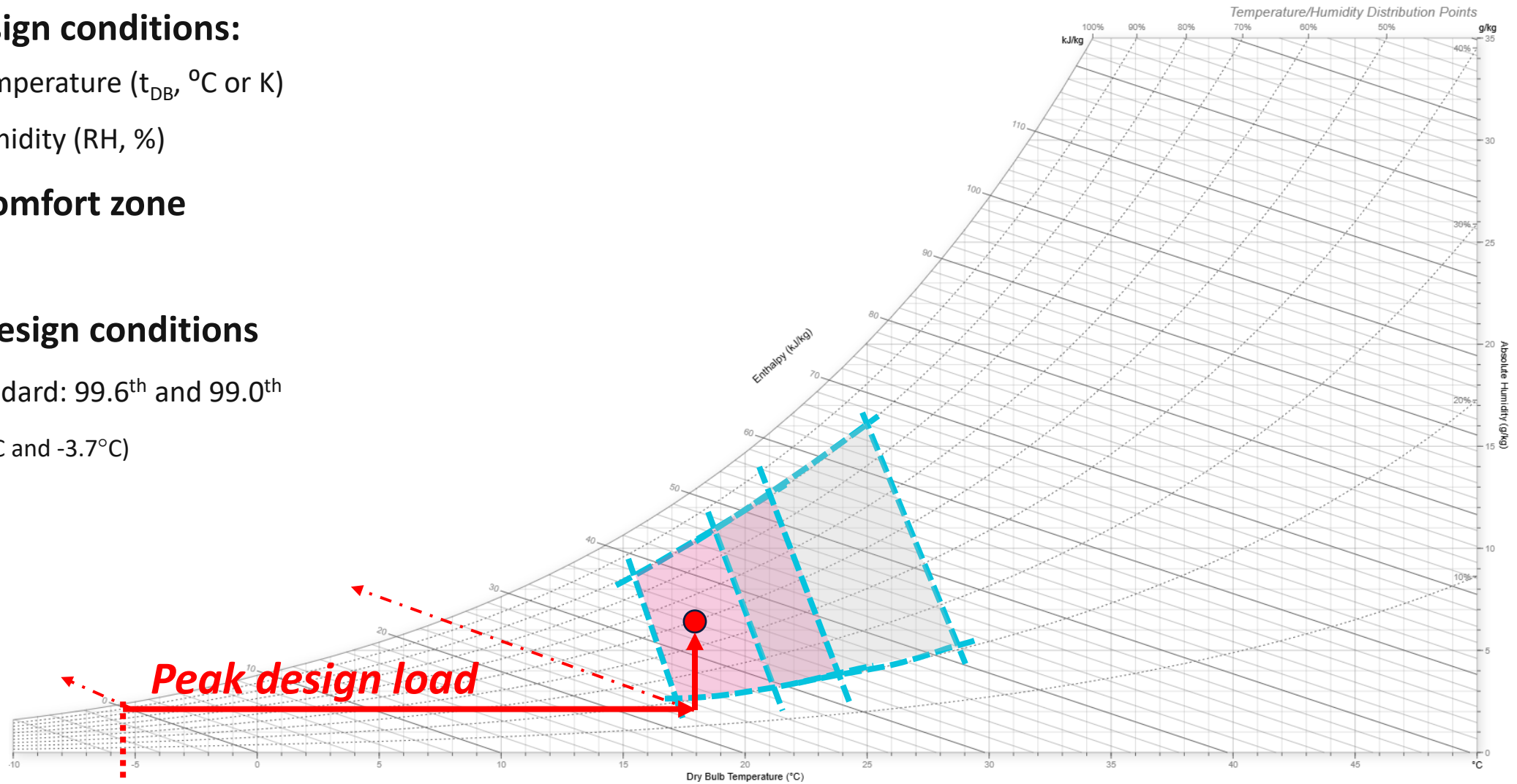


Outdoor design conditions: -5.5°C

Indoor design conditions: 18°C, 50%

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**Thermal comfort zone**

-ASHRAE-55

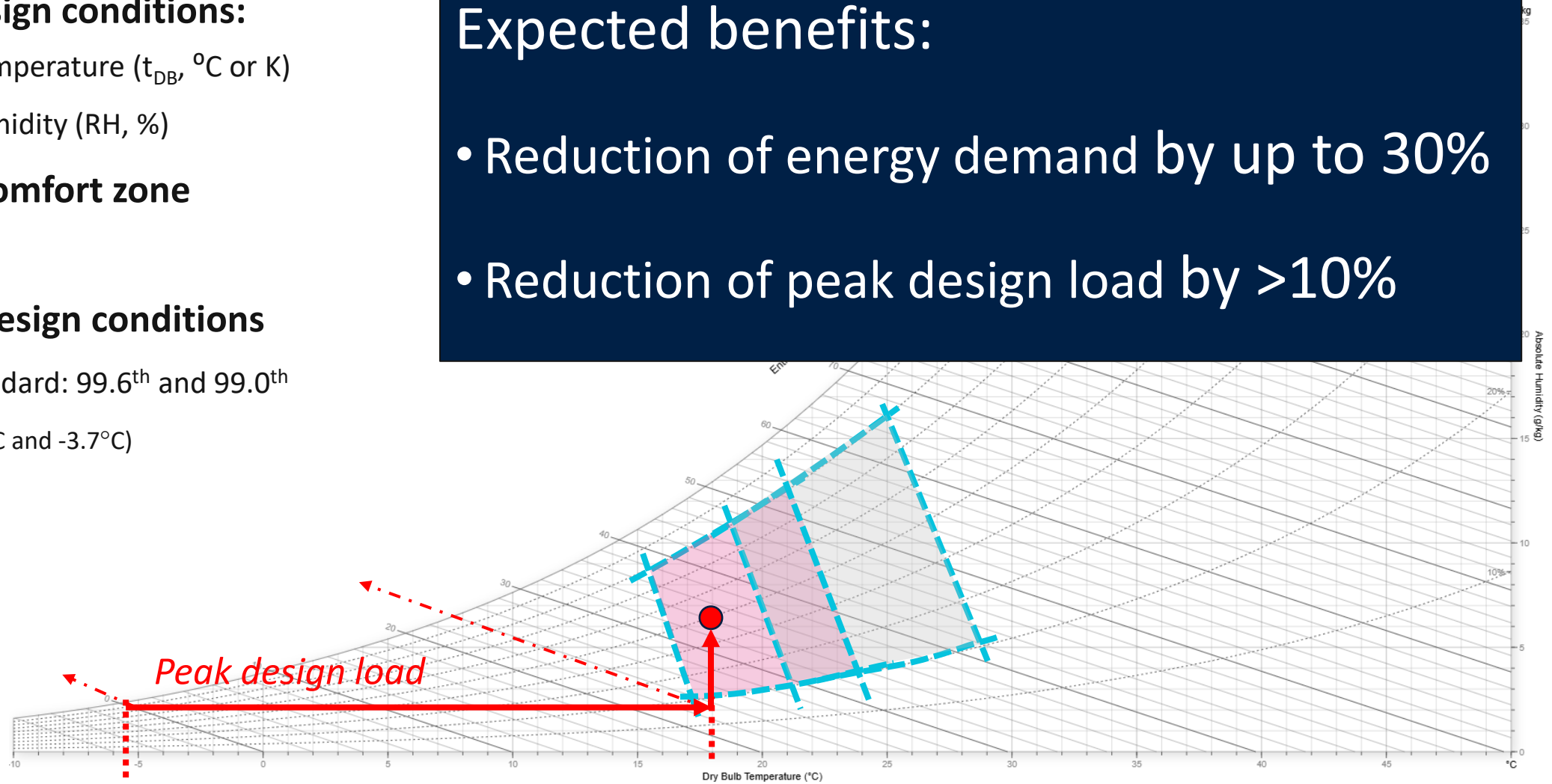
**Outdoor design conditions**

-ASHRAE standard: 99.6$^{th}$ and 99.0$^{th}$

In Oxford (-5.5°C and -3.7°C)

## Expected benefits:

- Reduction of energy demand by up to 30%
- Reduction of peak design load by >10%

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# Oxford city councillors do battle in 'thermostat war'

23 January 2024

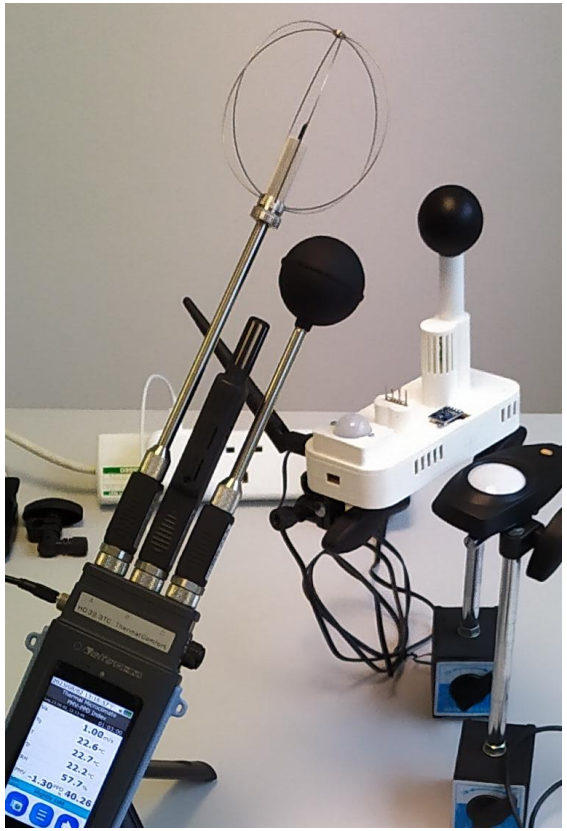
By Noor Qurashi
Local Democracy Reporting Service

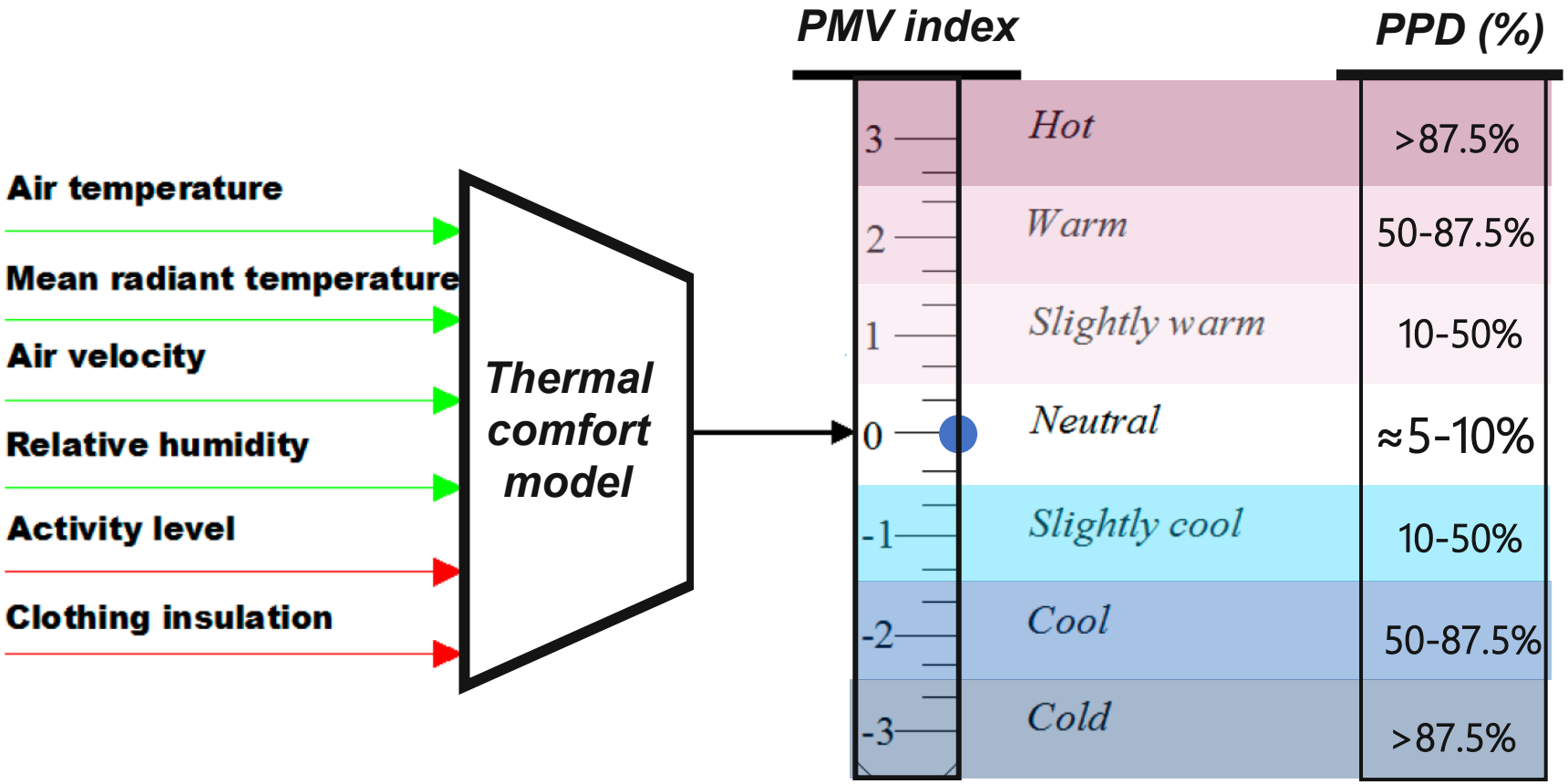
**Radiators were padlocked in a town hall after a "thermostat war" was declared, a councillor has claimed.**

Temperature knobs in the Oxford City Council public building were kept


Ms Railton, cabinet member for Zero Carbon Oxford and Climate Justice, said: "Clearly someone has lost their temper and thought 'right I'm going to solve this problem'."

# What can be measured can be controlled






**Predicted Mean Vote (PMV) index**

**Predicted Percentage of Dissatisfied (PPD)**

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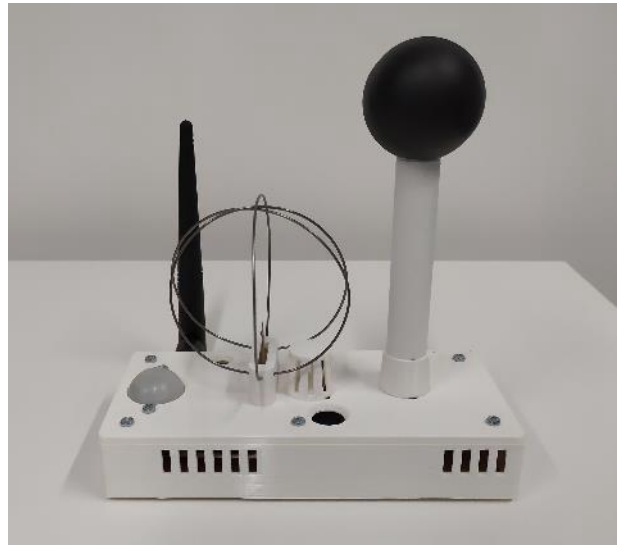

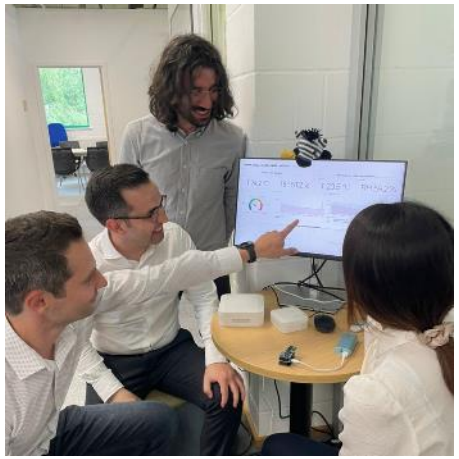

*Lizana, J., Wheeler, S., et al. (2024). Integrated post-occupancy evaluation and intervention that achieve real-world zero-carbon buildings. Energy & Buildings, 113766. https://doi.org/10.1016/j.enbuild.2023.113766*

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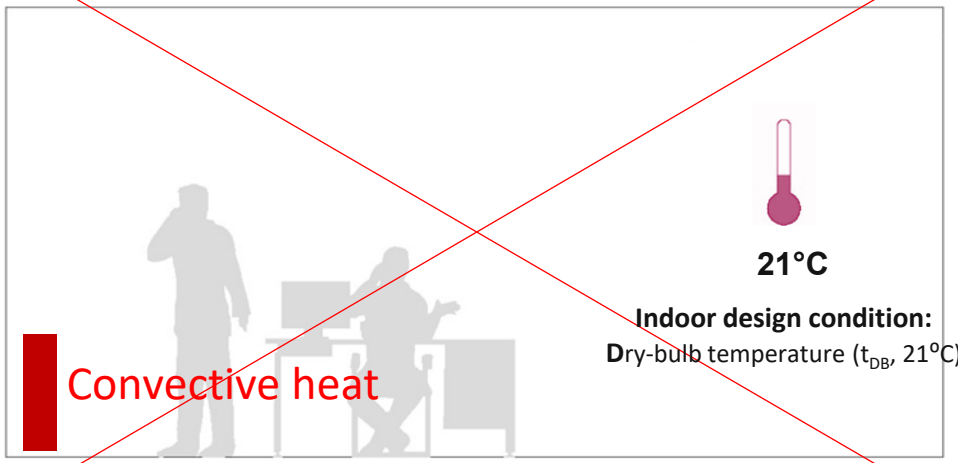
# 1) Hybrid indoor design conditions

## a, The classical approach







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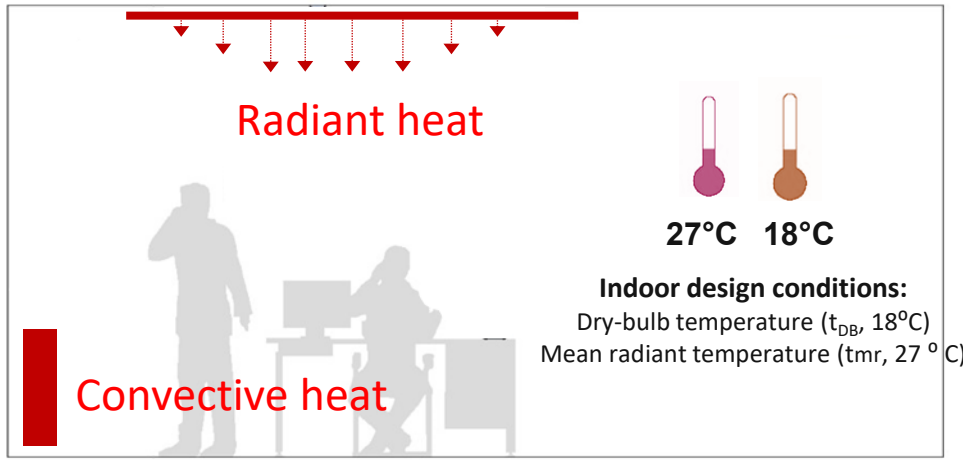
# 1) Hybrid indoor design conditions

## b, The hybrid approach




**Indoor design conditions:**
Dry-bulb temperature ($t_{DB}$, 18°C)
Mean radiant temperature (tmr, 27 °C)

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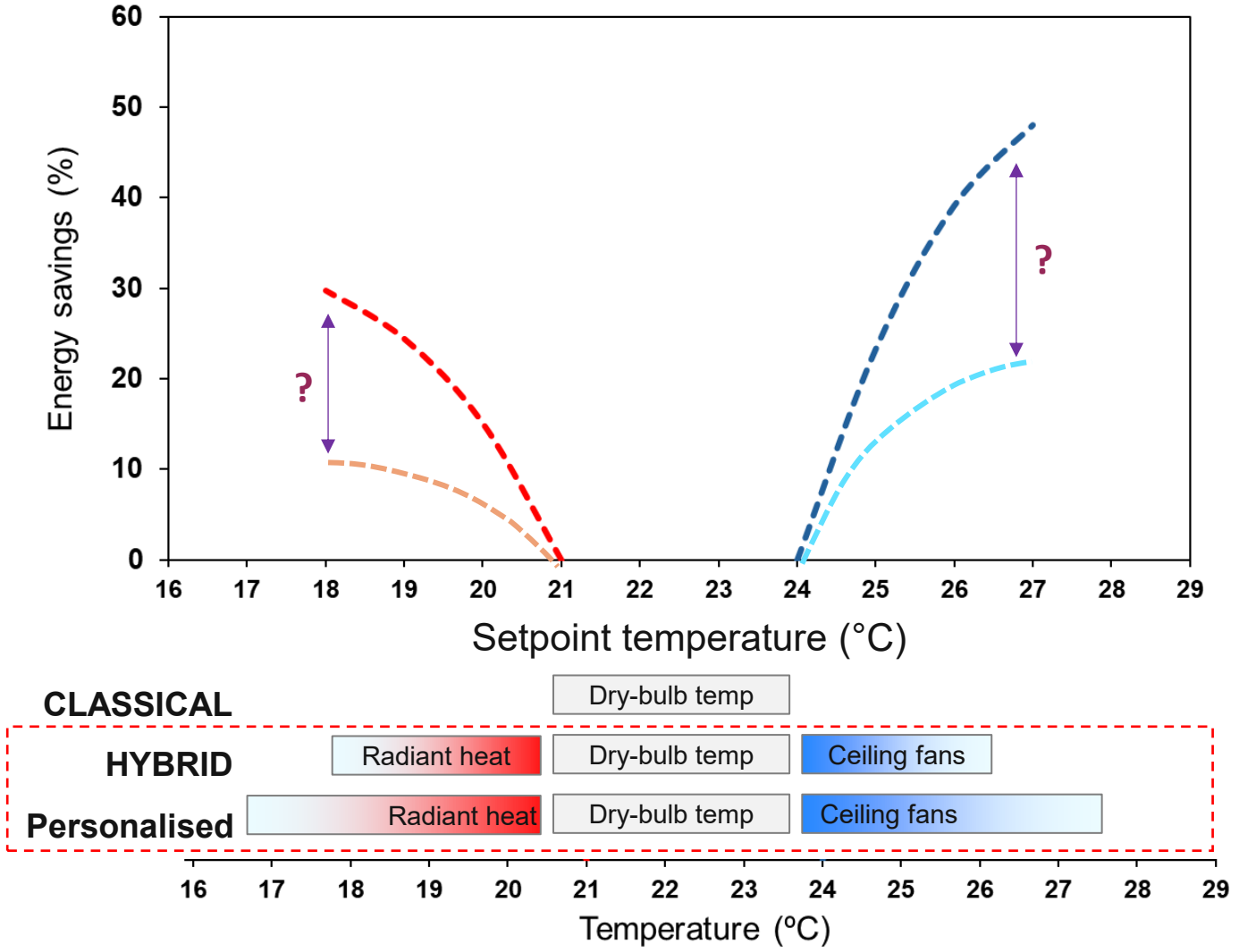
# Key research question

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# It's time to stop over-engineering systems for managing peak loads

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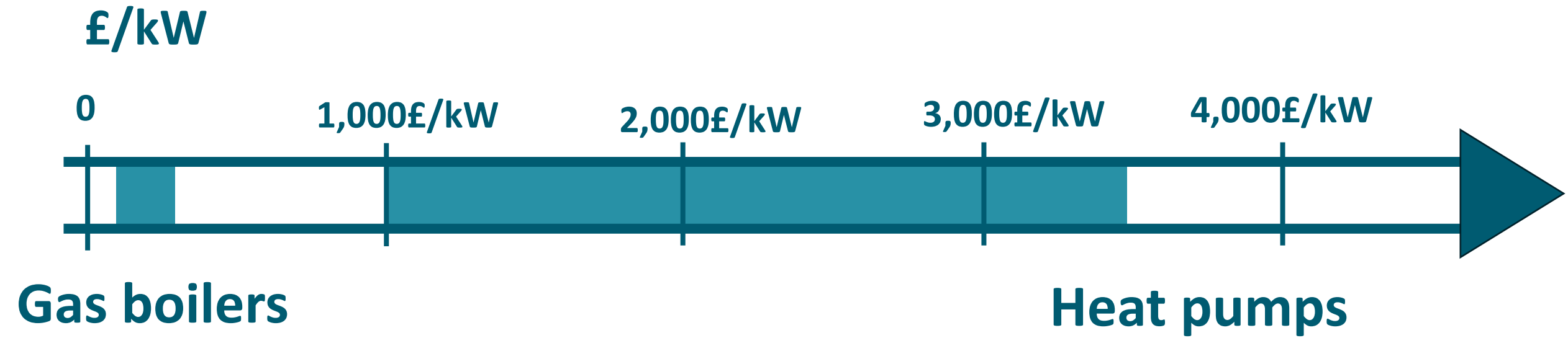
# Cost of heating tech per kW

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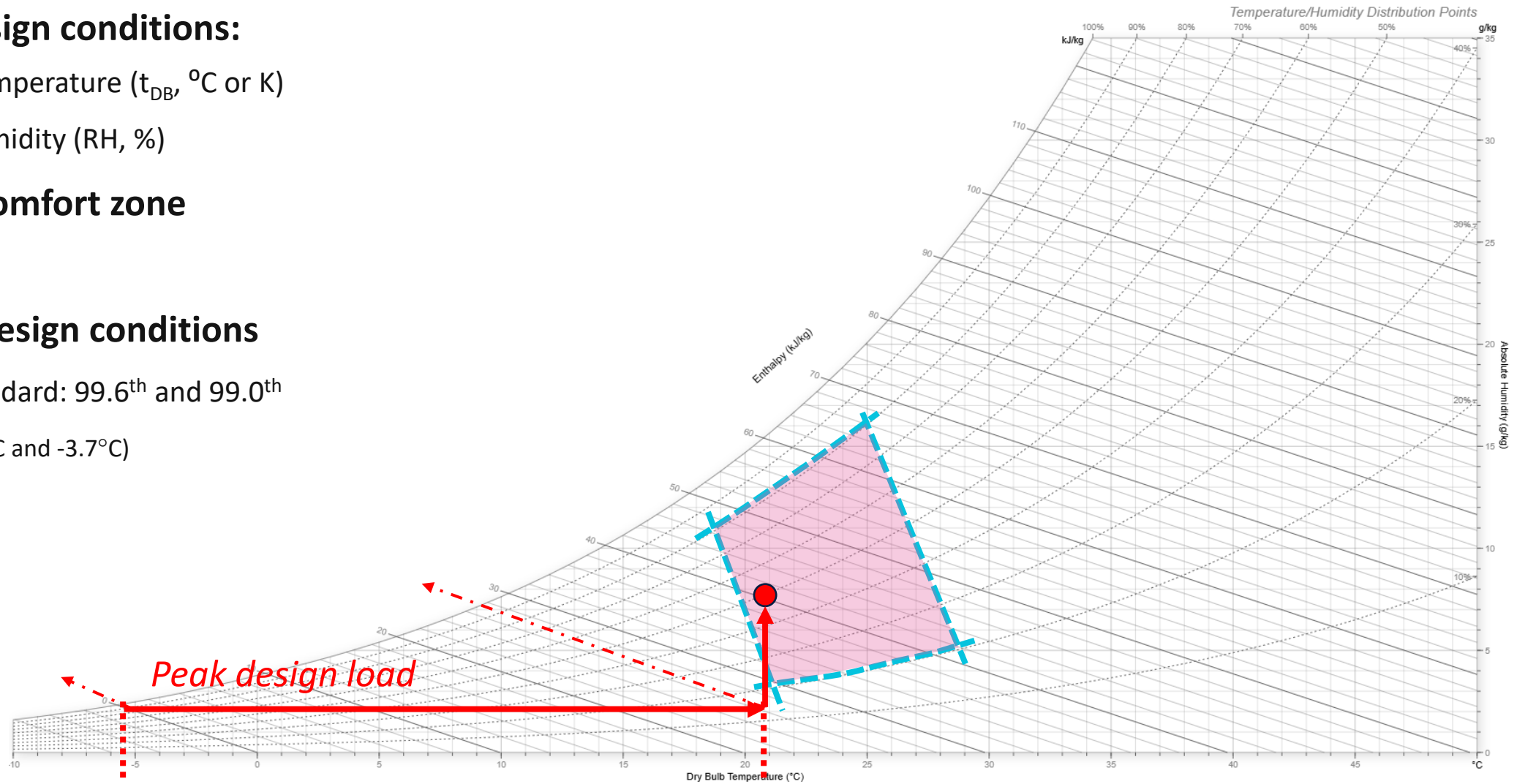


Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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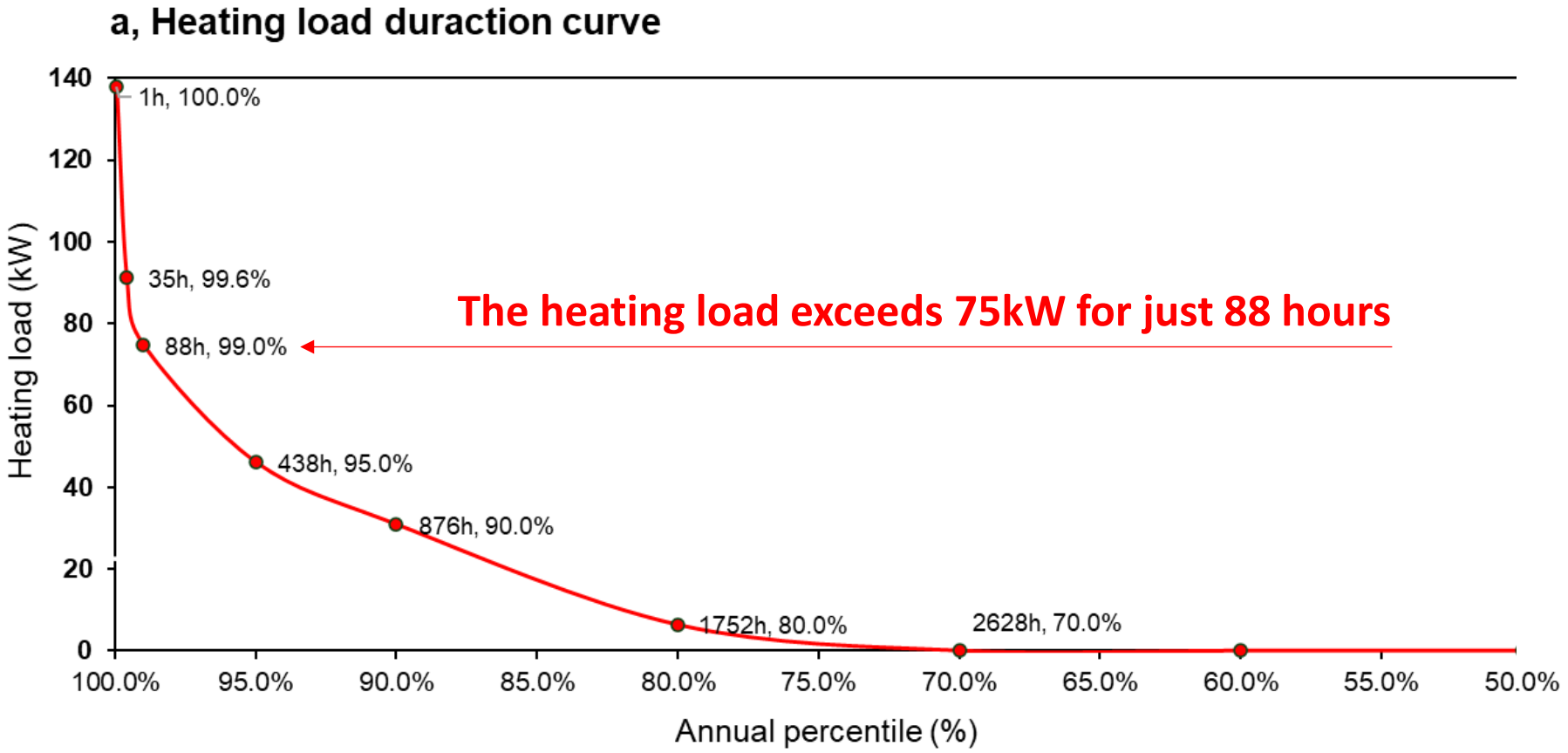
# 2) Optimal sizing of heating systems

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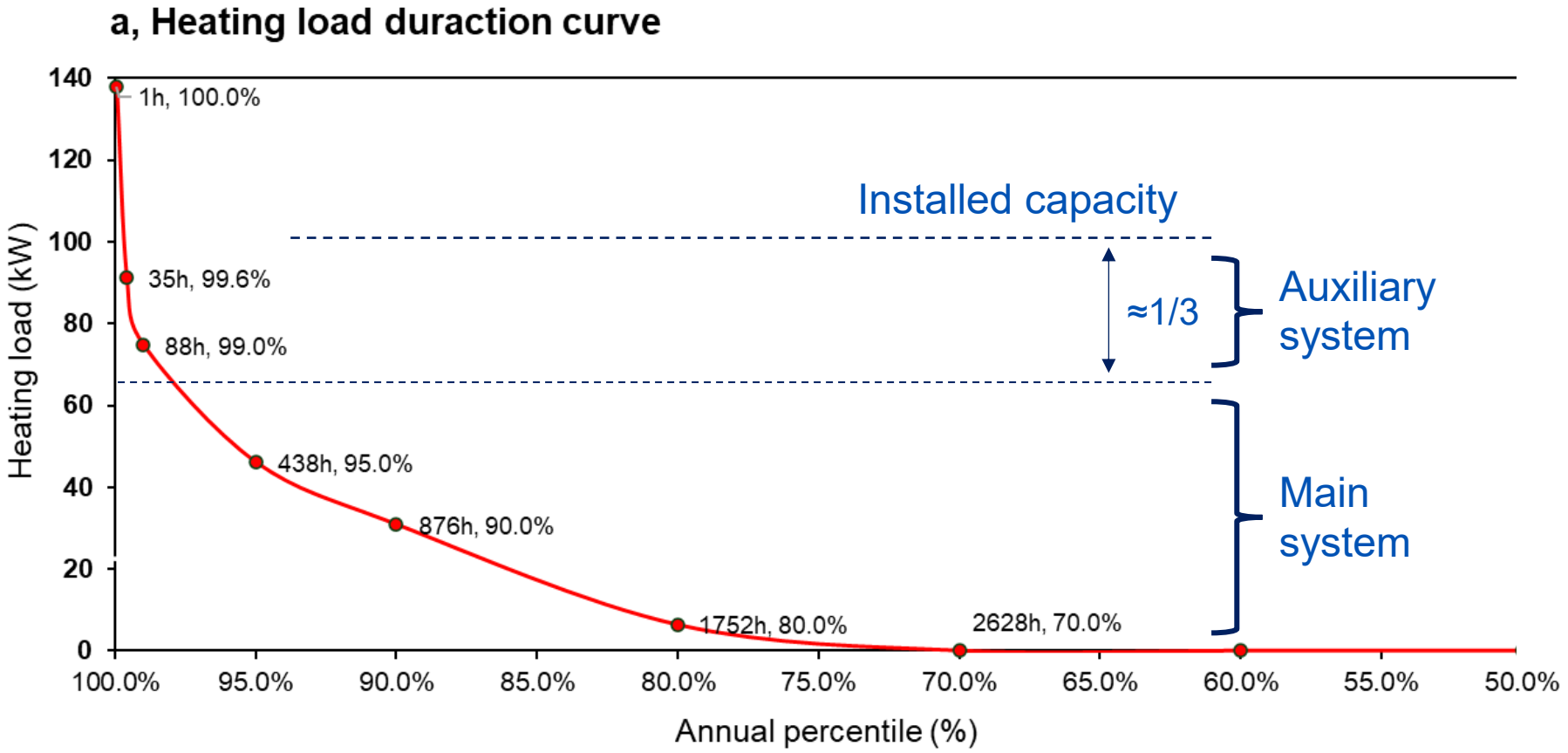


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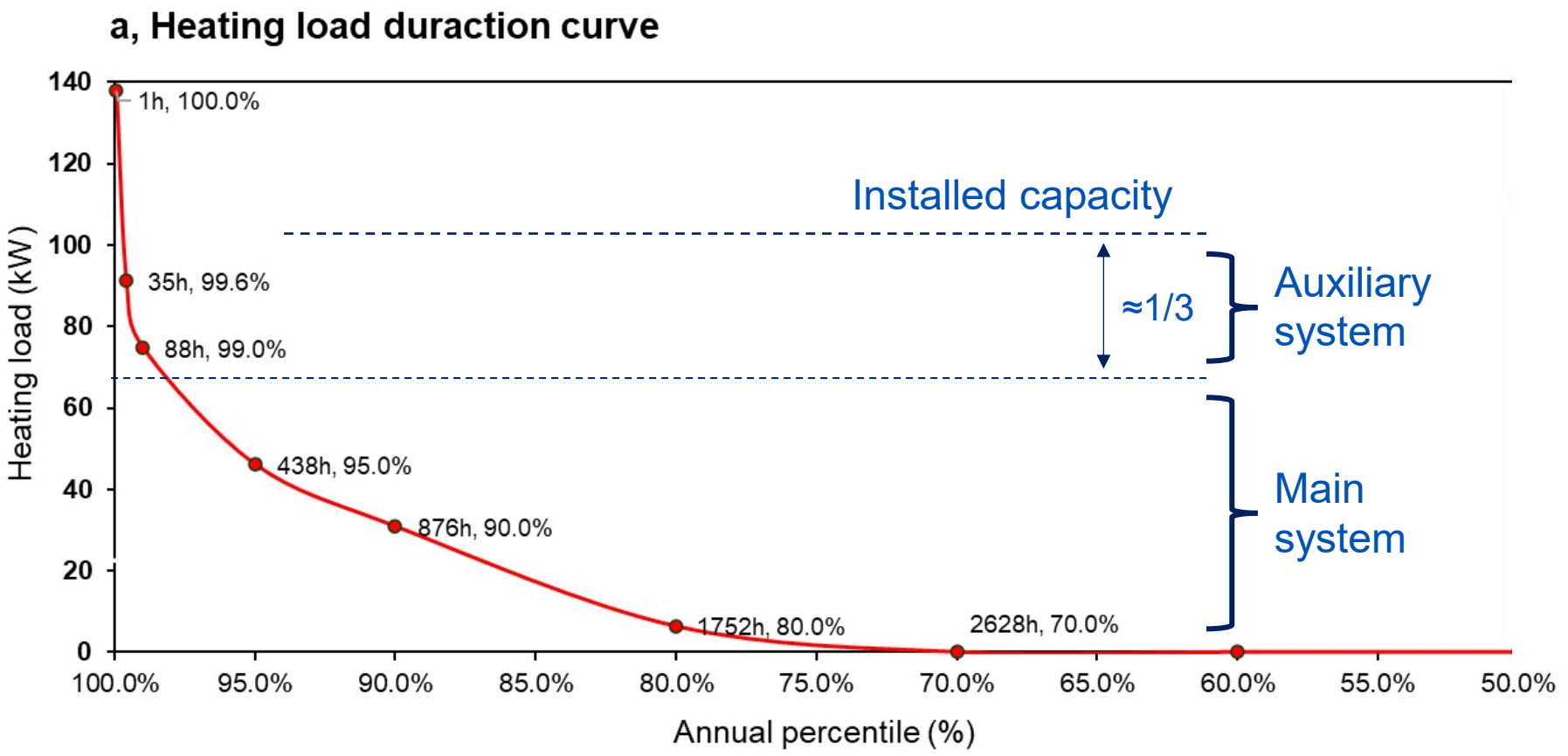
# 2) Optimal sizing of heating systems

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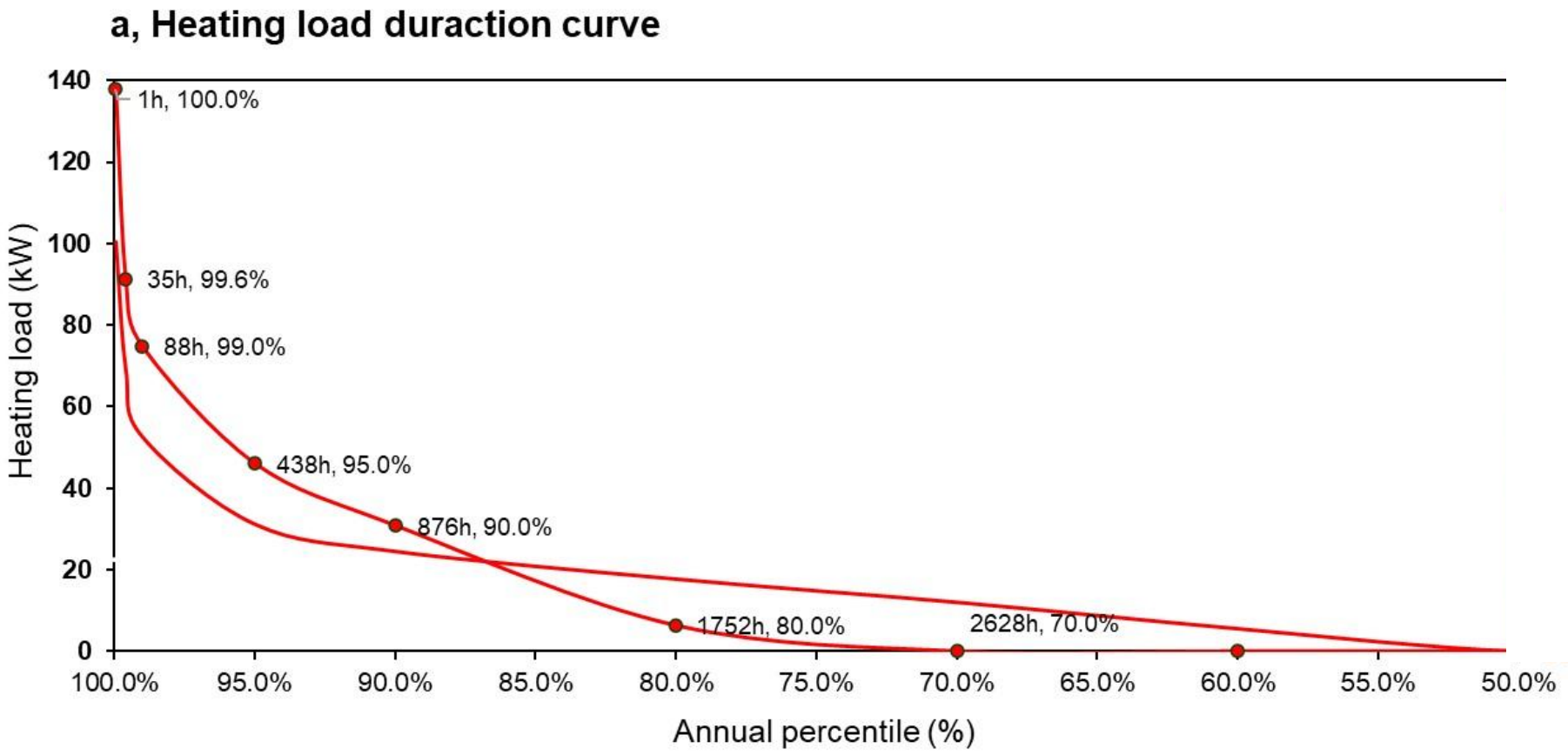
# 2) Optimal sizing of heating systems

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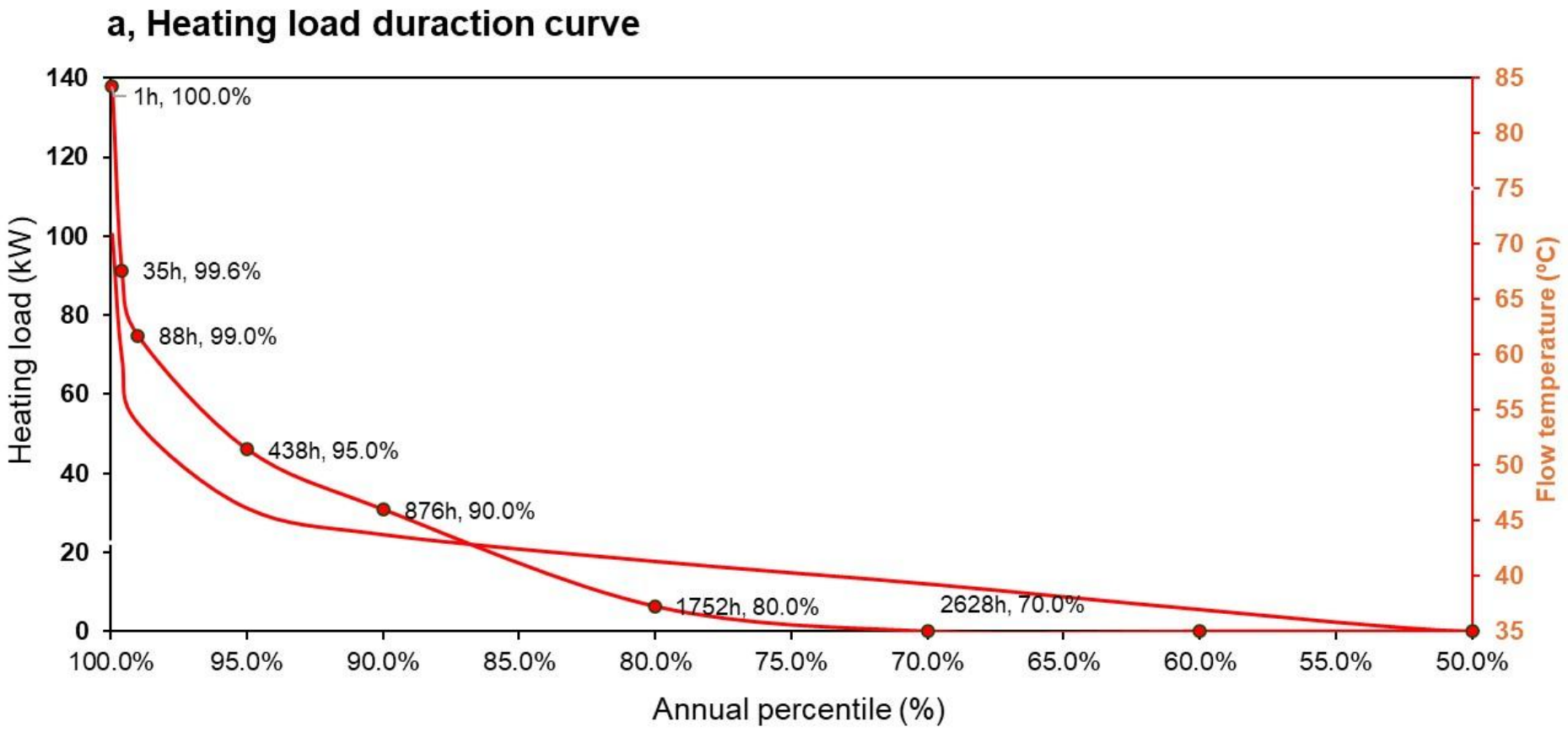
# 2) Optimal sizing of heating systems

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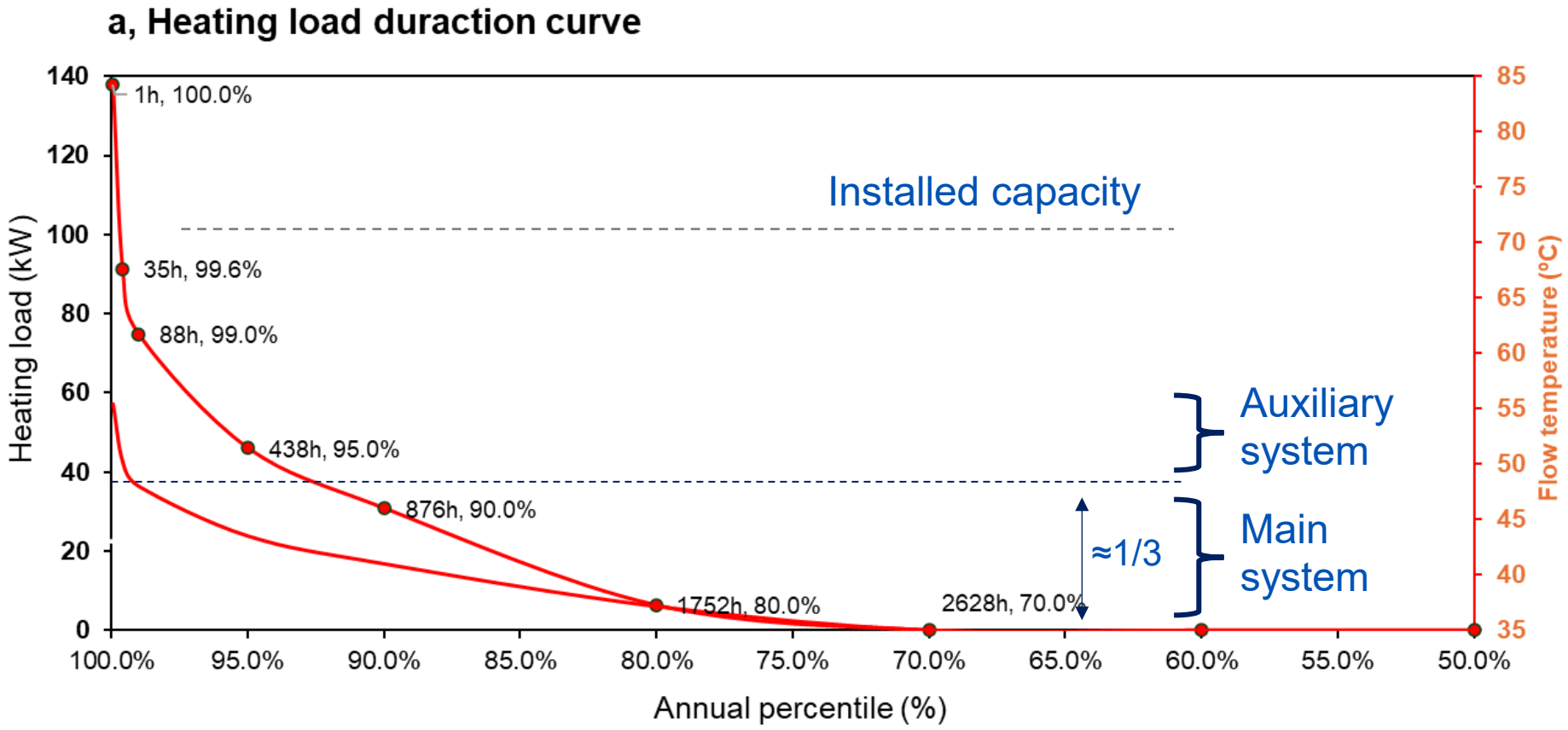
# 2) Optimal sizing of heating systems

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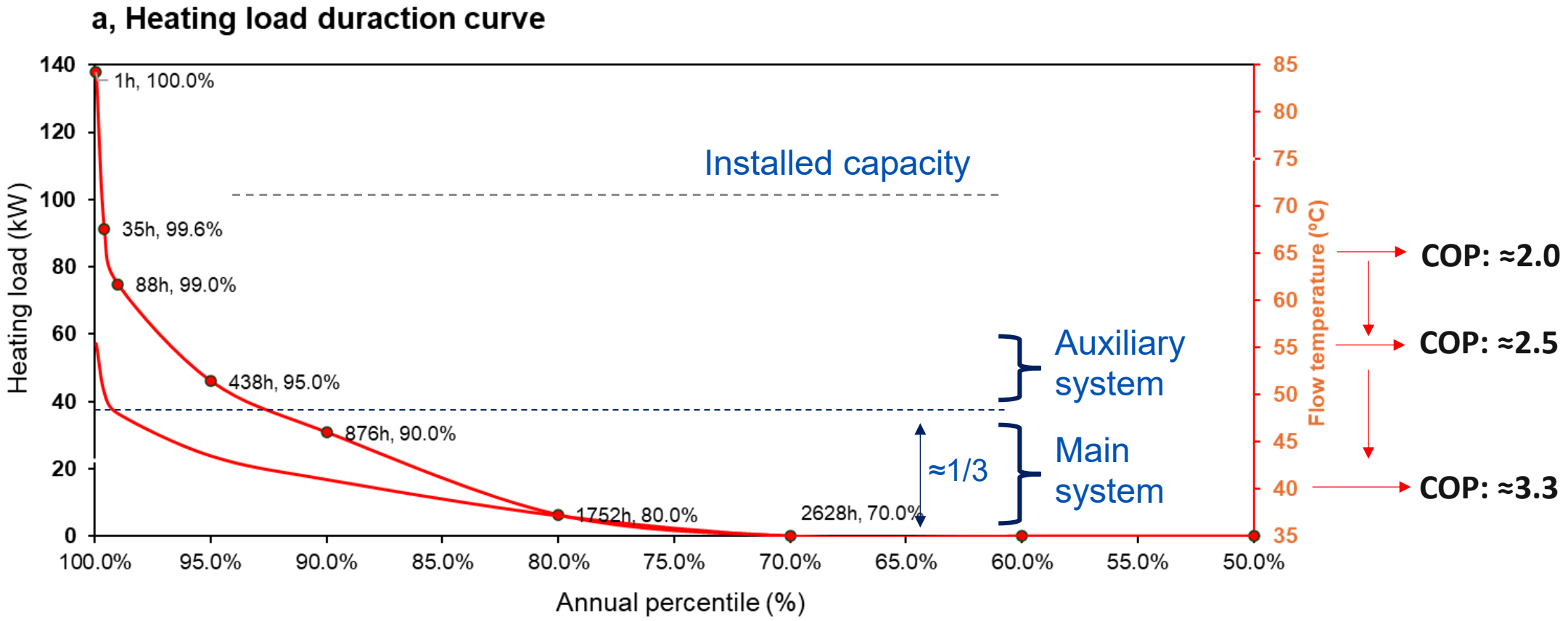
# 2) Optimal sizing of heating systems

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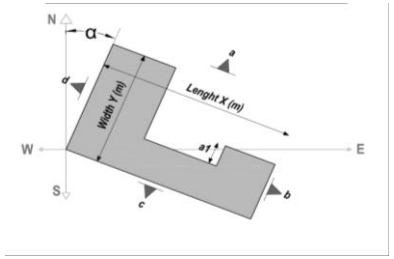
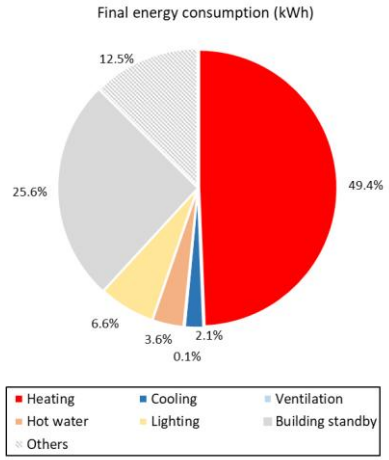
# 2) Optimal sizing of heating systems

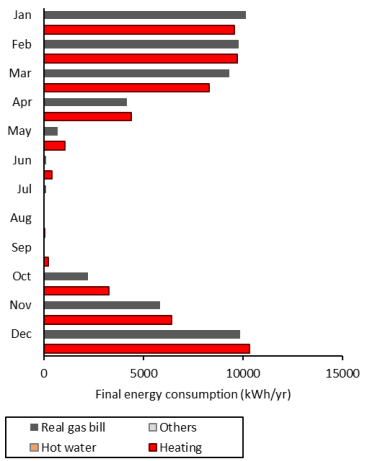
## openBES software to create cost-effective solutions for achieving net zero objectives

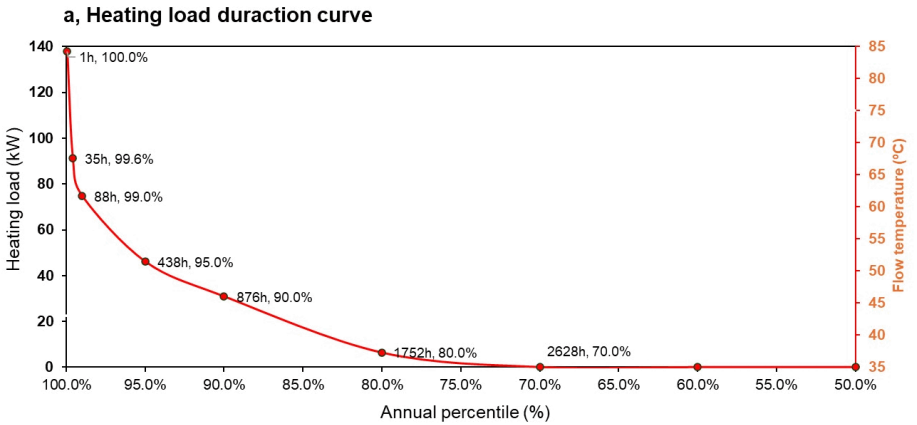
**Minimum input values** → **Physics-based building model** → **Data-driven calibration using energy bills** → **Optimal sizing of heating systems**

**Early-stage decision-making process**

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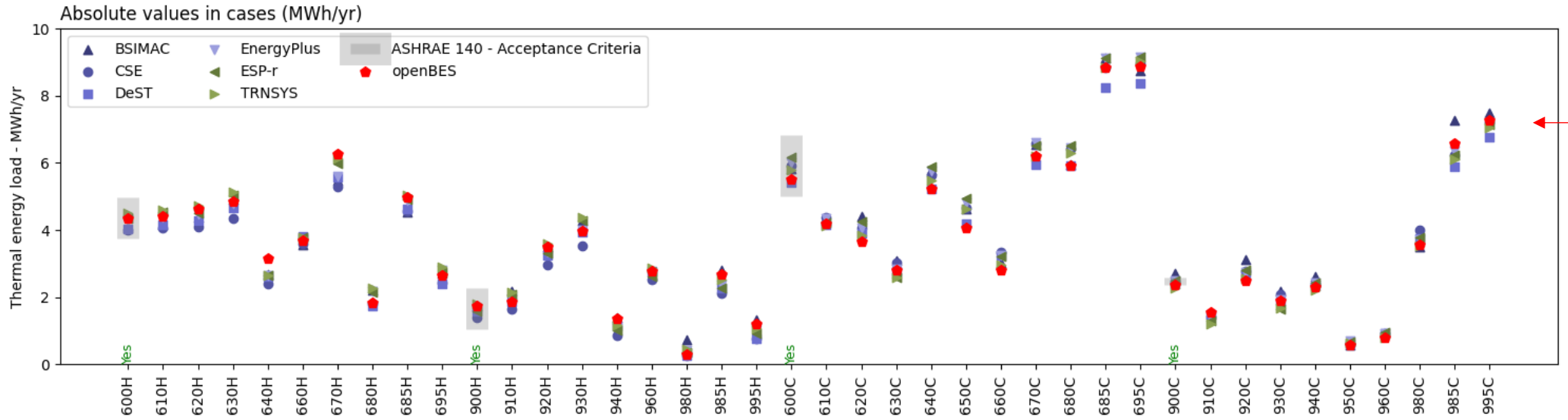
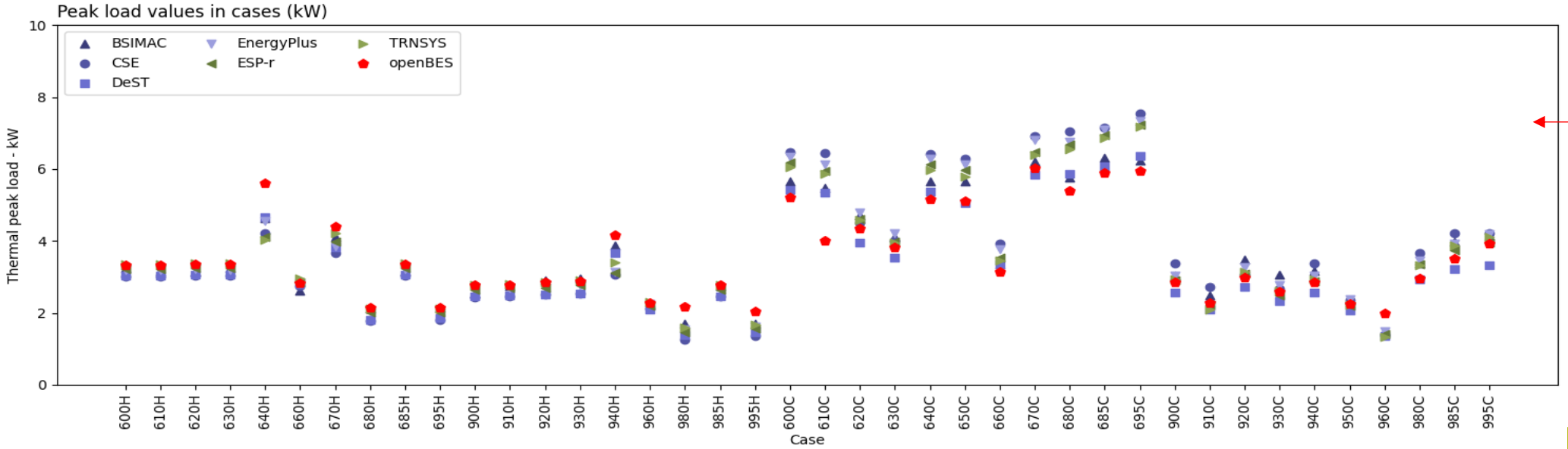
# Software validation




Thermal Energy (MWh/yr)




Peak load (KW)

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# Investment in an auxiliary system for just ≈96 hours a year doesn’t make sense

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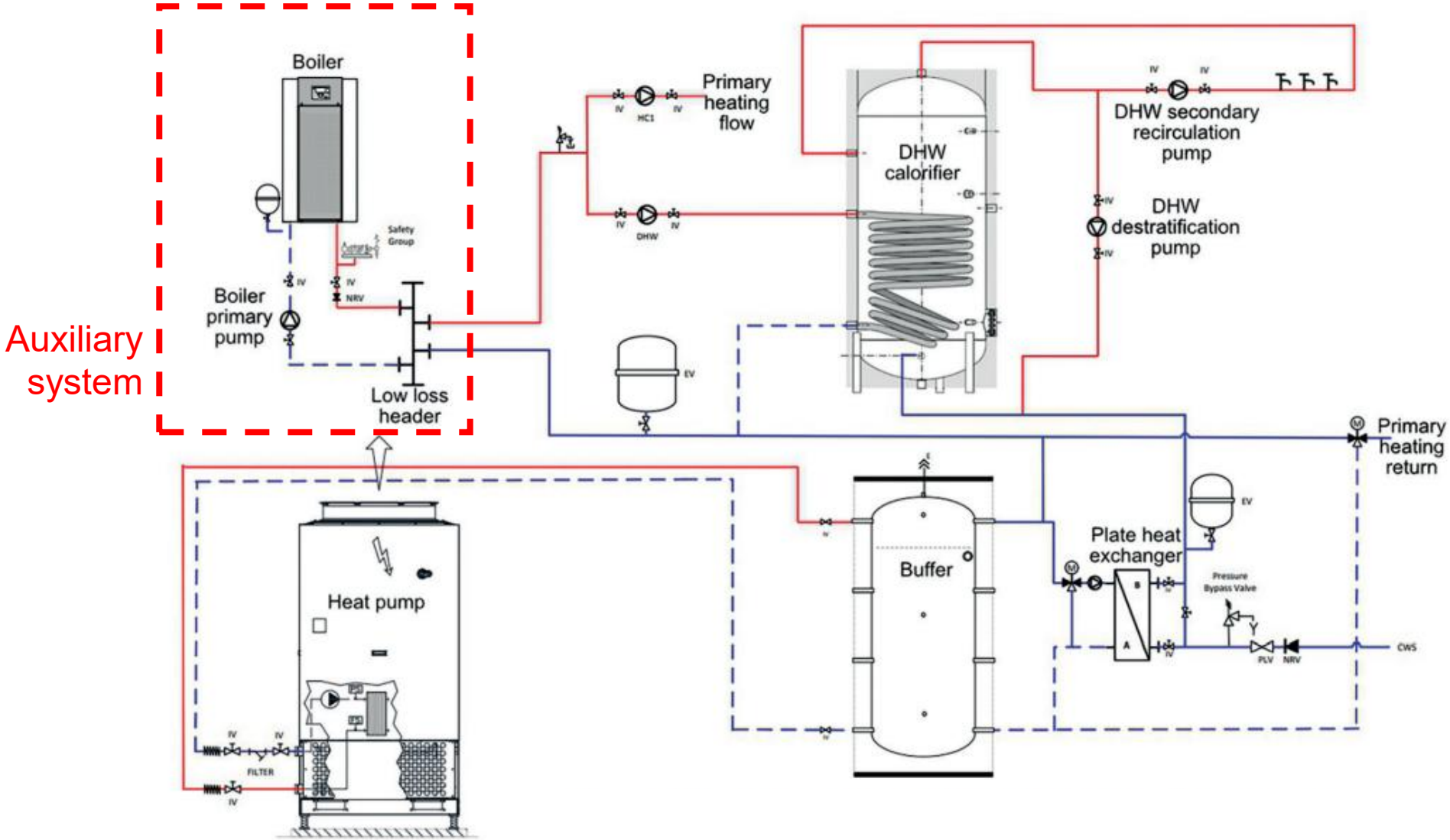
# Best practices in heating systems




Source: CIBSE journal

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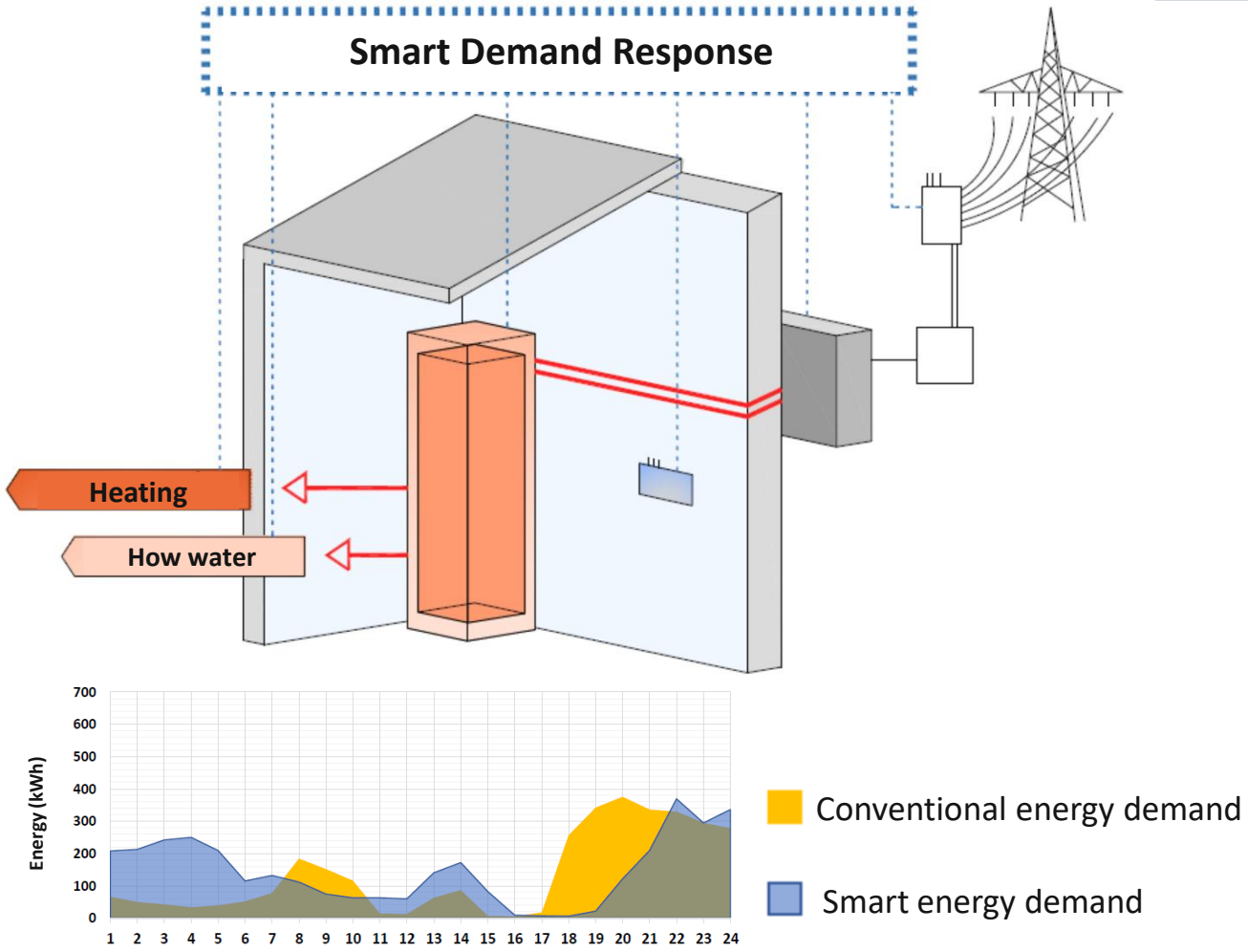
# Not only for peak loads but also for…

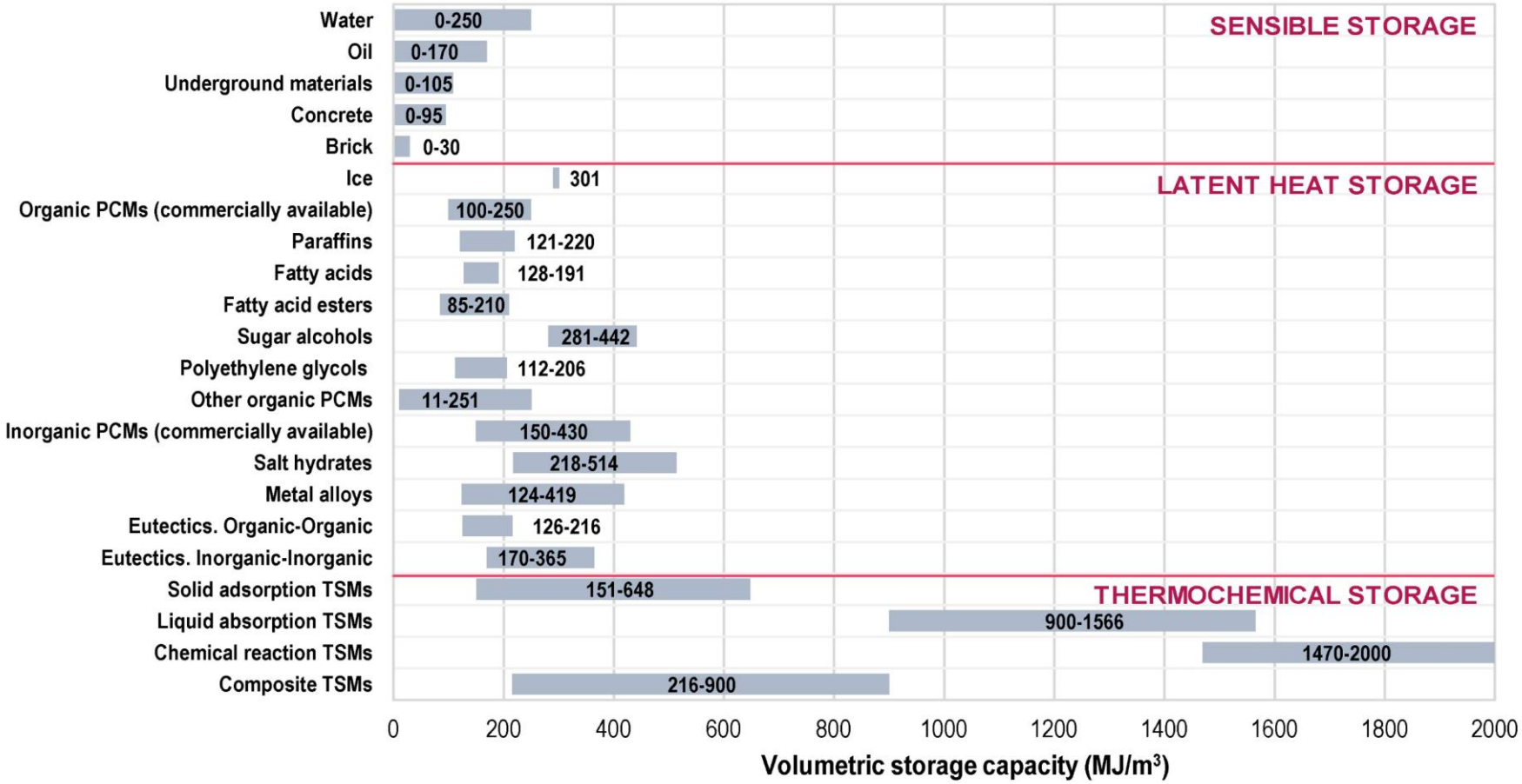
## Energy flexibility




J. Lizana, et al., Energy flexible building through smart demand-side management and latent heat storage, Applied Energy. 230 (2018) 471–485. https://doi.org/10.1016/j.apenergy.2018.08.065.

Jesus Lizana | jesus.lizana@eng.ox.ac.uk

# Thermal energy storage in buildings




Comparison of thermal energy storage materials

J. Lizana, et al., Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review, Applied Energy. 203 (2017) 219–239. https://doi.org/10.1016/j.apenergy.2017.06.008.

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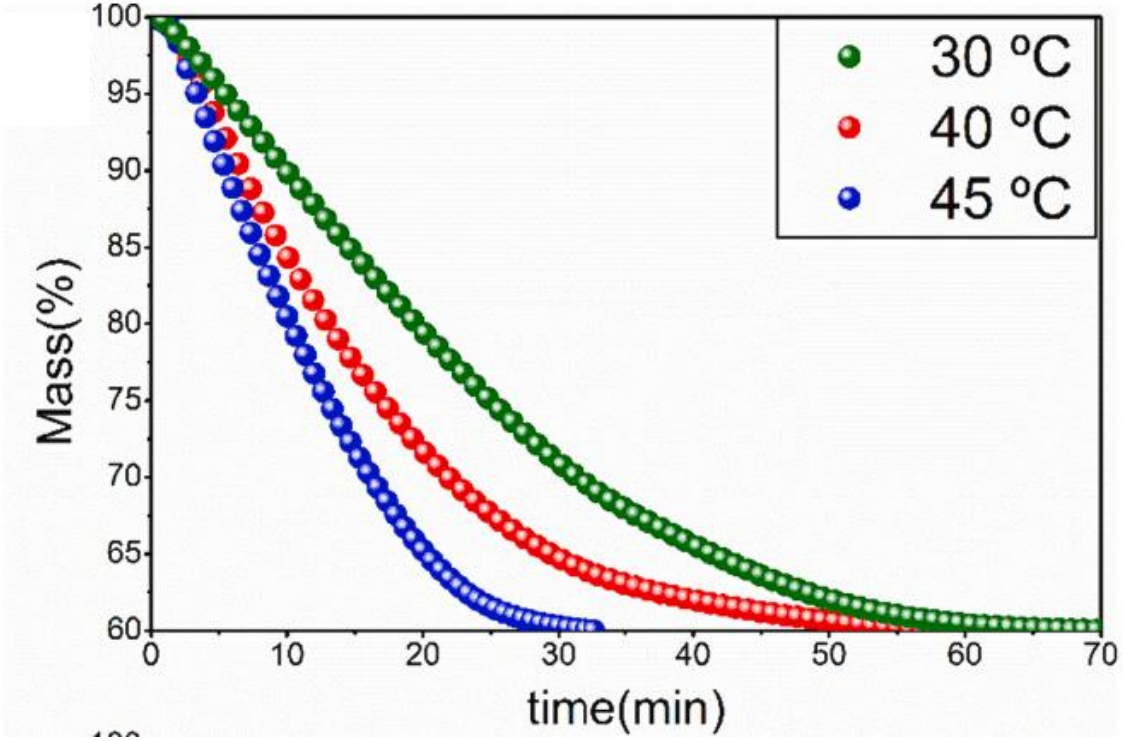
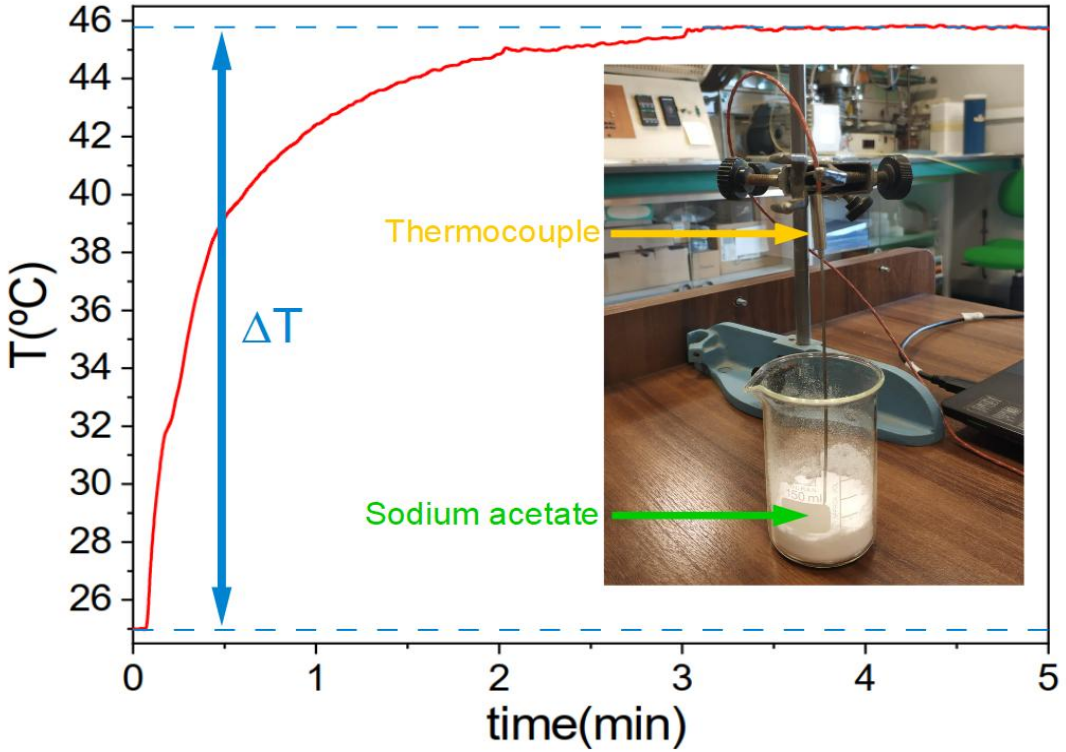
# SA-based composite material

## Charging process - Dehydration




## Heat release - Hydration




J. Arcenegui-Troya, J. Lizana et al. Sodium acetate-based thermochemical energy storage with low charging temperature and enhanced power density, Journal of Energy Storage. 86 (2024) 111310. https://doi.org/10.1016/j.est.2024.111310.

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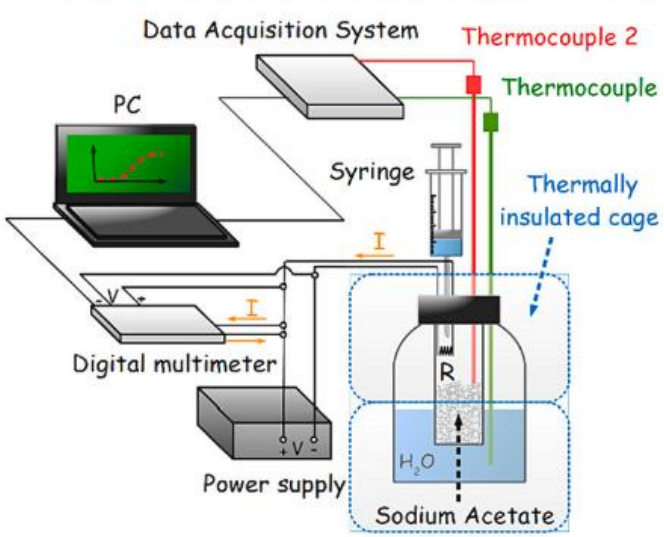
# 3 ) A better auxiliary system for heating systems

## TRL3
## “proof of concept”




J. Arcenegui-Troya, J. Lizana et al. Sodium acetate-based thermochemical energy storage with low charging temperature and enhanced power density, Journal of Energy Storage. 86 (2024) 111310. https://doi.org/10.1016/j.est.2024.111310.

## TRL4-5

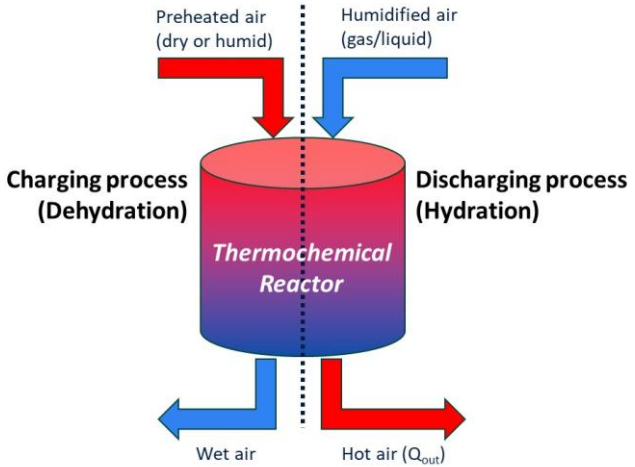
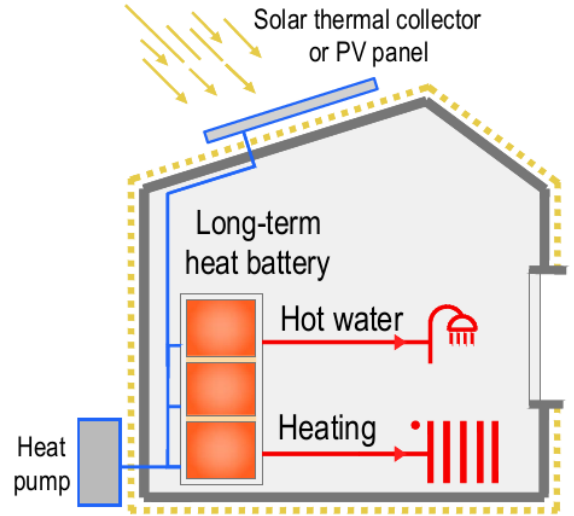



***Figure 1***. *Schematic diagram of the bed reactor for thermochemical heat storage.*

**Project ThermoReact:**
**low-temperature TCES reactions**

## Vision

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# Zero-Carbon Heating and Cooling

**Leading research – Enabling collaborations in Oxford and abroad - With global impact**

in heating and cooling — standing on the shoulders of giants — in science, policy, and practice

**HEATING** ← → **COOLING**

| climate change **MITIGATION** | climate **RISK** | climate **ADAPTATION** |
|---|---|---|
| Heating decarbonisation - net-zero targets | Climate-related hazards – exposure - vulnerability | Mitigation of rising cooling needs - Resilience |

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# Designing for the future requires a deeper understanding of future climates

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# Citizen science for accurate climate information

## Global climate modelling

***Citizen-driven distributed computing***

Climate scale: global (macro and meso)

Spatio-temporal resolution: **6h at 60km²**

Platform: Climateprediction.net (CPDN)

Model: HadAM4

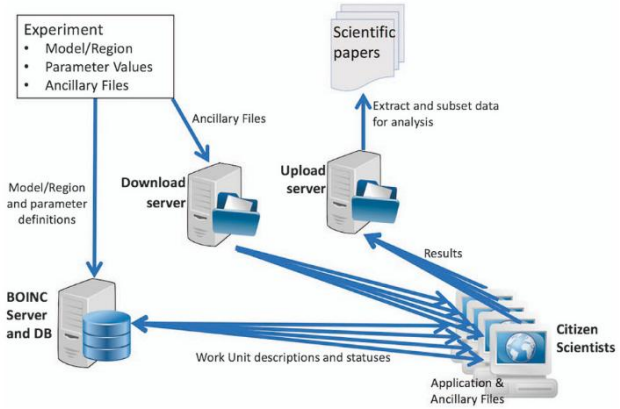


Fig. 1. Workflow of publically volunteered computers for climate modelling

## Local climate information

***Citizen weather data***

Climate scale: city (local and micro)

Spatio-temporal resolution: **1h at 1km²**

Platform: Netatmo, Wunderground

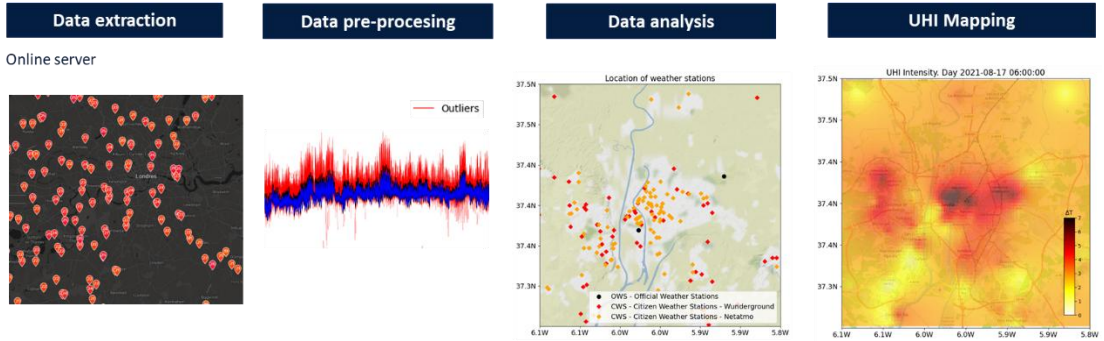


Fig. 2. Workflow of citizen weather data for high-resolution urban climate mapping

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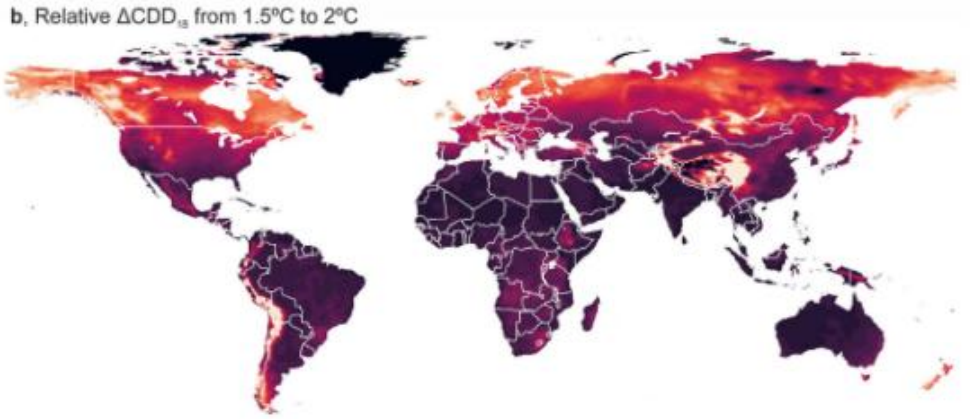
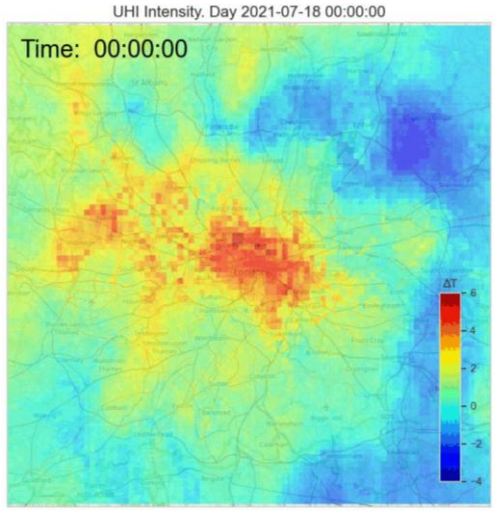
# Climate observation and projections

## a, Global CDD and HDD
## Resolution: 6 hours at 60km²




## b, Urban Cooling Degree Hours
## Resolution: 1 hour at 1km²

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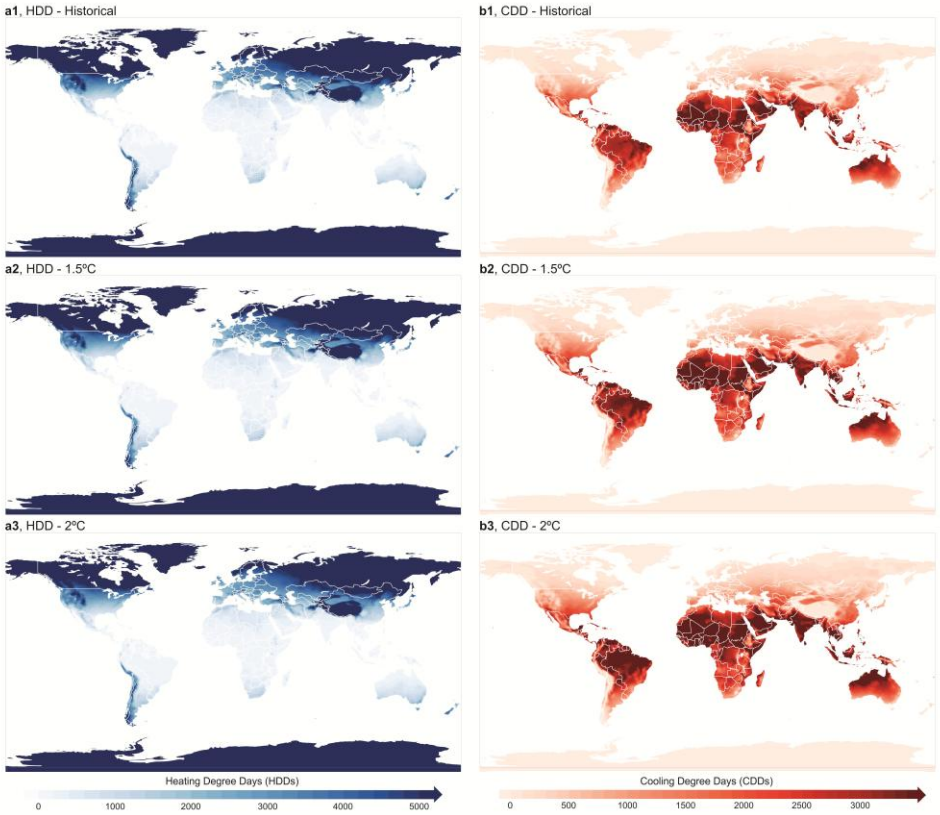
# Global dataset of CDD and HDD




- ***New global dataset of heating degree days (HDD) and cooling degree days (CDD).***
- ***3 global mean temperature rise scenarios***— *1.0°C, 1.5°C, and 2.0°C —regardless of the pathways leading to these levels.*
- ***30 gridded maps characterising climate variability through five statistical descriptors per variable and scenario*** *over a representative 10-year period*

Lizana et al. (2025) Nature Sustainability
Dataset available in ORA

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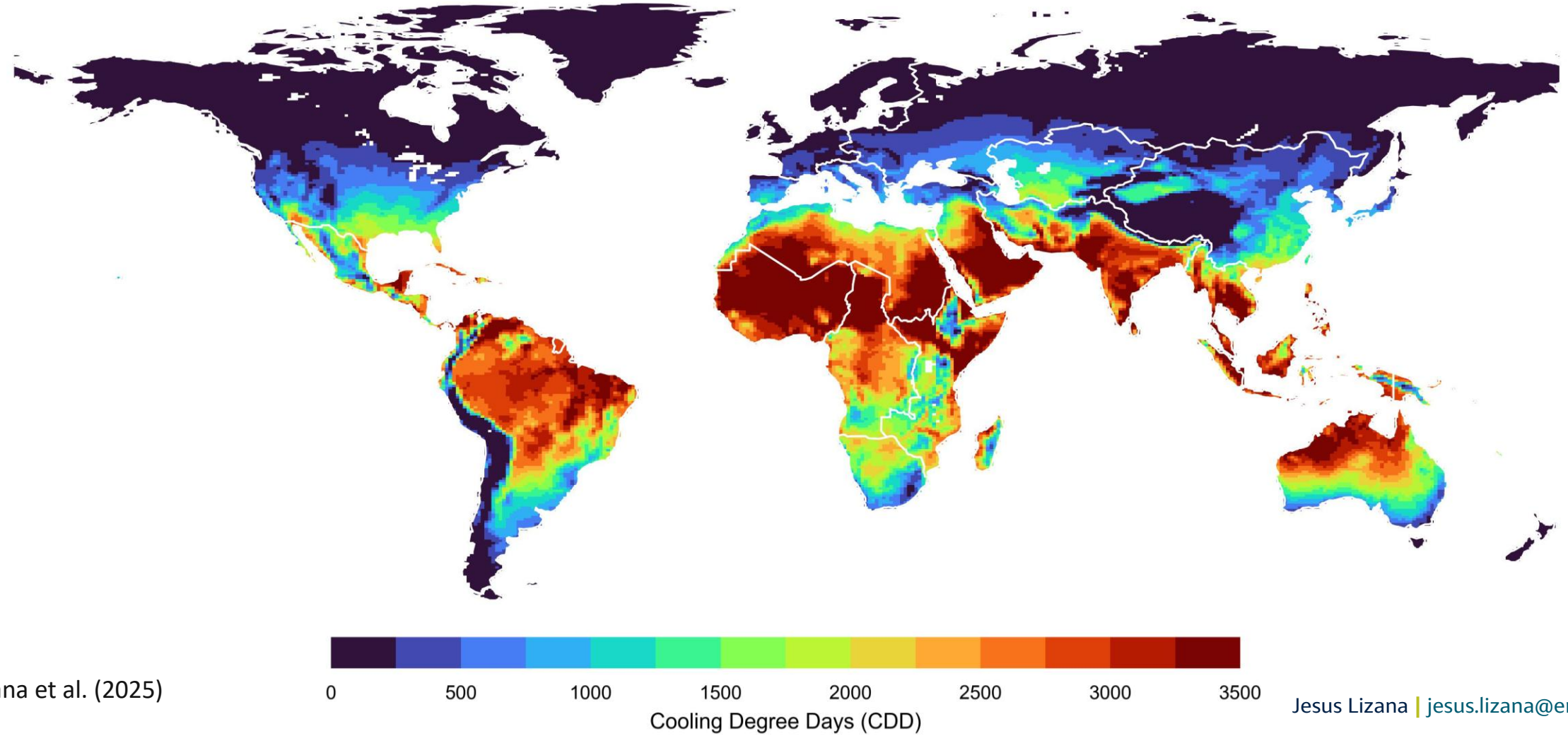
# Cooling Degree Days

a, Scenario 1.0°C (2006-2016)




Lizana et al. (2025)

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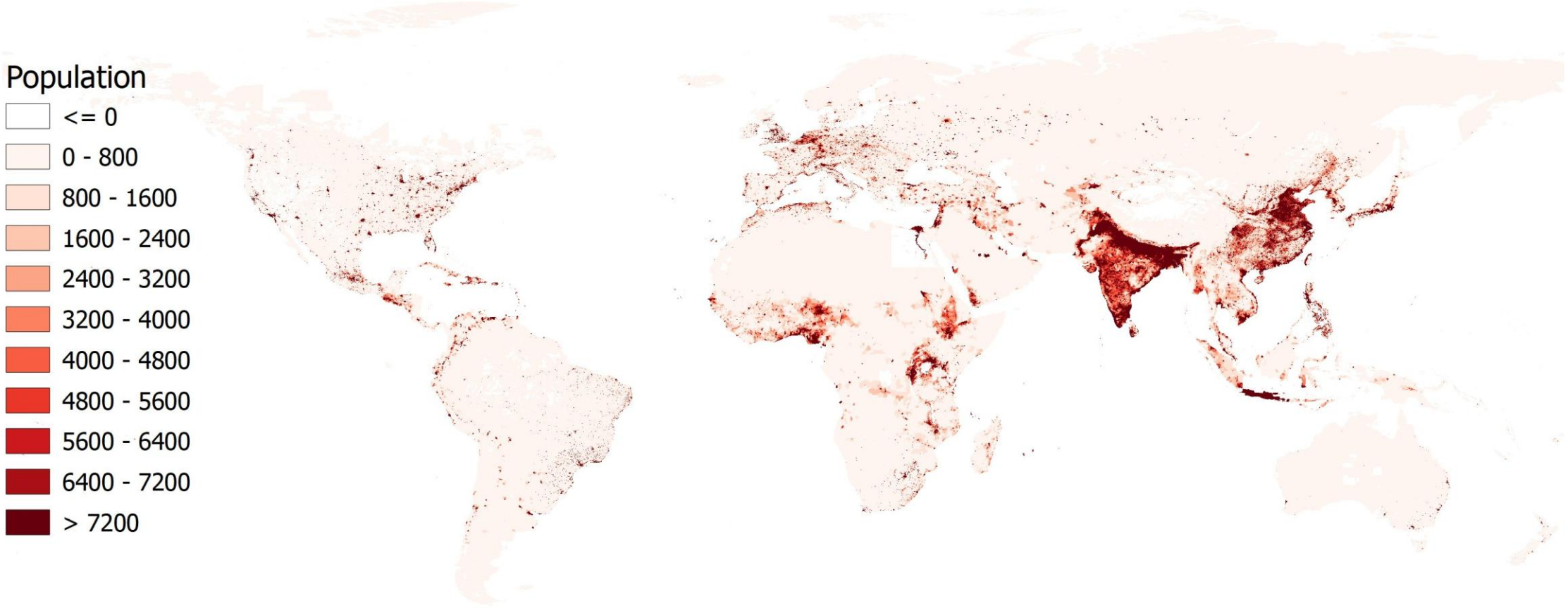
# Population




Lizana et al. (2025)

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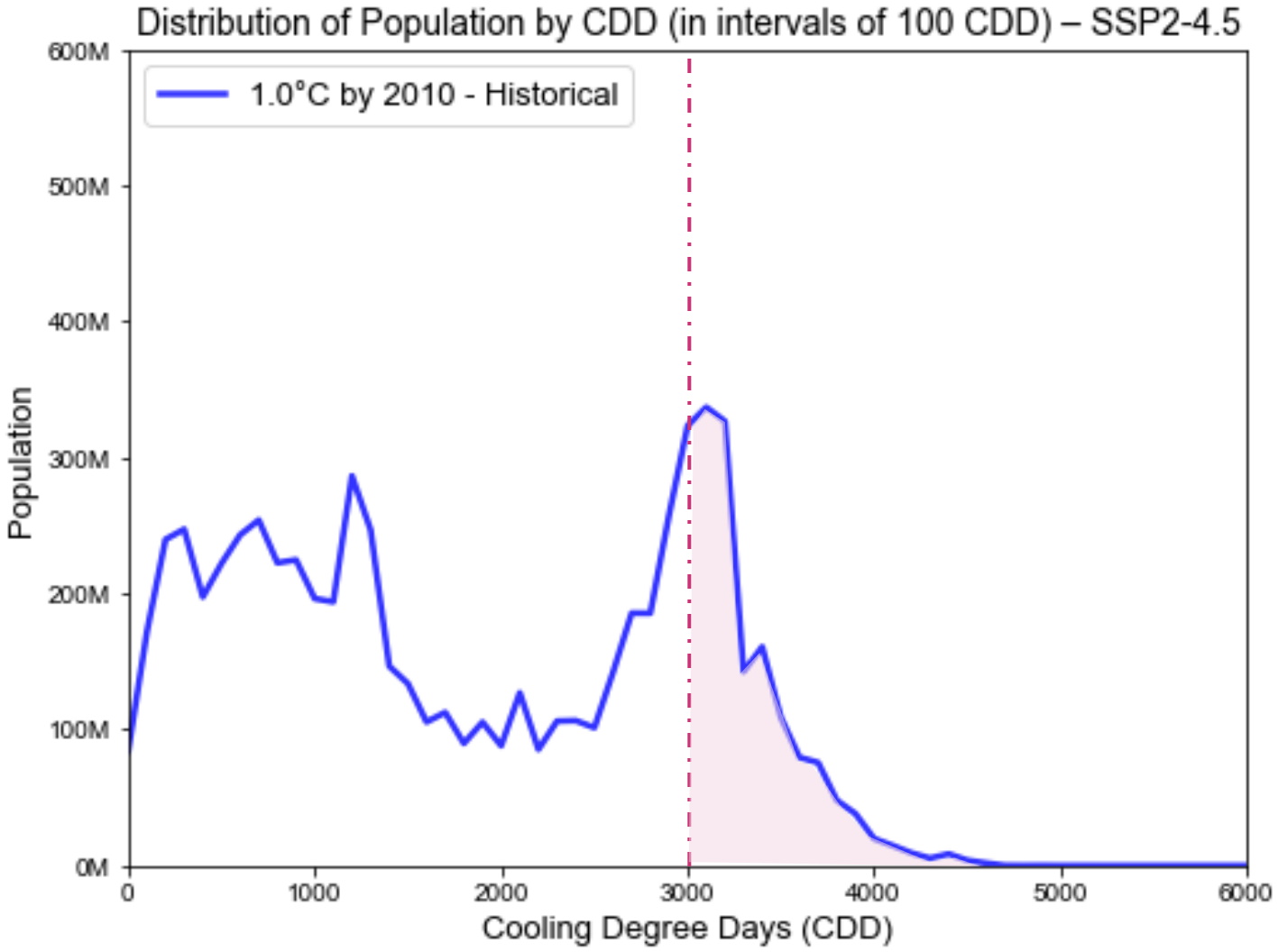
# Cooling Degree Days & Population




**Population exposed to > 3000 CDD:**

- **2010 – 23% (≈1.54 billion)**

Lizana et al. (2025)

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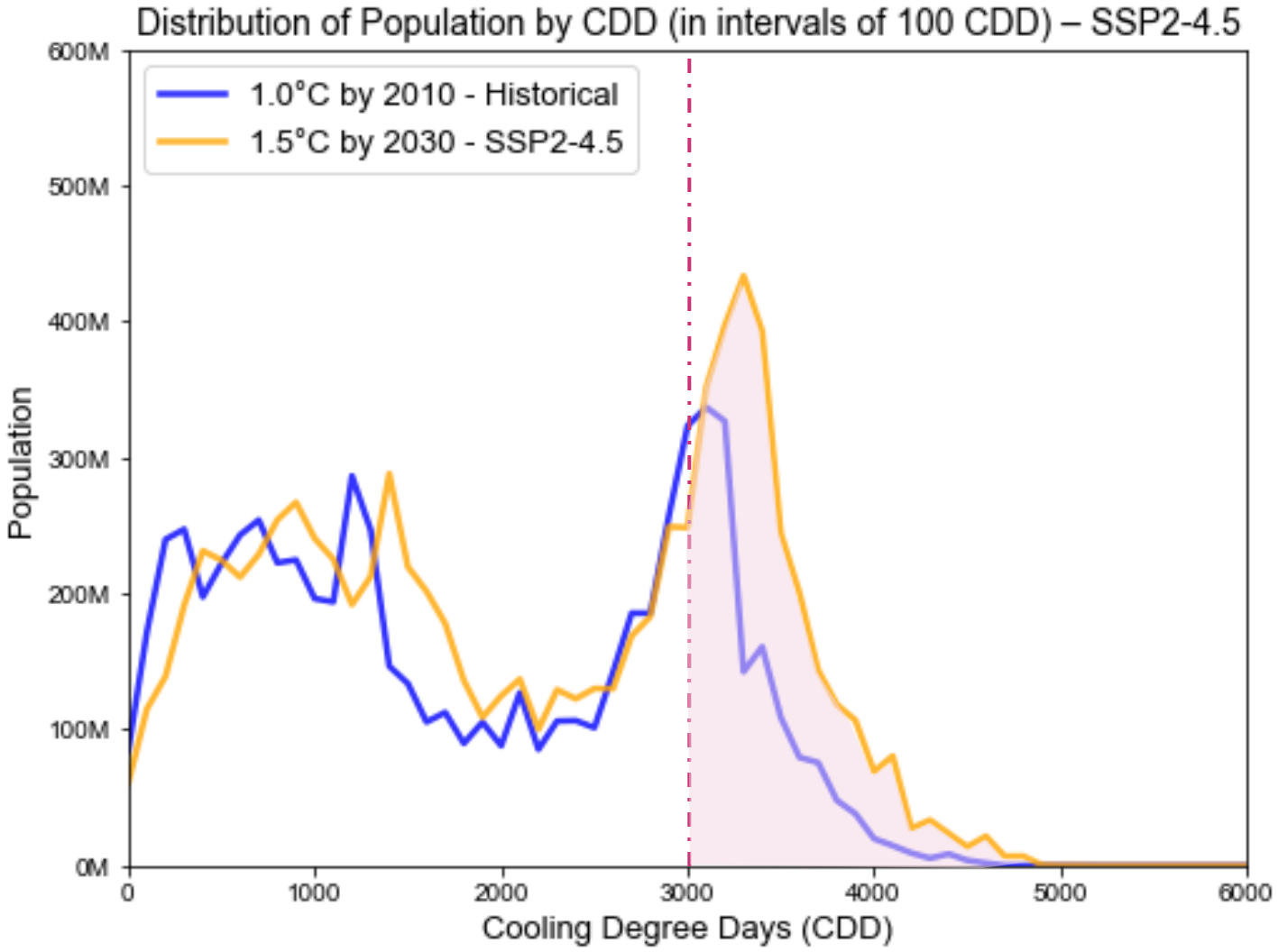
# Cooling Degree Days & Population




**Population exposed to > 3000 CDD:**

- **2010 – 23% (≈1.54 billion)**
- **2030 - 34% (2.80 billion)**

Lizana et al. (2025)

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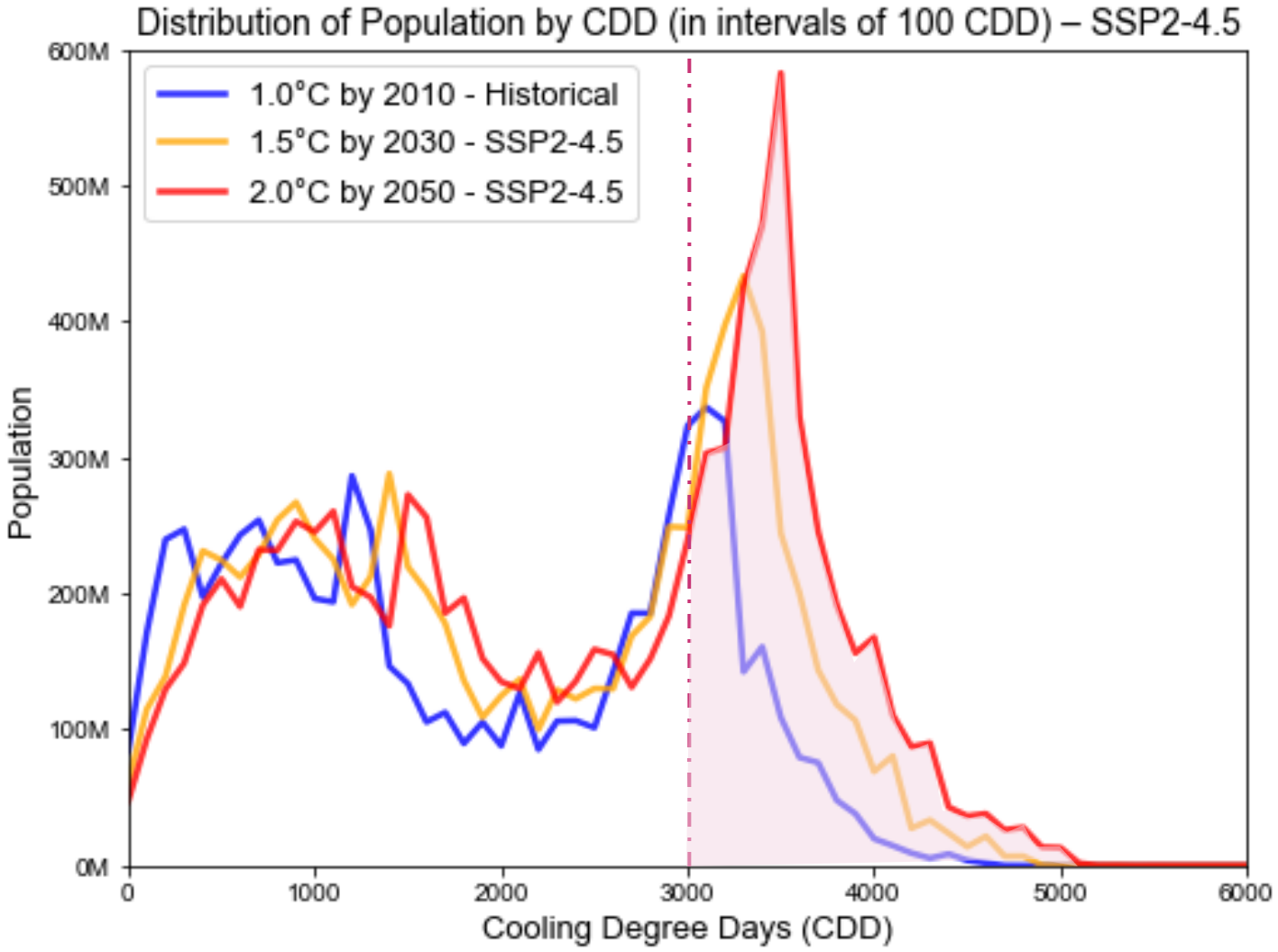
# Cooling Degree Days & Population




**Population exposed to > 3000 CDD:**

- **2010 – 23% (≈1.54 billion)**
- **2030 - 34% (2.80 billion)**
- **2050 - 41% (3.79 billion)**

Lizana et al. (2025)

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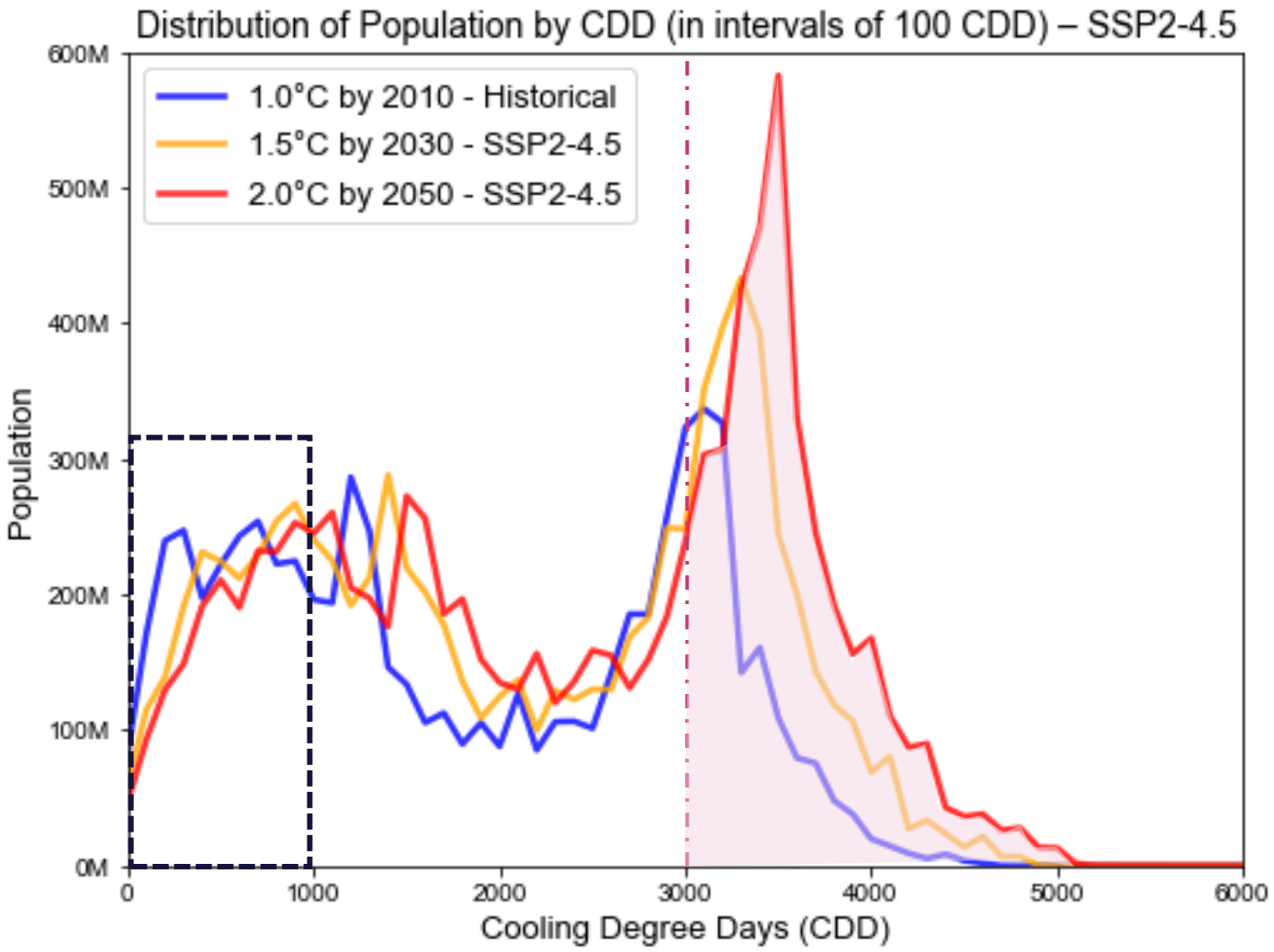
# Cooling Degree Days & Population




**Population exposed to > 3000 CDD:**

- **2010 – 23% (≈1.54 billion)**
- **2030 - 34% (2.80 billion)**
- **2050 - 41% (3.79 billion)**

Lizana et al. (2025)

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# Metabolic rate decreases from 1 met to 0.7 met




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# Key messages

- **Thermal comfort is not only about temperature**
  1°C can save 5-10% of heating/cooling demand
- **It's time to stop over-engineering systems for managing peak loads.** HP size can be reduced to 1/3 of the peak load
- **Investment in an auxiliary system for just ≈96 hours a year doesn’t make sense.** High-density TES can support peak load and be used throughout the entire year for energy flexibility.
- **Ultra-low-cost cooling should be the next research priority**

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ZERO Institute

# Innovations for zero-carbon heating and cooling:

*the path to net-zero buildings by 2050.*


## Jesus Lizana

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Programme Leader Zero-Carbon Space Heating and Cooling | ZERO Institute
Governing Body Fellow | Wolfson College
University of Oxford
jesus.lizana@eng.ox.ac.uk

*+ contributions from Barbara Rossi, Scot Wheeler, Juan Arcenegui, Zeynep Tekler, Amr Suliman, and many others!*

# Appendix

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# Climate Change in Oxford

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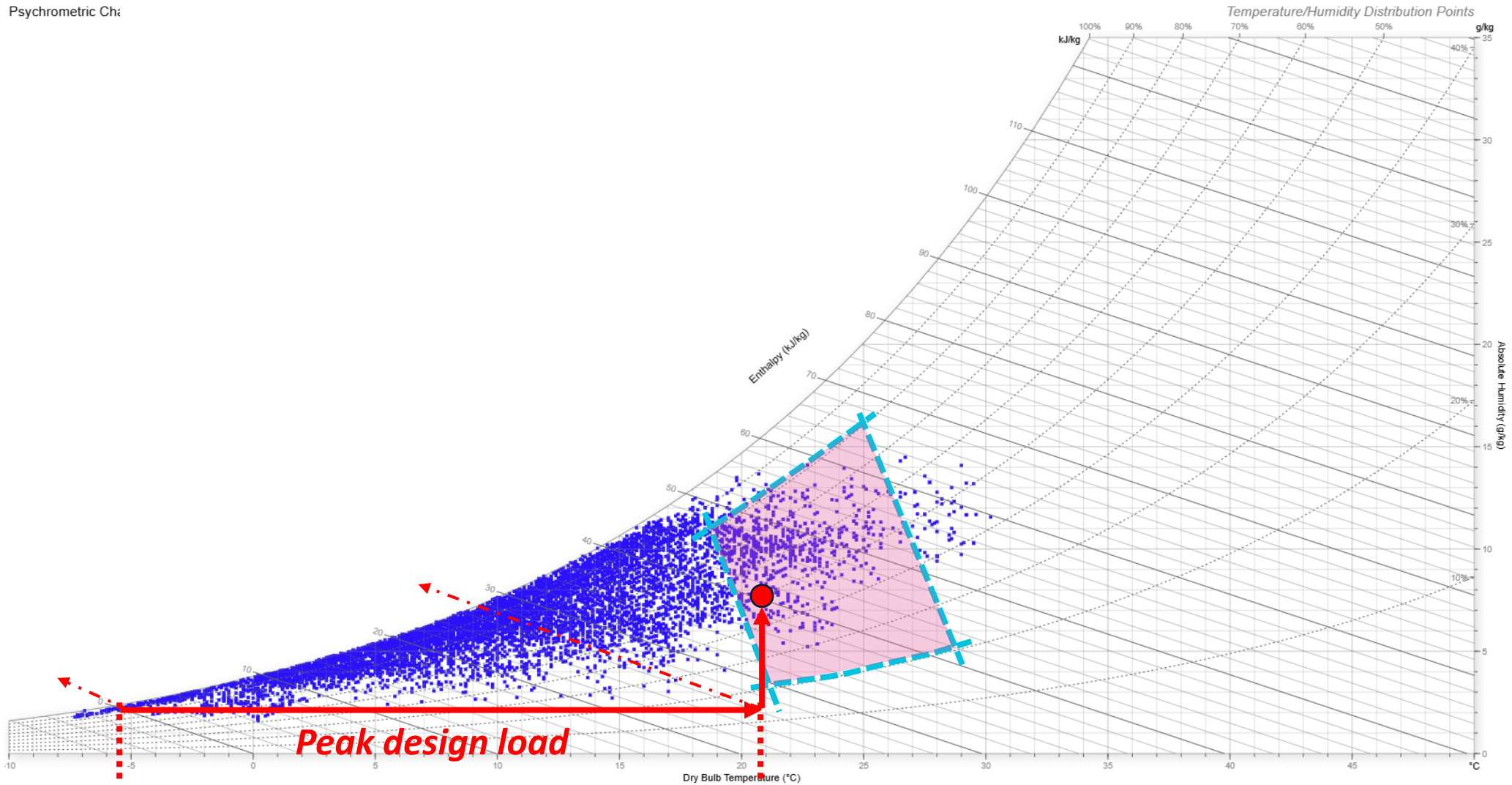
# Psychrometric chart – 2009-2023




Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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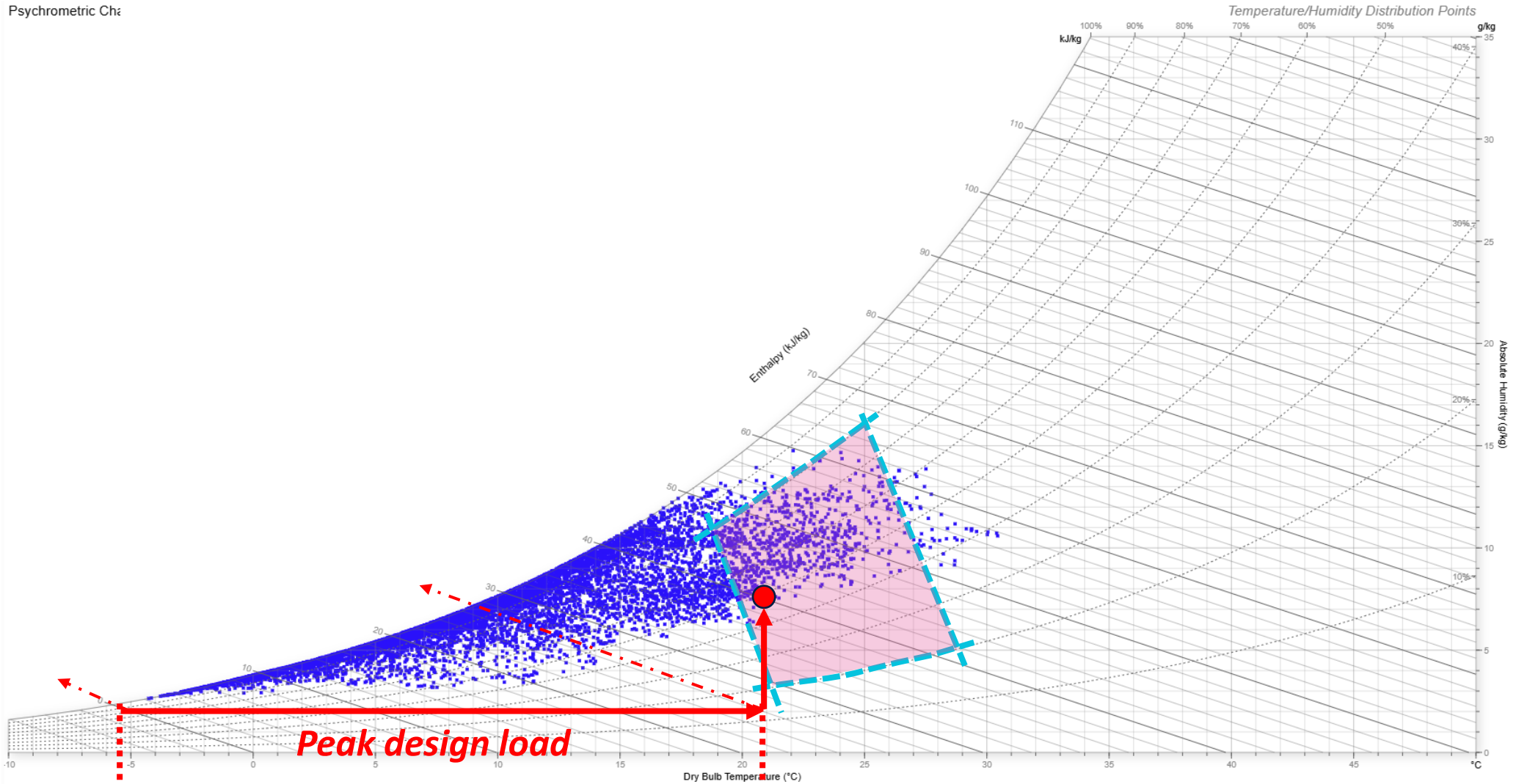
# Psychrometric chart - 2023




Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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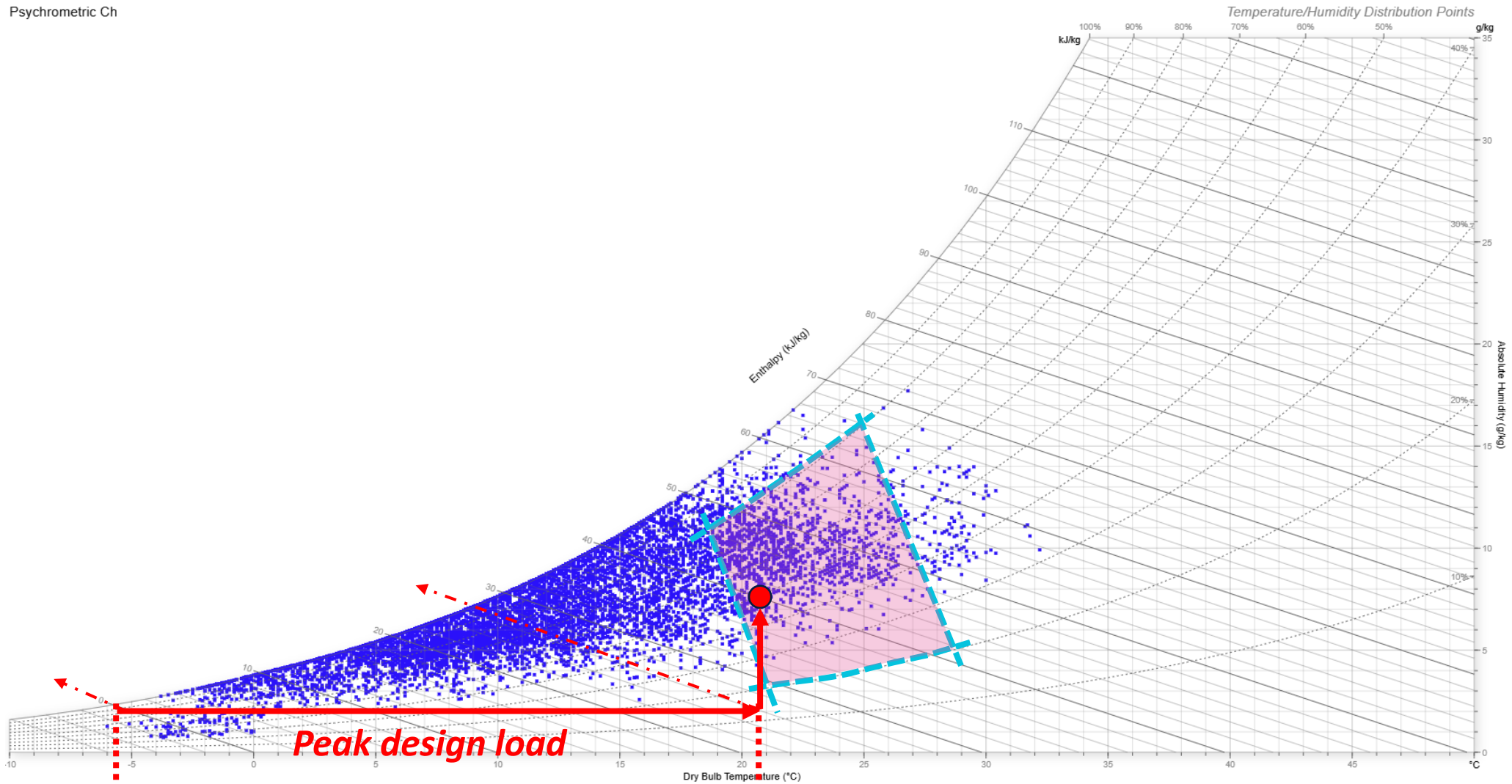
# Psychrometric chart – 2050




Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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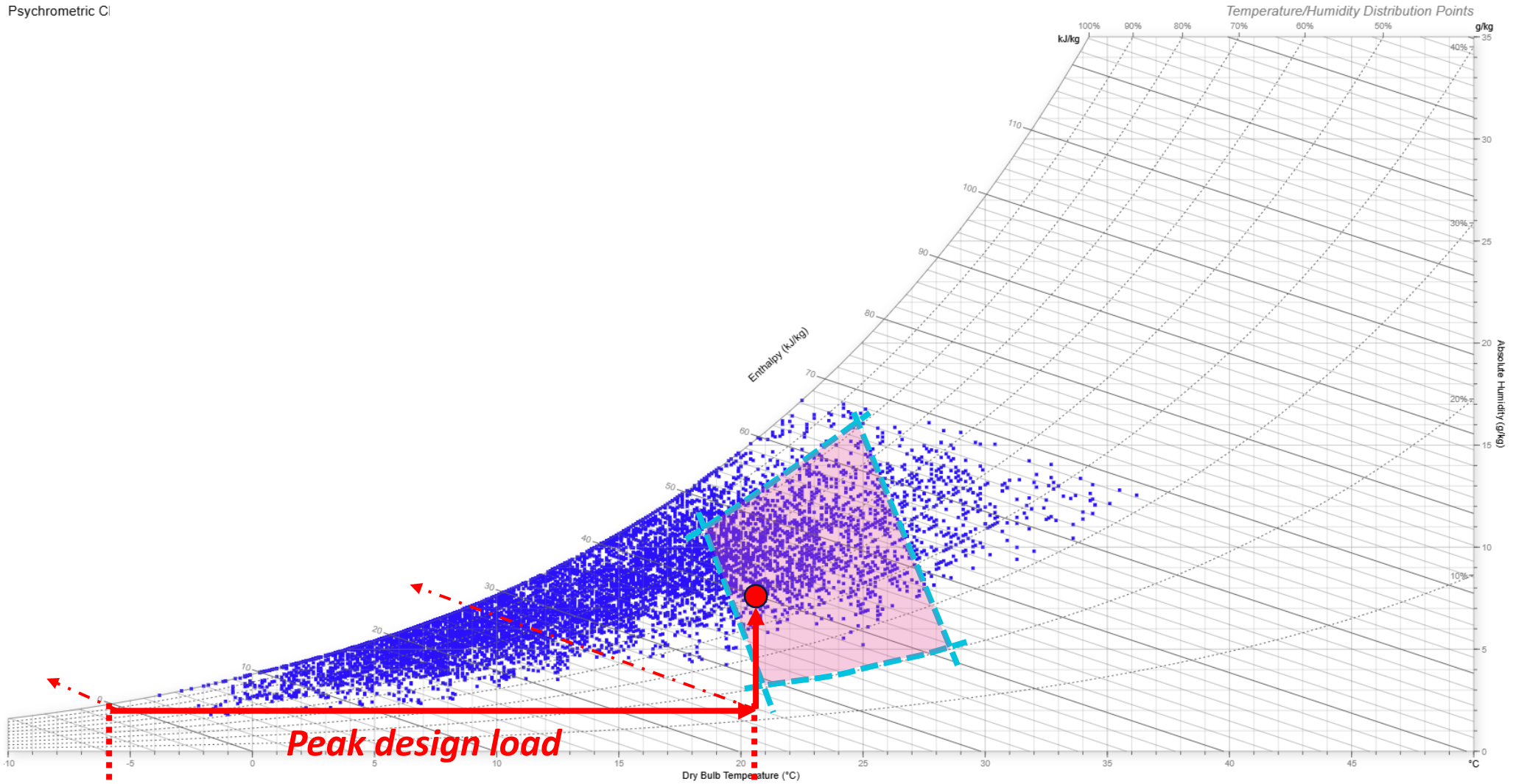
# Psychrometric chart – 2080




Outdoor design conditions: -5.5°C

Indoor design conditions: 21°C, 50%

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