CoolDown Work Package 2: building stock, cooling and demand response analysis for two ENWL substations

List of abbreviations

AC – Air Conditioning
BEIS – former UK government Department for Business, Energy and Industrial Strategy
CIBSE – Chartered Institution of Building Services Engineers
CSNOW – Climate Services for a Net Zero World
DSR – Demand Side Response
DSY – Design Summer Year
ENWL – Electricity North West Limited
EPC – Energy Performance Certificate
IPPC – International Panel on Climate Change
MW – Mega Watt
RCP – Reference Climate Pathway
SEER – Seasonal Energy Efficiency Ratio
UCL – University College London
UKCP – UK Climate Projections
UPRN – Unique Property Reference Number
VOA – Valuation Office Agency

Introduction

In this work package we have developed and implemented a methodology for deriving high-resolution predictions of cooling demand and demand response. The methodology uses details of the thermophysical characteristics of the individual buildings, served by specific secondary substations, and the activities which are undertaken in them to understand cooling demand on a half-hourly basis which is then used to assess the potential impact of demand response measures. The novel approach outlined in this report has two significant advantages over methods applied in previous studies:

- Uptake of cooling systems is based on modelled overheating risk for each building, not broad assumptions about uptake levels across a whole stock or region. This has the advantages that cooling is installed where it is needed, and cooling load is derived for each building.
- This, in turn, means that it is possible to see areas in which a high number of co-located buildings have cooling loads. The high-resolution modelling approach adopted in this study provides a high-fidelity estimate of cooling demand at the individual secondary sub-station level and thus allows much more precise identification of assets at risk of exceeding capacity in summer peaks.

The modelling workflow applied is based on open-source data and software, meaning that it can be applied to any network area for which geolocated service point data is available by secondary substation.

Approach

Assessment of potential cooling demand was undertaken as follows:

- Identification of case study sub-stations and associated buildings, confirmation of future years for which demand would be assessed.

- Processing and cleaning of building stock data
- Characterisation of existing cooling systems
- Definition of cooling uptake rates
- Assessment of overheating risk
- Assessment of cooling demand
- Assessment of demand response potential

These steps are explained in more detail below:

1. Case study selection

Existing network data was analysed by Electricity North West (ENWL) to identify secondary substations which already experience peak loads in summer rather than winter. Two secondary substations were selected from this data: Union Road, which serves a predominantly domestic load and Cattle Market, which serves a predominantly non-domestic load. Cooling demand was assessed for 2030 and 2050, matching the time periods analysed in two existing government publications: Cooling in the UK [1] and Climate Services for a Net Zero Resilient World (CS-NOW) [2]. Weather conditions for 2030 and 2050 were modelled using Design Summer Year (DSY) files. These represent a year with an atypically warm summer, based on the latest UK Meteorological Office's probabilistic projections for future climate (UKCP18). The climate change scenario modelled is based on Representative Concentration Pathway 2.6 [3] [3], representing a best estimate global average temperature rise of 1.6°C by 2100 compared to the pre- industrial period. In line with Cooling in the UK and CS-NOW, climate projections for London were used to represent the whole UK. Although this results in a higher number of overheating hours in Manchester than might be expected, this is the IPCC scenario with the lowest temperature increases.

2. Processing and cleaning of building stock data

Network data in the form of geolocated service points was provided by ENWL for the two substations. A spatial join was used to combine these points with Ordnance Survey Address Base data containing Unique Property Reference Numbers (UPRNs) and building height and footprint data. This data was then combined with data from the Valuation Office Agency (VOA) property tax data to identify cases where multiple premises share a building or single premises cover more than one building. This ensures a higher fidelity representation of the building stock and means that different activities can be assigned on a floor-by-floor basis. Since building energy consumption is closely linked to the activities which are undertaken within them, VOA data was also used to identify the use of each premises [4]. Finally, domestic and non-domestic Energy Performance Certificate (EPC) data was linked to individual premises using UPRNs, providing additional data on building fabric, condition as well as heating and cooling systems.

EPC data is only available for around 50% of premises and consequently a clustering approach was used to impute missing data: the strength of the relationship between all the data points (height, age, etc.) was assessed using the Pearson correlation coefficient [5] and highly correlated fields were discarded so that the clustering was not biased. K-prototypes clustering [6] was used to separate the data into distinct clusters. This is a machine learning method which can accommodate continuous data (for example, numerical values for energy performance rating and categorical data, for example, age bands. The in-cluster variance was then measured as a function of the number of clusters. A value of n=7 clusters of building characteristics was found to give a relatively low variance, while increasing the number of clusters beyond 7 gave only minor further improvements. Typical values for each data field were then extracted from these clusters, cross-referenced with SAP ratings and used to construct 7 construction archetype profiles. The result was that buildings without EPC data had their data estimated from similar buildings.

3. Characterisation of existing cooling systems

The EPC data for each building was used as the starting point to assess which buildings already had space cooling. For the chosen substations, this showed no domestic cooling uptake, and some non-domestic cooling.

However, the data required some close examination as there are several fields in the EPC data relating to cooling:

- one indicating whether a building has air conditioning and
- another describing the main building environment (e.g. natural ventilation and heating, or air conditioning).

As these sometimes contradict one another advice was sought from a UCL colleague with deep knowledge of these certificates who recommended that the main building environment column is more reliable than the air conditioning indicator.

It should also be noted that EPC certificate data relates to a point in time and will not capture cooling installed later. This may have been the case for the two schools served by the Union Rd substation which did not have evidence of cooling in the EPC database, but from the summer peaking displayed in the substation monitored data it was concluded that they may have cooling already, and this was assumed in the model.

In total 13 buildings served by the Cattle Market Substation currently have cooling installed, all are non-domestic.

4. Definition of cooling uptake rates

There is no single validated method of predicting cooling uptake in the UK. Several different approaches have been used in previous projects:

- ENWL's commissioned Air Conditioning Demand Assessment [7] extrapolated current UK market trends to create one scenario and used uptake curves from abroad for another;

National Grid use very simplistic assumptions about AC adoption by 2050[8]

- BEIS [1] assumed a relationship between outdoor temperature and cooling uptake adapted from work carried out in the USA [9].

Each method contains unvalidated assumptions.

The approach deemed most robust for this project was to base cooling uptake on predicted indoor overheating in the actual buildings connected to each substation, under future weather conditions. In this approach, cooling is assumed to be retrofitted into buildings which are shown in simulations to overheat.

Indoor overheating is defined using a nationally agreed set of criteria [10]; this is explained fully in Appendix 1. In summary, three tests are applied to each zone of a building, related to the "operative temperature", which is the mean of the indoor air temperature and radiant (i.e. indoor-facing surface) temperature. If a zone (here, a floor) fails two out of the three tests it is technically defined as overheating. Note that the feeling of being overheated is also related to other factors, such as relative humidity, air speed and clothing levels as well as psychological factors, however the technical definition is kept deliberately simplistic.

The relationship between overheating and uptake of cooling in the UK is currently under-researched. However, basing cooling uptake on publicly available, nationally agreed overheating criteria is a transparent and thus defensible approach. Furthermore, it is sensible to use the same building model to assess overheating and to attribute cooling to buildings, then to determine the cooling load and demand response potential of those same buildings.
This approach is different and complementary to those used in previous work where cooling uptake is based on an exogenous relationship with e.g. future weather or market trends.

5. Assessment of overheating risk

There were two purposes to the building simulation: assessing overheating (and therefore where to install cooling) and determining cooling electricity load in buildings which had cooling installed. An overview of the modelling process for one year, 2030, is shown in Figure 1.

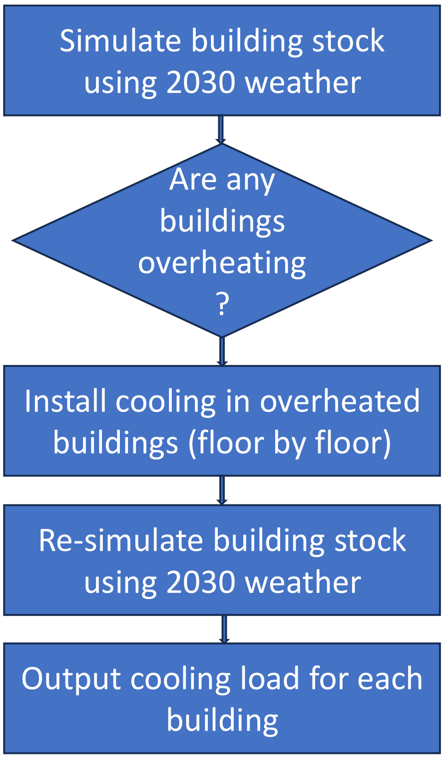

Figure 1: Modelling process for 2030 simulations, 2050 simulations follow the same process.

Modelling was undertaken using SimStock, an automatic modelling platform developed by UCL which is used to translate the building stock data described in section 2 into input files for EnergyPlus. EnergyPlus is a widely used, open-source dynamic simulation engine developed by the US Department of the Environment which allows the energy flows to be calculated on a sub-hourly basis, taking account of the building fabric, local context and internal loads and activities.

For this project, each premise was modelled at a half hourly timestep with realistic schedules for occupancy and equipment internal heat gains. In buildings without cooling, windows were assumed to open once the temperature reached 22˚C, in accordance with the overheating calculation methodology referenced above. In buildings with cooling, windows were assumed to be closed.

6. Assessment of cooling demand

The model gives as an output cooling load in thermal Watts which is then divided by the assumed technological efficiency of the cooling system to give a cooling load in electrical Watts. The technological assumptions used were linearly interpolated from an International Energy Agency report on the future of cooling [11]; this is the same method as used by BEIS [1] but for different years of interest.

The assumed cooling efficiencies are given in Table 1. Under these assumptions, no differentiation is made between systems installed in domestic, small non-domestic and large non-domestic buildings. The aforementioned BEIS analysis [1] assumed that domestic properties are more likely to install portable systems in the near future and transition to fixed systems as the climate warms. Since portable systems only cool a small space, and the model used in CoolDown applies cooling to whole floors, it was not possible to model portable cooling. However, its efficiency is roughly half that of fixed systems (Table 1) and, it is expected to be installed in only some spaces per floor, therefore the resulting electricity consumption is likely to be similar to that of fixed systems. A cooling set point of 21°C was assumed throughout where AC was installed.

Fixed cooling systems in homes consist of air conditioning and reversible air-to-air heat pumps, which are the same technology and therefore have the same efficiency in cooling mode. Other possible technologies exist such as ground-to-water heat pumps providing passive cooling; however, these are likely to be rare compared to air-to-air systems.

Table 1. Cooling efficiencies (SEER) used in modelling. [1]

	BEIS assumption	BEIS assumption	CoolDown assumption	CoolDown assumption
Year	2025	2075	2030	2050
SEER: Portable cooling	2.4	3.4	2.5	2.9
SEER: Fixed cooling	5.2	7.5	5.4	6.3

7. Assessment of cooling demand response potential

The potential for load shedding from space cooling was investigated by simulating demand response in buildings. Studies suggest that this is normally implemented by adjusting air temperature setpoints to a higher level to reduce electricity demand. There is no universal temperature threshold above which building occupants feel too hot during cooling load shedding events; instead, literature provides a range of values which have been used in different types of buildings [12]. However, several studies have found comfort not to be substantively compromised if indoor temperatures were allowed to increase to 25-26°C, therefore in CoolDown a setpoint of 26°C was used to investigate demand response potential.

For this exploratory analysis a simple assumption was used in which demand response was implemented when the aggregated building load surpassed a certain level: this level was designated as 10% above the mean summer value. Therefore, at any time during summer, if the aggregated building load exceeded this 10% margin, every building with cooling had its setpoint raised to 26°C. The results can be considered as a maximum technical potential for demand response.

Results

In Figure 2, the distribution of building usage in the two simulated areas is depicted. The Union Road dataset is predominantly composed of domestic buildings, with only two non-domestic buildings, both of which are schools. Conversely, the Cattle Market substation dataset is characterised by a predominance of non-domestic buildings, mainly shops, alongside mixed-use buildings and a smaller number of terraced houses.

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[1] The term “SEER” stands for Seasonal Energy Efficiency Ratio and represents the cooling output over a typical cooling season divided by the electricity input.

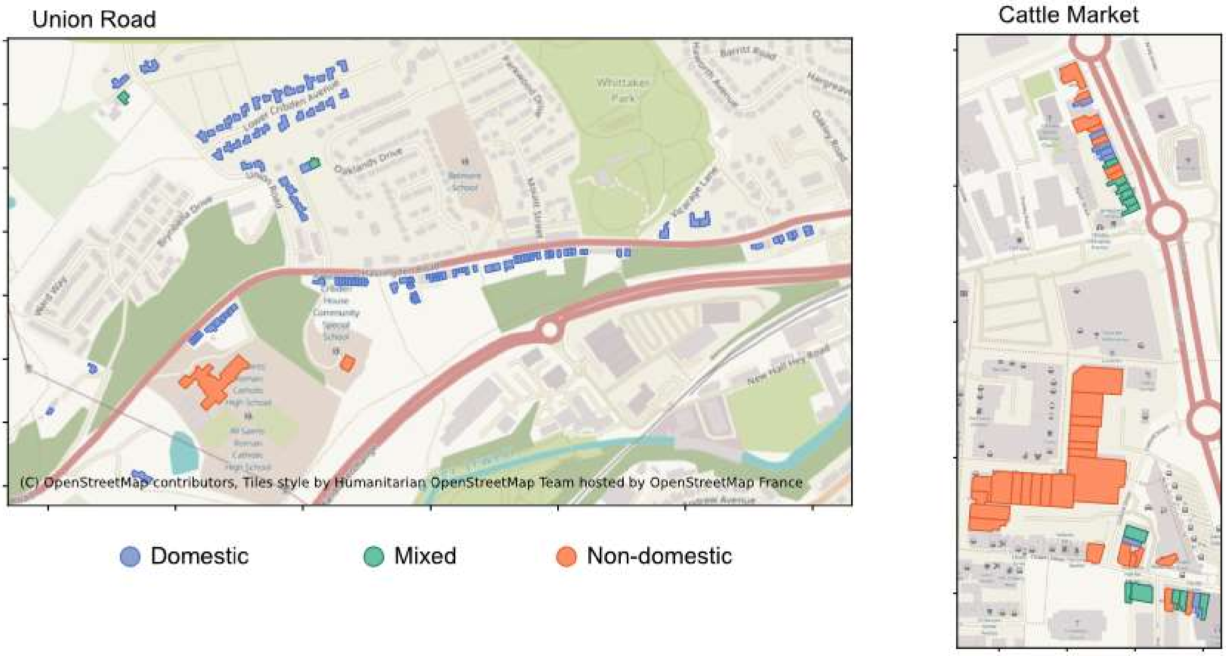


Figure 2: Overview of building usage

Figure 3 and Figure 4 present simulation results for the years 2023, 2030, and 2050 for the Cattle Market and Union Road substations, respectively, assuming no additional cooling uptake beyond the 2023 levels. By 2050, the simulations indicate that 16 out of 46 buildings served by the Cattle Market substation are projected to experience overheating, while 80 out of 121 buildings served by the Union Road substation are expected to face overheating.

As outlined in Section 4, buildings that experience overheating on any floor in each year are subsequently provided with cooling on that floor in the following simulations, allowing for the modelling of cooling uptake. Consequently, the simulations predict that by 2050, an additional 16 buildings served by the Cattle Market substation (bringing the total to 29) and 80 additional buildings (bringing the total to 82) served by the Union Road substation will be equipped with cooling systems. Broken down by usage, the Union Road area sees domestic cooling increase from 0 to 64 in 2030, and then to 78 in 2050. The number of non-domestic buildings with cooling remains at 2 throughout. For the Cattle Market area, the number of domestic buildings with cooling increases from 0 to 1 in 2030 and then to 4 in 2050. Non-domestic buildings with cooling initially number 13; this increases to 20 in 2030 and then 25 in 2050.

Table 2: Predicted cooling uptake - Cattle Market

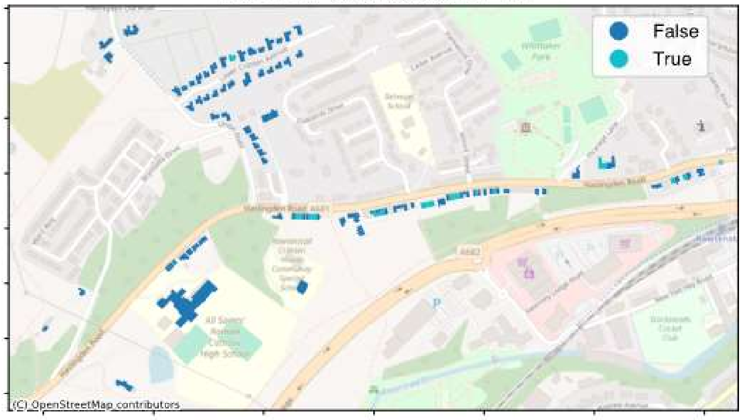
	Total buildings	No. of buildings with cooling in 2024 data	No. buildings with cooling in 2030	No. buildings with cooling in 2050
Domestic	7	0 (0%)	1 (14%)	4 (57%)
Non-domestic	39	13 (33%)	20 (51%)	25 (64%)

Table 3: Predicted cooling uptake - Union Road

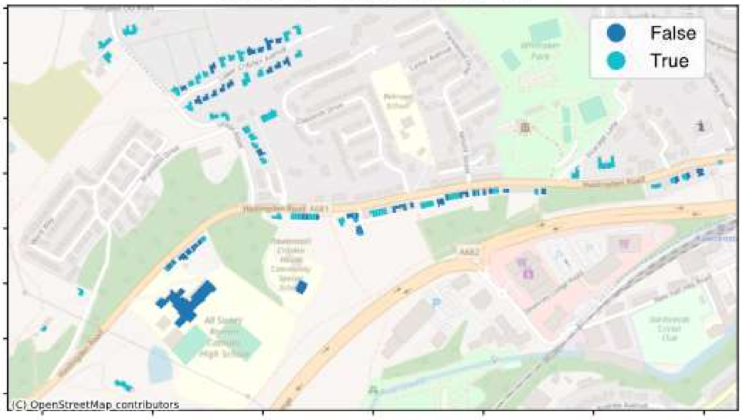
	Total buildings	No. of buildings with cooling in 2024 data	No. buildings with cooling in 2030	No. buildings with cooling in 2050
Domestic	117	0 (0%)	64 (55%)	78 (67%)
Non-domestic	4	2 (50%)	2 (50%)	2 (50%)

Figure 3: Simulated overheating for the years 2023, 2030 and 2050 in the Cattle Market dataset given constant 2023 levels of cooling

2023: 23 overheated of 121



2030: 66 overheated of 121



2050: 80 overheated of 121

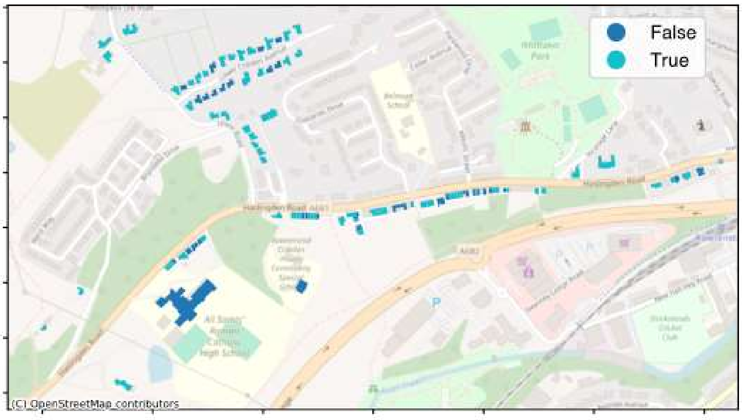


Figure 4: Simulated overheating for the years 2023, 2030 and 2050 in the Union Road dataset given constant 2023 levels of cooling

Figure 5 depicts the simulated aggregate summer cooling loads for the Union Road substation incorporating modelled cooling uptake. It shows the cooling loads for the summers of 2030 and 2050, both with and without demand-side response (DSR), as detailed in Section 6 above.

In the 2030 scenario without DSR, the region faces substantial cooling demand from both non-domestic and domestic premises, peaking at approximately 0.17 MW and 0.12 MW, respectively. Notably, the non-domestic cooling load is entirely attributed to two schools in the area.

Moving to the 2050 scenario without DSR, the domestic cooling load escalates further, while the non-domestic cooling load remains relatively constant compared to 2030, showing only a slight increase.

However, in both years, the implementation of DSR leads to a significant reduction in cooling load, halving the peak demand in late July/August. It is worth noting that in both DSR and non-DSR scenarios, no buildings exceeded the defined threshold for overheating outlined in Appendix 1, indicating that DSR can be successfully deployed without causing overheating issues.

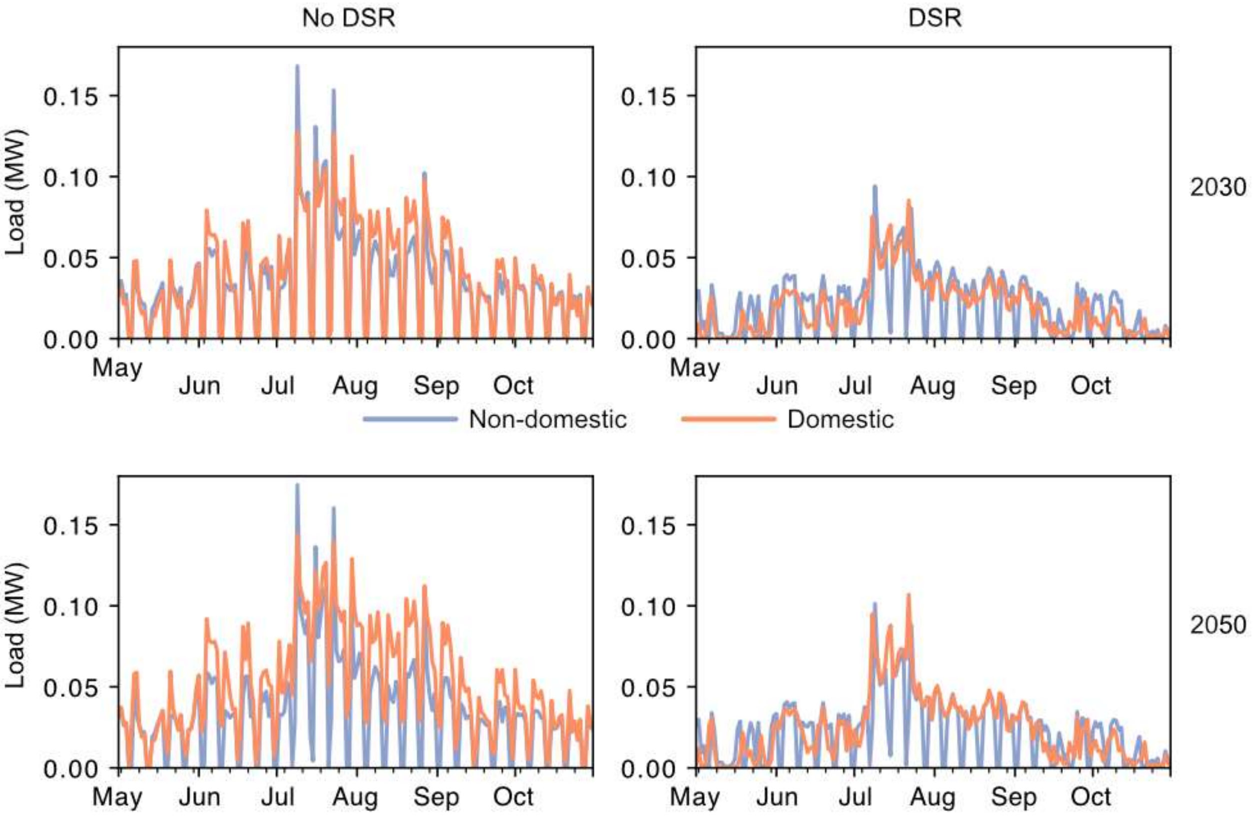


Figure 5: Simulated cooling load profiles for Union Road

Figure 6 displays the corresponding findings for the Cattle Market substation dataset. In contrast to the Union Road substation, the cooling load in all scenarios is primarily driven by non-domestic contributions, reflecting the composition of the building stock in this region.

In 2030, without DSR, the non-domestic cooling load peaks at around 0.17 MW and averages over 0.04 MW throughout the summer. Transitioning to the 2050 scenario without DSR, the non-domestic load remains relatively stable compared to 2030. This is attributed to the additional buildings modelled to experience overheating, thus requiring extra cooling, primarily consisting of domestic and mixed-use buildings in the dataset. Consequently, the domestic share of the cooling load in the area exhibits a slight increase, whereas the non-domestic load already peaked in 2030. The application of DSR is simulated to reduce cooling loads across the summer period in both 2030 and 2050. However, the reductions are not as substantial as those observed in the Union Road data set. Nevertheless, like the buildings served by the Union Road substation, neither the DSR nor non-DSR scenarios in either year resulted in overheating, indicating that DSR implementation can effectively alleviate cooling demands without causing significant discomfort to occupants.

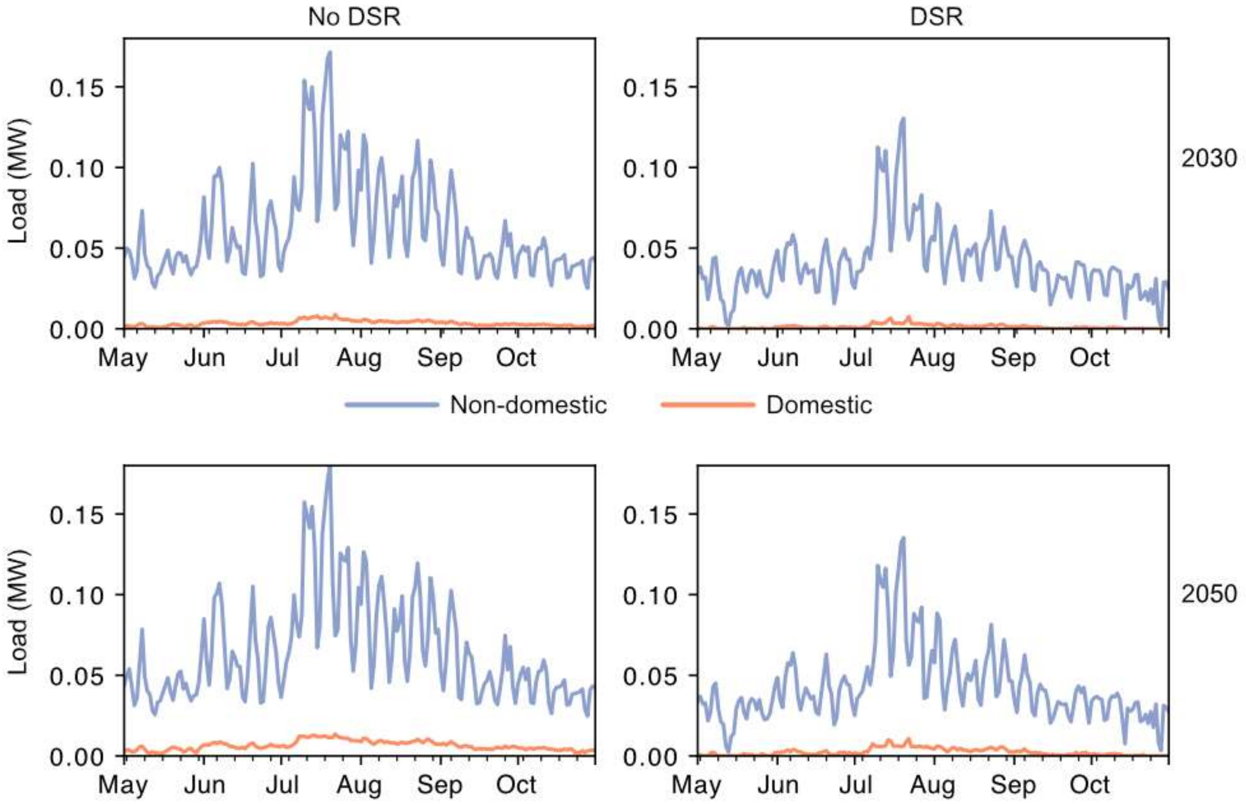


Figure 6: Simulated cooling load profiles for Cattle Market

Conclusion

This work package has demonstrated a method for predicting future cooling load and demand response potential for a given substation, by mapping the electricity network onto the building stock, collating building data, and running a dynamic thermal model.

Energy Performance Certificate data and substation load data indicate that currently cooling is present in 13 of 46 buildings served by the Cattle Market substation and 2 of the 121 buildings served by the Union Road substation.
Simulation results show that both domestic and non-domestic buildings experience overheating by 2030 and by 2050, an additional 16 buildings served by the Cattle Market substation require cooling and an additional 80 buildings served by the Union Road substation require cooling.

This results in a 250% increase in the peak cooling load for non-domestic buildings served by the Cattle Market Substation, from 0.067 MW currently to 0.17 MW in 2030 and a further 0.01MW increase by 2050. The domestic peak cooling load increases from 0 to 0.009MW by 2030 and by a further 0.004MW by 2050 to 0.013MW, an increase in total cooling load of 288% compared with 2023.

The Union Road substation sees a 350% increase in peak non-domestic cooling load by 2030 from 0.045MW to 0.16MW and a further 0.01MW increase by 2050 to 0.17MW. The corresponding peak domestic cooling load increases from 0 to 0.12MW by 2030 and by a further 0.02MW to 0.14MW by 2050, an increase in the total cooling load of 689%.

Initial modelling of demand response potential shows that significant reductions in peak loads can be achieved, with only limited effects on comfort.

The results of this study demonstrate that the timing and magnitude of peak cooling loads are strongly influenced by building type, use and set point schedules. Consequently, these factors are also critical in determining the impact of demand response. This highlights the importance of a building-by-building approach to understanding the potential for demand response.

Future work will focus on refining the model developed here to incorporate diverse occupancy and set-point schedules and to develop a stronger evidence base for cooling behaviours.

References

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Appendix 1: definition of overheating in buildings

The Chartered Institution of Building Services Engineering (CIBSE) sets out three criteria, of which two must be met in order that a building does not overheat. Otherwise put, if a building fails two or more criteria, then it overheats.

Criterion	Explanation
T_{op} should not exceed T_{max} by more than 1 degree for more than 3% of occupied hours during the months of May to September.	This criterion is about the **duration** of overheating: the number of hours over summer that the indoor temperature exceeds a certain threshold
T_{op} should not exceed T_{max} by more than 6 degree-hours per day	This criterion is about the **level** and **duration** of overheating within single days

T_{op} should never exceed T_{max} by more than 4 degrees	This criterion is about the **level** of overheating: it limits the maximum indoor temperature

Where:
T_{op} is the mean of the air temperature and the radiant temperature.

T_{max} is a temperature threshold defined using the outdoor temperature as follows:

$T_{max} = 0.33\ T_{rm} + 21.8$

T_{rm} is a weighted running mean of the outdoor temperature (T_{od}), most heavily weighted for most recent days:

$T_{rm} = (_{Tod-1} + 0.8\ T_{od-2} + 0.6\ T_{od-3} + 0.5\ T_{od}\text{-}4 + 0.4\ T_{od-5} + 0.3\ T_{od-6} + 0.2\ T_{od-7})\ /3.8$