net-zero research network

A Network+ for the Decarbonisation of Heating and Cooling

Engineering and Physical Sciences Research Council

INTERIM REPORT

NETWORK-H+C
CALL 2

PROJECT DETAILS

Grant number

HC2-005

Award holding organisation

Organisation	Cardiff University

Title of research project

Increasing urban overheating risk from cooling decarbonisation by heat pumps

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Final project report (up to 10A4 pages)

1. Introduction

With the intensification of climate change, urban regions are increasingly vulnerable to climate hazards such as heatwaves and extreme temperatures. These environmental challenges have direct repercussions on public health, energy consumption, and city planning (Santamouris and Kolokotsa, 2015). Increased temperatures can exacerbate cardiovascular and respiratory diseases, placing the elderly and those with pre-existing health conditions at heightened risk (Sun et al., 2016). In addition to health concerns, there is the strain on energy systems. As residents seek to escape the heat, energy consumption increases due to increased reliance on air conditioning and cooling systems. Surges in demand could stress the grid, causing blackouts, and increase greenhouse gas emissions and therefore exacerbate global warming (Stone et al., 2021).

The UK government actively promotes heat pumps as part of its net-zero emission goal by 2050, with an ambition to increase the share of heat pumps in heating systems to around 53% by 2050, which is a significant rise from less than 1% in 2020 (UKERC, 2020). As climate change intensifies, heat pumps, traditionally used for heating in the UK, are poised to play a dual role in both cooling and heating (BIES, 2021).

Recent research highlights the environmental feedback of air conditioners. Modelling work by Salamanca et al. (2014) suggests that the use of air conditioners in Phoenix, US, could elevate urban air temperatures by as much as 0.5°C during the day. Similar results are reported by Kikegawa et al. (2022) for Osaka, Japan. Moreover, Wang et al. (2018) pointed out that in Hong Kong, the anthropogenic heat generated from extensive air conditioner usage can reach up to 300 W m^{-2}, potentially raising the urban air temperature by up to 2°C. Such results underscore the concerns associated with heat pumps, particularly their potential role in exacerbating the urban heat island.

Considering these challenges, this research aims to explore the overheating risks in both urban- and building-scales due to the increased adoption of air-source heat pumps (ASHPs) across varied scenarios. Our approach involves employing a building-urban climate modelling scheme by accounting for the heat released into the atmosphere because of ASHP operations.

2. Methods

In this research, we use the local-scale land surface model Surface Urban Energy and Water Balance Scheme (SUEWS) (Järvi et al., 2011; Ward et al., 2016) and building energy simulation tool EnergyPlus (U.S. Department of Energy, 2020) models to explore the effects of cooling of heat pumps on a neighbourhood-scale outdoor climate in a future London scenario.

2.1.Neighbourhood-scale climate modelling

SUEWS has been widely used and well evaluated in different climate globally (e.g., Table 3 of Lindberg et al. (2018) and Table 1 of Sun and Grimmond (2019). It is based on the land surface energy balance (Ward et al., 2016):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \qquad (1)$$

Where Q^* is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the turbulent sensible heat flux, Q_E is the latent heat flux and ΔQ_S is the net storage heat flux.

In SUEWS, the calculation of Q_F follows Sailor and Vasireddy's (2006) equation:

$$Q_F = \rho_{pop}[a_{F0} + a_{F1}CDD + a_{F2}HDD] \qquad (2)$$

Where ρ_{pop} is the population density. The coefficient a_{F0} refers to the base value of Q_F, which is the integrated heat flux per ρ_{pop} from all sources relative to a base human comfort temperature. Coefficients a_{F1} and a_{F2} represent the dependence of Q_F on heating degree days (HDD) and cooling degree days (CDD), which enables modelled Q_F to vary with temperature to reflect the changing demand for building heating or cooling. A diurnal profile specified in the model input files enables sub-daily variation in Q_F.

The coefficients $a_{F0,1,2}$ can be estimated in different ways. Conventional, energy consumption data at different scales are used to derive these coefficients (Ao et al., 2018; Järvi et al., 2011; Sailor and Vasireddy, 2006; Ward et al., 2016).For example, in London the coefficients for weekdays are estimated to be a_{F0} = 0.3743, a_{F1} = 0, and a_{F2} = 0.0073, and for weekends, they are a_{F0} = 0.3412, a_{F1} = 0, and a_{F2} = 0.0067, based on city-scale energy use data (Ward et al., 2016). As air conditioning use is low in the UK (Abela et al., 2016), it is assumed no increase in Q_F at high temperatures associated with extensive air conditioning use, so a_{F1} was set to zero (Kotthaus and Grimmond, 2014; Ward et al., 2016). However, in cases where there is increased installation of heat pumps, the coefficients, especially a_{F1} which is related to cooling demands, will need to be modified.

We employ the Design Summer Year (DSY) data sourced from the UK Climate Projections (UKCP09) (Eames et al., 2011) to simulate the potential effects of climate change. Our simulations target the climate projections for the 2050s, which capture potential conditions spanning 2040–2059. We consider the medium emissions scenario as the baseline, aligning with the IPCC A1B scenario, representing a condition of balanced use of fuel and non-fuel energy (WMO, 2000).

2.2.Anthropogenic heat from buildings

Anthropogenic heat (Q_F) emission from buildings can be calculated in different methods. Here we follow the method of Liu et al. (2022). In this approach, Q_F is calculated as the internal heat gain within the building, energy consumption by the cooling/heating system minus the heat stored in the building.

To assess the impact of adopting heat pumps on outdoor local climate, two systems are considered: a heat pump serving both cooling and heating functions, and a traditional gas boiler only for heating — the current prevalent system. The gas boiler is assumed to operate with a consistent efficiency of 0.8. When the ASHP runs in cooling mode, the relationship between the cooling load and energy consumption of the heat pump system can be presented with the coefficient of performance (COP), which is defined as the ratio of cooling load $Q_{cooling}$ to the energy consumption Q_{EC}:

$$COP = \frac{Q_{cooling}}{Q_{EC}} \qquad (3)$$

The COP of ASHPs is dependent on the outdoor air temperature. Empirical observations suggest that there is typically a linear relationship between the COP and outdoor air temperature. As an example, typical linear relationships of ASHPs in London are identified in CIBSE AM16 (CIBSE, 2021):

$$COP_{cooling} = -0.14T_o + 7.31 \qquad (4)$$
$$COP_{heating} = 0.07T_o + 3.20 \qquad (5)$$

2.3.Building characteristics

Our analysis focus on the archetype of a UK detached house (8.8 m L x 8.5 m W x 7.5 m H), as shown in Fig. 1. Detached houses account for a notable portion of housing types in England, constituting 17% according to the English Housing Survey (Department for Communities and Local Government, 2013). The building's geometry and construction parameters are based on Porritt (2012) and Liu (2017). Given that our study considers a scenario in the UK for the 2050s, we model the building as well-insulated, ensuring the archetype integrates walls insulated post-1996. The specific construction details can be found in Table 1. For our analysis, the residence is presumed to be occupied by an elderly couple who remain at home throughout the day. Their daily activities and schedules are set based on Porritt (2012).

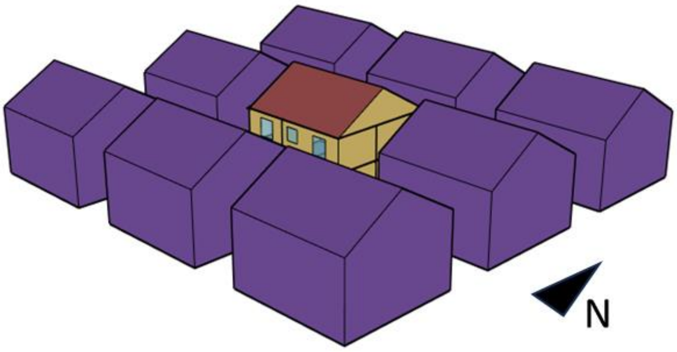

Fig. 1. Modelled building archetype in an idealised neighbourhood with a plan area fraction of 0.5.

Table 1: Constructions and thermal characteristics of the modelled building envelope (Liu, 2017).

	Constructions	U value (W m^{-2}K)
External wall (Insulated cavity wall)	105 mm brickwork outer leaf 100 mm air layer (Air gap>25mm) 50 mm EPS Expanded Polystyrene (Standard) 105 mm brick, inner leaf 13 mm plaster (dense)	0.5
Internal partition	15 mm gypsum plasterboard 50 mm air layer 15 mm gypsum plasterboard	1.79
Internal floor	10 mm plasterboard (ceiling) 200 mm air layer 20 mm timber flooring 5 mm carpet/textile flooring	1.33
Ground floor	50 mm EPS Expanded Polystyrene 150 mm concrete roof/floor slab 50 mm flooring screed	0.5
Roof	10 mm concrete roof tiles 250 mm min wool quilt 10 mm plasterboard (ceiling)	0.16
Doors	35 mm oak	2.25
Windows	6 mm generic clear glass 13 mm air 6 mm generic clear glass	2.71, SHGC = 0.7

We consider an idealised neighbourhood typified by homogenous buildings that collectively occupy 50% of the plan area. This configuration simulates a fairly dense residential setting. For neighbourhood building simulation, the approach by Xie et al. (2023) is used to consider the radiative components and wind field surrounding the building.

The heating and cooling set points are 20 and 24 °C, respectively (Wang et al., 2009). In scenarios where heating or cooling systems are operational, we've assumed that windows remain shut, leading to an infiltration rate of 0.5 ACH. Conversely, when evaluating the effects of ASHP integration in the neighbourhood on buildings that rely on natural ventilation, the assumption is that windows are perpetually open.

3. Impact of ASHPs on outdoor and indoor climate in different scenarios

ASHP used for occupied rooms only vs. whole building operation.

Previous research addressing the effects of air conditioners on the urban climate often assume fully air-conditioned floor areas (Salamanca et al., 2014; Wang et al., 2018). However, in practical residential settings, it is unlikely for unoccupied rooms to be continuously air-conditioned. Given this, we consider two contrasting scenarios for ASHP operation: the first scenario restricts use of ASHP to only occupied rooms, offering a more realistic representation, while the second one covers the entire building, representing a maximal energy consumption case. For this analysis, the meteorological data sourced is based on London's 2050 medium emissions DSY projections.

To obtain the coefficients in Eq. 2 for SUEWS QF calculation, the relationships between annual daily mean Q_F and outdoor air temperature of both scenarios are obtained (Fig. 2). With a population density ρ_{pop} of 134 people per hectare (2 people per building), the coefficients are derived, as shown in Table 2.

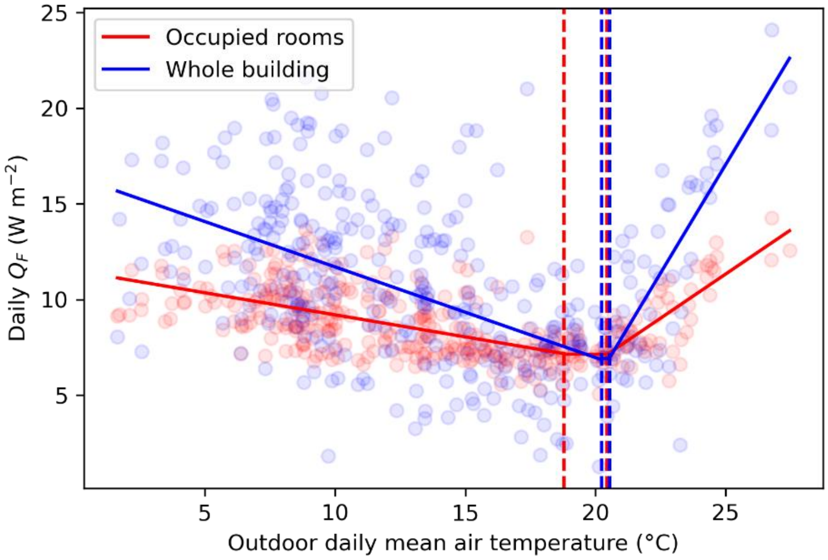

Fig. 2. Relationships between daily anthropogenic heat emission (Q_F) and outdoor mean air temperature for buildings with ASHPs in different operating conditions. Solid lines are derived linear relationships between daily Q_F and outdoor air temperature. Dashed lines are base temperatures for cooling and heating.

Table 2: Coefficients for SUEWS Q_F calculations (Eq. 2) for different ASHP operating conditions

	ASHP – occupied rooms	ASHP – whole building
a_{F0} (base) [W m^{-2} (cap ha^{-1})$^{-1}$]	0.0267	0.0259
a_{F1} (cooling) [W m^{-2} (cap ha^{-1})$^{-1}$]	0.0035	0.0085
a_{F2} (heating) [W m^{-2} (cap ha^{-1})$^{-1}$]	0.0009	0.0018
$T_{base,\ heating}$ (°C)	18.9	20.3
$T_{base,\ cooling}$ (°C)	20.4	20.6

Assuming all buildings in the neighbourhood use heat pump for cooling, the influence of heat pump on summer outdoor climate is modelled. We spotlight the warmest day (21 July) to demonstrate the effect of increased anthropogenic heat due to heat pump on outdoor temperatures (see Fig. 3). The use of heat pumps for cooling leads to an increase in Q_F of up to 6.3 W m^{-2}, with an ensuing rise in 2 m air temperature (T_2) of up to 0.031 °C. The temperature sensitivity to anthropogenic heat peaks in the mornings and dips during the day. On this particularly hot day, the sensitivity fluctuated between 0.0036 to 0.0077 °C W^{-1} m^2. In the scenario where ASHPs air-condition the entire building, the Q_F differential reaches up to 12.6 W m^{-2}, prompting a T_2 increase of up to 0.065 °C. This represents almost a doubling in comparison to the case where just the occupied rooms receive air-conditioning by ASHP. However, the underlying sensitivity showcased consistency across both situations.

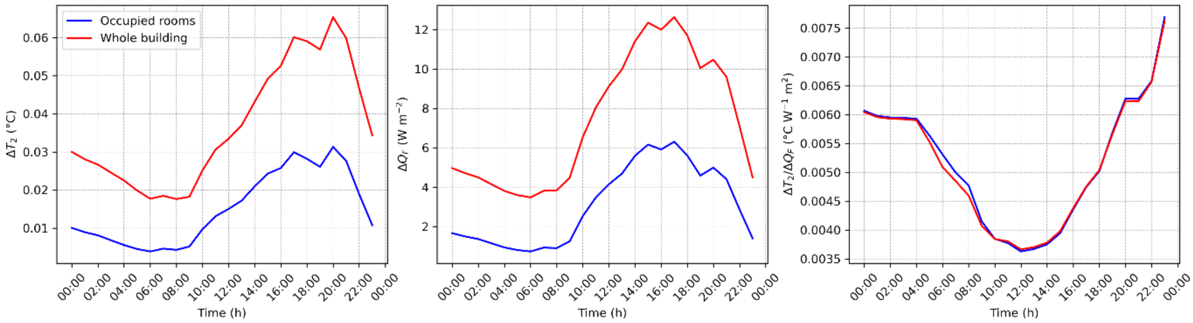

Fig. 3. Diurnal changes of differences between using the heat pump and gas boiler in outdoor 2 m air temperature (ΔT_2), anthropogenic heat emission (ΔQ_F), and their ratios on a typical 2050s hot day (21 July).

Furthermore, we examined the implications of this increase in outdoor temperature on indoor overheating risks. Employing the SUEWS-EnergyPlus modelling scheme (Tang et al., 2021; Xie et al., 2023), we simulate its influence on a naturally ventilated building within the neighbourhood. Fig. 4 shows the indoor operative temperature alterations. For the partially air-conditioned building, the peak increases are 0.0096°C in bedrooms and 0.0075°C in occupied living spaces. While for buildings where every room was air-conditioned, these differences reached 0.0236°C in bedrooms and 0.0185°C in living rooms. Notably, these elevations in indoor temperatures are minimal and typically do not significantly alter thermal comfort levels.

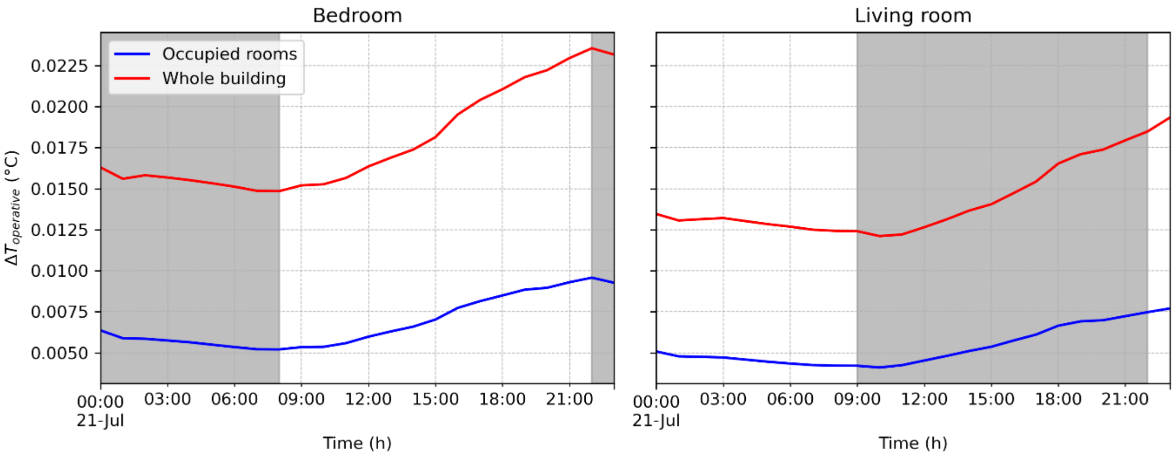

Fig. 4. Diurnal changes of differences (c.f. neighbourhood without ASHPs) in indoor operative temperature in two rooms with ASHPs in different operating conditions. Occupied periods are shaded.

London 2050s medium emissions vs. high emissions

We further consider a high emissions scenario, in alignment with the IPCC A1FI scenario(WMO, 2000). This specific scenario represents an intensive reliance on fossil fuels. The DSY data is obtained from the same source as the medium emissions data (Eames et al., 2011).

For high emissions scenario, a typical hot day 9 July is selected for comparisons between the medium and high emissions scenarios. Our results suggest that the discrepancies between medium and high emissions scenarios are relatively small. Specifically, for the high emissions scenario, the increased Q_F compared to buildings without ASHPs is up to 6.6 W m^{-2}, and the increase is T_2 differences are up to 0.035 °C. Both values are slightly larger than the medium emissions scenario, which has QF up to 6.3 W m^{-2}, and T_2 of up to 0.031 °C. The sensitivity of T2 to QF ranges from 0.0043 to 0.0080 °C W^{-1} m^2, similar to the range of 0.0036 to 0.0077 °C W^{-1} m^2 obtained from the medium emissions scenario.

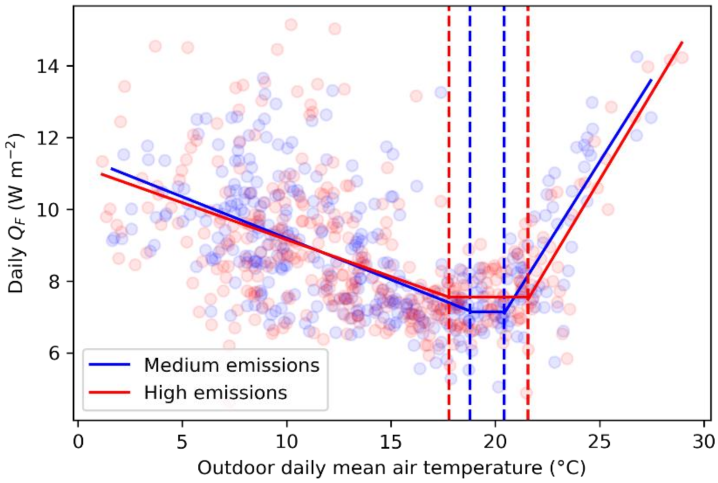

Fig. 5. Relationships between daily anthropogenic heat emission (Q_F) and outdoor mean air temperature for buildings with ASHPs in London 2050s medium and high emissions scenarios.

Table 3: Coefficients for SUEWS Q_F calculations (Eq. 2) for different London 2050s emissions scenarios

	ASHP – Medium emissions	ASHP – High emissions
a_{F0} (base) [W m^{-2} (cap $ha^{-1})^{-1}$]	0.0267	0.0282
a_{F1} (cooling) [W m^{-2} (cap $ha^{-1})^{-1}$]	0.0035	0.0036
a_{F2} (heating) [W m^{-2} (cap $ha^{-1})^{-1}$]	0.0009	0.0008
$T_{base, heating}$ (°C)	18.9	17.8
$T_{base, cooling}$ (°C)	20.4	21.6

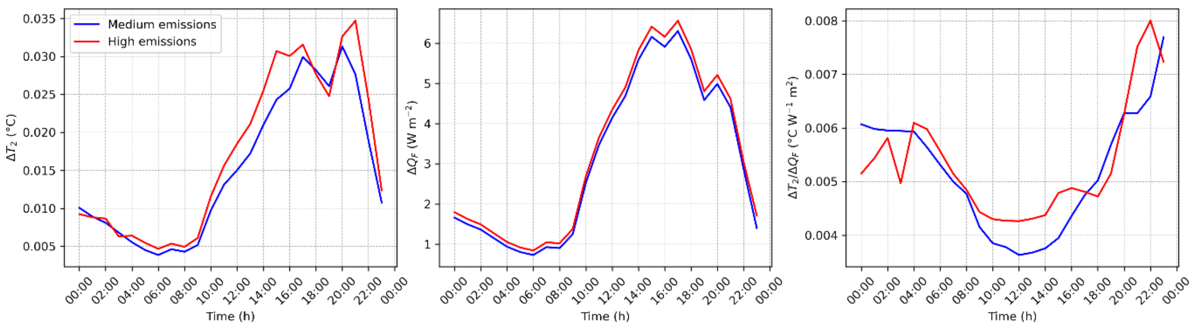

Fig. 6. Diurnal changes of differences between using the heat pump and gas boiler in outdoor 2 m air temperature (ΔT_2), anthropogenic heat emission (ΔQ_F), and their ratios on typical 2050s hot days (21 July for medium emissions and 8 July for high emissions).

4. Discussions and conclusions

Due to the predominant low-rise residential buildings with sparse populations leading to modest cooling demands, our findings indicate small temperature rises due to heat pump use in such low-rise low-density neighbourhood in London, compared to studies in other cities. For example, Wang et al. (2018) reported that using air conditioners can increase the T_2 by around 2 °C in dense urban areas in Hong Kong, although the Q_F increase due to air conditioners is as large as 300 W m^{-2} due to the intense usage. Other potential reasons of the differences include variations in the assumed COP for systems, divergent Q_F definitions in other research, and building envelopes with superior insulation. Despite of different model settings, our results regarding T_2 sensitivity to Q_F align with previous work. Recent review by Wang et al. (2023) suggested the ranges between 0.001 to 0.05 °C W^{-1} m^2 varying with different factors, while Bohnenstengel et al. (2014) reported a similar sensitivity of approximately 0.008 °C W^{-1} m^2 in London and Wang et al. (2018) reported a value of around 0.007 °C W^{-1} m^2 in Hong Kong. The consistence with the existing literature suggests the good reliability of our findings.

Our research indicates that the integration of ASHPs in low-rise residential neighbourhoods in the UK may have a minimal impact on the local climate. This finding positions ASHPs as a potentially feasible and promising solution for the decarbonisation of cooling within the UK without compromising the outdoor thermal environment. Nevertheless, there is a scope for broadening the research parameters. Future studies could focus on regions characterised by higher population densities and a more intensive reliance on heat pumps, especially in compactly built commercial areas. Additionally, understanding the long-term impact of ASHPs on larger urban ecosystems and assessing their economic and environmental feasibility in different contexts can further enrich the discussion on sustainable urban cooling and heating solutions.

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