The impact of teleworking on domestic energy use and carbon emissions: An assessment for England

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ABSTRACT

Despite decades of research on the environmental impacts of teleworking, most studies have neglected building-related energy use and emissions. Even fewer studies have explored the relative influence of different variables on those emissions. This study therefore explores the building-related emissions from teleworking in England using data from the UK Energy Performance Certificate (EPC) database over the period 2008 to 2022. We use a building energy model to estimate the additional emissions associated with different patterns of teleworking, including variations in heated area and internal temperature. We combine our results with a separate set of estimates of the transport-related emissions. We also employ global sensitivity analysis to identify the relative importance of different variables.

We find that English teleworkers have significantly higher emissions than non-teleworkers. Considering both transport and domestic building emissions, working from home 3–5 days/week leads to 3% less to 17% more carbon emissions than conventional work patterns depending on the heating area, heating system heating time and required temperature. We find that heating area has the biggest influence on building emissions, followed by the number of heating hours, wall insulation and the efficiency performance and carbon intensity of the heating system.

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1. Introduction

The climate crisis requires urgent change across all sectors of the economy. Climate change mainly results from burning fossil fuels to power daily activities such as transportation and heating. Multiple solutions are required, such as encouraging electric vehicles, improving home insulation and deploying carbon capture and storage technologies. One option that is receiving increasing attention following the Covid-19 global pandemic is working from home one or more days a week - so-called 'teleworking'. Increased uptake of teleworking should reduce the number of commuting trips and, over the longer term, may reduce the number and size of workplaces and/or their average occupancy. These changes, in turn, should reduce carbon emissions from transport and non-domestic buildings as well as providing broader economic and social benefits. However, teleworking may also have unintended consequences that increase energy use and carbon emissions. For example, teleworkers may take more non-commute trips on the days when they are working from home and may use more energy within their home. Hence, estimates of the net effect of teleworking must take all of these factors into account (Fig. 1).

As indicated in Fig. 1, changes in emissions from buildings may potentially account for a large proportion of the total climate impacts of teleworking. The additional energy use and emissions from domestic buildings may be particularly important, since there is no guarantee of any offsetting reductions in energy use and emissions from workplaces. In the UK, domestic energy use accounts for about a third of total energy consumption according to the Department for Business, Energy and Industrial Strategy [4], so the additional energy use from working at home may be comparable in size to the energy savings from fewer commutes. However, most empirical studies of the climate impacts of teleworking neglect domestic buildings altogether, and instead focus solely upon transport-related energy use and emissions [21,40]. As a result, the contribution of changes in building emissions remains both uncertain and underexplored. Furthermore, since few studies employ an engineering model, there is little evidence on the relative importance of different variables in shaping building-related energy use and emissions. For example, we have little evidence on the impact that fabric improvements and changes in household heating technologies may have on the emission savings from teleworking. To explore these issues further, this study employs a simple engineering model to estimate the changes

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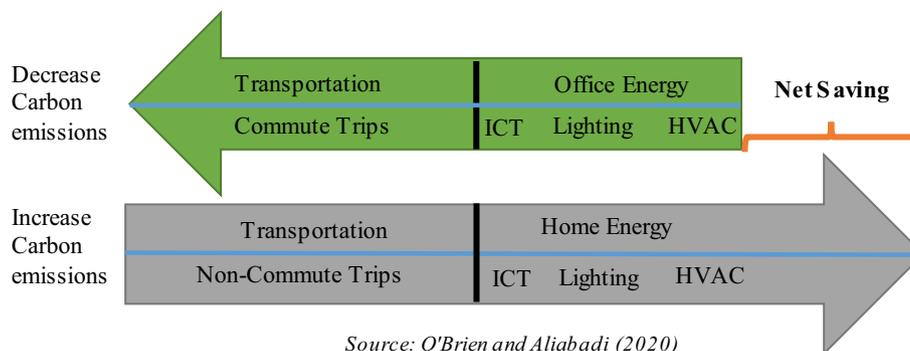
Source: O'Brien and Aliabadi (2020)

Fig. 1. Teleworking's main effects **on** carbon emissions.

in building-related energy use and carbon emissions from working at home. It then compares these estimates with separately-derived estimates of changes in transport-related energy use and emissions from teleworking [47]. This study does not include estimates of changes in office-related energy use and emissions. In practice, office-related energy and emission savings may be small or non-existent since many offices will continue to be occupied, heated and lit when teleworkers are at home [34,12].

The paper uses simulation techniques to estimate the uncertainty in the estimates of building-related energy use and emissions, and then uses Sobol indices to rank the relative importance of different variables to those estimates. Sobol indices are appropriate where there are correlations between the relevant variables, e.g., floor area and insulation level. Our main research questions are:

(1) What factors influence the change in household energy demand and carbon emissions when people work from home, and what is their relative importance?
(2) How do the changes in household emissions from teleworking compare to the changes in transport-related emissions?

The following section reviews the literature in this area, focusing upon the limited number of studies that estimate the impact of teleworking on both transport and building-related emissions. Section 3 outlines our methodology, while Section 4 describes our data sources. Section 5 to 6 present our results, while Section 7 concludes. We find that working from home 3 to 5 times a week leads to additional household emissions that are around 2–4 times larger than the emission savings from transportation if teleworkers heat the entire property. The most important variable influencing household emissions is the floor area for heating, followed by the U-value of the walls, the carbon intensity of the heating fuel and the thermal efficiency performance of the heating system.

2. Literature review

The literature review has two parts. First, we review the small number of studies that assess the impact of teleworking on building-related energy use and carbon emissions. Second, we briefly review the main factors affecting energy use and carbon emissions from domestic buildings in the UK.

2.1. Teleworker's domestic energy and emissions

We combined the results of two earlier review papers [21,40] with Google Scholar searches using combinations of the keywords "teleworking", "work from home", "energy" and "emission". We identified 15 studies that considered both transportation and household energy use and/or carbon emissions, but only one study that used a comprehensive building model [48] and only two studies that addressed uncertainty in a systematic way, i.e., simulation [30,48]. Table 1 summarizes the methods and findings of each study.

Due to lack of data on teleworkers' household energy use and emissions, most studies use assumptions and scenario analysis. We can distinguish between top-down and bottom-up approaches. The former typically divide aggregate domestic energy use by the number of residents at home, and then adjust by the assumed teleworking frequency, e.g., one-day teleworking will save 1/7 of total domestic energy [39,35,46,53,17,38,45]. The bottom-up method typically: a) assumes the teleworker's weekly usage patterns for different types of equipment (hours/day); b) assumes the energy efficiency of that equipment (e.g. HVAC, lighting, ICT); and c) estimates the total energy use and/or emissions from these activities [45,30,38,2,18,46].

The results of the studies vary widely, owing to differences in context, methodology and the assumptions for variables such as teleworking frequency, energy-using behaviors and building archetypes. As a result, the studies provide no consensus on whether teleworking saves energy or reduces emissions. Seven studies find that the energy and emission savings from reduced commuting and office use outweigh the increased energy use and emissions at home [39,30,35,32,46,53,17,31]. Röder and Nagel [45], however, cast doubt on the possibility of overall savings, since they assume that office energy use is unaffected by teleworking, and find that the increase in home energy use approximately offsets the savings in transport energy use. Two studies on Japan and one study on Canada also agree that overall energy savings depend upon whether there are any office-related energy savings [38,48,29].

None of these studies considers the impact of different building archetypes on building-related energy use and emissions. Only one study considers building archetypes in a systematic way by using a building energy model [48]. This study estimates energy use for buildings in Osaka City, Japan, including heating, cooling, appliances (TV, video, desk lamp, and computer), lighting, kitchen and hot water. It uses average values of building archetypes and assumptions for individual behavior and combines these with an occupant schedule model to simulate the additional energy use from working at home. Shimoda et al. find that teleworking for 30% (60%) of the time increases household energy use by 1.1% (2.1%). They also make simple assumptions for changes in office energy use and find that if this remains unchanged, 100% teleworking in Osaka City would increase building energy use by 0.5%. If office area shrinks in proportion to the number of people teleworking, 60% teleworking would reduce building energy use by 0.6%. However, Shimoda et al. [48] do not use the statistical distributions from building archetypes in their building energy model; instead,

Table 1
Review of studies on teleworker's domestic energy demand and carbon emissions.

Studies	Country	Method	Findings
Banister et al. [2]	UK	Estimate emissions from heating, lighting and computing, assuming a teleworker occupies one room with gas heating at 17 °C.	Preliminary results show that 1 day per week per worker emits extra 173 kg CO_2; 5 days emits extra 865 kg CO_2. Increased home energy use is equivalent to about 80% of transportation saving for commute trips
Crow and Millot [13]	EU, China, US	Compare the load curve differences of electricity and fuel between weekday and weekend	On average for the whole EU, a day of working from home increased household energy consumption by between 7% and 23% compared with a day working at the office
Fu et al. [17]	Ireland	National residential energy/number of residents/365 day/24 h*8h ≈ 0.027 GJ per worker for 8 h	5.4% of workers can shift to teleworking; if 5% shifts, it will save only 0.14% of total final energy consumption
Guerin [18]	Australia	Local sensitivity analysis to identify the most important factors affecting teleworker's carbon emissions. The input variables considered are percentage of employees commuting by car, one-way commute distance, office energy use, office space reduced, home energy use, number of heating/cooling hours at home.	Teleworking was more beneficial if an employee travels over 30 km each workday, if home offices have greater energy efficiency, if office buildings have less energy efficiency, and if renewable energy is used more in home offices than in office buildings.
Huebner et al. [24]	UK	Survey 1711 households during the pandemic times when 25% of people work from home compared to 6.5% before the pandemic	Around 60% of people who spent more time at home reported more heating hours, and energy use from laptops, desktops and tablets saw the largest increase.
Kitou and Horvath [30]	US	Estimate energy use from ICT devices, electric appliances (e.g., clothes washer), lighting and HVAC. Run Monte Carlo simulation with distribution patterns of energy data.	Teleworking decreases carbon emissions, considering transportation and building energy together. One-, three- and five-day of teleworking decreases carbon emissions by 2–80%.
Larson and Zhao [32]	US	Use standard urban model, teleworkers with a budget constraint will find a balance in teleworking adoption, commuting cost, housing location and its cost, and domestic energy cost. Model energy demand which consists of commuting fuel, domestic electricity and others.	20% of teleworking reduces transportation energy by 23%, increases lot sizes by 7.4%, increases home electricity by 5.3%, and increases consumption by 0.1%.
Matthews and Williams [35]	US, Japan	Estimate the energy change from HVAC, ICT devices and lighting. Central heating is prevalent is the US, so teleworker's extra energy is estimated as 10% * (average energy when at least 1 person at home – average energy when no one is at home). Room-by-room heating is prevalent in Japan, so teleworker's extra energy is estimated as a third of total household energy for 12 h a day.	Teleworking for 16% of total worker days (i.e. 50% of all information workers, 4 days/week) saves 1.2% of total energy in the US and 1.3% in Japan, assuming 70% of office energy use is saved.
Williams [53]	Japan	Similar as above in the Japan estimation of Matthews and Williams [35]	For a 4-day teleworking scenario, the increase in energy use in homes is ∼ 22% of the energy savings from reduced commuting trips and almost offsets the energy savings from reduced office use.
Nakanishi [38]	Japan	Multiply energy efficiency of a typical desktop, desk lamp, air-conditioning, and ceiling light by 8 h a day. Adjust the estimation down considering 36% teleworkers share space and equipment at home.	If the office is closed, 15–27% of building and transport energy use can be saved. If the office is not closed, the net increase is 100% of office energy, which is 1.0–6.8 kWh per worker per day
Röder and Nagel [45]	Germany	Estimate teleworker's extra energy use by dividing aggregate national residential energy use by the population. Adjust the estimate considering the differences of hourly energy load during working time.	Teleworking increases home energy use by about as much as the energy savings from less transport. Hence, teleworking does not reduce energy consumption as teleworkers still use energy in transport.
Roth et al. [46]	US	Estimate extra energy use from ICT devices and lighting, and their impact on HVAC, but no direct estimation of teleworker's HVAC energy use. Assume teleworkers work for 9 h per day with either 2 desktops or 1 notebook at active, sleep or off mode, lighting efficiency is 150 W.	The increase in domestic carbon emissions is less than 10% of the reduction in carbon emissions from transport. Energy use from lighting and ICT devices are the main drive, followed by HVAC. If 3.9 million (around 1% of the US population) teleworked frequently, primary energy consumption would fall by 0.13–0.19%, depending on whether office space is reduced.
Shimoda et al. [48]	Japan	Consider building energy only, not transportation energy. Use building engineering models to simulate heating, cooling, appliances, and hot water energy use with assumptions on teleworker and his/her household members' behaviors. Use occupant schedule model with 500 datasets to simulate the hourly energy load, considering energy from HVAC, TV, video, desk lamp, hot water, kitchen, computer and lighting.	Teleworking for 30% (60%) of the time increases domestic energy use by 1.1% (2.1%). If office area does not decrease, 100% teleworking in Osaka City gives around 0.5% increase in building energy; if office area shrinks in proportion to teleworking, 60% teleworking results in a 0.6% energy saving.
Villeneuve et al. [52]	Canada	Survey 278 knowledge-based workers when they worked from home due to the pandemic	Teleworkers reported using more energy for computers and office equipment, entertainment, cooking, lighting, and HVAC. More teleworkers reported lower overall energy use.

they use national average values of five building variables, namely insulation level, internal temperature, energy efficiency of appliances, share of heating fuel and thermal characteristics. In addition, Shimoda et al. [48] do not consider changes in transport energy use.

Only two papers employ a systematic approach (simulation) to assess the uncertainty of energy and emission savings from teleworking [30,48]. Kitou and Horvath [30] model emissions from commute and non-work travel, as well as home and office emissions, and find that one-, three- and five-day teleworking decreases overall carbon emissions by 2–80%. They assume that the energy use of HVAC, lighting, and electronic and electrical appliances follows either a normal or a uniform distribution, and assume either mean and standard deviation values, or minimum and maximum values to specify these distributions. In a five-day teleworking scenario, they estimate that the additional emissions from home heating, lighting, and electrical equipment offset 66%, 2% and 26% respectively of the emission savings from reduced transport. Sim-

ilar, they estimate that the emission savings from office heating, lighting, and electrical equipment add 7%, 4% and 4% respectively to the emission savings from transport.

Shimoda et al. [48] also use Monte Carlo simulation. They input 500 datasets of hourly energy load in Japan in an occupant schedule model to simulate the difference of energy use between people staying at home and people not staying at home, which they consider equivalent to the difference between teleworker's and non-teleworker's domestic energy use. However, as mentioned above, this simulation does not reflect the variation in building archetypes, and hence does not analyse how these factors affect teleworker's energy use. Moreover, Monte Carlo simulation assumes that the input variables are independent from each other, which may not be the case for variables such as floor area and insulation level.

Only one study investigates the factors influencing the energy or emissions savings in a systematic way. Guerin [18] uses a local sensitivity analysis to study teleworker's transport, home and office emissions in Australia by changing variables one at a time and measuring the effect. Guerin bases his assumptions on interviews with employees of a corporation with large offices across Australia. He finds that the most influential factors affecting emissions are the percentage of teleworkers commuting by car, their one-way commute distance and their home energy use. The carbon emissions from teleworking double if the percentage of teleworkers commuting by car increases by 20%, more than triple if one-way commute distance increases by 50%, and increase by around 10% if the number of heating hours is reduced from 7 to 6. Guerin [18] does not consider induced travel and finds that teleworking is more beneficial if the employee commutes over 30 km each workday.

This study aims to fill three gaps in the literature, namely the lack of use of building energy models, the lack of systematic modelling of uncertainty, and the lack of evidence on the relative importance of different variables. To fill the gaps, we use an engineering model to estimate household energy use (Reduced Data Standard Assessment Procedure 2012 version 9.94 - RdSAP 2012); historical simulation to deal with uncertainties with the existence of correlated variables; and global sensitivity analysis to assess the relative contribution of different variables.

2.2. Key factors influencing UK household energy demand

The determinants of building energy use are complex and vary significantly from one building type to another. Table 2 summarizes seven studies of UK households that rank the impact of different variables on household energy demand.

Factors affecting space heating are the main determinants of domestic energy use, since space heating accounts for almost two thirds of domestic energy consumption (Fig. 2). The key variables affecting energy demand for heating are floor area, fabric heat loss, internal temperature and external temperature. The following paragraphs elaborate on these variables.

The main factors affecting fabric heat loss are the U-values of the walls, roof and floor. U-values measure the rate of heat transfer through a structure, and thus indicate how well insulated it is. The wall U-value is the most important of the three [26,19,20].

Floor area is also important [22,23]. However, since reducing floor area is not always practical, multi-zone control is another option, which involves controlling the temperature of different rooms in a property and reducing heating of unused space. For example, Cockroft et al. [11] simulated a UK semi-detached house and bungalow with different occupancy patterns, and found that multi-zone control could achieve 8–37% energy savings. Beizaee [7] studied a matched pair of British houses and found that over an 8-week winter period, the house with zonal control used 12% less gas for space heating compared to a conventionally controlled system.

Internal and external temperature are also important for household energy demand. Internal temperature (or demand temperature), is not only found to significantly influence energy use [16,25,26], but also the validity of energy modelling such as Standard Assessment Procedure (SAP) [28,27].
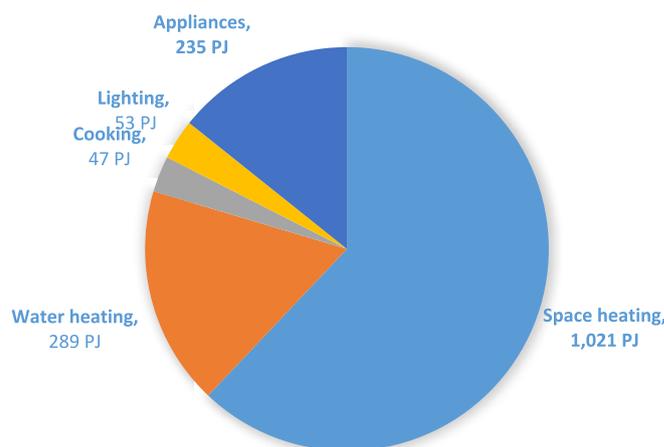
Fig. 2. 2020 UK household energy consumption by end use.

Table 2
Studies of determinants of UK household energy demand and emissions.

Studies	Methods and data sources	Key factor rankings
Huebner et al [22]	Survey of 924 English households	1. floor area; 2. dwelling type; 3. household size; 4. fuel type of energy system.
Hughes et al. [25]	Local sensitivity analysis and simulations with English Housing Survey (EHS) data and 2009 Standard Assessment Procedure (SAP) Model	1. internal temperature; 2.3 heating system efficiency; 3. External temperature; 4. Floor area; 5. Storey height; 6. Heating time (thermostat setting).
Hughes et al. [26]	Similar to above [25] but with global sensitivity analysis	1. wall U-value; 2. demand temperature; 3. roof U-value; 4. window U-value; 5. floor U-value.
Gupta and Gregg [19]	Analysis of retrofitting potential with Energy Performance Certificate (EPC) data	1. wall insulation; 2. loft insulation; 3. floor insulation; 4. boiler efficiency; 5. heat pump; 6. photovoltaic panel.
He et al. [20]	Simulation using EHS data in EnergyPlus software to assess the cost and effectiveness of retrofitting opportunities	1. wall insulation; 2. loft insulation; 3. double-glazing.
Ren et al. [44]	Study of a British semi-detached house with actual internal load schedules from 666 houses from Smart Meter data	1. infiltration treatment (draught proofing); 2. wall insulation.
Firth et al [16]	Local sensitivity analysis of domestic carbon emissions with Community Domestic Energy Model and Building Research Establishment Domestic Energy Model (BREDEM)	1. demand temperature; 2. heating time; 3. external air temperature; 4. storey height; 5. boiler efficiency.

Note: unless otherwise mentioned, any study in the Table focuses on domestic energy, not emissions.

Fig. 3. Methodology.

3. Methodology

The study focuses on modelling teleworker's home energy use and emissions following a similar approach from Shi et al. [47] (Fig. 3). First, we create a deterministic model, and draw probability distributions from the observations in our datasets. However, instead of Monte Carlo simulation that does not consider correlations between variables, we run a historical simulation that considers all variables of each observation at the same time. For instance, we input all building archetype variables of one property as one iteration, then input other variables such as external temperature into the same iteration; repeat with combinations of variables of another property and another temperature; and carry on until we have run $\sim 400,000$ iterations with $\sim 400,000$ residential properties. We compare these estimates with separate estimates of the changes in transport emission associated with teleworking derived from Shi et al. [47]. From this comparison, we identify the relative contribution of domestic building to the overall impacts of teleworking on energy use and emissions - thereby answering research question (2).

Next, we use global sensitivity analysis to assess how different variables influence the change in household carbon emissions from teleworking. We employ Sobol indices, which decompose the total variance of the output of our model and indicate how much each input contributes to this variance. This gives a ranking of variables in terms of their influence on a teleworker's additional household carbon emissions. Sobol indices provide a global rather than a local sensitivity analysis because they consider the impact of the correlations between input variables on the variance of the outputs. As there is correlation between our input variables (e.g., between wall insulation and floor insulation), global sensitivity analysis is preferred.

The deterministic model has three steps. Step 1 (Equation 1) calculates a non-teleworker's annual carbon emissions ($CO2_N$) as the sum of annual transport emissions ($CO2_{Ntravel}$), and home ($CO2_{Nhome}$) emissions. Step 2 (Eq. 2) does the same for a teleworker ($CO2_{TW}$), while Step 3 (Eq. 3) calculates the difference in carbon emissions between the two ($\Delta CO2$). We exclude office carbon emissions because a) there is not enough data on UK office building archetypes; and b) energy may continue to be used for office heating, lighting and ICT even when the teleworker is not there; c) previous studies suggest that the change in office energy demand is relatively small compared to the additional home energy demand [51,6,37,12,34]. However, we include a discussion of office energy estimates in Section 7 based on a recent study [34].

$$CO2_N = CO2_{Ntravel} + CO2_{Nhome} \qquad (1)$$

$$CO2_{TW} = CO2_{TWtravel} + CO2_{TWhome} \qquad (2)$$

$$\Delta CO2 = CO2_{TW} - CO2_N = \Delta CO2_{travel} + \Delta CO2_{home} \qquad (3)$$

Our estimate of the difference in transport emissions ($\Delta CO2_{travel}$) is based on Shi et al. [47]. Section 3.1 describes how we estimate the difference in household emissions ($\Delta CO2_{home}$).

To accommodate limitations in processing power, we reduce the number of variables in the global sensitivity analysis. While we use the full samples from historical data for simulation, we only use average values for the global sensitivity analysis. We also exclude variables that contribute little to the variance in the output from the sensitivity analysis. These variables include external temperature, estimated window area, floor level, whether there is a heat corridor, whether it is top floor for flats, and the proportion of low-energy lighting.

In addition, we conduct an additional analysis assuming all homes have replaced gas boilers with air-source heat pumps but leaving other variables unchanged. This is based on UK proposals to grow the installation of electric heat pumps from 30,000 per year to 600,000 per year by 2028 [50].

3.1. Deterministic model of domestic carbon emissions

To estimate household carbon emissions, we use a domestic building energy model, namely the 'Reduced data Standard Assessment Procedure 2012 version 9.94' (RdSAP 2012) (Allinson, 2013). This model is the UK Government's National Calculation Methodology for assessing the energy performance of dwellings. It is used to facilitate the implementation of Building Regulations and for the production of Energy Performance Certificates (EPCs) [9].

In addition to the assumptions within RdSAP 2012 [9], we assume that:

1. Both teleworkers and non-teleworkers work 8 h a day, 5 days per week;
2. Teleworkers have the same living conditions, i.e., building archetypes, as non-teleworkers;
3. Teleworkers use extra heating, only turn on lights in one room, and do not use electrical appliances except ICT devices for work purposes;
4. All properties have length to width ratio 1.5:1, no roof opening, and no basement, and have 20% of windows and doors draught proofed[1]. Flats have half of the walls facing outside. Houses have two floors.

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[1] Draught proof means that unwanted gaps around windows and doors are blocked [15].

5. All properties have only one heating system with multi-zone control that allows temperature control within each room.

3.2. Additional home CO_2 – $\Delta CO2_{home}$

Our literature review demonstrates that teleworking's main influence on domestic energy use is the additional energy required for heating, lighting and ICT during working hours [21,40]. Hence, the difference between teleworker's and non-teleworker's domestic carbon emissions (ΔE_{home}) is estimated as the sum of changes in heating, lighting and ICT emissions.

$$\Delta CO2_{home} = \Delta CO2_{heat} + \Delta CO2_{light} + \Delta CO2_{ICT} \quad (4)$$

3.3. Additional home heating CO_2 – $\Delta CO2_{heat}$

The difference between one teleworker and one non-teleworker's annual heating carbon emissions is estimated using the RdSAP 2012 model [1]. The differences between our model and RdSAP 2012 are: (a) heat gain G_m only comes from ICT devices for work purposes and lighting; (b) the size of heating areas (ΔSZ_h) is modified according to different assumptions about teleworker's behavior; (c) teleworking frequency f_{TW} is added to the model; (d) extra heating time per teleworking day t is modified according to different assumptions about teleworker's behavior; and (e) internal temperature $T_{i,m}$ and external temperature $T_{e,m}$ are adjusted to working-hour temperature.

The difference of home heating carbon emissions (kg) between teleworker and non-teleworker:

$$\Delta CO2_{heat} = CF_a * E_{H,a} \quad (5)$$

where CF_a is carbon emission conversion factor for the fuel for heating system a, since different dwellings have different heating systems and therefore different heating fuels. $E_{H,a}$ is the annual consumption of heating fuel by heating system a (kWh).

Modified from RdSAP 2012 [1], $E_{H,a}$ is space heating requirement for heating system a (kWh)

$$E_{H,a} = \sum_m t * n_m * [H * (T_{i,m} - T_{e,m}) - \cup_m * G_m] * f_{TW}/\eta_a \quad (6)$$

where t is the number of extra heating hours on a teleworking day, n_m is the number of teleworking days in the month m (assumed to be 21.75), $\cup_m$ is utilization factor for gains in the month m, G_m is total heat gain (*Watts*) for the month m, H is the heat transfer coefficient (*W/K*), $T_{i,m}$ is the working-day mean internal temperature (°C) for the month m, $T_{e,m}$ is working-time external temperature (°C) for the month m, f_{TW} is teleworking frequency (days/week), η_a is the Coefficient of Performance (COP) for heating system a. See Appendix for more details.

$\Delta CO2_{heat}$ and $E_{H,a}$ depend upon the area the teleworker uses for heating, and the time for heating. We assume two scenarios for the area of heating.

Area of heating

Senario 1 : *teleworker heats the whole home, while non*
        − teleworker does not.

Senario 2 : *teleworker heats one extra room in the property, while non*
        − teleworker does not.

Based on the 2011 Energy Follow-up Survey statistics showing that people heat an extra 1.3–1.5 h/day on the weekend than weekdays [8], we estimated that teleworkers heat an extra 1–3 h per day compared to non-teleworkers. Therefore,

Heating time

Senario 1 : *teleworker heats* 1 *more hour per teleworking day than non*
        − teleworker.

Senario 2 : *teleworker heats* 2 *more hours per teleworking day than non*
        − teleworker.

Senario 3 : *teleworker heats* 3 *more hours per teleworking day than non*
        − teleworker.

We assume that a non-teleworker requires no heating at home during working hours (9 am – 5 pm) and make three different assumptions for required internal temperature.

Required temperature

Senario 1 : *teleworker requires* 19°C.

Senario 2 : *teleworker requires* 20°C.

Senario 3 : *teleworker requires* 21°C.

3.4. Additional home lighting CO_2 – $\Delta CO2_{light}$

We also use RdSAP 2012 to estimate the teleworker's additional carbon emissions from lighting over the course of a year:

$$\Delta CO2_{light} = \alpha_1 * (\Delta SZ_{room})^{0.4714} * L_{LE}/L * t * f_{TW} * CF_E \quad (7)$$

where α_1 is a conversion factor, ΔSZ_{room} is the area of one room (m^2), L_{LE}/L is the proportion of low-energy lighting outlets, CF_E is the carbon emission conversion factor for electricity (kg CO_2/kWh). We base our assumption for the carbon intensity of electricity on the UK generation mix in 2021. However, we expect UK electricity generation to be near fully decarbonized by 2035, so the carbon emissions associated with electricity use may fall rapidly.

Additional Home ICT CO_2 – $\Delta CO2_{ICT}$

We estimate the additional carbon emissions from ICT at home from:

$$\Delta CO2_{ICT} = CF_E * Eff_C * t * f_{TW} \quad (8)$$

where CF_E is the carbon emission conversion factor for electricity (kg CO_2/kWh), Eff_C is the rate of energy use by a laptop (*W*), which we assume to be 50 W on average. We assume 2 h per day for videoconferencing and 6 h for other usage. Based upon Ong et al. [41] and Pothitou et al. [42], videoconferencing uses 76 W and other applications use 40 W, considering both network operating and terminal operating energy.

4. Data and assumptions

We obtain data on UK domestic buildings from an online database of Energy Performance Certificates (EPCs) published by the Department for Levelling Up, Housing & Communities [33]. The EPC database provides information on both the energy performance of buildings on a scale from A (very good) to E (very poor), and their construction features and heating systems. The EPC database includes all compulsory EPCs [33], except when the holder of the certificate has chosen to opt out of the online database or when it is confidential for national security reasons. We select all available EPCs from the database in six English regions that include a variety of building archetypes, namely: Brighton and Hove, Croydon, North Norfolk, East Staffordshire, Newcastle upon Tyne and Cornwall. The reason for choosing these areas is that they represent different geographical regions and climates (northwest, south,

etc.) and range from small villages in rural areas to large cities, thereby ensuring a diversity of building archetypes in our sample. We choose all available EPCs from the database for period of years 2008–2021, because it became compulsory in the UK from 1st October 2008 for almost all buildings to have an EPC when constructed, sold or let.

As indicated in Table 3, we combine the EPC data with data from other sources and assumptions. We take data on the carbon intensity of fuels from 2021 UK Government Greenhouse Gas Conversion Factor [5] and data on external temperature for the period 1884–2021 from the UK Meteorological Office (Met [36]).

After obtaining the raw data from EPC database, we clean our sample. First, where there are duplicate certificates for the same property, we selected the newest certificate. Second, to remove outliers, we confine the sample to properties with 20–400 m² total floor area, and between 5–100 m² average room area (which we estimate by dividing total floor area by the number of habitable rooms in each property). This gives a total of 406,745 properties. Fig. 4 and Fig. 5 show the age band and property type in the dataset.

The EPC database does not provide data on U-values but has descriptive data on the wall, roof, floor and window of a property, such as its material and insulation condition. We use these descriptions to match with information in RdSAP 2012 to estimate U-values. For example, to estimate the wall U-value, we adapt Table 6 from RdSAP 2012 (Table 4). Over 95% of our data is successfully matched, and we assume a wall U-value of 0.5 W/m2K for the unmatched properties' (based on the Building Regulations that walls in existing dwelling being renovated should achieve at least 0.30 W/m2K for internal or external insulation and 0.55 W/m2K for cavity insulation ([49]: Table 4.3)). Fig. 6 shows the wall U-values after matching. We can see that some U-values are large because they represent uninsulated walls or older properties, while others are very small as they represent insulated walls or newer properties. Additionally, we estimate the heating efficiencies of properties by matching to one of the discrete numbers of main heating system categories from EPC database with Table 4a in RdSAP 2012 (see Fig. 7) (Allinson, 2013).

Table 5 summarizes the main variables obtained from EPC database.

Next, we obtain the carbon intensity of fuels from 2021 UK Government Greenhouse Gas Conversion Factor [5]. These carbon intensity factors relate to direct emissions and therefore exclude emissions from the production and distribution of the fuel. The exception is electricity, where the data includes the emissions from electricity generation. We match these factors to the fuel types defined in the EPC database (Table 6).

The Met Office does not provide data on temperature during working hours (9 am to 5 pm). We estimate the average working-hour temperature for each month from the average daily mean and maximum temperature for that month:

$$working\ hour\ mean\ temperature \approx (3 * maximum\ temperature + mean\ temperature)/4 \qquad (9)$$

In Eq. (9), we use daily average temperature of 12 months for all the available years 1884–2021 from Met Office to estimate a probability distribution of daily working-hour temperature by month. We assign a higher weight (75%) to maximum temperature than to mean temperature (25%) to adjust for the fact that daytime working-hour temperature is higher than the daily average temperature and overall temperature has risen over the last 138 years. Table 7 compares our estimates of daily working-hour mean temperature by month with 24-hour mean temperature in 2020 and 2021 [14]. Our working-hour mean values are slightly higher than Smart Meter's estimates of daily average temperature.

Table 3
Variables and data sources.

Variable	Definition	Unit	Data source
C_o^m	average external temperature (corrected for working hours) for the month m	ºC	UK Meteorological Office, 1884–2021 (Met [36]
CF_e	Emission intensity of energy type e (electricity, gas, etc.)	kg CO_2/ kWh	2021 UK Government Greenhouse Gas Conversion Factor [5]
SZ_h	Floor area of the property	m²	Energy Performance Certificate Database [33]
SZ_r	Average room area (total floor area divided by the number of habitable rooms, including kitchen, living room and bedroom)	m²	
U_{wl},	Estimated U-values of wall, roof, floor and window.	W/m²K	
U_r,	Obtained by matching their descriptions with RdSAP 2012 [1]		
U_f,			
U_{wd}			
Ef_h	Coefficient of Performance (COP) of the space heating system h (gas, electricity, heat pump, etc.)	Fraction	
p_l	Proportion of low energy lighting	Fraction	
C_r	Required internal temperature	ºC	Assume 19, 20 or 21
t_h	Heating time at home when teleworking	hours/day	Assume 1, 2 or 3
t_l,	Lighting and ICT usage times when teleworking	hours/day	Assume 8
t_{ICT}			
f_{TW}	Teleworking frequency	days/ week	Assume 1, 3 or 5
Ef_{ICT}	Power of ICT devices for work purposes	Watt	Assume 50
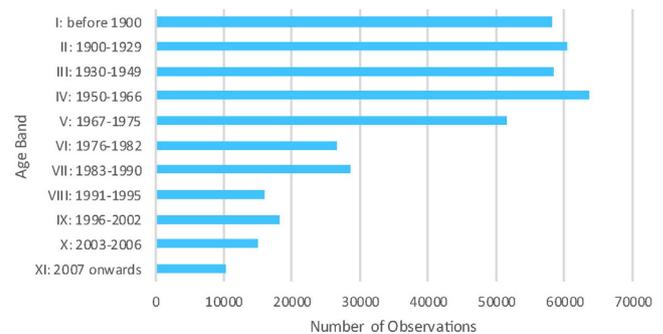
Fig. 4. Number of observations by age band in our sample.
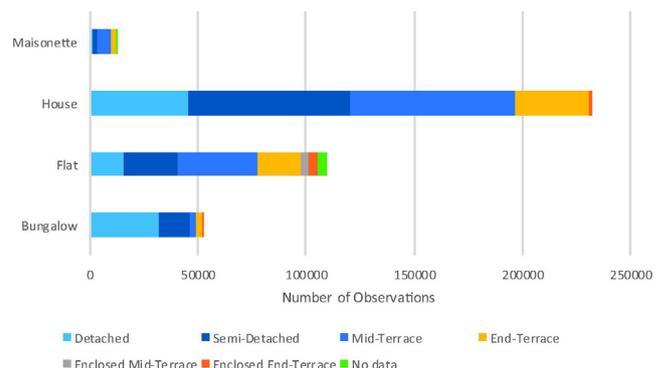
Fig. 5. Number of observations by property type and built form.

Table 4
Adapted Wall U-Value Table from RdSAP 2012.

Age Band	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Unit: W/m²K											
Cavity wall, as built, no insulation	1.5	1.5	1.5	1.5	1.5						
Cavity wall, filled cavity	0.7	0.7	0.7	0.7	0.7	0.4	0.35	0.35	0.35	0.35	
Cavity wall, as built, insulated							0.24	0.24	0.21	0.19	0.17
Cavity wall, as built, partial insulation						0.45					
System built, as built, no insulation	2	2	2	2	1.7						
System built, with external insulation	0.35	0.35	0.35	0.35	0.35						
System built, as built, insulated									0.21	0.21	0.17
Solid brick, with internal insulation	0.32	0.32	0.32	0.32	0.32						

Note: age band I to XI represents a range from the oldest to the newest property, see Fig. 4.
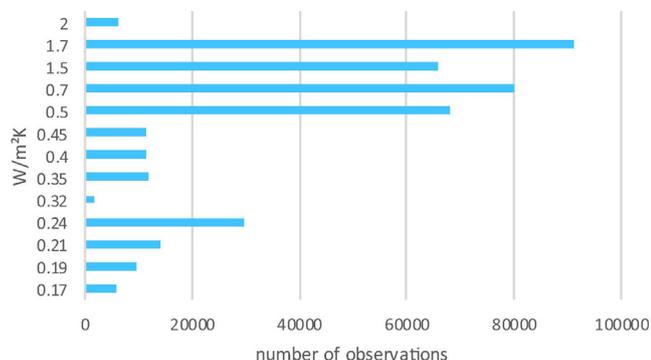
Fig. 6. Number of observations by estimated wall U-values.

We take our estimate of teleworker's transport emissions from a previous study [47]. Shi et al. [47] estimate the change transport emissions associated with teleworking using a similar methodology as in this paper, i.e., Monte Carlo simulation with probability distributions. They estimate that people who telework 3–5 times/week have 6% lower transport emissions than non-teleworkers on average, while those who telework 1–2 times a week have around 40% more transport emissions than non-teleworkers.

5. Simulation results

Using observations from EPC database and UK Meteorological Office (Section 3), we run a historical simulation to estimate the *additional* domestic energy demand and carbon emissions from teleworking. We then compare our estimates with a non-teleworking baseline scenario where people do not work from home. Table 8 compares the *additional* annual domestic energy demand of a full-time (5 days/week) teleworker with the *total*

energy demand of a non-teleworker. Table 9 does the same for carbon emissions.

We can see from Table 8 and Table 9 that heating makes the biggest contribution to the additional domestic energy demand and carbon emissions from teleworking. Even assuming the teleworker heats a single room to only 19 °C for one hour a day, we estimate that the additional heating energy demand is seven times larger the additional ICT energy demand and 40 times larger than the additional lighting energy demand. Hence, the energy and emission savings from teleworking will be particularly sensitive to heating patterns, desired internal temperatures, the thermal integrity of the dwelling and the efficiency performance of the heating system. For example, we estimate that increasing heating time from 1 h/day to 3 h/day and internal temperatures from 19 °C to 21 °C, will approximately double the additional energy demand and carbon emissions.

Table 8 and Table 9 show that if a full-time teleworker only heats one room at home, he/she will have 16–85% higher energy demand and carbon emissions than a non-teleworker, depending upon the choices made for heating time and required temperature. However, if he/she heats the whole property, this figure increases to 58–117%. This difference indicates the importance of reducing heating area.

Next, we compare our estimates of the changes in *domestic* emissions associated with teleworking with separately derived estimates of the changes in *transport* emissions from Shi et al. [47]. The transport estimates derive from an analysis of data from the English National Travel survey over the period 2017 to 2019. Shi et al. [47] demonstrate that workers who telework three or more days a week have *lower* carbon emissions for travel than non-teleworkers, while workers who telework once or twice a week have *higher* carbon emissions. These differences were the net result of differences in commuting frequency, commuting distance and non-commute travel between the two groups.
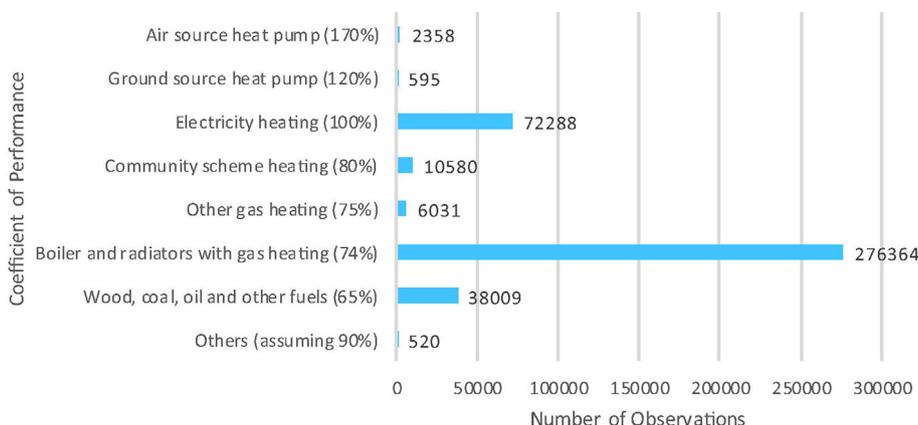
Fig. 7. Number of observations by estimated Coefficient of Performance.

Table 5

Summary statistics of building archetypes from EPC database.

	Min.	1st Qu.	Median	mean	3rd Qu.	Max.	s.d.
Total floor area (m^2)	20	61	78	87	101	400	42.8
Average room area (m^2)	5	17	20	21	23	100	5.3
Window area (m^2)	1.9	10.9	15.3	15.7	18.6	58.7	6.4
Wall U-value (W/m^{2}K)	0.2	0.5	0.7	0.9	1.5	2.0	0.6
Floor U-value (W/m^{2}K)	0.2	1.2	1.2	1.1	1.2	1.2	0.3
Roof U-value (W/m^{2}K)	0.0	0.2	0.2	0.4	0.4	2.3	0.7
Window U-value (W/m^{2}K)	2.0	2.0	2.6	2.5	2.8	4.8	0.4
Coefficient of Performance of heating system	0.7	0.7	0.7	0.8	0.7	1.7	0.1
Low energy lighting proportion	0%	23%	57%	55%	90%	100%	35.6

Note: room area is estimated by dividing total floor area by the number of habitable rooms in a property. Some roof U-values are zero because there is another floor above the flat.

Table 6

Tabulation of carbon intensity of fuel types.

	biomass	gas	electricity	LPG	oil	coal	missing data
carbon intensity (kg CO$_2$/kWh)	0.02	0.18	0.21	0.21	0.25	0.31	assume 0.20
number of observations	3,039	283,672	75,238	5,677	27,239	739	11,141

Note: LPG stands for liquified petroleum gas. Some heating fuel data is missing from EPC database.

Table 7

Comparison of our estimation with daily mean in Smart Meter (England).

	Our Estimation of Working-Hour Temperature							Smart Meter	
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	s.d.	2020 mean	2021 mean
degree Celsius (°C)									
January	0.4	5.5	6.3	6.3	7.6	9.7	1.7	3.6	6.7
February	0.1	5.7	7.1	6.8	8.0	10.9	2.0	5.2	6.7
March	5.5	7.9	9.4	9.2	10.3	13.3	1.7	7.0	6.7
April	9.1	11.1	11.9	12.0	12.9	16.9	1.5	6.5	10.3
May	12.6	14.5	15.6	15.5	16.5	18.4	1.3	10.1	12.7
October	10.3	12.9	13.5	13.5	14.2	17.2	1.3	12.2	10.7
November	5.8	8.6	9.3	9.3	10.3	12.2	1.3	7.9	9.0
December	1.4	6.1	7.4	7.0	8.1	12.0	1.6	6.8	5.6

Note: the number of observations is 138 years, from year 1884 to year 2021.

Table 8

Additional annual domestic energy demand from full-time teleworking.

Scenarios			Estimations			
Non-teleworking baseline			*Unit: kWh/(year*person)* Space heating 4578		Appliances 1052	Lighting 239
	Extra heating time *(hours/day)*	Required temperature (°C)	Heating one office room	Heating the rest of property	ICT	Lighting
Teleworking extra	*1*	*19*	+749	+1897	+104	+17
		20	+837	+2130		
		21	+925	+2368		
	2	*19*	+989	+2525		
		20	+1102	+2827		
		21	+1215	+3134		
	3	*19*	+1223	+3138		
		20	+1360	+3506		
		21	+1498	+3880		

Fig. 8 shows our mean estimates of the annual carbon emissions of non-teleworkers and teleworkers assuming teleworkers heat the whole property at home for an additional two hours per day at a required internal temperature of 20 °C. We provide separate estimates for low-frequency teleworkers who work from home one or two days a week, and high-frequency teleworkers who work from home 3 to 5 days a week. We compare the difference in emissions between teleworkers and non-teleworkers in five categories,

namely commute travel, non-commute travel (shopping, visiting friends, etc.), heating, lighting and ICT. For each category, we show the estimated emissions of non-teleworkers on the left, followed by low-frequency and high-frequency teleworkers.

As explained in Shi et al. [47], if we confine attention to transport emissions alone, we find that high-frequency teleworkers have *slightly lower* emissions than non-teleworkers. This is because their emission savings from fewer commutes offset their additional

Table 9

Additional annual domestic carbon emissions from full-time teleworking.

Scenarios			Estimations			
			Unit: kg CO$_2$/(year*person) Space heating		Appliances	Lighting
Non-teleworking baseline			878		202	46
	Extra heating time *(hours/day)*	Required temperature *(°C)*	Heating one office room	Heating the rest of property	ICT	Lighting
Teleworking extra	*1*	*19*	+143	+364	+20	+4
		20	+160	+408		
		21	+177	+454		
	2	*19*	+189	+484		
		20	+211	+542		
		21	+233	+601		
	3	*19*	+234	+602		
		20	+261	+672		
		21	+287	+744		
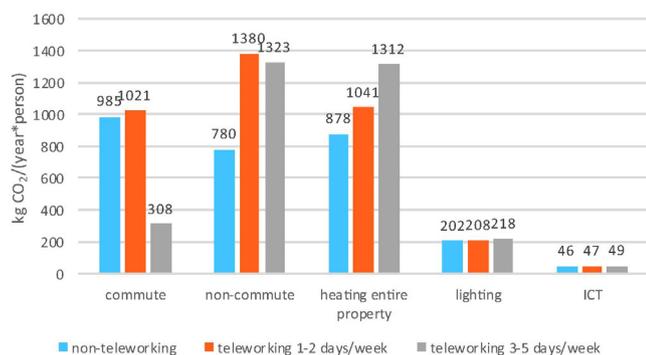
Fig. 8. Estimated difference between one teleworker's and one non-teleworker's average annual carbon emissions.

emissions from more non-work travel. In contrast, low-frequency teleworkers have *higher* emissions than non-teleworkers. This is because they live further from their workplace than non-teleworkers, so their additional emissions from longer commute trips more than offset their emission savings from fewer commute trips. These combined with their additional emissions from more non-work travel give higher emissions overall.

Fig. 8 highlights the importance of reducing emissions from home heating for teleworkers. With existing heating technologies, the additional heating emissions for high-frequency teleworkers (3–5 days/week) are 3 times larger than their transport emission savings assuming the teleworker heats the whole property for an extra 2 h per teleworking day at 20 °C required temperature. Hence, the additional domestic emissions more than offset the transport emission savings. Low-frequency teleworkers already have *higher* transport emissions than non-teleworkers, owing largely to additional non-work travel. Adding in their additional domestic emissions, we find low-frequency teleworker's total carbon emissions are 28% higher than for non-teleworkers with the same assumptions.

Table 10 summarizes our estimates of the percentage difference in total (transport plus domestic) annual emissions for low-frequency and high-frequency teleworkers compared to non-teleworkers. We present these estimates for different assumptions for heating area, heating time and required internal temperature, and for both maintaining current heating systems and replacing gas boilers with air source heat pumps.

When we consider transport and building emissions combined (Table 10), we find that both low-frequency and high-frequency teleworkers have higher emissions than non-teleworkers in the current scenario. This raises questions about the environmental

benefits of teleworking. We estimate that low-frequency teleworkers and high-frequency teleworkers have 26–30% and 6–17% more carbon emissions a year than non-teleworkers respectively; assuming teleworkers heat the whole home. If teleworkers only heat their home office area, these figures reduce to 24–25% and 0–4% respectively. This means that to gain the biggest environmental benefits from teleworking, it will be important to minimise heating area through multi-zone heating control. Reducing heating area is especially significant for high-frequency teleworkers who use heating at home more often than low-frequency teleworkers.

We also find that *high-frequency* teleworkers have lower total emissions (i.e. transport and domestic emissions combined) than *low-frequency* teleworkers, mainly because the additional saving in transport emissions for the former outweighs the associated increase in domestic emissions. This suggests that increasing teleworking frequency may help reducing the negative impact of teleworking on the environment.

Table 10 also shows that replacing current heating systems with heat pumps can significantly reduce the domestic and hence the total emissions associated with high-frequency teleworking, assuming no change in the carbon intensity of electricity. Decarbonising the electricity system will reduce these emissions further. However, this change has the opposite impact on the total emissions of low-frequency teleworkers, since these have high transport emissions and only have additional heat requirements for one or two days a week. With the assumptions used in this exercise, we estimate that teleworkers will only have lower total emissions than non-teleworkers if:

- they telework 3–5 times a week;
- they heat their home office on teleworking days rather than their entire home;
- they heat this office for no more than 3 h to a temperature of no more than 21 °C.
- they use air source heat pumps rather than other heating systems such as gas boilers;

These conclusions are contingent upon other variables remaining unchanged, including the observed difference in one-way commute distance between teleworkers and non-teleworkers, and the carbon intensity of electricity generation. Changes in these and other variables will change these conclusions.

6. Sensitivity results

Fig. 9 and Fig. 10 show the global sensitivity of the difference of domestic carbon emissions between teleworkers and non-

Table 10
Total transport and domestic carbon emissions of non-teleworkers and teleworkers.

non-teleworking baseline		current scenario 2891		unit: kg CO$_2$/(year*person) heat pump scenario 2419	
Extra heating time *(hours/day)*	Required temperature (°C)	heating one room	heating entire property	heating one room	heating entire property
teleworking 1–2 days/week					
1	19	+23.7%	+26.0%	+27.4%	+27.8%
	20	+23.9%	+26.5%	+27.5%	+27.9%
	21	+24.1%	+26.9%	+27.6%	+28.1%
2	19	+24.2%	+27.2%	+27.6%	+28.2%
	20	+24.4%	+27.9%	+27.8%	+28.4%
	21	+24.6%	+28.5%	+27.9%	+28.6%
3	19	+24.7%	+28.5%	+27.9%	+28.6%
	20	+24.9%	+29.2%	+28.0%	+28.8%
	21	+25.2%	+29.9%	+28.2%	+29.1%
teleworking 3–5 days/week					
1	19	+0.0%	+6.1%	−2.6%	−1.5%
	20	+0.5%	+7.3%	−2.3%	−1.1%
	21	+0.9%	+8.6%	−2.1%	−0.7%
2	19	+1.3%	+9.4%	−1.9%	−0.4%
	20	+1.9%	+11.0%	−1.6%	+0.1%
	21	+2.5%	+12.7%	−1.3%	+0.6%
3	19	+2.5%	+12.7%	−1.2%	+0.7%
	20	+3.3%	+14.6%	−0.8%	+1.3%
	21	+4.0%	+16.6%	−0.4%	+1.9%

teleworkers. Global sensitivity here is measured by Sobol indices in the two figures; the higher the indices, the more important a variable is in contributing to the uncertainty of extra domestic carbon emissions in teleworking, which indicates the significance of the variable in explaining teleworker's extra domestic emission. As Sobol indices considers the impact from correlations between input variables, the importance of a variable includes not only the effect from itself but also the influence from its correlations with other variables. Fig. 9 assumes that teleworkers heat the whole property while Fig. 10 assumes that they only heat one room. Both figures present results for high-frequency teleworkers, i.e., working from home 3–5 days a week.

Fig. 9 indicates that if a high-frequency teleworker heats their entire home, then total floor area is the most important variable influencing their additional domestic emissions. This highlights the importance of reducing heating area when people work from home. As mentioned in Section 2.2, multi-zone control is a good option to reduce heating area, which requires teleworkers only heat the area s/he needs. The number of heating hours is the second most important variable and may be reduced through improving the building fabric to increase heat retention. The carbon intensity of heating fuel and the efficiency performance of the heating system make a smaller contribution to the variance in additional household emissions. However, it is important to note that these estimates reflect the *current variance* in carbon intensity and heating efficiency performance. Since most households use gas boilers, this variance is relatively limited. In future, electricity will become progressively decarbonized and heat pumps will significantly improve heating efficiencies. Hence, both variables will play a much more important role in the future in determining overall household emissions [3].

Fig. 9 suggests that the U-values of the walls, roof and floor are less important than heating area and heating time, while variables related to building structure, such as property type (e.g. house, flat, maisonette), built form (e.g. detached, semi-detached) and the number of rooms are the least important. This appears odd at first sight, since detached, four-bedroom houses tend to have larger emissions than one-bedroom flats. However, property type and built form correlate strongly with floor area, and we have already controlled for the contribution of floor area. Property type, built

form and the number of rooms may influence emissions in other ways - such as through the number of external walls, or space separation within the property - but the results suggest that these additional variables are relatively unimportant.

As indicated in Fig. 10, the results from heating one room (Fig. 10) are similar to the results from heating the entire property (Fig. 9). Room area is still the most important variable, which again shows the importance of multi-zonal control. However, wall U-value is now the second most important variable, which may be explained by two reasons: a) heating one room requires significantly less energy than heating the entire property, and good wall insulation may suggest that the heating system runs on an efficient energy-saving mode instead of full capacity. b) The ratio of external wall area to floor area is higher for a home office room than for the entire property, so wall insulation is more important. Carbon intensity is the third most important, which shows the importance of reducing carbon intensity in energy generation by using more sustainable resources. The number of heating hours is the fourth important.

Taken together, the results suggest that the thermal performance of the building contributes less to the difference in emissions than behavioral variables such as the area heated. Wall U-value is an exception, being important in helping reducing heating-off time when people heat one room; however, variables such as built form, property type or window U-value are much less important. In contrast, reducing heating area, reducing heating time, switching to lower carbon energy or improving heating efficiency performance are very important in reducing domestic carbon emissions when people work from home.

7. Discussion and conclusion

This study has estimated the additional carbon emissions from the use of heating, lighting, and ICT devices when people work from home in England. We based our analysis upon the observed variation in a wide range of building-related variables for a representative sample of 400,000 + English dwellings. We then combined our estimates with the results of one study that estimated
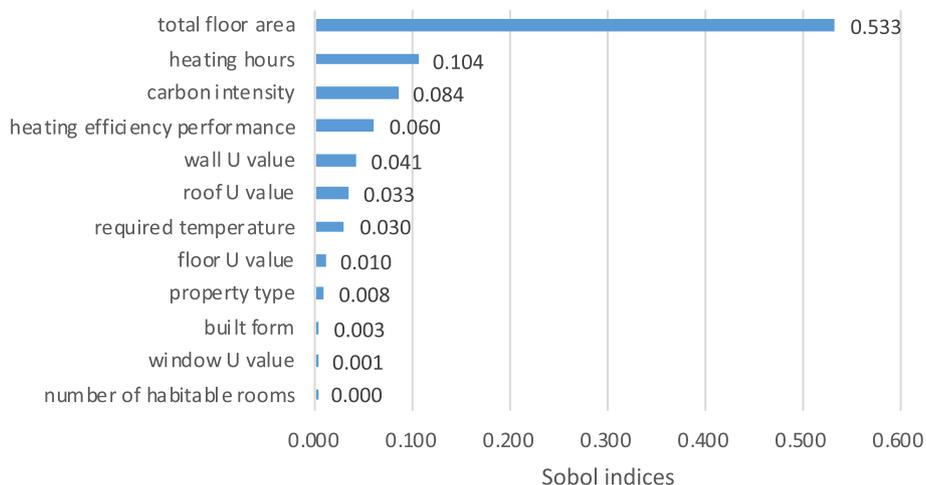
Fig. 9. Global sensitivity of teleworker's extra domestic carbon emissions when heating the entire property.
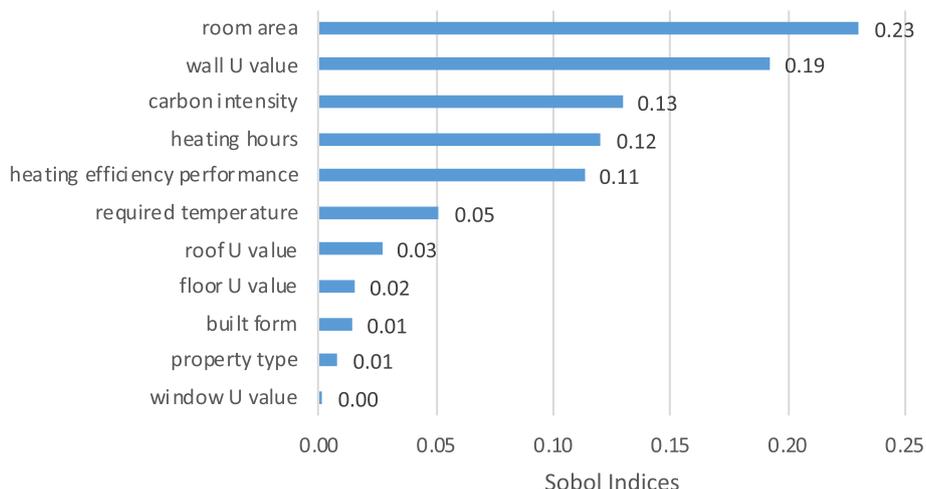
Fig. 10. Global sensitivity of teleworker's extra domestic carbon emissions when heating one room.

the difference in transport-related emissions between English teleworkers and non-teleworkers [47].

Our main finding is that, on average, English teleworkers have significantly higher emissions than non-teleworkers. This finding runs counter to the common expectation that teleworking reduces emissions and has two explanations. First, the savings in transport-related emissions from teleworking are either small or non-existent, owing to teleworkers having longer commutes than non-teleworkers, as well as engaging in more non-commute travel in the days when they work from home. Second, teleworkers heat and light their dwellings when they work from home, and this leads to significant additional emissions - particularly if they choose to heat their entire dwelling rather than a single room.

Specifically, we estimate that a full-time teleworker (5 days/week) has 117% higher domestic energy demand and carbon emissions than a non-teleworkers if they heat their entire home for three hours per teleworking day to 21 °C, but only 11% higher if they heat only one room for one extra hour to 19 °C. When considering transport and domestic carbon emissions combined, we estimate that high-frequency teleworkers (3–5 days/week) have 24–30% higher emissions than non-teleworkers, while low-frequency teleworkers (1–2 days/week) have 0–17% higher emissions. These ranges reflect different assumptions for heating area, heating time

and internal temperature during the periods when the teleworker is working from home, and each estimate employs the mean difference in transport emissions between teleworkers and non-teleworkers derived from the earlier study by Shi et al [47]. Domestic emissions make a bigger contribution to the overall difference in emissions for high-frequency teleworkers because they heat their houses for more days in the week. In contrast, transport emissions make a bigger contribution to the overall difference for low-frequency teleworkers because their longer commute distances more than offset their savings from fewer commutes (Fig. 8). The overall difference in emissions between teleworkers and non-teleworkers therefore depends in a complex way upon both transport-related and building-related variables that vary between individuals and change over time. However, our results strongly suggest that, in aggregate, teleworking has achieved little or no emission savings in England in the recent past.

Our results also indicate that teleworker's additional domestic energy demand is much higher than the reduction in office energy demand. Based on a study of post-pandemic office energy demand in the UK [34], teleworking 1.5–2 days a week reduces the utilisation rate of office space from 85% to 60%, which reduces the energy demand of an 8890 m^2 office with 575 workstations from 969 MWh to 874 MWh a year, equivalent to 165 kWh per worker per

year. Our results show that teleworking 5 days a week requires 870–4001 kWh more energy at home depending on the heating time and required temperature (Table 8; this means teleworking 1.5–2 days a week requires 261–1600 kWh more energy at home, which is 58–870% higher than the reduction in office energy demand estimated by Mantesi et al. [34].

To capture the environmental benefits from teleworking in England, it will be essential to reduce the emissions associated with household heating. This conclusion also applies to other regions in cold climates, such as France and Germany, where heating energy demand is significant and sensitive to occupancy. In contrast, emissions from household air-conditioning may be a major concern in warm regions such as Southern China, Japan and Indonesia. Emissions from heating and cooling are especially significant for high-frequency teleworkers, whose additional domestic emissions currently outweigh their transport emission savings by a factor of 2 to 4. It is particularly important to reduce the area heated when working from home. For example, we estimate that confining heating to a single room would reduce domestic emissions by $\sim 60\%$. However, domestic emissions will become less important in the future as households shift from gas boilers to air source heat pumps and as electricity generation shifts to low carbon sources. For example, we estimate that installing air source heat pumps would halve the additional domestic emissions from teleworking, even if the carbon intensity of electricity generation remained unchanged.

Our estimates of the additional domestic energy use and emissions from teleworking exceed those from earlier studies [30,48,13]. The reasons for this difference are unclear, although the poor-quality housing in England may play a role. In addition, our results contradict several previous studies that found that teleworkers have lower energy demand and emissions than non-teleworkers (e.g., [35,17,46]). This difference primarily results from our assumptions for the transport emissions associated with teleworking. Based upon the results from Shi et al. [47] and Caldarola and Sorrell [10], we assume that English teleworkers have transport emissions that are comparable to or greater than those for non-teleworkers owing to their longer commutes and additional non-commute travel.

We also conduct a global sensitivity analysis to assess the relative importance of variables contributing to the variance of teleworker's domestic carbon emissions. We find that behavioral factors are more important than building factors, but the standard of wall insulation is very important. The most important variable is the area heated when working at home, which illustrates the importance of multi-zonal control. The next most important variables are carbon intensity of heating fuel, the number of heating hours, and energy efficiency performance of heating system----which indicates the importance of reducing heating times and switching to efficient and low carbon heating systems.

There are at least four limitations to this study. First, the carbon emissions are estimated by combining a building engineering model with data on building archetypes, but real energy meter data is not used. The reliability of the results depends on the model. Second, the study only considers heating, lighting and ICT use at home that may underestimate teleworker's domestic emissions, because teleworkers probably use other appliances more often at home than non-teleworkers such as washing machine, cooker and showers. Third, this study uses monthly average external temperature instead of heating degree-days following the building model RdSAP 2012. Measuring the difference between internal and external temperature may not be as accurate as estimating the number of days when heating actually happens. Fourth, although historical simulation considers correlations between variables, it neglects some values that did not occur in historical data [43]; Markov Chain Monte Carlo simulation may be a better option for future studies.

Data availability

Data availability All data created during this research is openly available from the Mendeley Data Archive at [DOI:10.17632/yrzjjcpms8.1].

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yao Shi reports financial support was provided by Centre for Research on Energy Demand Solutions (CREDS).

Appendix – Our model

Our model is modified based on Reduced Data Standard Assessment Procedure 2012 version 9.94 (RdSAP 2012) [1]. The extra assumptions we made are underlined.

Energy and carbon emissions

Assume each property only has one heating system a, then annual space heating fuel (kWh)

$$E_{H,a} = \sum_{m=1-5\&10-12} E_{H,m}/\eta_a + \sum_{m=6-9} E_{H,m}/\eta_a/2 \qquad (1)$$

where $E_{H,m}$ is space heating requirement in the month m (kWh), η_a is Coefficient of Performance (COP) of the heating system a. RdSAP 2012 assumed that no space heating is required in June, July, August and September, so does our model.

Annual additional carbon emissions from space heating for one teleworker compared to one non-teleworker

$$\Delta CO2_{heat} = CF_a * E_{H,a} \qquad (2)$$

where CF_a is carbon emission conversion factor for the fuel for heating system a.

Modified from RdSAP 2012 Item 13, Table 9c Allinson [1], space heating requirement in the month m (kWh)

$$E_{H,m} = 0.008 * n_m * (L_m - \cup_m * G_m) * f_{TW} \qquad (3)$$

where the constant is changed from 0.024 to 0.008 since working hours in a day is approximately 8 h instead of 24 h, n_m is the number of working days in the month m (assumed to be 21.75), $\cup_m$ is utilization factor for gains in the month m, G_m is total heat gain for the month m, f_{TW} is teleworking frequency.

Heat loss rate for the month m (Watts)

$$L_m = H * (T_{i,m} - T_{e,m}) \qquad (4)$$

where H is the heat transfer coefficient, $T_{i,m}$ is the working-day mean required internal temperature for the month m, $T_{e,m}$ is external temperature for the month m.

Total heat gains in the month m (Watts)

$$G_m = G_{I,m} + G_{S,m} \qquad (5)$$

where $G_{I,m}$ is total internal gain for the month m, $G_{S,m}$ is total solar gain for the month m.

The following paragraphs will explain, internal gain, solar gain, heat transfer coefficient which leads to dwelling dimensions and ventilation rate, and mean internal temperature.

Internal gains

Assume teleworker only has metabolic gains, lighting gains from his/her home office area, appliances gains from ICT devices, and cooking gains.

Metabolic gains in the month m (Watts)

$$G_{pl,m} = 60 * n_{pl} \qquad (6)$$

where n_{pl} is the number of occupants (assumed to be one because we are calculating one teleworker's energy and emissions).

Lighting energy used in the month m (Watts)

$$E_{L,m} = E_L * [1 + 0.5 * cos(2 * \pi * (m - 0.2)/12)] * n_m/365 \qquad (7)$$

where E_L is annual lighting energy used, n_m is the number of working days in the month m (assumed to be 21.75 days).

Lighting gains in the month m (Watts)

$$G_{L,m} = 0.85 * 1000 * n_m * E_{L,m}/24 \qquad (8)$$

Appliance energy used in the month m (Watts)

$$E_{A,m} = E_A * \left(1 + 0.157 * cos\left(2 * \pi * \frac{m - 1.78}{12}\right)\right) * n_m/365 \qquad (9)$$

where E_A is annual appliance energy used, here it is only from ICT devices.

Appliance gains in the month m (Watts)

$$G_{A,m} = n_m * E_{A,m} * 1000/24 \qquad (10)$$

where $E_{A,m}$ is energy use for appliances in the month m.

Cooking gains in any month m is assumed to be 10 Watts

$$G_{C,m} = 10 \qquad (11)$$

Pumps and fans gains in any month m is assumed to be 10 Watts

$$G_{PF,m} = 10 \qquad (12)$$

Total internal gains in the month m (Watts)

$$G_{I,m} = G_{pl,m} + G_{L,m} + G_{A,m} + G_{C,m} + G_{PF,m} \qquad (13)$$

Solar gains

Solar gain factor

$$SGF = 0.9 * SA * A_{wd} * T * FF \qquad (14)$$

where SA is winter solar access factor (assumed to be 0.77), T is transmittance (assumed to be 0.63), FF is fill factor (assumed to be 0.7).

Solar gains in the month m (Watts)

$$G_{S,m} = \sum SGF * R_m \qquad (15)$$

where R_m is solar radiation for the month m.

Heat transfer coefficient

Fabric heat loss (W/K)

$$Q_f = \sum A_i * U_i \qquad (16)$$

where A is net extra area one teleworker uses compared to one-teleworker (m^2), explained in "Dwelling dimensions" Section below, U is U-value (W/m^2K), i is solid door, window, ground floor, exposed floor, external wall and roof.

Heat capacity

$$C_m = \sum A_i * K_i \qquad (17)$$

where K is K-value (kJ/m^2K), assumed to be 20 for exposed floors, 9 for roofs, 190 for external walls, 180 for party walls, 40 for party floors.

Thermal mass parameter

$$TMP = C_m/TFA \qquad (18)$$

where TFA is total floor area one teleworker uses compared to one non-teleworker (m^2).

Total fabric heat loss

$$Q_t = Q_f + TMP \qquad (19)$$

Ventilation heat loss

$$Q_v = 0.33 * EAC * V \qquad (20)$$

where EAC is effective air change rate, explained in "Ventilation rate" Section below, V is dwelling volume, explained in "Dwelling dimensions" Section.

Heat transfer coefficient (W/K)

$$H = Q_t + Q_v \qquad (21)$$

Heat loss parameter (kJ/m^2K)

$$HLP = H/TFA \qquad (22)$$

Dwelling dimensions

As there is no data on internal dimensions in the EPC database, we estimate window area, door area, wall area, and roof area.

Window area is estimated according to its age band (Table 1a). Assume external door area is 1.85 m^2

$$A_{dr} = 1.85 \qquad (23)$$

Assume the length to width ratio (θ) is 1.5:1, then property width is $\sqrt{TFA/\theta}$, length is $\theta\sqrt{TFA/\theta}$; hence, we can obtain external wall area (Table 1b).

Assume every house has two floors and no basement floor, then roof area for flat/maisonette is the same as total floor area, roof area for house is estimated as

$$A_{rf} = 1/2 * TFA/cos(30^o) \qquad (24)$$

Roof area for bungalow is

$$A_{rf} = TFA/cos(30^o) \qquad (25)$$

Dwelling volume

$$V = \sum TFA * h \qquad (26)$$

where h is average floor height (m).

Ventilate rate

Assume the numbers of ventilation-related items follow Table 1c, then ventilation rate is 50 m^3/h.

According to assumptions in Table 1c, air changes (m^3/h)

Table 1A
Window Area (m^2).

Age band	House/bungalow	Flat/maisonette
I, II & III: before 1949	$A_{wd} = 0.1220TFA + 6.875$	$A_{wd} = 0.0801TFA + 5.580$
IV: 1950–1966	$A_{wd} = 0.1294TFA + 5.515$	$A_{wd} = 0.0341TFA + 8.562$
V: 1967–1975	$A_{wd} = 0.1239TFA + 7.332$	$A_{wd} = 0.0717TFA + 6.560$
VI: 1976–1982	$A_{wd} = 0.1252TFA + 5.520$	$A_{wd} = 0.1199TFA + 1.975$
VII: 1983–1990	$A_{wd} = 0.1356TFA + 5.242$	$A_{wd} = 0.0510TFA + 4.554$
VIII: 1991–1995	$A_{wd} = 0.0948TFA + 6.534$	$A_{wd} = 0.0813TFA + 3.744$
IX: 1996–2002	$A_{wd} = 0.1382TFA - 0.027$	$A_{wd} = 0.1148TFA + 0.392$
X & XI: 2003 onwards	$A_{wd} = 0.1435TFA - 0.403$	$A_{wd} = 0.1148TFA + 0.392$

Note: this table is adapted from Table S4 in RdSAP 2012 [1]. TFA is the extra total floor area (m^2) that one teleworker uses compared to one non-teleworker.

Table 1B
External Wall Area (m^2).

Built form	External wall area
Detached	$A_{ew} = 2*(\theta+1)*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$
Semi-detached	$A_{ew} = (2*\theta+1)*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$
Mid-terrace	$A_{ew} = 2*\theta*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$
End-terrace	$A_{ew} = (2*\theta+1)*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$
Enclosed mid-terrace	$A_{ew} = \theta*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$
Enclosed end-terrace	$A_{ew} = (\theta+1)*\sqrt{TFA/\theta}*h - A_{wd} - A_{dr}$

Table 1C
Ventilation Rate.

Item	Ventilation rate ($m^3/hour$)	Assumed number
Chimney	40	1
Open flues	20	0
Intermittent fans	10	1
Passive vents	10	0
Flueless gas fires	40	0
Total	**50**	

$$AC = 50/V \tag{27}$$

Window infiltration

$$I_w = 0.25 - 0.2 * \varnothing \tag{28}$$

where $\varnothing$ is the percentage of windows and doors draught proofed (assumed to be 0.2).

Assume every property has no draught lobby, then infiltration rate

$$I = AC + I_w + I_s + I_f \tag{29}$$

where I_s is structural infiltration, I_f is floor infiltration.

Assume every property has masonry construction, sealed suspended wooden floor, then

$$I_s = 0.25, I_f = 0.35 \tag{30}$$

Assume 2 sides of a house is sheltered, 4 sides of flat/maisonette are sheltered, then infiltration rate incorporating shelter factor

$$Isf = I * (1 - 0.075 * n_s) \tag{31}$$

where n_s is number of sides sheltered.

Wind adjusted infiltration rate

$$Iw = Isf * w_m/4 \tag{32}$$

where w_m is average wind speed for the month m.

Effective air change rate

$$EAC = 0.5 + 0.5 * Iw^2 \tag{33}$$

Required internal temperature

Required internal temperature is assumed to be 19, 20 or 21 °C (°C)

$$T_i = 19, 20 \, or \, 21 \tag{34}$$

Time constant

$$\tau = TMP/3.6/HLP \tag{35}$$

where *TMP* is thermal mass parameter (kJ/m²K), *HLP* is heat loss parameter (kJ/m²K).

Temperature constant

$$T_c = 1 + \tau/15 \tag{36}$$

Temperature without heating (°C)

$$T_{SC,m} = R * (T_{e,m} + \eta * G_m/H) \tag{37}$$

where *R* is responsiveness of main heating system (assumed to be 1), $T_{e,m}$ is external temperature for the month m, η is utilization factor (assumed to be 1), G_m is total heat gain in the month m, H is heat transfer coefficient.

Temperature reductions (°C)

$$u_t = \begin{cases} (T_i - T_{SC}) * (T_{off} - 0.5 * T_c)/12, if T_{off} > T_c \\ T_{off}^2 * \frac{(T_i - T_{SC})}{(24*T_c)}, if T_{off} \leq T_c \end{cases} \tag{38}$$

where T_{off} is teleworking day heating off hours, assumed to be 5, 6 and 7 h out of 8 h per working day, so heating time is 3, 2 and 1 h accordingly.

Teleworking-day mean internal temperature for the month m (°C)

$$T_{i,m} = T_i - u_t \tag{39}$$

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