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Reguis, Antoine; Currie, John; Tunzi, Michele

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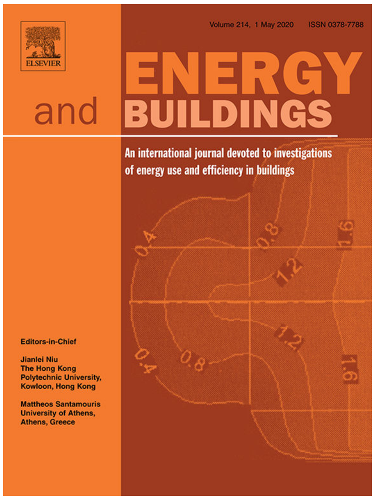

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Authors

Antoine Reguis, Edinburgh Napier University, 10 Colinton Road, EH10 5DT, Edinburgh – UK (corresponding author: a.reguis@napier.ac.uk)

John Currie, Edinburgh Napier University, 10 Colinton Road, EH10 5DT, Edinburgh - UK

Michele Tunzi, Technical University of Denmark, Kgs. Lyngby - DK

Title

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Abstract

As part of the decarbonization of its existing building stock the UK needs to replace gas boilers with heat pumps and low-temperature heat networks. Both technologies are efficient at supply temperatures of 55°C, with a maximum of 70°C for heat networks, when existing systems have been designed to operate at 82°C. Most space heating systems are expected oversized and operate most of the year in part-load, which facilitate the temperature reduction, but little is known about the degree of oversizing. This paper uses the case study of a pre-1919 school in Edinburgh to evaluate the true oversizing of its heating system and its consequences on minimum supply temperatures. This building is still equipped with single glazing and is therefore a worst-case scenario. An oversizing of 32% was estimated which enables the use of a supply temperature below 70°C all year round. Moreover, the supply temperature can be kept below 55 °C all year round during daytime due to internal heat gains. In conclusion, this building shows a nascent readiness for low-temperature heat. It would benefit from energy efficiency measures such as double-glazed windows, but this is not pre-requisite. Those results are important for the heat network industry when sizing their systems, but also energy and asset managers when they schedule renovation programmes to have their buildings low-temperature-ready.

Highlights

- A pre-1919 primary school with single glazing in Edinburgh has an oversizing of its space heating system of 32% at design conditions.
- Supply temperature can be operated below 70°C all year round.
- Supply temperatures can be reduced below 55°C all year-round during daytime.

Keywords

Oversizing, low temperature, space heating system, public buildings, 4GDH, district heating, non-domestic, Scotland, UK

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1 Introduction

The United Kingdom has set a target to reach net-zero emissions by 2050 and Scotland has the aim to reach this target by 2045 [1]. Heat represents 53% of the total final energy consumption in Scotland [2] and relies dominantly on the consumption of natural gas. The new building standards in Scotland highlights that new or fully replaced heating systems needs to be zero direct emissions at the point of use. This new standard is enforceable by the 1st of April 2024. District heating and heat pumps are expected to play a significant role [3], along with direct heating [4], [5]. District heating is more frequently called heat network in the UK. Heat networks delivered 0.8 TWh of heat in Scotland in 2021 and 90% of them operate using natural gas [6]. The heat delivered by heat networks should reach 2.6 TWh by 2027, 6 TWh by 2030 [7], and 7 TWh by 2037 [8]. They must rely on low-carbon, low-temperature heat. Such low-temperature heat networks facilitate the integration of renewable energy, sector coupling, flexibility within a wider energy system, and can harvest low-grade heat which are widely available throughout EU [9], [10], [11], [12]. Space heating systems in existing buildings in the UK have been designed to operate at 82/72 °C when the new generation of district heating (4th generation, or 4GDH) and heat pumps need to operate at supply temperatures not higher than 55°C to maximize their efficiency. For heat networks, it is deemed acceptable to increase the supply temperature to 70 °C during the coldest days [13]. More generally, 55 °C is the maximum flow temperature in newly installed or fully replaced heating systems in England and Wales [14], [15]. In Scotland, the new “Net Zero Public Sector Buildings Standard” highlights the need to heat buildings with low-temperature heat [16].

As 80% of existing buildings will still be in use in 2050 [17], this raises the question of their ability to operate with reduced temperatures. This question has been explored extensively in Scandinavia where it is widely accepted that existing heating systems have a “nascent readiness” for low-temperature heat [18], [19]. This readiness is the result of heating systems being oversized for the true heat load of the building. They are sized for extreme conditions (design conditions) which rarely occur; therefore, they operate all year round in part-load, which enables a reduction in the operating temperatures. Internal Heat Gains (IHG) and retrofit programmes are also reducing the heat load [20] while space heating systems are usually replaced like for like [21]. If a building shows some limitations to use low-temperature heat, this is expected to be related to faults or malfunctions in the hydraulic system, like bypasses, or faulty controls or valves [22], [23].

Heat networks are widely deployed in Scandinavian countries where the 3rd generation of district heating (3GDH) is a mature technology. The transition towards reduced temperature (4GDH) enables DH to have a central role in a 100% renewable energy system [24] but has implications on all components of the existing infrastructure, from the production units, pipelines, thermal substations, and heating systems within buildings [25]. In the UK, the development of new heat network schemes presents an opportunity to size them for reduced operating temperatures at design stage and will make them fit for purpose.

The challenge lies in the existing building stock which needs to be able to use those reduced temperatures.

Research and findings in Scandinavia should be carefully exported into a UK context [19] as the building stock in the UK is one of the oldest in the EU and performs poorly compared to other EU countries. This is particularly true for post-1990 buildings with mechanical ventilation, especially in windy condition [26]. This is illustrated by the fact that when a domestic building is retrofitted with a heat pump it is often assumed that some heat emitters are large enough. A typical replacement rate is 20% in Denmark [27] and this goes up to 33% to 50% in the UK [28]. An initiative to implement a heat pump in a non-domestic building without retrofit of the envelop was undertaken by London South Bank University but the heat pump is a high temperature one able to match the supply temperatures of gas boilers [29]. This highlights the likely differences between Scandinavia and the UK.

There are two factors to consider in evaluating if a heating system can operate with reduced temperatures. The first is the energy performance of the building and the second is the oversizing of its heating system.

Energy efficiency measures will improve the U-value of the envelope and its airtightness, and they are at the core of national energy transition strategies. For example, the Scottish Government has announced a target to reach an energy use performance of 67 kWh.m^{-2}.year^{-1} for every school replaced or upgraded under its Learning Estate Investment Programme [30]. All buildings in Scotland are expected to go through energy efficiency measures and the details and timescale of the renovation work is currently discussed in the "Heat in Buildings Bill consultation" [31]. This is well in line with the revised European EPBD which provides targets to reduce the energy used by the building sector [32]. The pace of annual deep renovations, currently 0.2%, should be increased to 3% to reach 2030's targets [33]. Such measures will facilitate the use of low-temperature heat, but they might not be implemented when a building needs to connect to a low carbon source. Schedules for retrofit programmes can be different from the schedules of heat network roll-out.

A well-functioning space heating system in the UK can operate below 70 °C for 98% of the year and below 55 °C for 71% of the year [34] but this is affected by the energy performance gap of the building and the oversizing of its heating system. The performance gap is defined as the difference between the design and as-built energy use. Previous work from the authors has highlighted the scale of the performance gap of Scottish public buildings but showed that temperature reduction is possible. This reduction is especially possible in older buildings, as they have a limited performance gap compared to more recent constructions [34]. However, more recent buildings are often equipped with underfloor heating which makes then suitable for reduced temperature, even if they show a significant performance gap. This previous work was based on average daily outdoor temperature, a typical approach to evaluate building performances, but which overlooks intraday specific load.

Investigations relating to the oversizing of heating systems in the UK are very limited and often focus on the boiler's capacity which can differ significantly from the sizing of heat emitters installed. For example, the plant room can be designed with redundancy capacities. The size or oversizing of the space heating system does not show any correlation with the classic building parameters [35], [36]. To better understand the performance of the building stock, the Scottish Government has introduced in 2023 the Building Assessment Report (BAR). This duty applies to non-domestic buildings that Scottish public authorities have an interest in as specified by section 67 (a) of the Heat Networks (Scotland) Act 2021 [37], [38]. Buildings with an annual energy use of less than 73 MWh are excluded from the duty. Although it is mentioned that this duty is "to help assess the suitability of a non-domestic property for connecting [34] to a heat network", limitations are also highlighted as "The primary use of BAR information is to inform decisions on the particular suitability of areas for the construction and operation of a heat network, and subsequently to inform designation decisions, should these areas be progressed for consideration for designation". In conclusion, the completion of BAR will not provide a direct assessment of the ability to connect a property. For example, the capacity of the heating system is based on the rated thermal output (peak output) of the heat sources (gas boiler in most buildings) while the true enablers to use low-temperature heat are the final emitters.

The development of new district heating schemes relies on the connection of public buildings as they provide anchor loads and contribute to de-risk projects [3], [39]. Public building stock are mainly constituted of education buildings (82% in Scotland). The largest group of buildings is the post-war group (1946-1979) which were built before the introduction of maximum U-Values in UK building regulations introduced in 1979 [34]. In Edinburgh, the second largest group is the pre-1919 one with 23% of the floor area. Finding the right balance between heat demand reduction and decarbonisation of heat supply is a complex but essential question and [40] highlights that there is not a definitive answer. At a municipal level, planning the energy transition is a complex challenge [41] but a widely accepted approach is the need to better understand the energy performance of anchor load buildings. This is of high importance for energy and asset managers when they set-up retrofit programmes to have their buildings low-temperature ready. It is also of significant importance to help energy supply companies when they seek to size their systems or calculate the expected efficiencies.

Aim and Novelty: The aim of this paper is primarily focussed on evaluating the oversizing of the space heating system in a pre-1919 school in Scotland, and how it impacts its ability to use low-temperature heat.

The novelty of this paper lies in the definition and evaluation of an oversizing for space heating systems in non-domestic buildings in the UK. To the best of our knowledge, such investigation does not exist. It also lies in the intra-day heat load profiles to evaluate the maximum and minimum supply temperatures which can be adopted.

Outcomes from this paper are of interest for the heat network industry, asset managers as they need to have their buildings "low-temperature-ready", and the research community when it comes to supporting retrofit strategies towards net-zero targets for the built environment.

The methodology is described in section 2 and the case study in section 3. The results are detailed in the section 4, with the evaluations of the installed and required capacities presented in section 4.1 and 4.2, the calculation of the optimised supply temperature in section 4.3. A sensitivity analysis for the heat losses through the internal pipe system and the boiler's efficiency is provided in section 4.4. The discussion with directions for further research is discussed in 5, with the conclusions in section 6.

2 Methodology

The investigation is based on the evaluation of the oversizing factor (OsF), sometime called radiator factor, of the space heating at design conditions. Knowing the OsF for design conditions enables calculation of the supply temperature of the space heating system. To calculate the OsF, it is necessary to evaluate the installed capacity of the heating system and the required capacity, as per Equation (1).

$$OsF = \frac{Installed\ Capacity\ (W)}{Required\ Capacity\ (W)} \qquad \text{Equation (1)}$$

The installed capacity of the space heating system includes the addition of the capacity of all the heat emitters in the system. The required capacity is an evaluation of the heat demand of the building in real operation. The OsF enables calculation of the degree of part load of the heating system and associated supply temperatures. OsF is evaluated for design conditions, but also daytime period and daily average conditions, as those loads have specific profiles. The methodology is detailed in section 2.1, 2.2, and 2.3 and summarised in the Figure 1.

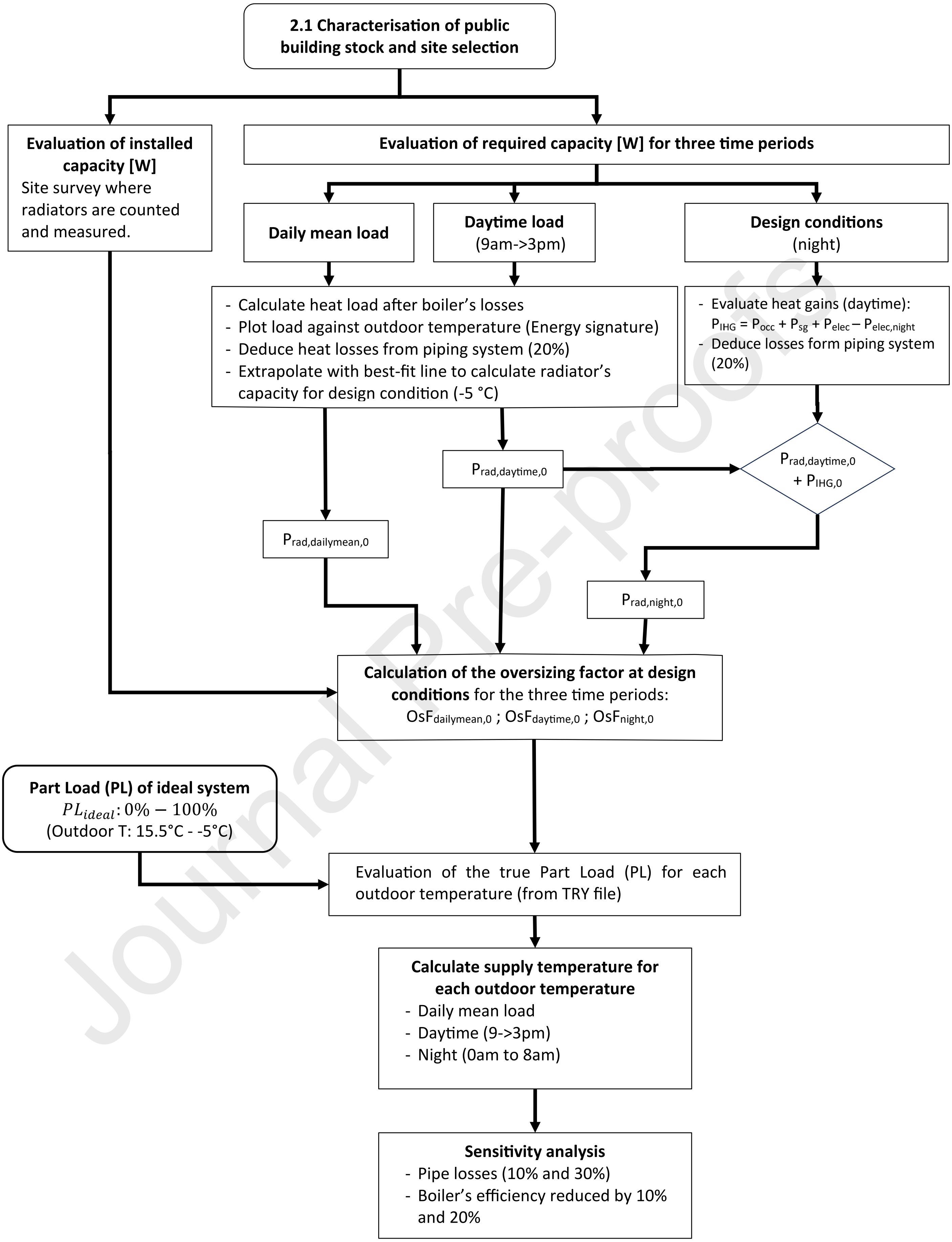

Figure 1: Methodology to evaluate oversizing of heat emitters.

2.1 Evaluation of the installed capacity

The evaluation of the installed heating capacity relies on a site survey where all radiators were counted and measured. Those characteristics were then compared with specifications from manufacturers like [42] or by using the tool developed by the Danish Technological Institute [43] to know their heat output capacities. For bare pipes used as heat emitters, heat outputs were evaluated with the guidance provided in [44]. The setting of all TRVs were recorded as this can impact on the minimum supply temperature required.

2.2 Evaluation of the required capacity

The evaluation of the required capacity of the heating system is based on the heat demand in real operation. Those values are provided by the Automatic Meter Reading (AMR) gas meter from the gas supply company and are recorded in kWh [45].

2.2.1 Daily and Daytime load

The method to calculate the required capacity of the radiators for daily and daytime period is similar. The average daily capacity is based on 24hr energy use, and the daytime is measured from 09:00 until 15:00. The mean outdoor temperature is used for those periods. The heating season considered for this study is from the 15th of October 2018 to 30th of April 2019. This is to avoid bias linked to the two 'lockdowns' related to the Covid-19 pandemic in March-June 2020 and December-April 2021, which have created disruptions in the school's occupation. Outdoor conditions come from the Met Office's weather stations in Edinburgh (Gogarbank and the Royal Botanic Garden) where hourly outdoor temperatures were retrieved. Filters have been applied to remove the holiday periods and weekends, but also Fridays, as schools in Edinburgh finish around lunch time on Fridays.

The power from the gas boiler ($P_{heating,daytime}$ and $P_{heating,daily}$) are provided by the half hour gas meters ($Q_{halfhour}$) for those time periods, and the efficiency of the gas boiler (η_{boiler}) is included as in Equation (2) and Equation (3):

$$P_{Heating,daytime}(W) = \frac{1}{6.5} \cdot \frac{1}{\eta_{boiler}} \sum_{i=09:00}^{i=15:00} Q_{gas,halfhour}\,(Wh) \qquad \text{Equation (2)}$$

$$P_{Heating,daily}(W) = \frac{1}{24} \cdot \frac{1}{\eta_{boiler}} \sum_{i=00:00}^{i=23:30} Q_{gas,halfhour}\,(Wh) \qquad \text{Equation (3)}$$

The gas boilers have a reported seasonal efficiency (η_{boiler}) of 79%. As those boilers are 20 years old, it is possible that their rated efficiency has deteriorated over time, however, there is little evidence of the degradation of efficiency of old gas boilers in literature. A loss of 10% and 20% of the performance would mean an efficiency reduction from 79% to 71% and 63% respectively. This has a direct impact on the evaluation of the heat demand from the building. A sensitivity analysis is carried out with those reduced values. The heat released in the building by the heating system ($P_{heating}$) comes largely from the heat emitters (P_{rad}) but also from the heat losses in the distribution system (P_{losses}) as in Equation (4).

$$P_{Rad} = (1 - R_{losses}) * P_{Heating}$$

Equation (4)

Those losses are estimated between 10% and 30% of the heat load [46], [47], [48]. A loss of 20% is used as a central value in this study. A sensitivity analysis is undertaken for values of 10% and 30%.

The power required at the radiator is plotted against the outdoor temperature. This method is called the energy signature, also called the change-point method. It is a simple, robust, and accurate method to characterise a building's energy use against outdoor climatic conditions [49], [50], [51].

The energy signatures for those two specific time periods are extrapolated to the design outdoor temperature to calculate the required power ($P_{Rad(dailymean),0}$ and $P_{Rad(daytime),0}$).

Finally, the ratio between the required capacity and the installed capacity provides the oversizing factor (OsF) for daily and daytime periods. The OsF enables calculation of the supply temperature for each outdoor temperature, as detailed in section 2.3.

2.2.2 Design conditions

The sizing of a heating system follows the traditional steps which are the identification of a design outdoor temperature and the evaluation of the heat load under steady-state mode, without internal or solar heat gains (IHG). For existing buildings, those design conditions rarely happen. At night, when there are no IHGs, most buildings in the UK are not in steady state mode as intermittent heating is the most common form of operation of heating system [52]. Intermittent heating is traditionally based on a timer which reduces the required room temperature to a lower setting during the night (night set-back) to provide energy and cost savings. This results in the heating system usually being switched off for the night. The re-start of the heating system is either based on a fixed clock/time but more and more frequently based on 'optimum start', a flexible time related to the outdoor temperature. During the daytime, a heating system operates more in steady state mode, but IHG reduces the heat demand. This is illustrated in the Figure 2.

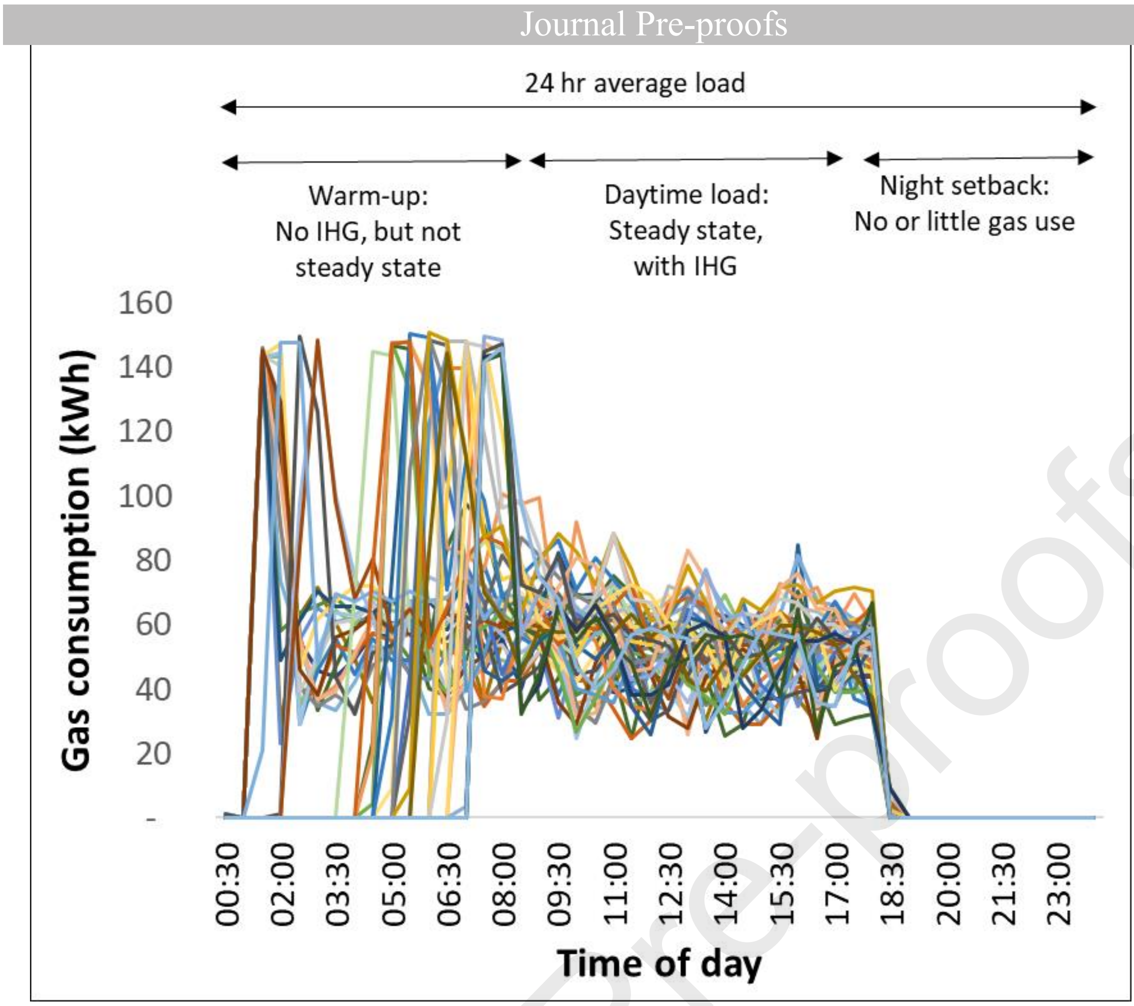

Figure 2: Typical gas use profile of a plant room for an intermittent heating system in a non-domestic building (half hour values for gas consumption during wintertime)

Therefore, to evaluate the heat demand in design conditions, IHGs are calculated and added to the daytime load, as per Equation (5).

$$P_{Rad(night)} = P_{Rad(daytime)} + P_{occ} + P_{elec(daytime)} - P_{elec(night)} + P_{sg}$$

Equation (5)

Where:

$P_{Rad(night)}$ [W]: Heat output from radiators during the night.

$P_{Rad(daytime)}$ [W]: Heat output from radiators during daytime.

P_{occ} [W]: Internal heat gain from the occupants.

$P_{elec(daytime)}$ [W]: Internal heat gains from the electrical consumption, during the day.

$P_{elec(night)}$ [W]: Internal heat gains from the electrical consumption, during the night.

P_{sg} [W]: Solar gains

The internal heat gains from the occupants (P_{occ}) relies on a work from [53] who calculated that heat gains are 51 W for a 5-year-old child and 92 W for a 12-year-old child. The average value of 73 W is used in this study for the children and a gain of 85 W per adult. For the internal heat gains from appliances (P_{elec}), it is considered that 100% of the electrical usage is eventually converted into heat [54].

The electrical consumption is measured by the Automatic Meter Reading (AMR) meter and values are recorded in kWh [45]. The electric consumption during the daytime is an internal heat gain. The electricity use at night ($P_{elec(night)}$) is deducted from the heat demand as they are considered permanent gains reducing the heat load. The electrical loads during daytime and nighttime are averaged where their typical load profile can be identified, with the following equations:

$$P_{elec(daytime)}(W) = \frac{1}{6.5} . \sum_{i=daytime\ profile\ (start)}^{i=daytime\ profile\ (end)} Q_{elec,halfhour}\ (Wh)$$ Equation (6)

$$P_{elec(night)}(W) = \frac{1}{4} . \sum_{i=night\ profile\ (start)}^{i=night\ profile\ (end)} Q_{halfhour}\ (Wh)$$ Equation (7)

Results from Equation (6) and Equation (7) are plotted against the outdoor temperatures to identify trendlines.

Solar gains (P_{sg}) are evaluated from the solar radiation data provided by the Met Office. The radiation reaching the windows are calculated using the sun's position [55], orientation and glazing area of the building.

The energy signature obtained is extrapolated to the Design Outdoor Temperature (-5 °C for Edinburgh) to find the required heat load for the radiators ($P_{Rad,o}$).

2.3 Calculation of supply temperature

The supply temperature is calculated for the three specific time windows: Night-time (00:30 – 08:30), Daytime (09:00 – 15:00), and over 24hr period. The 00:30-08:30 interval is chosen as this covers the coldest outdoor conditions; where the heating system needs to maintain the indoor set-point temperature during cold spells when the outdoor temperature is at its lowest and there is no IHGs. The 09:00-15:00 interval is chosen because the building is in steady state, and it represents the occupancy period in the school and the supply temperature can be reduced to a minimum. The mean daily outdoor temperature is sometime used to assess the capacity of a heating system. It is therefore interesting to compare it with the two other periods considered.

With the OsF evaluated for each period, the "true" part-load (PL) of the heating system is calculated. The part-load of an ideal system (PL_{ideal}) is between 100% at design condition (ie. Outdoor temperature of -5 °C for Edinburgh) and 0% when there is no heating demand (outdoor temperature of 15.5 °C). Space heating systems are not ideally sized, the true part load is therefore calculated using equation (*8*).

$$PL = \frac{PL_{ideal}}{1 + OsF}$$ equation (8)

The PL of a heating system is calculated for each outdoor temperature provided by a Test Reference Year (TRY). As the supply temperature can be expressed as a function of the PL, the supply temperature can be calculated for each day of a typical year, for each time period considered in the study. TRY files are available from CIBSE and are "weather file represents a typical year and is used to determine average energy usage within buildings. The weather file consists of average months selected from a historical baseline” [56].

The supply temperature T_s can be calculated from Equation (*9*) and equation (10). This enables calculation of T_s for each value of PL, where P (W) is the power at specific part-load and P_0 (W) the power at design condition.

$$PL = \frac{P}{P_o} = \left(\frac{LMTD}{LMTD_o}\right)^n$$ Equation (9)

$$LMTD = \frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)}$$ equation (10)

LMTD is the Logarithmic Mean Temperature Difference (McIntyre, 1986) between the radiator’s surface and the ambient room temperature T_i (°C), assumed as 20°C. The radiator exponent (n) has the typical value of 1.3 for standard radiators [58]. At design conditions, the supply temperature Ts_0 and the return Tr_0 are assumed 82 °C and 71 °C [59], [60].

T_r is the return temperatures from the radiator. The temperature-drop (ΔT) across the heating system is assumed constant at 11 °C as per equation (11). The assumption of a temperature drop of 11 °C across the heating system is not consistent with the definition of the 4GDH which recommends 55/25 °C, i.e. a drop of 30 °C. However, as space heating systems in the UK have been designed with a high flow and low ΔT, achieving a low return temperature in such systems, while desirable, might prove challenging. In this situation it can be preferable to keep a high flow/high return approach to optimise the supply temperature [61]. An optimised supply temperature with a limited temperature drop is therefore the preferred approach.

$$\Delta T = \Delta T_0 = T_s - T_r = 11°C$$ equation (11)

Equation (9), equation (10) and equation (11) are numerically recombined to express T_s as a function of the other variables, as detailed by equation (12) to equation (16).

$$PL = \left(\frac{\ln\left(\frac{T_{s0} - T_i}{T_{r0} - T_i}\right)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)}\right)^n$$ equation (12)

$$PL^{\frac{1}{n}} = \frac{\ln\left(\frac{T_{s0} - T_i}{T_{r0} - T_i}\right)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} = \frac{\ln\left(\frac{T_{s0} - T_i}{T_{s0} - \Delta\mathrm{T}_0 - T_i}\right)}{\ln\left(\frac{T_s - T_i}{T_s - \Delta\mathrm{T} - T_i}\right)} \qquad \text{equation (13)}$$

$$\ln\left(\frac{T_s - T_i}{T_s - \Delta\mathrm{T} - T_i}\right) = PL^{-\frac{1}{n}} .\ln\left(\frac{T_{s0} - T_i}{T_{s0} - \Delta\mathrm{T}_0 - T_i}\right) \qquad \text{equation (14)}$$

$$\frac{T_s - T_i}{T_s - \Delta\mathrm{T} - T_i} = e^{\left(PL^{-\frac{1}{n}}.\ln\left(\frac{T_{s0} - T_i}{T_{s0} - \Delta\mathrm{T}_0 - T_i}\right)\right)} \qquad \text{equation (15)}$$

For simplification purpose, we can write $A = e^{\left(PL^{-\frac{1}{n}}.\ln\left(\frac{T_{s0} - T_i}{T_{s0} - \Delta\mathrm{T}_0 - T_i}\right)\right)}$

Hence $T_s = \frac{(\Delta\mathrm{T} + T_i).A - Ti}{A - 1}$ equation (16)

3 Case study

The building stock of Scottish local authorities is largely composed of educational buildings with a large proportion of pre-1919 buildings in Edinburgh. Those solid stone buildings are often considered “hard-to-treat” and therefore they represent a special interest with regard to understanding their ability to use low-temperature heat [62]. Consequently, a pre-1919 primary school was selected for this study, with the selection criteria detailed in Table 1.

Table 1: Exclusion criteria to choose site for study.

Criteria
• Pre-1919 (date of build)
• Single type of use (no shared use with community centre)
• No swimming pool

The school selected for this study is a primary school built in 1894 (Photo 1). The school has a total floor area of 2,061m^2, spread over 4 floors. The ground floor and first floor occupy the whole footprint of the buildings while the basement and top floor have a small number of rooms. Ceilings heights vary from 2.5 to 4.9m. Windows are single-glazed sash and case. Occupancy is 269 children (aged 5-12) and 27 adults, which include teachers, admin, and support team [63]. The school is in use from 07:45 until 18:00 daily [64], however, most children arrive between 08:30 and leave the school between 15:00 and 15:30. During the heating season 2018-2019, heating was provided by 3 non-condensing boilers "Hamworthy Purewell 100", each with a nominal output capacity of 100 kW. They were installed in 1998 with an efficiency of 79% [65]. Heat emitters throughout the school were changed in 2021, with like-for-like installed capacity, and the new system comprised pressed steel radiators. They were connected in parallel and with Top-Bottom-Opposite-End (TBOE), which is in line with the manufacturer's recommendation to achieve nominal performance (Photo 2). The energy use intensity of this building is 169 kWh.m^{-2}.yr^{-1}. This is slightly better than the average performance of pre-1919 buildings in Edinburgh (174 kWh.m^{-2}.yr^{-1}) and significantly better than the average performance of pre-1919 non-domestic buildings across Scotland (211 kWh.m^{-2}.yr^{-1}) [34].

Photo 1: External view of the primary school. Main façade.

The temperature in the radiator circuits was weather compensated directly from the boiler, where the temperature can vary between 30 °C and 80 °C, as illustrated in the Figure 3, copied from the Building Energy Management System software. All radiators were equipped with Thermostatic Radiators Valves (TRV). Some bare pipes with casing were present in toilets and changing rooms. Domestic Hot Water was provided by a calorifier heated by 3x3 kW electric immersion elements with a secondary circulation pump. Internal heat gains from the school kitchen are limited as meals are prepared and cooked off-site.

Photo 2: Typical wall radiator, with insulated pipes and Top Bottom Opposite End (TBOE) connection.

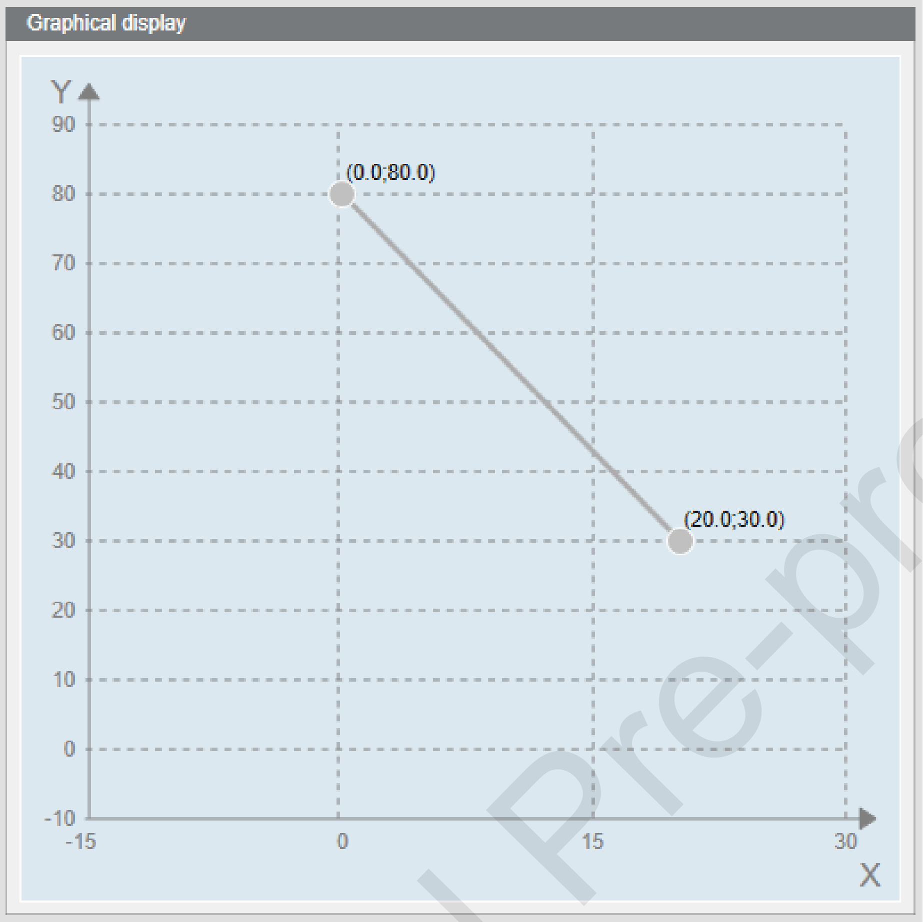

Figure 3: Weather compensated heating curve for the flow temperature in the radiator circuit.

4 Results and discussions

4.1 Evaluation of the installed capacity

The building was surveyed in December 2022 and all radiators were counted and measured. The total heat output capacity of the emitters is 196 kW, as detailed in Table 2. Heat output from the bare pipes and their casing represents less than 2% of the total installed capacity.

The capacity of the plant room (300 kW) exceeds by 53% the capacity of the final emitters (196 kW). The typical design recommendations are to have the boiler's capacity exceeding the heating system's capacity by 10 to 20%. This confirms the risk in evaluating a heating system's capacity based solely on the size of the plant room boilers.

Table 2: Capacity of installed heating system

Floor	Installed Capacity (kW)

Basement	11.9
Ground floor	92.2
First floor	79.3
Top floor	12.6
Total capacity	196.0 kW

The survey of the 64 radiators and their TRVs shows that they are set on a diversity of levels as illustrated in Figure 4. The TRV setting for a room temperature of 20 °C is “3” on a typical scale of 0 to 6. Figure 4 and Table 3 show the disparity of TRV setting throughout the school and within the same room. The uneven setting of TRV’s within the same room reduces the capacity of the heating system to use low supply temperature and increases the return temperature [66]. This highlights the importance of a regular check of TRV setting to enable a reduction in the operating temperatures. This is not currently a key metric for the performance of existing heating systems in the UK as most of the gas boiler in non-domestic buildings are non-condensing boilers. With the development of heat networks, it will be a necessity to have TRVs correctly set.

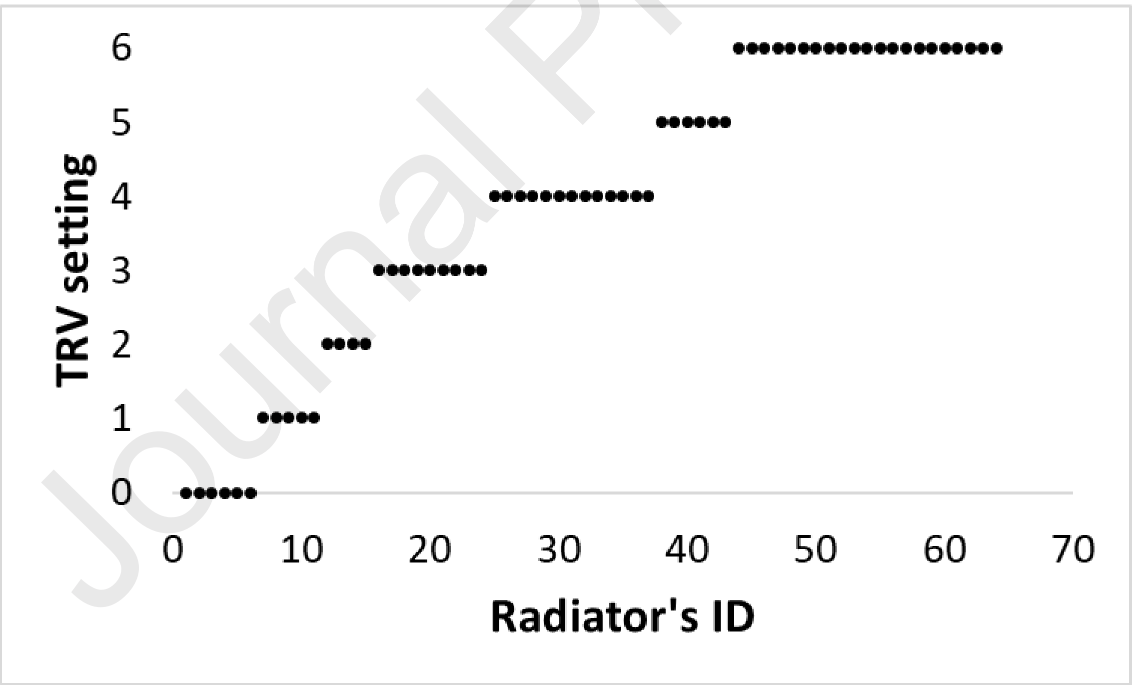

Figure 4: TRV settings for the 64 radiators in the school.

Table 3: TRV settings in rooms with more than one radiator.

Room type	TRV setting				
Classroom	0	6	6		
Classroom	0	6	6		
Classroom	6	6	4	6	3
Classroom	0	1	0		
Classroom	6	3	4	0	
Classroom	4	4	6		
Classroom	4	4	5	3	
Classroom	5	4	1		
Classroom	6	4			
Classroom	4	1	1	2	
Dining hall	6	6			
Gymnasium	5	4	4		
Office	6	6			
Office	6	5			
Office	4	2			

4.2 Evaluation of the required capacity

The daily pattern of half-hourly gas consumption for the winter months is shown in Figure 2. It clearly shows the warming up phase which starts between 01:00 and 08:00, the steady state phase when the school is occupied between 08:30 and 18:30, and the night set-back after 18:30. During the night set-back, the heating system is not in operation. The sharp peak is associated with the warmup of the space heating system which is linked to its volume of water and thermal inertia. This peak is an illustration of the capacity of the plant room, not the emitters [67]. A method to evaluate the emitter's required capacity is described in the following sections. The capacity is evaluated for the daily heat load, average day load, and design condition's load.

4.2.1 Daily and daytime load

The loads required at the radiators (P_{Rad}), calculated from Equation (2), Equation (3), and Equation (4), are plotted against the outdoor condition. The results for daily average and daytime loads are shown in Figure 5 and Figure 6.

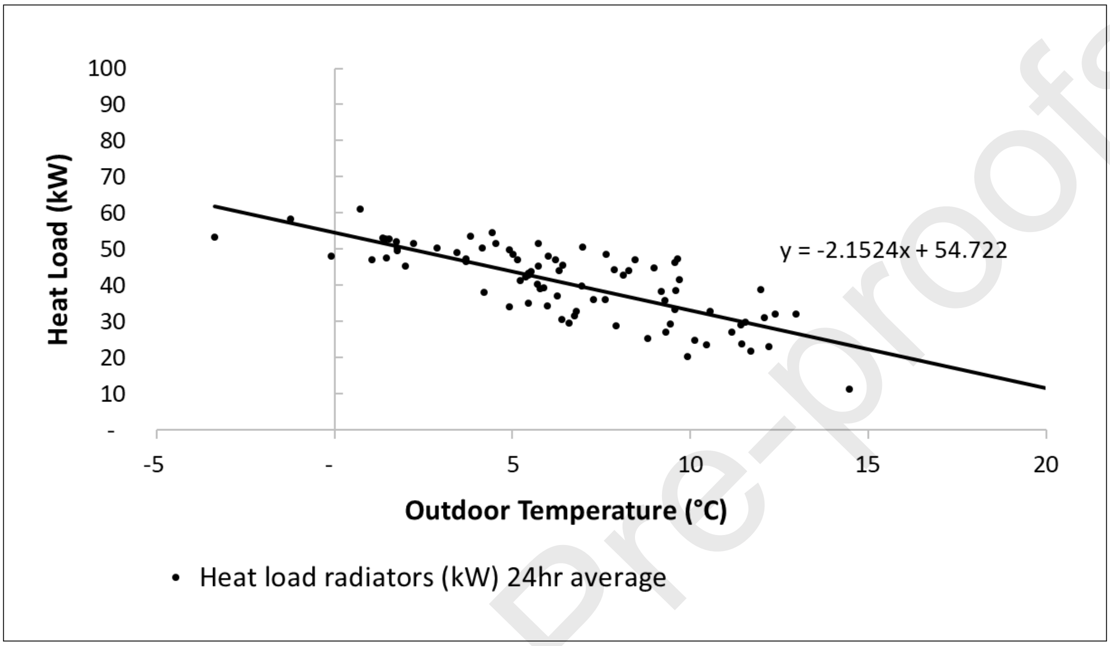

Figure 5: Daily average heat load at radiators.

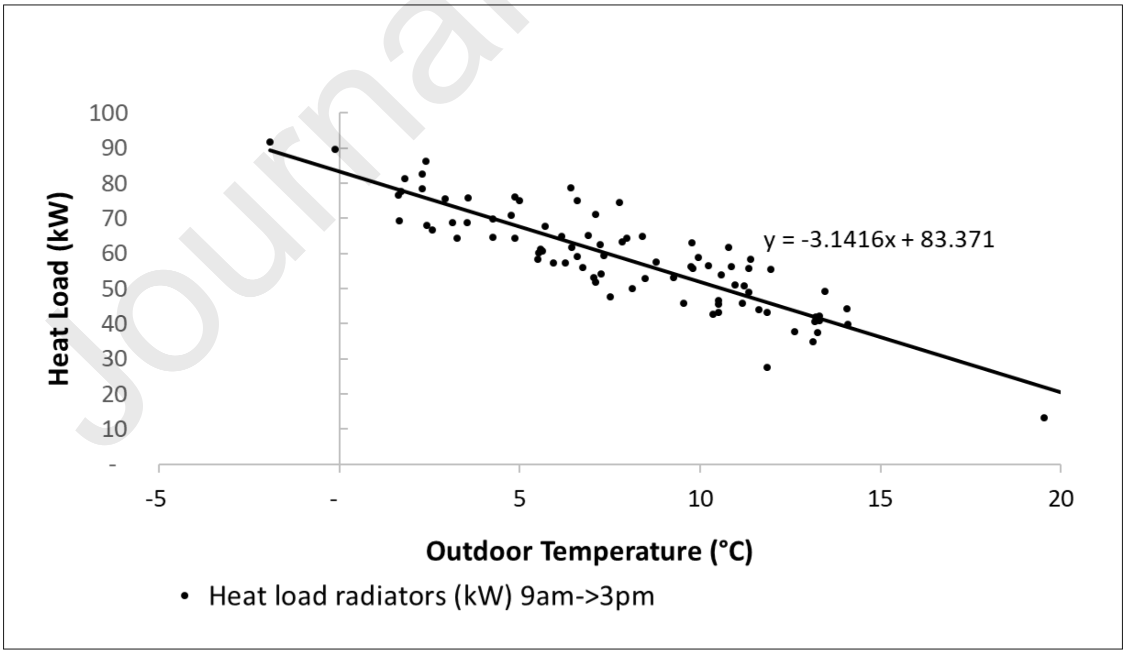

Figure 6: Daytime average heat load at radiators.

The best fit trendline enables to calculate the required capacity of the radiators at design conditions:

$$P_{rad(daily)}(\mathrm{W}) = -2.15 * T_{outdoor} + 54.72 \qquad \text{Equation 17}$$

$$P_{rad(daytime)}(\mathrm{W}) = -3.14 * T_{outdoor} + 83.37 \qquad \text{Equation 18}$$

It is worth noting that the heat load at the radiators is lower for the 24-hr average than the daily demand. Although this is counterintuitive, it is due to the night setback during which there is no gas demand.

The outdoor design temperature of -5 °C is introduced in the Equation 17 and Equation 18 to calculate the required power at the radiators for daily average load and daytime period. The results are 65kW and 99kW respectively. From this result, the oversizing factor can be calculated:

$$OsF_{daily\ average} = \frac{196}{65} = 3.0\ (ie.\,200\%)$$

$$OsF_{Daytime} = \frac{196}{99} = 2.0\ (ie.\,100\%)$$

The oversizings of the heating system are 200% and 100% for the average daily load and daytime load respectively.

4.2.2 Design conditions (peak load)

The internal heat gain from the electricity consumption shows two distinctive patterns with daily use ($P_{elec(daytime)}$) and night baseload ($P_{elec(night)}$). The daily pattern starts at 05:00 and finishes at 18:30 (Figure 7). Those energy loads are averaged for daytime and night time. Those loads are plotted against the outdoor temperature (Figure 8) and fitted with a linear trendline.

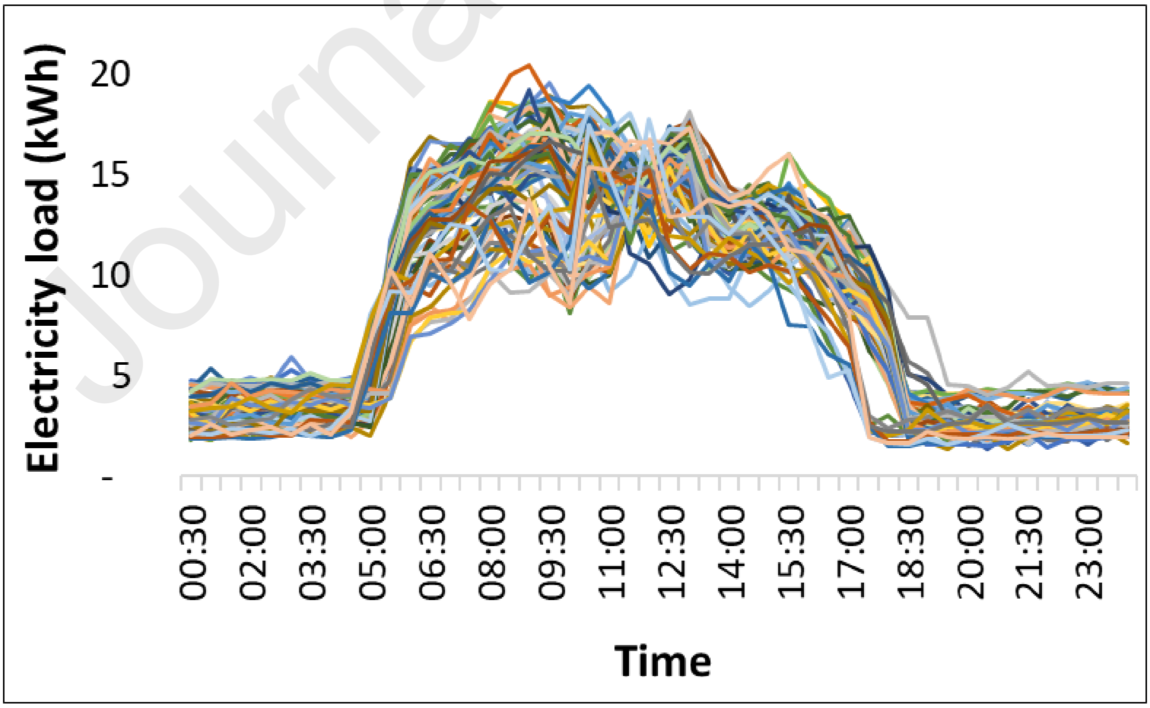

Figure 7: Daily pattern of electrical consumption (Half hour values, October 2018 to April 2019, Monday to Thursday).

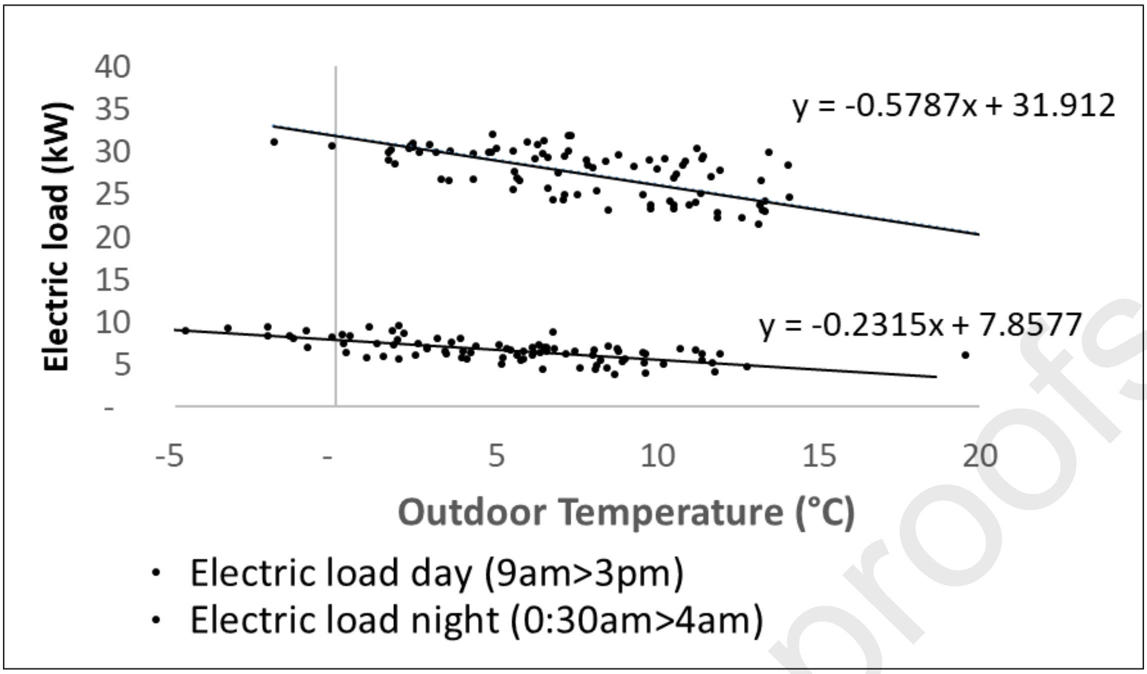

Figure 8: Energy signature of average electric load at night and daytime.

The internal heat gains from the occupants are calculated in Table 4 and are estimated to be 21.9 kW.

Table 4: Internal heat gains from occupants (P_{occ}).

Occupant	Number of occupants	Heat gain per person (W/person)	Total per group (W)
Adults	27	85	2,295
Child	269	73	19,637
	Total heat gains from occupants (P_{occ})		21,932

Solar gains (P_{SG}) are calculated between 2 kW and 38 kW, as shown in Figure 9.

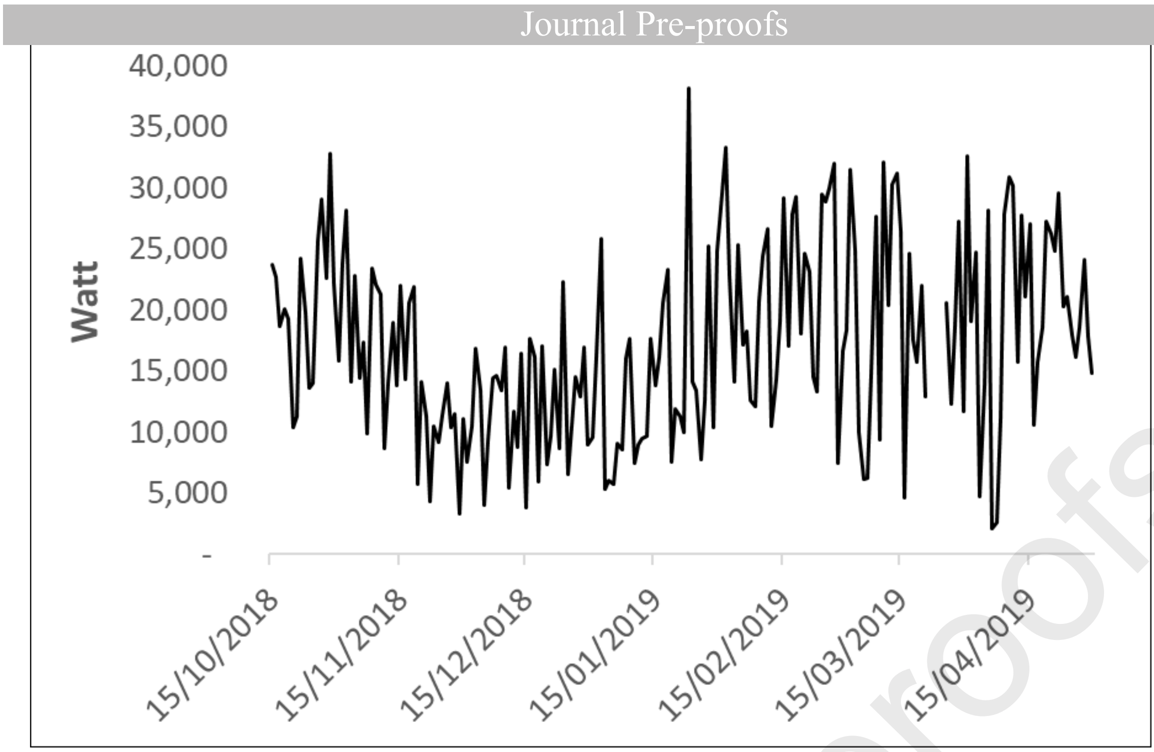

Figure 9: Calculated solar gains.

The total required capacity of the radiators (P_{rad}) can be calculated from the Equation (5):

$$P_{Rad(night)} = P_{Rad(daytime)} + P_{occ} + P_{elec(daytime)} - P_{elec(night)} + P_{sg}$$

Where:

$P_{Rad(daytime)} = -3.14 * T_{Outdoor} + 54.72_{Rad(daytime)}$

$P_{Occ} = 21{,}9\ (kW)$

$P_{Elec(daytime)} = -0.58 *\ T_{Outdoor} + 31.91$

$P_{Elec(nightime)} = -0.23 *\ T_{Outdoor} + 7.86$

$P_{SG} = \text{cf. Figure 9}$

The result is shown in Figure 10, and the equation of the trendline is represented by the Equation 19.

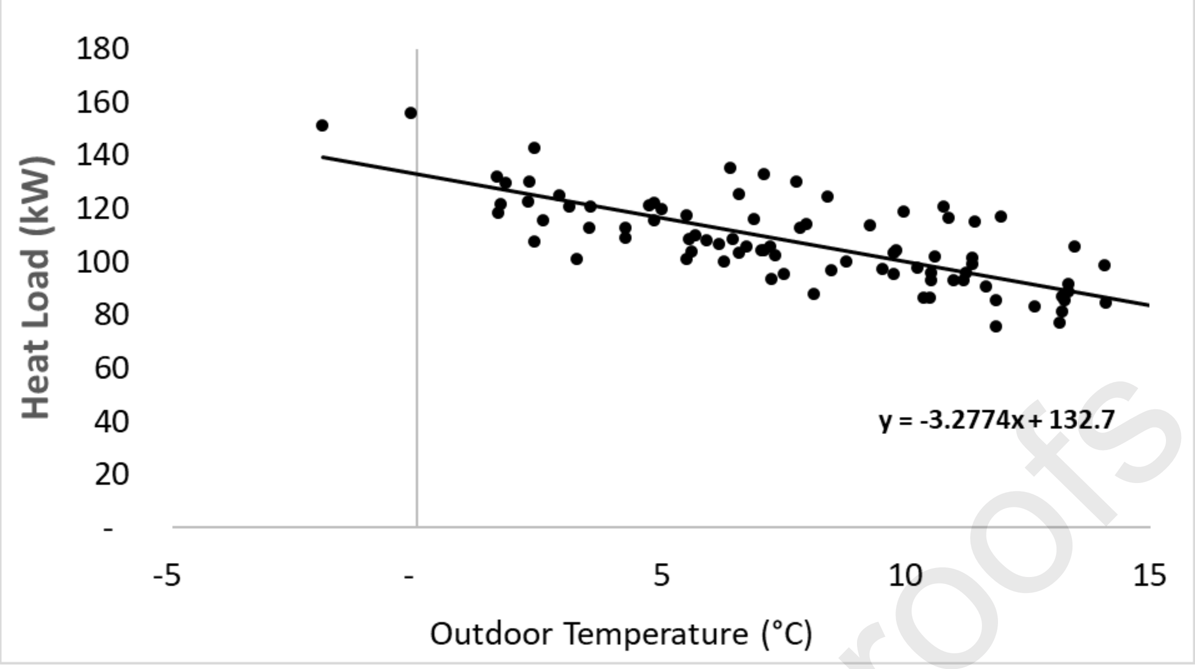

Figure 10: Calculated expected power output from the radiator without IHGs ($P_{Rad(night)}$)

$$P_{rad,night,0}(\mathrm{W}) = -3.2774 * T_{outdoor} + 132{,}7 \qquad \text{Equation 19}$$

Equation 19 enables to calculate the capacity of the radiators at design condition, where $T_{outdoor}$ is replaced with the outdoor design temperature (-5 °C). The result is 149 kW. With an installed capacity of 196 kW, the oversizing of the heating system (OsF_0) at design conditions is:

$$OsF_0 = \frac{196}{149} = 1.32\ (ie.32\%)$$

An oversizing of 32% is not significantly over the recommended value of 20%. The building has not been through specific energy efficiency measures. For example, windows are style single glazed, therefore, this case study is likely to represent a worst-case scenario.

4.3 Calculation of supply temperature

The oversizing factor of 1.32 at design condition (OsF_0) can also be expressed as a part-load ratio $PL = \frac{1}{OsF}$. At design conditions, the heating system operates at a part-load (PL_0) of 76%. For the daytime period, the oversizing factor of 2.0 indicate a maximum PL of 50%, and for a 24hr average approach, the maximum PL is 33%. Those results are used to calculate the supply temperature (T_s) for each time periods, based on TRY for Edinburgh, for the 365 days of the reference year. Results are shown in Figure 11.

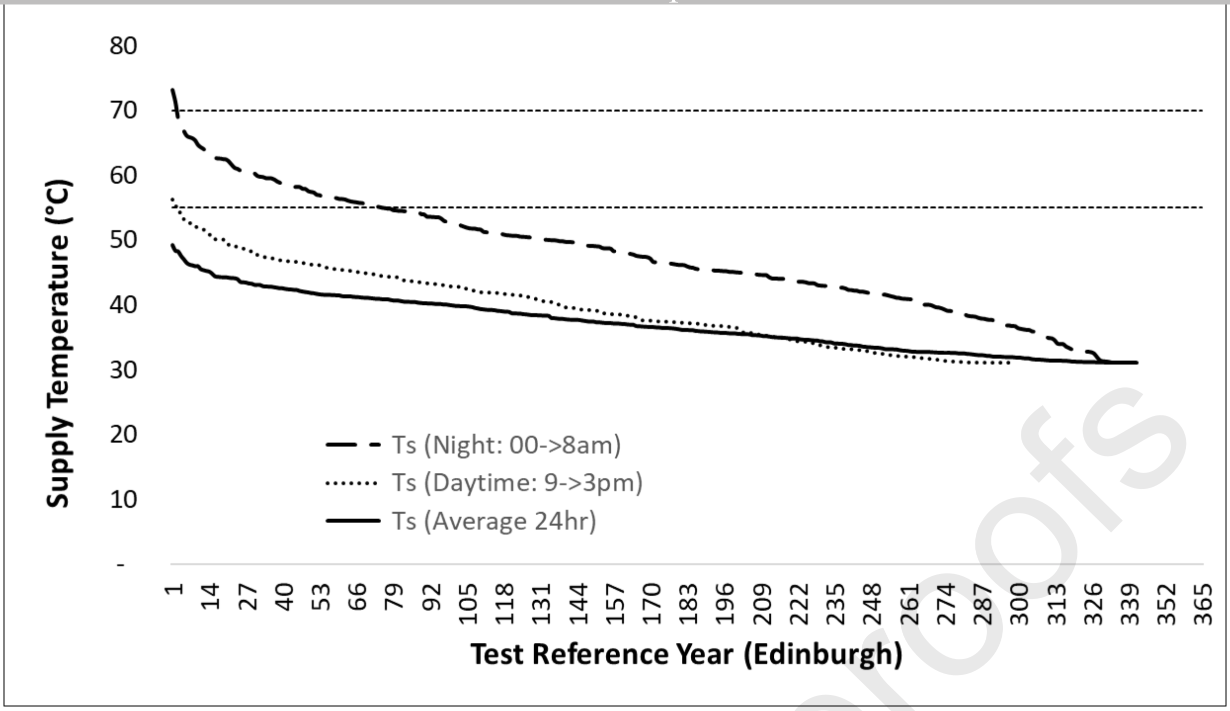

Figure 11: Supply temperature to meet heat demand at night, daytime, and 24h average.

These results illustrate than an oversizing of 32% enables a reduction of the supply temperature below 70°C all year round (99.2% of the year) if continuous heating is adopted for the coldest nights. It also shows that once the IHGs occur, the supply temperature can be lowered below 55°C all year round (99.7% of the year), increasing the efficiency of the heat source. It also shows that looking at the average daily load of a building which operates with night set-back underestimates the required supply temperatures by 23.9°C for the night and by 7.0°C for the daytime.

In conclusion, the building shows a nascent readiness for 4GDH as it can use supply temperature below 70°C all year round. However, the definition of the 4GDH given by Lund [13] recommends a supply temperature between 30°C and 70°C with a target to keep it below 55°C. An increase between 55°C and 70°C should be limited to the coldest periods. Those results are in line with research conclusions in Denmark and Sweden where buildings are expected able to use reduce operating temperature. This study presents results from a worst-case scenario and limited energy efficiency measures such as double-glazed windows will facilitate further the integration of low-temperature heat but are not pre-requisite.

Those supply temperatures are calculated with the aim to maintain an indoor comfort temperature of 20 °C, night and day, building empty or occupied. The setting indoor comfort temperature has been discussed by Toftum [68] who raises the question of the occupant's acceptance of a reduction of the indoor temperature for a limited number of days in the winter season, and for a short period of time. This is in line with the recommendations to size a heating system to reach 19 °C, and to rely on internal heat gains to reach higher set points, between 19 °C and 21 °C for a classroom [52]. Accepting the possibility that the indoor temperature is 19 °C or below when the occupants arrive in the morning during the coldest days in winter would enable a reduction in the size of the heat emitters and limit the need to raise the supply temperature. An optimised indoor temperature can provide peak shaving capacities [69]. This is comparable to having a slightly undersized system, and this would only be noticeable in the first hours of occupation in the morning, and especially on Mondays [70].

In the same way that the size of the radiators can be increased to facilitate temperature reductions, energy efficiency measures, like air permeability improvements and introduction of double-glazed windows, can reduce the heat demand. This would secure a readiness of the building for low-temperature heat during the peak load period and provide a lower return temperature to the heat network during daytime, increasing the efficiency of the system. More generally, as the occupant's behaviour is a key parameter, the introduction of a motivational tariff, where the occupant is financially incentivized to modify its behaviour, for example by making sure that TRV are set appropriately, can provide peak shaving and lower return temperature [71], [72].

Finally, global warming will likely reduce the heat demand but will also reduce the frequency of extreme events in the north of Europe regions [73]. This will contribute to reduce further the number of days where an increase of the supply temperature is necessary. On the other hand, pre-1919 buildings rely largely on natural ventilation strategy and often show poor indoor air quality [74]. The covid-19 pandemic has raised the attention about the risk of spreading disease in confined spaces and this could lead to new ventilation measures which will have an impact on the energy use.

4.4 Sensitivity analysis

4.4.1 Heat loss rate within the piping system

Various rates of heat losses in the internal space heating system (R_{losses}) have an impact on required heat output from the radiators. A sensitivity analysis was carried out within the value of 10% and 30% for the night period. Results in Figure 12 show that those range extremes lead to supply temperature of ±4.5 °C above and below the central assumption of 20% losses, at design conditions. A well-insulated system would need to see the supply temperature raised above 70 °C for 5 days while a system with a higher rate of losses enables to keep the supply temperature below 70 °C all year round. New or fully renovated heating systems will tend to have well-insulated pipes, with more limitations to reduce the supply temperature.

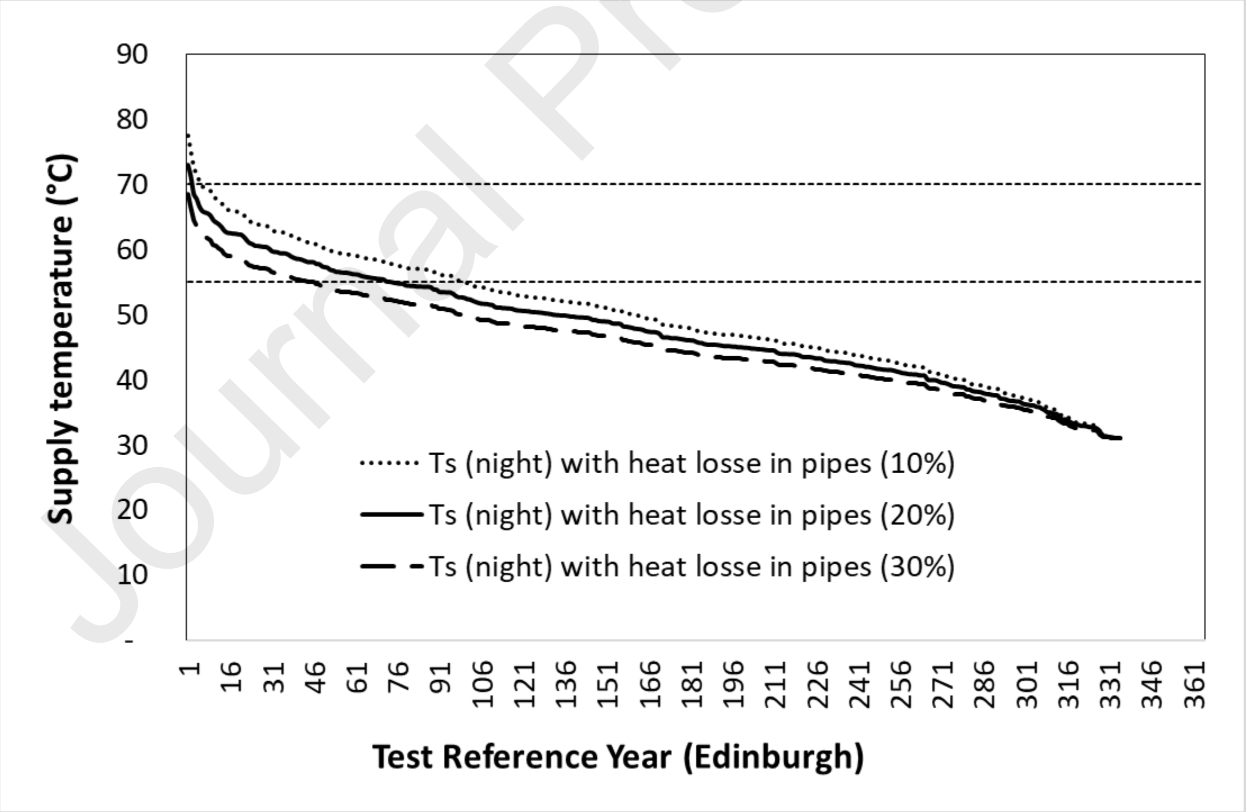

Figure 12: Supply temperature with various rate of internal heat losses.

4.4.2 Gas boiler efficiency

The efficiency of the gas boiler has an impact on the estimated heat supplied to the building. If the true efficiency of the gas boiler is below its specification of 79%, this overestimates the heat truly required by the building. If the boiler has an efficiency reduced by 10% and 20%, this leads to a supply temperature reduced by 2.5 °C and 5 °C at design conditions (Figure 13). The results presented in the study are therefore conservative, as reduced performance of the gas boiler would significate a reduced supply temperature in the radiator's circuits.

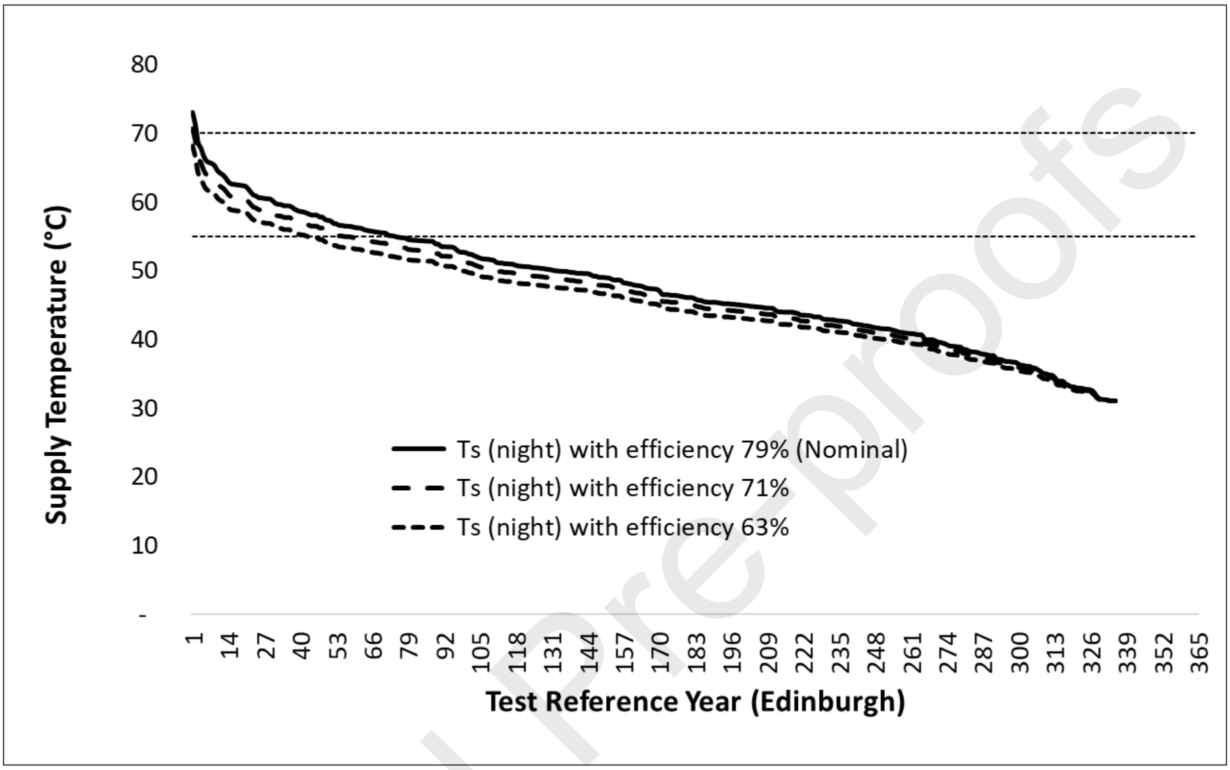

Figure 13: Supply temperature during peak demand (00:30 – 08:00) with various level of boiler efficiency

5 Direction for further research

This study does not investigate the heat load repartition per room and the radiators' capacity is likely to be uneven throughout the building. Stock et Al [75] highlights that radiators in hallways are often undersized although this does not represent a limiting capacity to reduce the operating temperatures. The identification of the critical radiators should be investigated further as proposed by Ostergaard and Svendsen [27]. This study provides an initial approach, but more complexity can derive from building's geometry, heating systems and occupancy schedule.

This study should lead to further research as follows:

- Replicate the methodology in a wider selection of buildings with various retrofit history and archetypes.
- Evaluate the impact of ventilation rates on heating load in naturally ventilated buildings.
- Investigate the role of critical radiators and the need to upsize them.
- Investigate the impact of a reduced indoor temperature setting.
- And finally, implement an optimized supply temperature in a larger sample of the building stock, to validate their low-temperature readiness.

6 Conclusion

This paper evaluates the oversizing of the space heating system of a pre-1919 non-domestic building in Scotland, using the energy signature method to calculate its heating load at design conditions. This building is still equipped with single glazing and hasn't been through energy efficiency measures. It is therefore a worst-case scenario. It shows that relying on the heating plant's capacity, estimated oversized by 101%, is misleading. The true enablers of temperature reduction are the final heat emitters, which were estimated with an oversizing of 32% at design conditions. An oversizing of 32% enables the use of a supply temperature below 70°C all year round. Moreover, during daytime, when internal heat gains occur, the supply temperature can be kept below 55 °C all year round, providing greater efficiency to the heat network. This article highlights also that using the daily mean outdoor temperature underestimates the required supply temperatures by 23.9°C for the night and by 7.0°C for the daytime.

Several factors would increase the ability to reduce further the supply temperature like (i) the efficiency of the gas boiler which could overestimate the true heat load required by the building; (ii) global warming reducing the heat demand; (iii) This building has single glazed windows and a limited building fabric energy efficiency measures would facilitate further the adoption of low-temperature heat, and (iv) acceptance of an indoor temperature below the accepted 19-21°C for the early hours of the coldest days of the year.

On the other hand, several factors could limit this temperature reduction. They are (i) The uneven repartition of the heat emitters across the building as the supply temperature is set by the weakest component of the internal space heating system. It is therefore important to identify the critical radiators or rooms and carry out upgrading works in those areas; (ii) TRVs set to different level within the same room/zone. Finally, those findings highlight that relying on the boiler's capacity presents a risk to overestimates the building's ability to use low temperature heat, or the risk to oversize future Heat Interface Unit (HIU).

In conclusion, a Scottish pre-1919 non-domestic buildings which has not been through energy efficiency refurbishment measures has a nascent readiness for 4GDH. It would benefit from energy use reduction programme but this is not a pre-requisite. The Scottish Government has set targets to reduce energy use in the building stock and this will further facilitate the adoption of low-temperature heat.

These findings are of interest to heat network design and installation companies when sizing their systems. They are also of significant interest to sustainability, asset, and energy managers when planning refurbishment programmes and connecting buildings to low-temperature heat sources. Finally, they provide evidence for those in the research community who are looking at the link between the performance of existing buildings and decarbonisation strategies.

7 Abbreviations

$P_{elec(daytime)}$ [W]	Internal heat gains from the electrical consumption, during the day (09:00-15:00)
$P_{elec(night)}$ [W]	Baseline internal heat gains from the electrical consumption (00:30-08:30)
$P_{heating(night)}$ [W]	Heat provided by the heating system during the night
$P_{heating(daytime)}$ [W]	Heat provided by the heating system during daytime
P_{losses} [W]	Heat lost by the space heating system within the internal pipes
P_{occ} [W]	Internal heat gain from the occupants
P_{Rad} [W]	Heat released by the radiators

P_{sg} [W]	Heat gains from the solar radiations
OsF	Oversizing Factor
PL	Part Load
PL_{ideal}	Part Load of an ideal system
TRV	Thermostatic Radiator Valves
η_{boiler}	Efficiency of gas boiler
LMTD	Logarithmic Mean Temperature Difference between the radiator's surface and the ambient room temperature
T_i [°C]	Room temperature
T_s [°C]	Supply temperature
T_r [°C]	Return temperature
ΔT [°C]	Temperature difference between T_s and T_r
Indices:	
n	Radiator exponent, usually set to 1.3
0	Outdoor design temperature

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Declaration of interests

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