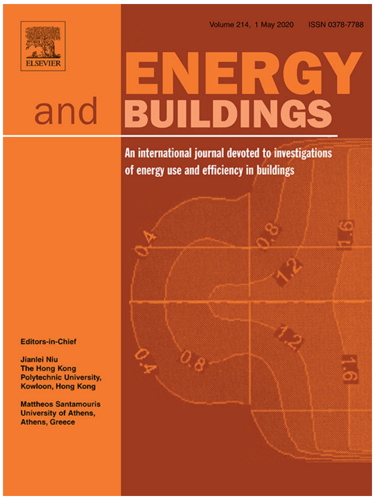

Energy performance of Scottish public buildings and its impact on their ability to use low-temperature heat

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Titles

Energy performance of Scottish public buildings and its impact on their ability to use low-temperature heat.

Authors

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Keywords

Performance gap, low-temperature heat, public buildings, 4GDH, district heating, non-domestic, Scotland, local authorities, radiator output, oversizing, U-values

Aim

Evaluate the energy performance gap in Scottish public buildings and its impact on the ability to use low-temperature heat.

Abstract

Decarbonising heat in the UK by 2050 will require the wider adoption of low-temperature heat. Current systems, largely relying on gas boilers, have design operating temperatures of 82/71°C (supply/return) while new standards for 4th Generation District Heating are 55/25°C. Local authorities must set-up strategies to get their buildings "Heat network ready" but this raises the question of the ability for existing buildings to use low-temperature heat. The aim and the novelty of this paper is to establish a relationship between an energy 'performance gap' in Scottish public buildings and their ability to use low-temperature heat. This performance gap has been evaluated for 121 non-domestic buildings, primarily schools, operated by The City of Edinburgh Council. Space heating system are assumed oversized by 10%. The results show that renovation of the building envelope, while highly desirable, is not a pre-requisite for using low-temperature heat in pre-1980 constructed buildings, which represent 64% of the stock. It also highlights that post-1980 buildings, predominantly utilising mechanical ventilation systems, demonstrate an increasing performance gap which could limit their ability to use reduced operating temperature, especially in windy conditions.

Key Outcomes

- A well-functioning space heating system can operate below 70°C for 98% of the year and below 55°C for 71% of the year.
- A correlation between building age group and energy performance gap has been identified.
- The performance gap between measured and calculated energy use is widening across building age groups, with a clear increase for post-1980 buildings.
- Pre-1980 buildings can operate with supply temperatures below 70°C for 96-99% of the year and below 55°C for 67-71% of the year.
- Building envelope improvement, whilst recommended, is not a pre-requisite for using low-temperature supply in pre-1980 buildings.
- Post-1980 buildings could have limitations in respect of using low-temperature heat under windy conditions.

Further work

Evaluate oversizing capacity of space heating systems for all age groups; Assessment of space heating system types in post-1980 buildings; Access larger data sets with full EPC reports for post-1980 buildings.

Nomenclature

4GDH	4th Generation District Heating
AMTD	Arithmetic Mean Temperature Difference
BEMS	Building and Energy Management System
CLASP	Consortium of Local Authorities Special Programme
DOT	Design Outdoor Temperature
EPBD	Energy Performance of Building Directive

EPC	Energy Performance Certificate
EU	European Union
EUI	Energy Use Intensity
HDD	Heating Degree Days
LHEES	Local Heat and Energy Efficiency Strategy
LMTD	Logarithmic Mean Temperature Difference
(n)	Radiator exponent
PL	Part-load
T_{Base}	Base temperature
T_{DMO}	Daily Mean Outdoor Temperature
Ti	Ambient indoor temperature
Ts	Supply temperature
Tr	Return temperature
TRV	Thermostatic Radiator Valves
TRY	Test Reference Year
VT	Variable Temperature
SEON	Energy Officers Network

Contents

1. Introduction and background

Scotland has set a target to reach net-zero emissions by 2045 (Scottish Government, 2019). Heat represents 51% of the final energy consumption in Scotland and relies dominantly on the consumption of natural gas (Matthews and Scherr, 2020). Heat pump and low carbon district heating are expected to play a significant role in phasing out gas-fired boilers (Committee on Climate Change, 2020) with both technologies designed to operate at low operating temperatures. Typical operating temperatures for 4th Generation of District Heating (4GDH) are 55/25°C with an increase to 70°C during the coldest days (Lund *et al.*, 2014).

By 2050, 80% of existing buildings will still be in use (European Commission, 2011) and this raises the question of their ability to use such reduced operating temperatures. This question was considered to be one of the major challenges for the development of 4GDH in Scandinavian countries in 2013 (Brand and Svendsen, 2013) and in Italy more recently (Guzzini *et al.*, 2020).

4GDH is deemed suitable for new buildings using less than 25kWh.m^{-2}.yr^{-1} and existing buildings using less than 150 kWh.m^{-2}.yr^{-1} *(Lund* et al.*, 2014)*. New buildings could be considered suitable for low-temperature heat as they are expected to be low-energy buildings (Olsen et al., 2014) but this is challenged by many publications, where it is highlighted that the most recent buildings do not always perform better than older ones and an identification of low-energy buildings by age group is not possible. This was highlighted in Sweden (Frederiksen and Werner, 2017), Denmark (Kristensen and Petersen, 2021), Switzerland (Aksoezen *et al.*, 2015) and in office buildings and recent hospitals in the UK (Potter, Jones and Booth, 1995; Bacon, 2014).

When the operating temperatures are reduced, the output capacity of heat emitters is reduced. However, this reduced capacity does not imply that the heating system cannot meet the heat demand, as space heating systems are designed for extreme weather conditions, which rarely occurs. Therefore, heating systems operate most, if not all, of the season in part-load. Part-load is the principle supporting the implementation of weather-compensated controls. It provides the ability to reduce operating temperatures in relation to the outdoor temperature. The extent of operation in part-load is also increased by several factors; like increased internal heat gains, heating systems designed with security factors which oversize components, and also because most buildings have gone through energy efficiency retrofit programs which reduces their heat demand (Skaarup, 2018). In addition, the number of days where the space heating system operates in part-load increases due to global warming, which reduces further annual heating demand but also makes episodes of extreme cold less frequent (Van Oldenborgh *et al.*, 2015).

In Scandinavia, district heating is a well-established technology and space heating systems are designed to operate with a large temperature difference between supply and return. This larger temperature difference is designed to reduce the return temperatures as this is a requirement related to the efficiency of district heating networks. However, a larger temperature difference reduces the heat output of heat emitters due to a lowering of the average emitter's temperature. Those systems can be described as 'low mass-flow'. Current district heating systems are dominantly characterised as 3rd generation, relying on operating temperatures of 90/60°C supply-return, with a push to implement a transition towards 4GDH. In Sweden, new systems are designed for a smaller temperature difference with 55/45°C as supply/return are typical (Frederiksen, S.; Werner, S. District Heating and Cooling. Studentlitteratur, Lund, Sweden, 2017). Those systems operate most of the year in part-load mode which enables them to achieve an average temperature difference of 22°C (Jangsten *et al.*, 2017). It is considered that most Scandinavian buildings can already connect to low-temperature heat (i.e. with a supply temperature of 55°C) without retrofit or with limited retrofit, and this is well documented (Brand and Svendsen, 2013; Harrestrup and Svendsen, 2013; Nord, Ingebretsen and Tryggestad, 2016; Skaarup, 2018; Rønneseth, Sandberg and Sartori, 2019; Averfalk *et al.*, 2021; Kristensen and Petersen, 2021; Tunzi *et al.*, 2023). If a building shows problems in meeting heat demand with reduced temperature, the attention of the Scandinavian industry and research community primarily focusses on the tracking of faults and errors within the space heating systems (Averfalk *et al.*, 2021; Sarran *et al.*, 2022).

In the UK, research relating to the ability of buildings to use reduced temperature is limited. The design standards applied in the UK have historically been for delivery of 82°C supply temperature and a 71°C return temperature, with appropriately sized heat emitters. Those systems are deemed 'high mass-flow'. Recent initiatives aimed at lower supply and return temperatures for condensing boilers or for heat pumps have seen some adoption in the domestic sector but did not see large scale adoption in the non-domestic sector. Nevertheless, it is highlighted by (BuroHappold Engineering, 2016) that a low-temperature supply of 50/30°C (supply/return) can meet 90% of the demand for office buildings in London, up to 99% if the operating temperatures are raised to 70/50°C during the coldest periods. This theoretical study assumed that the heating system is sized to meet 100% of the heat demand with an 82/71°C supply and return temperature at UK standards-based worst-case-design conditions, reflected in the Test Reference Year (TRY) 2011 for

London climate. Radiators are assumed oversized by some 10% which is the typical recommendation found in literature (Parsloe, 1995; Oughton and Wilson, 2015). This oversizing can be defined as "the ratio of the rated output of the radiators to the peak steady-state thermal demand" (BEIS UK Gov, 2021). Oversizing a space heating system enables reheat of a building after a night set-back, which is common practice in the UK. Different degrees of oversizing are applied to both the boilers and the heat emitters. Oversizing of the boiler is usually greater than that applied to heat emitters, primarily for back-up and redundancy purposes. However, the scale of oversizing measured by Crozier (Crozier, 2000) was commonly 50% and eventually up to 400%. Although, this was notably applied to the heating plant and not the final heat emitters but illustrates the wide range of oversizing metrics in the UK building stock. For domestic buildings, (Millar, Burnside and Yu, 2019) mentions that heating systems in the UK are notoriously undersized, and according to (BEIS UK Gov, 2021), under-sized systems are estimated to represent 23% of building stock, but most domestic buildings are expected to be oversized by 20-40%. This study tends to over-estimate the ability of buildings to use low-temperature heat (Reguis, Vand and Currie, 2021). However, it is worth noting that a system undersized for design conditions is still able to meet the heat demand under part-load operation. Lessons from Scandinavia should be imported with caution into the UK, and one of the key differences lies in the energy performance of UK buildings (Reguis, Vand and Currie, 2021).

The performance gap is the difference between predicted energy use at design stage and measured energy use at post occupancy stage (Van Dronkelaar *et al.*, 2016; Shi *et al.*, 2019). UK buildings are the worst-performing in the European Union (EU) (BPIE, 2011), and the performance gap of UK buildings is higher than in other countries, especially in schools and universities (Van Dronkelaar *et al.*, 2016). Air leakage/permeability is higher in UK buildings than in Scandinavian buildings (Oughton and Wilson, 2015) which makes UK buildings perform poorly during windy conditions, particularly for post-1990 buildings with mechanical ventilation (CIBSE, 1998; Tofield, 2012). The performance gap is a widely spread problem (Tofield, 2012; Tuohy and Murphy, 2015) and according to (Shi *et al.*, 2019), no correlation can be established between the magnitude of the performance gap and classic building parameters such as age, use, or archetype. However, the most energy efficient buildings tend to have the highest performance gap (Turner and Frankel, 2008). There is evidence from numerous studies that performance gaps can be related to faults in building construction, HVAC systems, and controls.

In its “Heat in Buildings Strategy”, the Scottish Government aims to have non-domestic buildings “Heat-network-ready”, with heat networks relying on heat pumps, surplus and waste heat, or eventually hydrogen, no later than 2040-45 (Scottish Government, 2021a). Understanding the performance of UK building’s is therefore paramount, as lowering temperatures is a long-term effort and should be prepared well in advance (Olsen et al., 2014). If retrofit is required, it should be planned and coordinated with other maintenance work to spread the costs.

Heat networks are expected to target densely populated areas like cities. Due to high investment cost, district heating is seen as high risk, but local authorities and public bodies can provide anchor loads which contribute to de-risk such projects (Committee on Climate Change, 2020). Scottish Government expects local authorities to assess potential connection to heat networks during the preparation of their Local Heat and Energy Efficiency Strategy (LHEES). Local authorities are also expected to coordinate technical studies and policy frameworks, with an early engagement to facilitate communication between public and private stakeholders to develop their own “heat zoning” policy (Wiltshire, Williams and Woods, 2014; Element Energy, 2018; Scottish Government, 2018, 2021b; Committee on Climate Change, 2020). For this reason, non-domestic buildings, and especially public buildings, are first in line to use low-temperature heat.

In conclusion, previous studies have investigated the use of low-temperature heat and the performance of different building types, however, to the best of our knowledge, there are no studies that have established a relationship between the performance gap and the ability of public buildings to use low-temperature heat. This information is valuable to local authorities who are tasked with getting their buildings "heat network ready" in the context of decarbonizing heat in the UK by 2050.

Therefore, the research questions for this work are:

- “What is the energy performance gap of Scottish public buildings?”
- “How the performance gap of Scottish Public Building affects their ability to use low-temperature heat?”

The novelty of this study can be summarized as follows:

- It is the first to investigate the impact of the energy performance gap on the ability of UK non-domestic buildings to use low-temperature heat,
- It is based on empirical data, retrieved from the building stock operated by the City of Edinburgh Council.

After a literature review in which Scottish public building's key characteristics are described in section 2, the methodology is detailed in section 3. The first step is to group buildings by age group (section 3.1) and calculate their energy performance gap by comparing measured and calculated energy use (section 3.2). This performance gap is combined with the heat output of typical wall panel radiators (section 3.3) to evaluate how the heat demand can be met all year round. This methodology is applied to the non-domestic building stock of The City of Edinburgh Council with results discussed in section 4. The conclusion in section 5 highlights the key lessons from this article and details further research that needs to be developed.

2. Characterisation of Scottish non-domestic buildings

There are around 220,000 non-domestic buildings in Scotland, including about 22,000 owned by the public sector (Scottish Government, 2021a). Non-domestic buildings are identified as non-dwelling buildings and can be public, commercial, or industrial buildings. They include offices, schools, hotels, hospitals, sports and leisure facilities (CIBSE, 2013). They vary widely in terms of size, use, and ownership, and this creates difficulties in benchmarking their performance (Choudhary, 2012). An energy benchmarking exercise can be performed by grouping buildings by their use, form/shape, geographical location, Energy Use Intensity (EUI), age, or archetype (Steadman *et al.*, 2000; Steadman, Bruhns and Rickaby, 2000). Some, like hospitals and industrial buildings, have energy use strongly impacted by their specific use and function, while others, like offices or schools have more generic energy use profiles (CIBSE, 2013).

The energy performance of a building is largely based on the capacity of its envelope to provide resistance to the transmission of heat, based on the U-value of the envelope components and their permeability. U-values are often used as one of the main thermal characteristics of the building and forms the basis of energy assessment tools like RdSAP and SBEM (Rhee-Duverne and Baker, 2013). The successive versions of building regulations have set up constraints on maximum U-values and air permeability. The thermal performance of the envelope is also the result of the construction method which sets the performance of the building at its time of construction and over its lifetime, with an inevitable degradation of the initial performance. Finally, the performance of a building or its envelope is impacted by the quality of construction which can result in a gap between calculated and measured U-value or permeability. Throughout the lifetime of the building, retrofit programmes can help restore or improve the building's performance.

To characterise Scottish non-domestic buildings, the following sub-sections review the successive changes in the building regulations (section 2.1), the significant changes in the technique of construction (section 2.2), the typical approach to retrofit of non-domestic buildings (section 2.3) and finally the performance gap between measured and calculated U-values (section 2.4). This is done to establish a classification of the building stock by age group.

2.1. Scottish building regulations for non-domestic buildings

The first building regulations were driven by concerns related to fire, health, or structural safety of construction, like the Public Health Act of 1875, Public (Scotland) Act 1897 and 1936. Insulation standards were first introduced with the model building byelaws in 1952 “but the requirements were very modest” (Foulger, 2004) and generally not considered as having a significant impact. In Scotland, following the publication of the Building (Scotland) Act in 1959, the first set of building standards were published in 1964 and include a chapter related to the conservation of fuel and energy (Bett, Hoehnke and Robison, 2003; Tricker and Algar, 2008). Those initial regulations were for dwellings only. Regulations for non-domestic buildings were introduced 15 years later, in 1979, after the ‘oil crisis’ of the 70’s. Coming into operation on 1st June 1979, the Building Standards (Scotland) Amendment Regulations 1979 was essentially focussed on the “Conservation of Fuel and Power” in its “section II” which is specific for buildings “other than houses”. Maximum U-values for walls and roofs were 0.6W/(m^2.K) (UK Government, 1979). In 1981, a section III was added to implement the automatic control of internal space temperature and weather-compensation systems for non-domestic buildings. Time controlled intermittent heating was also made mandatory for buildings which do not require continuous heating (UK Parliament, 1981). In 1990, Thermostatic Radiator Valves (TRVs) became mandatory. From 1990, the new Building Standards (Scotland) Regulations were supported by Technical Standards prepared by the Scottish Office (The Scottish Office, 1990; UK Parliament, 1991). In 1990, U-values for walls and roofs were tightened to 0.45W/(m^2.K), then further reduced to 0.3 for the walls and 0.25 W/(m^2.K) for the roofs in 2002 and 0.27 and 0.2 W/(m^2.K) respectively in 2010 (Scottish Executive, 2002; Scottish Government, 2010). In 2000, windows were required to have a maximum U-value of 3.3W/(m^2.K), 2.0-2.2 W/(m^2.K) in 2002, and 2.0 W/(m^2.K) in 2010. The importance of air tightness was mentioned in 2007 but acknowledged that “an air tightness industry is not yet fully established” (Scottish Government, 2007). In 2010, a recommended maximum value of 10m^3/(m^2.h) was proposed but testing was not deemed necessary, and values were expected to be 15m^3/(m^2.h) (Scottish Government, 2010). Mandatory testing for new buildings was introduced in 2011. In 2007, following the Energy Performance of Building Directive (EPBD) of 2002 (EU, 2002), an Energy Performance Certificate (EPC) was made mandatory for all buildings that were being sold or rented out, and public buildings over

1000m^2 floor area (Scottish Government, 2007). This was extended to buildings with floor area of 500 m^2 in 2012 (Scottish Ministers, 2012). A summary of those changes is shown in Table 1.

Date	**1979**	**1981**	**1990**	**2000**	**2002**	**2007**	**2010**	**2011**
Title	Building Regulations (Scotland) amendment 1979	The building standards (Scotland) Regulations 1981	Technical Standards 1990	5th Amendment of Technical Standards	6th Amendment of Technical Standards	Technical Handbook Non-Domestic 2007	Technical Handbook Non-Domestic 2010	Technical Handbooks 2011 Non-Domestic - Consolidated
Walls (U-Value) W.m^{-2}K^{-1}	0.6	N/A	0.45	N/A	0.3	N/A	0.27	N/A
Flat roof (U-Value) W.m^{-2}K^{-1}	0.6	N/A	0.45	0.35-0.45	0.25	N/A	0.2	N/A
Window (U-Value) W.m^{-2}K^{-1}	N/A	N/A	N/A	3.3	2.0 - 2.2 (wood, metal - PVC)	2.2	2.0	N/A
Air permeability	N/A	N/A	N/A	N/A	N/A	Importance highlighted. Default value assumed 15m^3/m^{-2}h^{-1}	Max 10m^3.m^{-2}.h^{-1} (Recommended)	testing mandatory (new buildings)
Controls / Other	N/A	Introduction heating controls	mandatory TRVs	N/A	N/A	EPC mandatory	N/A	N/A

Table 1: Significant changes related to "transmission of heat" in the building regulations for buildings "other than houses" (UK Government, 1979; UK Parliament, 1981; The Scottish Office, 1990; Scottish Executive, 2000, 2002; Scottish Government, 2007, 2010, 2011)

2.2. Non-domestic building archetypes

As described in the previous section, 1979 is a key date with the introduction of maximum U-values within the building regulations. This section looks at the dominant construction techniques used before 1979 in order to classify pre-1979 buildings by their architype.

The techniques of construction have an impact on the thermal performance of the building and how they degrade over time. The following section is a review of the construction techniques used across the UK and Scotland for non-domestic buildings to identify key periods in terms of thermal performance.

Prior to 1919, most building were constructed with solid walls and referred as traditional buildings (Birchall *et al.*, 2014). After the first world war, uninsulated cavity walls were introduced and widely used (BRE, 2002; Birchall *et al.*, 2014) and was considered the main method of wall construction between 1919 and 1945 (Bullocks, 2002).

In 1945, there was a need to build or rebuild large numbers of buildings (McCrone, 1991; Bullocks, 2002). The building industry, traditionally resistant to change, was pushed to experiment and develop new methods of construction based on economy of time, resources, and high productivity (Bullocks, 2002; Hashemi, 2013). As reducing construction standards was not an option, the forms of construction developed would focus on three aspects: (i) strength and stability, (ii) moisture penetration and (iii) sound insulation. Those were compared with traditional forms of construction (BRE, 2002). Thermal performance was not a focus for this construction programme (Bullocks, 2002). Construction techniques came from large companies and industry that had developed expertise and specific techniques during the previous war. They extensively used pre-cast concrete, steel or aluminium construction (Bullocks, 2002; Rabeneck, 2011).

Local authorities were significantly involved in the mass production of buildings with programmes like the Consortium of Local Authorities Special Programme (CLASP) which was largely used between late 1956 and 1980 (Rabeneck, 2011). There were many other programmes like SCOLA, ROSLA, MACE, SEAC but CLASP is often used as a generic term. Although the CLASP programme was initially designed to mass produce schools, it has also been used to build offices, libraries, health centres, hospitals, churches, and universities. The system involved was able to produce buildings of any shape and size (Bell, 1985). Lightweight steel-frame structures were largely used due to new construction techniques (Bell, 1985; Bullocks, 2002; Rabeneck, 2011).

The legacy of the 1945-1979 period of construction is that quality was neglected in favour of quantity (Hashemi, 2013). Schools were built in a “less durable fashion and with cheaper components and finishes” (Bullocks, 2002). Even before the beginning of the CLASP programme, in 1956, Bullock highlights that the quality of modern buildings was seen as “depressing” (Bullocks, 2002). In post-war schools, windows were as large as possible to increase the amount of natural light but those windows were mostly single glazed, creating poor thermal comfort and high energy use (Montazami, Gaterell and Nicol, 2015). The English primary and secondary construction programme, which peaked in 1970-71, was often associated with high maintenance cost, technical problems, buildings woefully thermally inefficient and poorly built (Bell, 1985; Rabeneck, 2011). CLASP buildings included many features that had extremely limited lifespan (Bell, 1985).

2.3. Retrofit of existing building stock

Publicly owned or occupied buildings account for 12% by area of the EU building stock. The public sector is expected to lead by example and renovate or regenerate its stock at the rate of 3% each year while other building are renovated at the rate of 1.2% to 1.5% (European Commission, 2011). Some categories of buildings are more likely to go through refurbishment programmes. Buildings with solid walls resist better against degradation of their envelope and have proved to be relatively easy to maintain (Rhee-Duverne and Baker, 2013). Post-war buildings and especially offices are more likely to go through deep energy renovation. Schools built in the 50s, 60s and 70s were regarded in 1994 as requiring extensive maintenance or refurbishment (BRE, 1994). In general, buildings with poor energy performance have significant energy saving potential and the return on investment is more attractive when a renovation programme is considered (Duran, Taylor and Lomas, 2015). The retrofit cycle for office building is estimated around 30 years (Garmston, 2017) and the service content of the CLASP building was expected to be entirely replaced over a period of 30-40 years (Bell, 1985). If not refurbished, buildings are removed from the building portfolio of institutional investors (Ball, 2003). CIBSE (2013) highlights that "Buildings built between the 60's and 90’s are the most commonly encountered in UK non-domestic refurbishment projects". It can reasonably be assumed that office buildings from the 50s-80’s owned by investment companies have been through refurbishment programmes as they are pushed by market expectations and financial targets. Buildings owned by local authorities, typically schools, are not exposed to similar pressure, or might have budget and space constraints that make them less prone to refurbishment.

Refurbished buildings have reduced heat demand, and if their space heating system was included in the refurbishment programme, it is possible that smaller radiators were fitted to reduce cost and save space (CIBSE, 2013). However, interviews undertaken by (Lamon, Raftery and Schiavon, 2022) show that designers tend to replace space heating systems with like-for-like equipment; as cost savings are negligible and this limits the risk of call-back from the client. This would indicate that old buildings with a reduced heat demand have oversized heat emitters.

2.4. Measured versus calculated U-Values

U-values are one of the main thermal characteristics of a building. If a variation exists between U-values used at design stage and the actual installed value, this can lead to performance gap and mislead retrofit programmes. Default values used in SBEM are pessimistic and lead to poor asset rating if left unchanged by an assessor (BRE, 2020).

Pre-1919 buildings with solid walls are assumed to be less efficient than other buildings, especially new buildings, but energy assessment tools often overestimate their energy use, probably due to inaccurate estimation of the thermal transmittance of the envelope (Baker, 2011; Rhee-Duverne and Baker, 2013). The Energy Saving Trust suggests to use a U-Value of 1.7W/(m^2.K) for traditional sandstone for pre-1919 period buildings (Baker, 2011) when the average U-value measured in solid walls is 1.4W/(m^2.K) (Rhee-Duverne and Baker, 2013). However, for (Walker and Pavía, 2015), the performance of solid walls is not necessary better than calculated as there are a wide diversity of situations. This wide diversity is confirmed by (Li *et al.*, 2015) who found that the distribution is very large, however the mean value measured is 1.3 W.m^{-2}.K^{-1} which is significantly lower than the standard CIBSE value of 2.1 W.m^{-2}.K^{-1} (Li *et al.*, 2015). We can conclude that the overall performance of solid walls (pre-1919 buildings) is generally better than assumed by calculation and modelling tools.

For cavity walls, calculated U-values are more aligned with in-situ measurements (Baker, 2011).

For post-1945 buildings, the U-value is significantly impacted by poor workmanship or degradation over time which reduces the efficiency of building components. A building's envelope airtightness generally deteriorates over time but this is a more acute problem in buildings from the 60's and 70's (CIBSE, 2013).

For post-1979 buildings, thermal elements might have U-values above building regulation's expectations as a degree of deviation or "trading off" between thermal elements was allowed (CIBSE, 2013; Bros-Williamson *et al.*, 2017).

This shows that the performance gap between calculated energy use and measured energy use can be impacted by the assumptions in the calculations. This performance gap would be limited for pre-1919 buildings, not impacted for interwar buildings, and increased for post-1945 buildings.

3. Methodology

A collaboration with the City of Edinburgh Council was established to access datasets relating to its non-domestic building stock. The main characteristics of those buildings and the dataset cleaning process are detailed in section 3.1, the evaluation of the performance gap and its impact on the ability to use reduced supply temperature is detailed in section 3.2 and 3.3. A flow chart of the methodology is shown in Figure 1.

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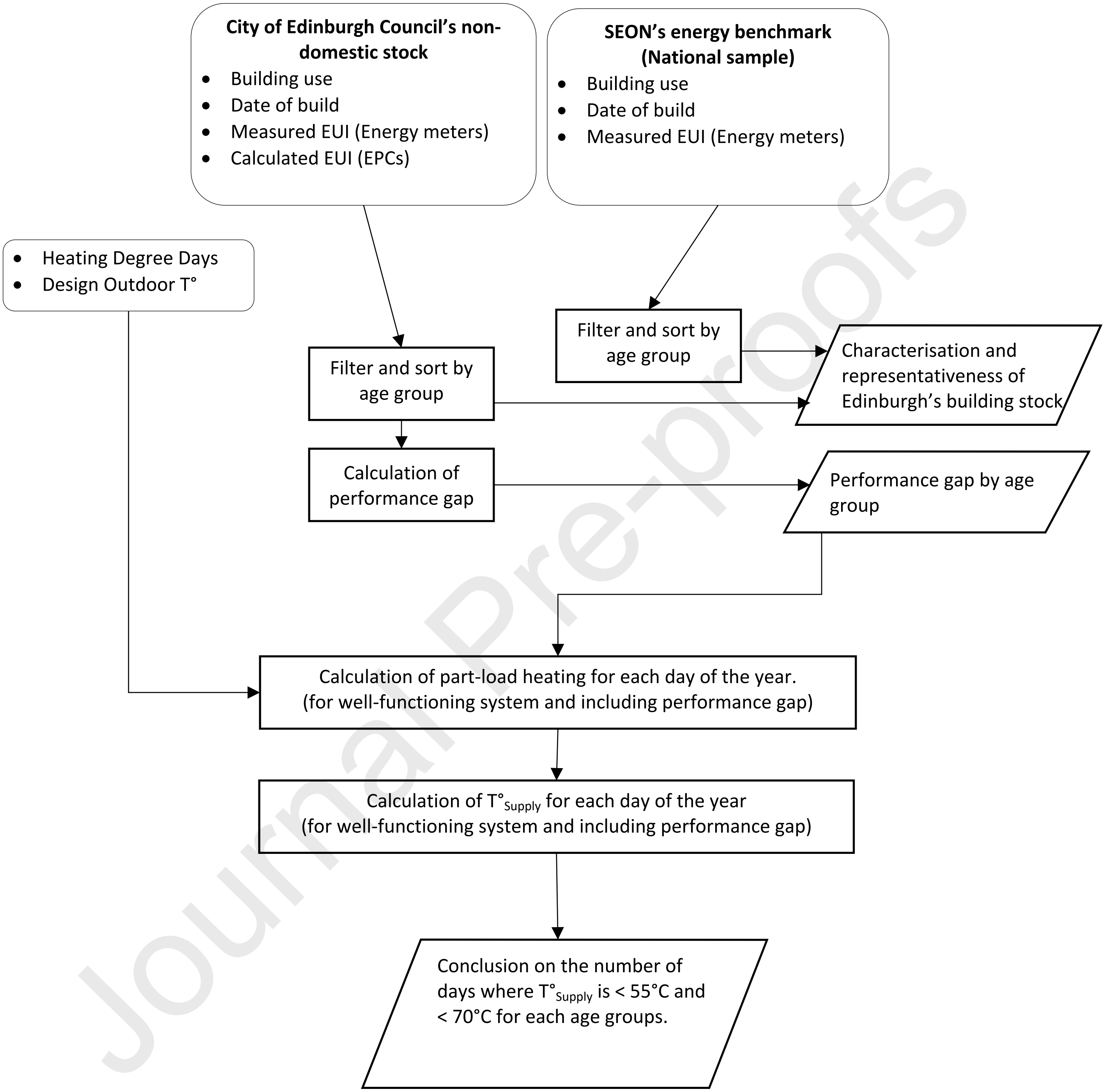

Figure 1: Flow chart of methodology

3.1. Classification of Scottish public buildings

Using the building stock from a single Local Authority/Council removes the uncertainty of various management practices as all buildings are managed by the same team. Those building characteristics are compared with a national dataset compiled from a benchmarking exercise undertaken in 2019 by University College London for the Scottish Energy Officers Network (SEON) (Ruyssevelt and Min Hong, 2019). It is worth noting that those samples might include some inaccuracy, especially related to the floor areas used; as floor area can sometime be produced for one purpose (i.e., calculated loosely for cleaning schedules or for EPCs) and then end up being taken as accurate. However, comparing the local and national samples provides an evaluation of the representativeness of Edinburgh's building stock.

The building stock was divided into seven groups, based on the date of construction (Table 2). A key date is 1979 with the introduction of maximum U-values within the building regulations. Pre-1979 buildings are grouped by dominant archetypes while post-1979 buildings are grouped by significant changes in the maximum compliance U-values for walls and roofs.

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Date of construction	**Pre- 1919**	**1920-1939**	**Post-1945**	**1979-1989**	**1990-2001**	**2002-2009**	**2010-present**
Type / significant change	Solid wall	Cavity walls, uninsulated	Post war reconstruction buildings	Maximum U-values introduced	Maximum U-values reduced	Maximum U-values reduced; Maximum U-value introduced for windows	Maximum U-values reduced

Table 2: Seven groups, divided by date of build based on significant changes in construction technique or maximum U-value for walls and roof.

Selection criteria were applied to both samples to remove outliers and non-representative sites. Those suppression criteria are detailed in Table 3.

Criteria	**Description**
Floor area below 50m^2	Several records were excluded due to missing floor area information and those with floor area below 50m^2 because they risked skewing the energy use intensity distribution
Gas use below 25kWh.m^{-2}.yr^{-1}	There were several records where the gas use was zero and 4 records with gas use between zero and 25 kWh.m^{-2}.yr^{-1}. They were removed as deemed unrealistic or representing buildings without gas heating
Calculated EUI (from EPC) greater than 1,000kWh.m^{-2}.yr^{-1}	Energy use above this threshold is deemed unrealistic and this removed one building where the EUI calculated in the EPC was 2,753 kWh.m^{-2}.yr^{-1}.
Buildings labelled as "Depot", "Convenience", "Venue" and "Other"	Those sites often have specific heating system like radiant ceiling, electric heating and AHU which might have unusual energy use and should be separated from the benchmark selection.
Buildings outside the geographical area of Edinburgh	Those buildings are exposed to different weather conditions and therefore might have specific energy use. Furthermore, they often are outdoor centres with specific hourly use.

EPC or Date of build unavailable	Those two criteria are required to measure the performance gap and classify buildings.

Table 3: Description of the exclusion criteria used during the filtering process.

3.2. Performance gap

The performance gap of the building is obtained using the ratio between measured energy use and calculated energy use, as per *equation (1)*.

$$Performance\ Gap\ (PG) = \frac{Measured\ energy\ use}{Calculated\ energy\ use} \qquad \text{equation (1)}$$

The measured energy use was provided by half-hourly gas meter data, mandatory since 2014 for all non-domestic buildings (Ofgem, 2016). Gas use data was retrieved from the year 2016/2017, starting 1st April to 31st March. They were weather-adjusted with the average 20-year weather data available from the MET office for the Botanic Garden in Edinburgh (1996-2016). Metered electricity use was also retrieved for the same period. This enabled the calculation of a gas/electricity use ratio for each building

The calculated energy use was based on the EPC provided for each building, the only readily available metric to assess at-scale the design or assessed energy use of a building. As the EPC report provides the total energy use of the buildings, the share of the gas consumption was calculated using the gas/electricity use ratio from the measured energy use. EPC reports have a validity of ten years and almost all of them were renewed in 2019 and 2020 across the City of Edinburgh building stock. Calculated energy use was therefore retrieved from EPCs issued in 2019 and 2020. Weather files used by SBEM to produce the EPC are based on a TRY (BRE, 2015) which was updated in 2016 to include monthly average values from 1984 to 2013 (Virk and Eames, 2016). As described by (Virk and Eames, 2016), “TRY 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”. It is used for energy analysis and for compliance with the UK Building Regulations. Finally, energy use datasets are not surface-weighted; therefore, each site has the same weight. This is to avoid large buildings distorting the results.

3.3. Flow temperature and radiator performance at varying outdoor design temperatures

The choice of the outdoor design temperature to size a heating system has varied over time. It was first mentioned in literature in 1955 with a Design Outdoor Temperature (DOT) of -1.1°C recommended for any site in the UK. This DOT was reduced to -2.8°C in 1965 for light-weight structures. The regionalisation of data in 1986 led to a DOT of -5°C for

Edinburgh (Reguis, Vand and Currie, 2021). A rules of thumb guidebook, which does not consider regionalisation, suggested the use of -1 or -4°C depending on the system's capacity in the 80's and 90's, and a unique -4°C since 2011 (Hayward, 1988; Hawkins, 2011). As design engineers tend to have a cautious approach to sizing, it is assumed in this paper that the DOT is -5°C, as this is the lowest figure available in the design literature. This equals 20.5 Heating Degree Days (HDD) using the standard 15.5°C base temperature (T_{Base}). Space heating systems are mostly designed for these extreme conditions which rarely occur. Most of non-domestic heating systems are equipped with weather-compensated controls which reduces the heating system supply temperature according to the measured outdoor temperature. This is done using a "heating curve (weather compensated)", often referred as "heat/heating curve". The heat demand can be considered a linear function of the outdoor temperature (Lindelöf, 2017). The indoor comfort temperature is assumed set at 21°C, which is typical for office and school buildings (CIBSE, 2019). The temperature drop across radiators is assumed to be 11°C as this is considered to be standard practice by British Standards (British Standard, 1988). The supply temperature in the radiators is assumed to vary between 82°C under lowest design conditions and 32°C for minimum heat demand, as per the traditional approach to heating system design in the UK. This design heating curve is compared to the heating curve currently implemented in non-domestic buildings. This heating curve is usually characterised within a Building Energy Management System (BEMS). Because of time and accessibility constraints in the study, a sample of 15 heating systems out of a total of 121 were checked. Those 15 buildings were chosen to represent the different construction age groups.

For each day of the year, HDD were calculated and presented in a decreasing order. They were calculated from the daily mean outdoor temperature (T_{DMO}) retrieved from the weather files provided by CIBSE for Edinburgh, as per equation (*2*).

$$HDD = T_{DMO} - T_{Base} \qquad \text{equation (2)}$$

CIBSE also provides weather scenario data for future climates. Those are based on different GHG emission scenarios (Low – Medium - High) and related to mitigation efforts. They were available for three different time periods with "2020" representing the period 2011-2040, "2050" representing 2041-2070, and "2080" representing 2071-2100. Each scenario was divided into percentiles which represents the likelihood that the mean air temperature will be lower than predicted (Virk and Eames, 2016). In this paper, a "High" emission scenario is considered for "2020" as it is the only one available, a “Medium” emission scenario is used for both “2050” and “2080”. The 50^{th} percentile (median) was used in all scenarios. Those long-term scenarios have an element of uncertainty but are the main source of future weather data used by the construction industry to ‘future-proof’ their buildings. Those future scenarios provide a daily mean temperature which is used to calculate the HDD for each day of the year. Once the HDD is known for each day of the year, the degree of Part-Load (PL) is given by equation (*3*) where HDD_0 is the HDD at design condition (ie.20.5°C).

$$PL = \frac{HDD}{HDD_0} \qquad \text{equation (3)}$$

Once the degree of part-load is known, the supply temperature (T_s) can be calculated, using equation (4) and equation (5), where Q is the heat demand at specific part-load condition and Q_0 is the heat load at design condition.

$$PL = \frac{Q}{Q_o} = \left(\frac{LMTD}{LMTD_o}\right)^n \qquad \text{equation (4)}$$

$$LMTD = \frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \qquad \textit{equation (5)}$$

LMTD is the Logarithmic Mean Temperature Difference between the radiator’s surface and the ambient room temperature (T_i), assumed as 21°C. (T_s) and (T_r) are the supply and return temperatures within the radiator. The radiator exponent (n) has the typical value of 1.3 for standard radiators (Young *et al.*, 2014). At design conditions, (T_s) and (T_r) are assumed 82°C and 71°C. LMTD is a better approximation of the mean surface temperature than the Arithmetic Mean Temperature Difference (AMTD), especially for ‘low mass-flow’ rates (Mcintyre, 1986).

The impact of the oversizing and/or the performance gap on the supply temperature is obtained from a recalculated PL (PL_2) using the equation *(6)*.

$$PL_2 = \frac{PL}{1 + OS - PG} \qquad \text{equation (6)}$$

In this paper, it is assumed that the temperature drop across the radiator is kept at 11°C. This is a different approach from the traditional aim to achieve a low return temperature in the district heating industry (20 to 30°C drop across the heat emitter/space heating system). This approach is based on the concept that heating systems in the UK have been designed to operate with high mass flow and low-temperature drop. It has been demonstrated that even in systems designed to operate with large temperature differences, 1% of faulty TRV's or bypass can significantly increase the return temperature (Tunzi, Østergaard and Svendsen, 2022). Space heating systems are rarely properly balanced (Ahern and Norton, 2015) and a heating system not properly balanced also limits the ability to achieve a low return temperature (Benakopoulos *et al.*, 2021; Østergaard *et al.*, 2022). It is therefore unlikely that existing space heating systems in the UK will achieve a low-return temperature without a retrofit of the entire heating system.

To assess the ability of existing systems in the UK to use low-temperatures, the approach proposed in this paper is one recommended by (Benakopoulos *et al.*, 2019) which is described as low supply temperature/high mass flow. This approach relies on a minimum supply temperature weather-compensated curve and high flow rate. It is a low-cost solution to achieve low return temperatures when the space heating system has faulty TRVs. In such cases, the simplest solution to improve the space-heating operation of an existing building is to modify its weather-compensation curve, which adjusts the supply temperatures according to outdoor temperatures (Østergaard *et al.*, 2022). This approach can be compared to the operation of underfloor heating systems, where an even temperature gradient is desirable (high mass flow) with an optimised supply temperature. For an underfloor heating system, the supply temperature would be capped at 55°C or below, depending on the nature of the floor construction. Another argument to support this approach is that a low-return temperature reduces grid losses but those are a minor component of district heating efficiency; where greater benefits derive from a low supply temperature (Averfalk and Werner, 2020). Moreover, a focus on optimal supply temperature, rather than low return temperature, will help reduce the risk of performance gaps in larger-scale heat pump installations. Heat pumps not achieving their expected COP metrics is identified as a risk in reaching national decarbonisation targets (Chaudry *et al.*, 2015).

It is widely assumed that space heating systems in non-domestic buildings in the UK are oversized, but there is little survey data mentioning the degree of oversizing. In this paper, an oversizing of 10% for terminal units is considered, as this is the recommended value used in industry (Parsloe, 1995; Oughton and Wilson, 2015). It is worth noting that most papers exploring the oversizing of heating systems are focussing on the plant's capacity, with oversizing of 50% to 100% deemed current practice and eventually up to 400% (Crozier, 2000). The oversizing of heat emitters is usually lower than for boilers, and a value of 10% is a conservative choice.

The final step of the methodology provides the number of days where the heat demand can be met with a supply temperature below 55°C, the typical supply temperature for 4GDH (Lund *et al.*, 2014), or below 70°C, the maximum supply temperature deemed acceptable for coldest days for 4GDH (Lund *et al.*, 2014).

4. Results and discussion

4.1. Scottish non-domestic stock

The City of Edinburgh Council provided datasets for a portfolio of 329 buildings with a total floor area of 823,240m^2. The main building group in this portfolio were "schools". This includes nursery, primary, secondary, and special schools which represents 63% of total floor area. After the filtering processes, 121 buildings with a total floor area of 523,243m^2 were selected and the "school" group represents 83% of the total floor area, as shown in Table 4.

Building category	**Raw data**		**Filtered data**	
	Floor area (sqm)	% (floor area)	Floor area (sqm)	% (floor area)
Total floor area	823,240	100%	523,243	100%
School	515,326	63%	428,621	82%
Office	60,934	7%	49,392	9%
Community centre	62,077	8%	3,838	1%
Library	44,377	5%	33,910	6%
Depot	41,174	5%	-	0%
Care home	37,305	5%	4,291	1%
Venue	23,888	3%	-	0%
Museum	4,536	1%	3,191	1%
Hostel	3,445	0%	-	0%
Convenience	1,063	0%	-	0%
Other	29,115	4%	-	0%

Table 4: Floor area per building type before and after cleaning process (City of Edinburgh Council).

The data provided by SEON's energy benchmarking report included energy use for 4,180 non-domestic buildings. After the same selection process, the resulting sample was reduced to 1,340 buildings, with a total floor area of 4.7Mm^2. The "school" group was also predominant for this sample, with 82% of the total floor area, as per Figure 2. The floor areas by age group were compared in Figure 3. This shows the specificities of Edinburgh's building stock compared to a national benchmark. Edinburgh has a larger proportion of pre-1919 buildings potentially due to the large proportion of historic buildings in their portfolio. The main age group in both samples is the post-war group (1946-1979). There were only two buildings in the most recent age group "2011-present" in the Edinburgh sample, but energy use intensity for this group is in line with the national sample as in Figure 4.

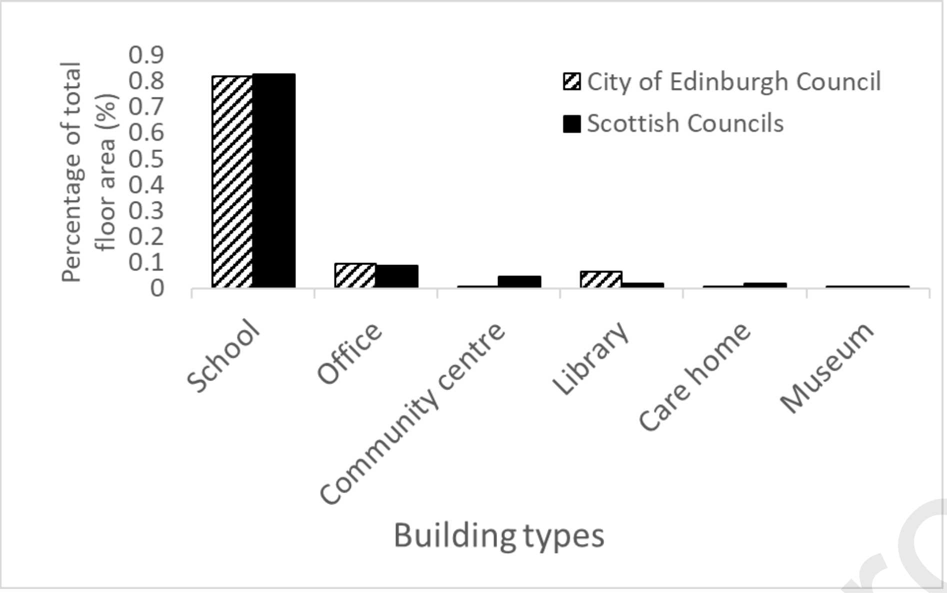

Figure 2: Building use per floor area, after applying filters. Comparison between Edinburgh Council and national benchmark.

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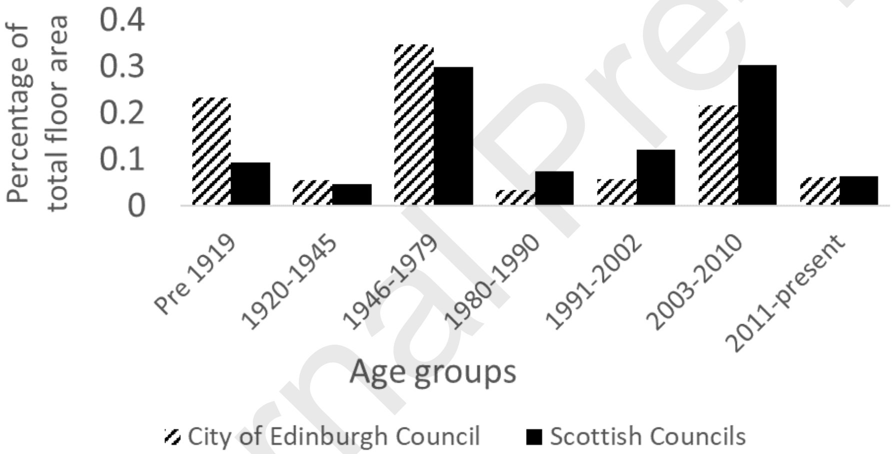

Figure 3: Repartition of floor area, per age groups, for public buildings, from Edinburgh and national benchmark.

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4.2. Measured energy use

The average EUIs across each year group were 178 kWh.m^{-2}.yr^{-1} for Edinburgh and 187 kWh.m^{-2}.yr^{-1} for the national sample (Figure 4). Both samples follow a similar pattern of results except for the pre-1945 buildings where there are significant discrepancies. Post-war buildings, group 3, commonly referred as the poorly performing group have a similar EUI with 175 kWh.m^{-2}.yr^{-1} and 176 kWh.m^{-2}.yr^{-1} in Edinburgh and the national sample respectively. These performances are below the average of the whole building stock. Such unexpected performances could be explained by previous retrofit programmes targeting post-war buildings which improved their thermal performance. The group with a clear above-average EUI is group 4 (1980-1990). Those were built after the newly introduced U-value regulations in 1979. These are counter-intuitive results; as it might be expected that the introduction of limitations in the transmission of heat would provide improved performance. However, a general trend is noticeable between 1980 and 2010, in groups 4, 5, and 6, with a consistent reduction in EUI; following tightening of U-values in the building regulations. This improved performance came to a halt with group 7, built since 2011, as their EUI shows an increase, while U-values were tightened by regulation. The local sample (Edinburgh) was limited to two buildings but the national sample, which includes 40 buildings, confirms an increase. A salient fact is that the most recent buildings have an EUI which is similar or barely below the pre-1919 group, often considered as large energy users and 'hard-to-treat' buildings.

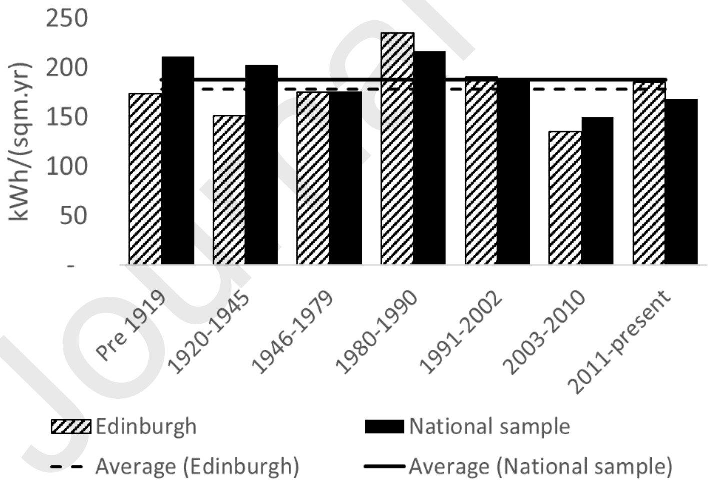

Figure 4: Measured energy use of public buildings for The City of Edinburgh Council and national benchmark, per age groups.

4.3. Calculated energy use

The calculated energy use in EPC's is largely based on the performance of the envelope of the buildings, its resistance to the transmission of heat, and air permeability. Maximum U-values have been reduced since 1979. Figure 5 shows how those maximum U-values have changed for external walls over time and the energy use calculated for each age group. EPCs were available for 43% of Edinburgh's building stock, and none from the SEON's benchmarking exercise. In Edinburgh, the calculated EUI shows a consistent reduction for all the groups since the introduction of the of maximum U-values in 1979, and their constant reduction in successive building regulations. Buildings built since 2011 are expected to be the most efficient buildings, with an EUI of 77 kWh.m^{-2}.yr^{-1}. None of the buildings in the study can be considered low-energy buildings, even the new ones, as this would require a performance of the building comparable with PassivHaus standards which is 15 kWh.m^{-2}.yr^{-1} for new buildings and 25 kWh.m^{-2}.yr^{-1} for existing retrofit projects (Li *et al.*, 2017). This confirm that the assumption that new buildings can be considered low-energy buildings (Olsen et al., 2014) can be challenged.

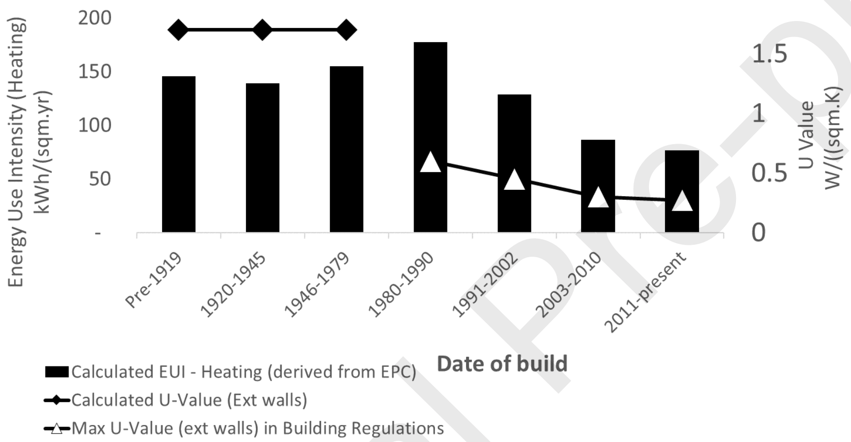

Figure 5: Calculated EUI, expected U-values for pre-1979 buildings and maximum U-values in the building regulations

4.4. Performance gap

The performance gap is defined as the ratio between the measured energy use and the calculated energy use (EPC). The performance gap calculated for each age group is illustrated in Figure 6. For all buildings built prior to 1979, the performance gap was shown to be below 20%. From 1980 onward, and with tighter U-value expectations, a steady increase was measured; with 32% for the group 4, 48% for the group 5 and 57% for the group 6. The results from the group 7 need to be backed-up with a larger validated sample size, but the EUI measured in the national sample (SEON benchmark) would tend to confirm a significant increase for this group.

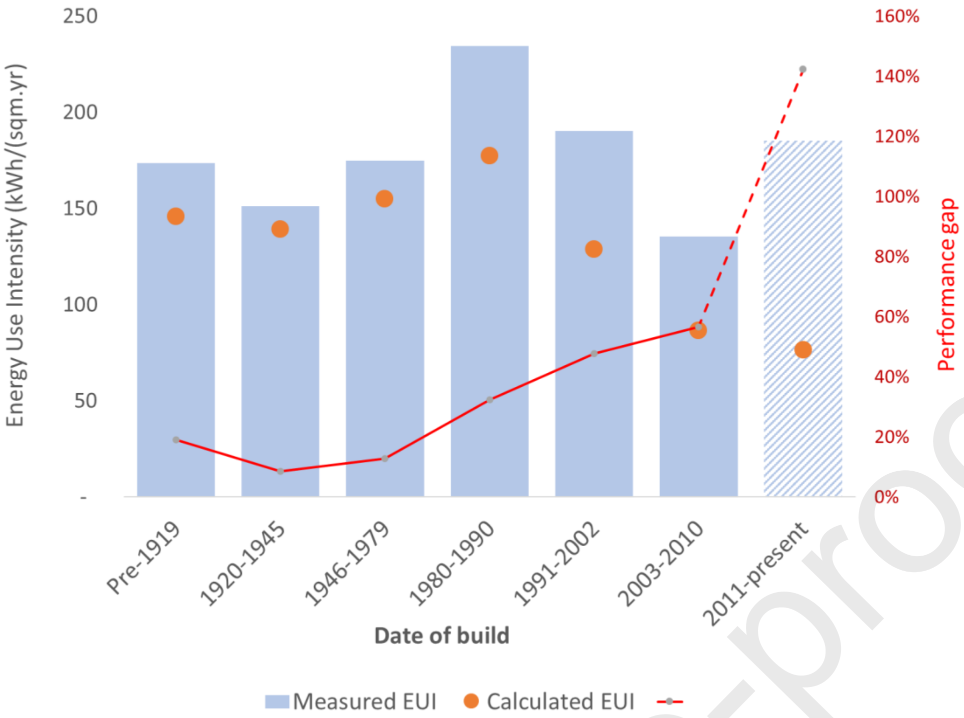

Figure 6:Energy use from EPC and energy meters with performance gap per age group, City of Edinburgh Council.

These results show that the age of a building could be a parameter by which to evaluate the performance gap of a building, thus challenging previous statements that no correlation with classic building parameters could be identified (Jones, Eckert and Gericke, 2018; Shi et al., 2019). These results support the findings from (Turner and Frankel, 2008) that the most energy efficient buildings have the higher performance gap.

Literature related to the performance gap is abundant (Bordass *et al.*, 2001; Van Dronkelaar *et al.*, 2016; Gupta and Kotopouleas, 2018; Shi *et al.*, 2019) and specific causes are identified. The rebound effect, misuse of control, occupant behaviour, or the difficulty of the construction industry to implement tighter energy regulations. This was already highlighted in 2012 by Tofield for whom "the traditional construction industry model cannot reliably deliver low-energy buildings" (Tofield, 2012). This latest point is illustrated by the move towards Passivhaus certification from the City of Edinburgh Council in 2019, which is driven by the need to achieve net-zero targets, but also to tackle a persistent performance gap. This was to provide an enhanced control over quality (Brown, 2020) as the performance gap for PassivHaus standards tend to be limited compared to current building standards (Pitts, 2017; Gupta and Kotopouleas, 2018; Hasper *et al.*, 2021).

4.5. Design heating curve vs implemented heating curves

15 heating control curves out of a sample of 121 buildings were surveyed. The results showed that the heating curves implemented in the BEMS were linear or near linear. They were are all set at 80°C flow for 0°C outdoor temperature and either 20°C or 30°C for an outdoor temperature of 20°C, as shown in Figure 7 and Figure 8.

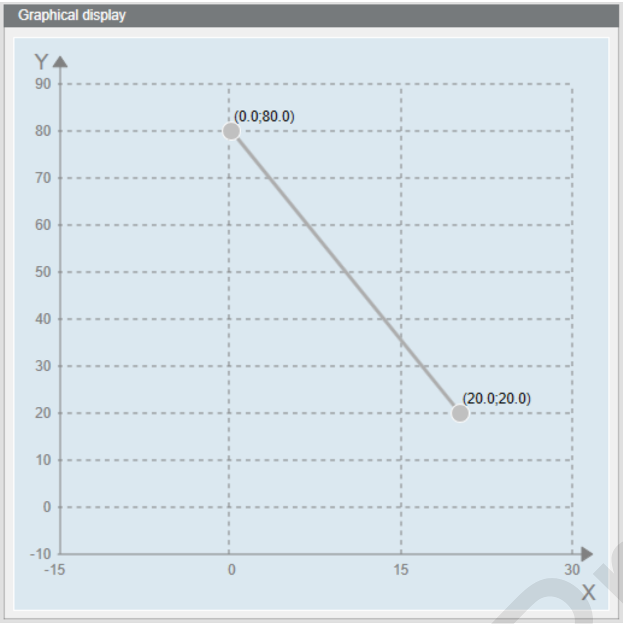

Figure 7: Screenshot of BEMS interface, showing the lowest heating curve recorded.

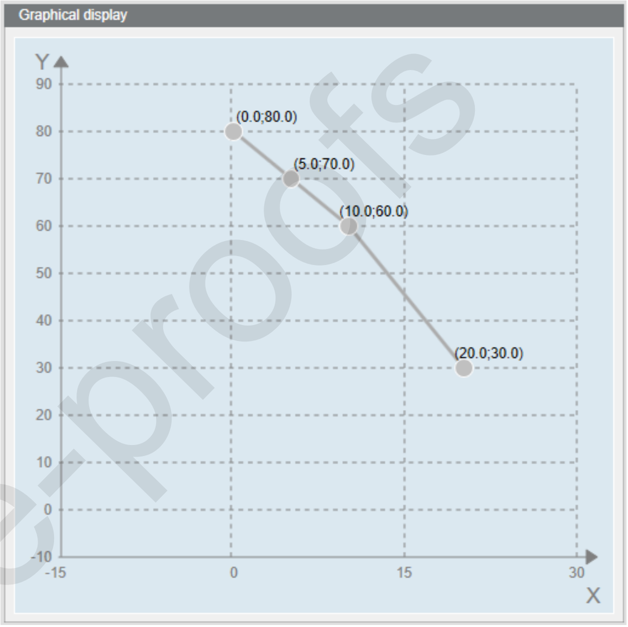

Figure 8: Screenshot of BEMS interface, showing the highest heating curve recorded, with additional setting points.

The values recorded are above the typical standard design curve and a comparison is shown in Figure 9. For the coldest days, current practice appears to have a supply temperature 10°C higher than the design curve. Higher setting provides a quicker reheat of the building, leaving localised control of room temperature to the TRVs or the ability of the occupant to open a window ('British thermostat') if the indoor temperature is too high. This higher setting presents limited risk of overheating and there is no benefit to having a well-adjusted heating curve in terms of energy efficiency, as most gas boilers are non-condensing.

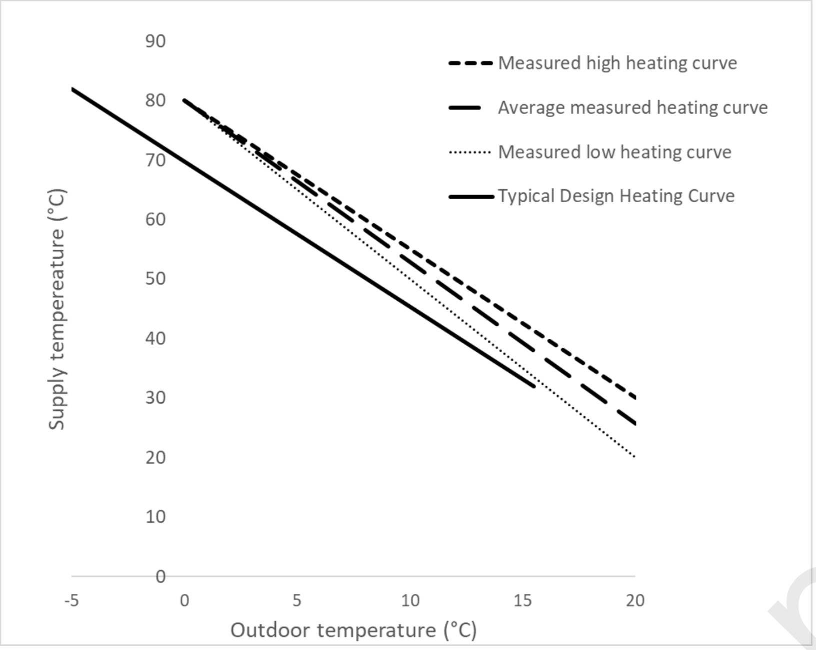

Figure 9: Comparison between typical design heating curve and heating curve currently used across non-domestic buildings in Edinburgh.

4.6. Part-load operation of a space heating system in Edinburgh

In this section, HDDs are calculated for 4 weather climates (current, 2020, 2050 and 2080) with results presented in Figure 10. This shows the expected decline in heat demand for high-emission scenarios (only available for 2020) and medium emission scenarios for 2050 and 2080. Under the conservative assumption of having a space heating system with radiators oversized by 10%, the maximum part-load varies from 86% to 76% for those weather scenarios.

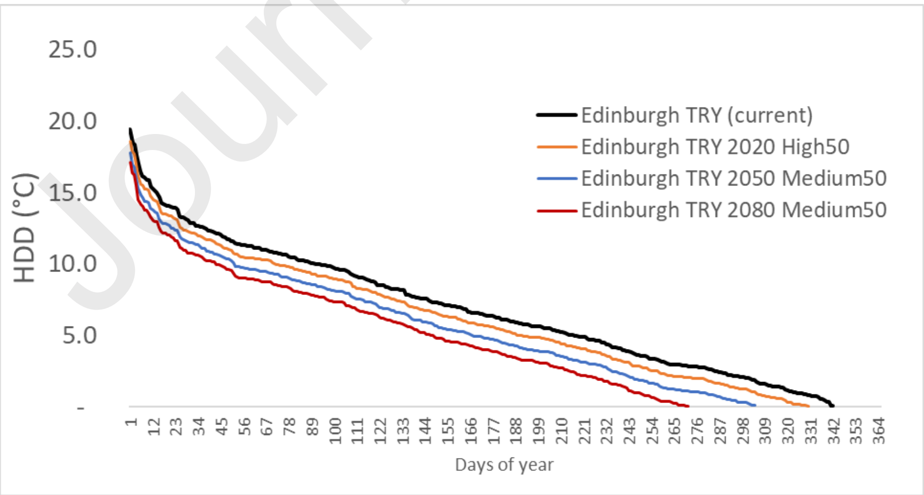

Figure 10: Annual Heating Degree Days (base 15.5°C) in decreasing order for various weather scenarios for Edinburgh.

Once the degree of part-load is known for each day of the year, the supply temperature can be calculated. The supply temperature of a well-functioning space heating system in Edinburgh is therefore able to remain below 70°C for 98% of the year with current weather files. The heating system can therefore be operated with a supply temperature below 55°C for 71%-86% of the year under the various weather scenarios. The peaks above 70°C are limited to 6 days under the current weather file and 4, 3 and 1 days for 2020, 2050 and 2080 scenarios. Those results are also shown in Figure 11 and Table 5.

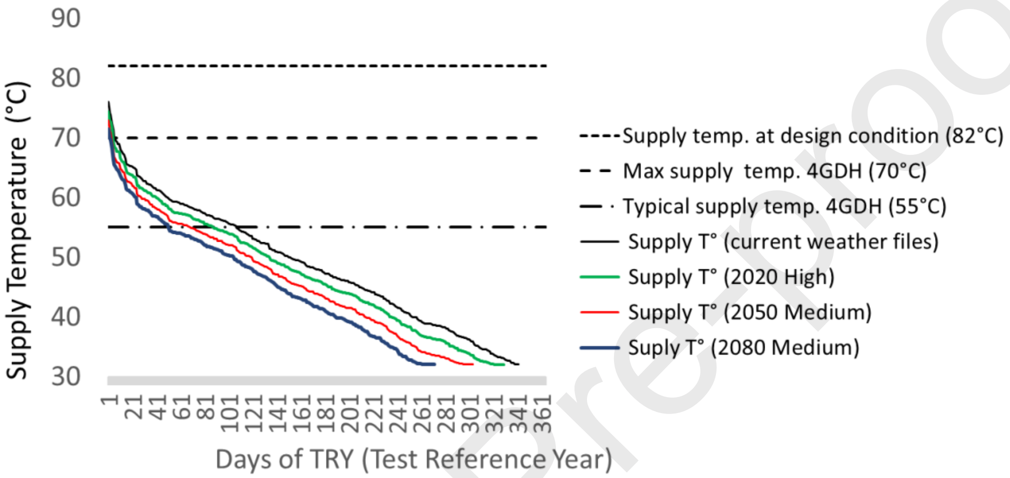

Figure 11: Supply temperature for various climate files (Edinburgh) – Radiators oversized by 10% - 11°C drop across space heating system.

Weather files (TRY Edinburgh)	**% of the year with a flow temperature**	
	below 55°C	below 70°C
TRY CURRENT	71%	98%
TRY 2020 High (50)	76%	99%
TRY 2050 Medium (50)	81%	99%
TRY 2080 Medium (50)	86%	100%

Table 5: Percentage of the year with supply temperature below 55°C and 70°C for various weather files for a standard space heating system in Edinburgh (TRY - CIBSE).

4.7. Impact of performance gap on the supply temperature

As described previously, the performance gap can have various causes. The impact of the performance gap on the ability to use reduced temperature depends on the reasons behind it. If the reason is related to the capacity of the envelope to restrict heat losses, be it by structural deficiency or poor air tightness, this has an impact on the ability to reduce operating temperatures. If the performance gap has other causes, like higher temperature set-point (rebound effect), occupant's behaviour, or misuse of controls, they do not have any impact of the ability to reduce the temperature.

Figure 12 shows the recalculated supply temperature where it includes the impact of the performance gap for each age group. It shows the supply temperature in the extreme and unlikely situation that the performance gap is attributed to defects in the performance of the envelope. It is therefore a worst-case scenario.

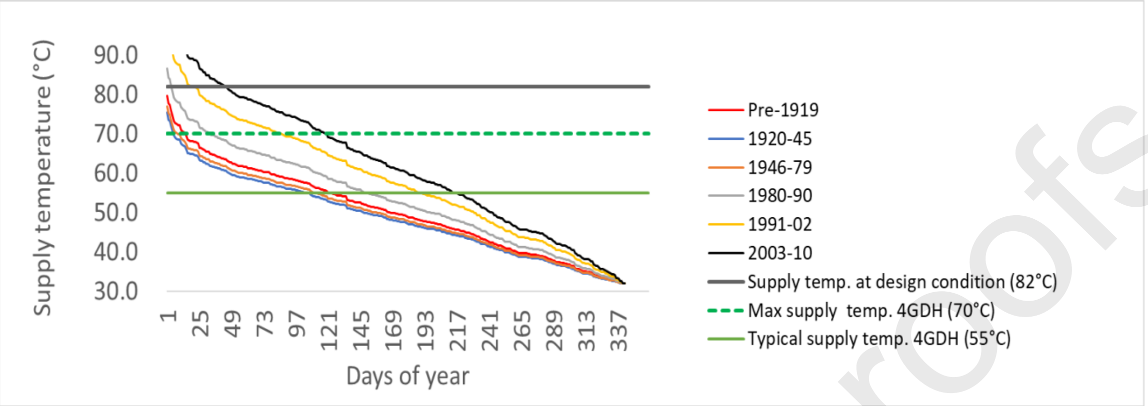

Figure 12: Supply temperature for each building group where performance gap is included - Current weather files - Edinburgh (2016)

The reasons behind the performance gaps for each age group are not part of this this study, but some lessons can already be drawn:

(i) Pre-1980 buildings can be operated with supply temperatures equal or below 70°C for 96-99% of the year according to the group/year considered. Also, for 67-71% of the year, the supply temperature can be equal or less than 55°C. Those buildings represent the largest share of building stock (64% of floor area). Furthermore, old buildings are likely to have been through retrofit programmes, which reduces their heat demand while their heating system is likely to have remained unchanged (see 2.3). This results in a relative oversizing of their heating system beyond the conservative value of 10% used in this study; increasing their ability to use low-temperature heat. Knowing the causes of the performance gap could highlight what actual impact this has on the heat demand, but it shows that energy renovation is not a pre-requisite for using low-temperature in their space heating systems.

(ii) Counterintuitively, post-1980 buildings, built under more stringent building regulations, show unacceptably poor energy performances compared to the other groups. And, unexpectedly, these buildings could be the bottlenecks for the transition towards low-temperature operations, if the cause of this performance gap lies entirely in defects in their envelope; as their heating system would not have capacity for adoption. As for the older buildings, it is necessary to investigate the causes of the performance gap, but air leakage is likely to play a role, as *(Potter, Jones and Booth, 1995)* showed that buildings with mechanical ventilation are more leaky than naturally ventilated buildings. It was also highlighted by (CIBSE, 1998; Tofield, 2012) that post-1990 buildings with mechanical ventilation perform poorly during windy conditions. This indicates that buildings with mechanical ventilation could have an inherent limitation to use low-temperature heat under windy condition. Finally, post-2011 buildings are commonly equipped with underfloor heating, which would likely make them ready for low-temperature heat. However, as they are the most recent buildings, they are less likely to undergo retrofit than older buildings. This means that the cost of eventual retrofit work prior to connection to low-temperature heat will not be spread across other renovation/maintenance work.

(iii) This study does not consider the heat distribution within each building. It is likely that distribution pipework and some heat emitters are the bottlenecks towards the use of low-temperature heat. It has been shown by (Østergaard and Svendsen, 2016) that it is possible to invest in replacing only those few radiators sufficient to secure comfort even on the very cold days. It is cheaper to do this rather than forcing the entire DH network to operate at higher temperatures (Østergaard and Svendsen, 2019).

Finally, as the government aims to have all non-domestic buildings "heat network ready", a cap of 55°C for the supply temperature must be implemented for all new and renovated buildings to make sure a growing number of buildings can adopt low temperature heat.

5. Conclusion

Decarbonising heat in the UK by 2050 in existing buildings will require the widespread roll-out of low-temperature heat networks, namely 4th generation district heating (4GDH), with public buildings being the first to connect. The aim of this paper was to evaluate the heating performance and energy performance gap in Scottish public buildings, and how this can affect their ability to use low-temperature heat. 4GDH operating temperatures are typically 55/25°C, with an increase to 70°C deemed acceptable during cold spells. Heating systems in the UK are designed to operate with a high mass flow and a small differential between supply and return temperatures, which presume that achieving a large temperature difference to match the definition of 4GDH is challenging. This study opted to use a low-supply/high-flow approach, which is more resilient to common faults resulting from stuck valves and bypasses, widespread in UK buildings. The aim and the novelty of this paper is to establish a relationship between energy performance gap in Scottish public buildings and their ability to use low-temperature heat, and on the use of empirical data, applied to non-domestic buildings. The performance of 121 non-domestic buildings forming part of the City of Edinburgh Council's portfolio has been assessed and compared with a national sample. A performance gap was calculated to evaluate the supply temperature of heat emitters, which were assumed oversized by 10%, a conservative assumption as true oversizing is expected to be higher, especially for older buildings.

This study shows that a well-functioning space heating system in Edinburgh designed to operate at 82/71°C with a design outdoor temperature of -5°C can operate 71% of the season with a supply temperature below 55°C, and 98% of the season below 70°C. The impact of global warming will further reduce the need to raise supply temperatures. The following step of this study was the evaluation of a performance gap for the City of Edinburgh Council non-domestic building stock, classified in 7 age group categories. It showed a steady increase in energy performance gap from the 1980 stock on; reaching 57% for post-2003 buildings, while the performance gap remained below 20% for pre-1979 buildings. Unexpectedly, post-2010 buildings were found to be using similar or less energy than pre-1919 buildings. The causes of the performance gap were not investigated in this study, however some lesson can be drawn. The first is that pre-1980 buildings can still operate with supply temperatures equal or below 70°C for 96-99% of the heating season, according to the group/year considered. Also, for 67-71% of the heating season, the supply temperature can be equal or below 55°C. Those buildings represent the largest share of the Council's building stock (64% of floor area). Furthermore, older buildings are likely to have oversized heating systems, higher than the conservative value of 10% used in this study, due to their historic retrofit. This shows that energy-focussed renovation of the envelope is not a pre-requisite for attaining low-temperature in space heating systems.

The second is that post-1980 buildings could unexpectedly be a bottleneck for the transition to low-temperature heat due to the high performance gaps identified, especially in windy conditions. However, this is a worst-case scenario, as many causes can also explain a performance gap in this group; including occupant behaviour, rebound effect, or misuse of controls, which would have no impact on the ability to use reduced temperatures. Fortunately, those buildings do not represent a significant share of the building stock, but they are the most recently constructed, and therefore less likely to be considered for refurbishment. This makes them less able to spread the cost of the "low-temperature-ready" retrofit work within wider maintenance programmes, should they be needed.

A cap of 55°C on the supply temperature must be designed and implemented for all new and renovated buildings in order to make sure that a wider and growing number of buildings can adopt low-temperature heat.

6. Direction for further research

To fully assess the ability of a building to use low-temperature heat, further research should investigate reasons behind the performance gap measured in post-1980 buildings; accessing full EPC reports and measured energy use for a larger number of post-2010 buildings, surveying the type and capacity of final heat emitters installed, and evaluating the oversizing of heating systems for all building typology and age. An investigation into intra-day outdoor temperature variations will provide a detailed assessment of building performance, especially during pre-heat periods, when the heating demand peaks, and during times of the day when supply temperature can be significantly lowered, as solar and internally generated heat gain prevails.

Once those criteria are assessed, tracking faults and malfunctions will be a next field of research. The increasing role of digitalization of demand side metrics will help service personnel to improve the operation of the systems and pinpoint faults and anomalies in the space heating systems. This will further help secure low-temperature in existing buildings (Østergaard *et al.*, 2022; Tunzi *et al.*, 2023). On-site trials with modified heating curves will become necessary in order to validate the ability of existing buildings to use reduced operating temperatures.

7. List of figures

8. List of tables

9. Acknowledgment

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