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Field measurements on lower radiator temperatures in existing buildings

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door
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Abstract

The energy required for space heating amounts to approximately 68% of the total energy demand for existing buildings in Europe. The heating power of a building is linked to the supply and return temperature of the radiator. A lower supply temperature enables more transition pathways towards sustainable heating with reduced carbon emissions. However, the minimum supply temperature that guarantees thermal comfort during design weather conditions is still unknown. In this study, the minimum supply temperature is determined by fitting a 2R-2C model to high-frequency measurement data from a representative set of 220 existing dwellings in the Netherlands, followed by a novel fully data-driven determination of the minimum supply temperature. The heating system in each dwelling was equipped with a pulse flowmeter and temperature sensors on both the supply and return side of the radiator system. Additionally, we collected data from the thermostat in the main living room and the gas boiler. The data was supplemented with weather data from a nearby weather station. The data-driven model shows that the minimum supply temperature can be lower than 55 °C for 60% of the dwellings during design weather conditions. Moreover, the minimum supply temperature is poorly correlated with the building typology, construction period or specific annual space heating demand (kWh/m^2). On the contrary, the ratio between the required and installed capacity of the radiator system proves a promising parameter to define the minimum supply temperature that guarantees a comfortable indoor temperature during design weather conditions.

Nomenclature

Symbol	Unit	Description
T_s	[°C]	Measured supply temperature at the gas boiler
T_r	[°C]	Measured return temperature at the gas boiler
T_i	[°C]	Measured/modelled Indoor temperature at the thermostat in the living room
T_e	[°C]	Modelled building envelope temperature
T_a	[°C]	Measured ambient temperature at the nearest weather station
Q_h	[W]	Measured/Modelled heat output from heating system
Q_s	[W/m^2]	Measured solar influx
A_w	[m^2]	Model parameter for effective window area for solar influx
R_{ie}	[°C/W]	Model parameter for thermal resistance between indoor space and building envelope
R_{ea}	[°C/W]	Model parameter for thermal resistance between building envelope and ambient conditions
C_i	[Wh/°C]	Model parameter for thermal storage in building interior
C_e	[Wh/°C]	Model parameter for thermal storage in building envelope
Q_d	[W]	Design heat output into the building
Q	[W]	Heat output to the heating elements
Q_a	[W]	Available, installed heat output in the building
ΔT_{sys}	[°C]	Differential temperature between gas boiler supply and return temperature ($T_s - T_r$)
ΔT_{LMTD}	[°C]	Logarithmic mean temperature difference, based on T_s, T_r and T_i; defined in section 2

Abbreviations

Abbreviation	Explanation
DHW	Domestic hot water
SH	Space heating
LTDH	Low-temperature District Heating

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Introduction

Background

Space heating is the most important end use in the European residential sector, accounting for 68% of the total building energy consumption (European Commission, 2022). In most countries fossil fuels are used for this energy demand. Decarbonization of the heat supply in the existing building stock is one of the challenges to meet climate policy goals for 2030 and beyond. The heat supply of existing residential buildings is not easy to decarbonize, as current systems offer a high level of thermal comfort.

The lower the supply temperature for space heating, the easier and cheaper it becomes to use sustainable heat sources such as thermal energy from surface water, wastewater, sand layers in the subsurface or datacenters. The efficiency of solar collectors also improves at lower production temperatures. Furthermore, the efficiency of air-source or ground-source heat pumps improves as the supply temperature reduces, which reduces investment costs (lower capacity) and operational costs (less electricity consumption) for such sustainable heat supply systems. Similarly, at lower grid supply temperatures, the thermal stresses and distribution heat losses in district heating grids are lower, thereby reducing the total cost of ownership of the grid.

The main question is: “How low can we go?”, while still achieving an acceptable level of thermal comfort. An equally important question for district heating grid operators is: to what extent can we reduce the return temperature in conjunction with a reduced supply temperature to maintain the thermal capacity of the district heating grid? A commonly recommended measure in existing buildings to apply low temperature space heating is to install dedicated low-temperature radiators or underfloor heating. Such measures are expensive, 5 to 10 k€ for a typical Dutch dwelling, while the added value of such an investment is not clear yet. We hypothesize that many existing dwellings in the Netherlands (and Europe) have oversized radiators, as mentioned by others in North-western Europe(Jangsten et al., 2017; Østergaard et al., 2022; Østergaard & Svendsen, 2018a). First, heating systems, designed until the late 1980s, were oversized due to the lack of advanced computer-aided design methods. Secondly, the insulation of many buildings has been improved over the years with wall-cavity insulation, floor or roof insulation and double glass windows. Finally, climate change results in a reduction of the heat demand and design heat demand. As an example, the number of heating degree days in the Netherlands has reduced by 20% over the past 5 decades.

State of the art

Many modelling studies have addressed the feasibility of LT-heating (LTH) in existing dwellings in combination with certain renovations. Low-temperature district heating at T_s = 55 °C is feasible most of the year in energy-renovated apartments, including the minimum renovation of the windows only (Harrestrup & Svendsen, 2015). Wang et al. (2015) came to similar conclusions for a Swedish archetype building: the archetype building can cope with low-temperature heating as low as 45 °C when any of 5 retrofit options was installed (Wang et al., 2015). Radiator temperatures in Norwegian apartments can be reduced from 80/60 to 60/40 (Rønneseth et al., 2019). Most of the available modelling studies do not address the required supply temperature during design conditions in existing buildings. Furthermore, the available modelling studies recommend light renovations before LTH is feasible.

A few studies linked the radiator oversizing factor to the feasibility of LTH. Reguis et al. concluded from a review in the UK that heating systems are usually oversized, mainly due to the design assumption on intermittent operation with night setback and practical design margins (Reguis et al., 2021). A Norwegian modelling study concluded that light renovation with a radiator oversizing factor of 30% could enable the use of 50 °C supply temperature with incidental temperatures up to 60 °C without modifications to the heating system (Nord et al., 2016).

Experimental studies on the feasibility of LT-heating in existing buildings have become available in the past 5 years. Jangsten et al. found no publications with actual measurements of supply and return temperatures in heating system until 2017 (Jangsten et al., 2017). Jangsten et al. (2017) analysed supply and return temperatures of 109 radiator systems in Gothenborg and found an average supply temperature of 64 °C (range 53 – 81 °C) and return temperature of 42 °C (range 28 – 57 °C) at the design outdoor temperature of –16 °C. The authors did not assess whether the supply temperature could be further reduced. Jangsten et al. (2017) also concluded that the observed supply temperature at the design outdoor temperature, was poorly correlated with the prevailing design supply temperature in the applicable construction year. A small-scale experimental project in five Danish single-family houses from the 1930s showed that supply temperatures can be lower than 55 °C during most of the year (Østergaard & Svendsen, 2018b). In 2 out of 5 dwellings, the return temperatures were found to be in the preferred range of 25 – 30 °C. Østergaard & Svendsen (2018b) did not make recommendations on the possible supply temperature reduction during design conditions.
A study on 1650 Danish dwellings concluded that most dwellings have oversized radiators at medium supply and return temperatures of 70 and 40 °C (Østergaard & Svendsen, 2018a). Even though the design capacity was manually acquired by plumbers, the results were consistent with earlier theoretical studies.

A reduction of the supply and return temperature may result in direct energy savings. (Benakopoulos et al., 2022) measured and modelled the impact of intermittent high-temperature and continuous low-temperature control strategies on the return temperature and energy savings in a large office building in Denmark from the 1970s. They reported energy savings of approximately 11% and 12 - 14 °C reduction in the return temperature, compared to the conventional high-temperature operation. Unfortunately, the mass flow rates and peak load reduction compared to the night-setback operation were not reported.

A striking conclusion from the available experimental studies is that mass or volume flow meters were not included in the experimental studies, implying that the heat flows to the heating system were not directly measured. However, there is ample evidence from modelling studies and small-scale experiments that the heating elements in most existing buildings have sufficient capacity to enable low-temperature heating most of the year. The last conclusion was confirmed by a very recent review study (Østergaard et al., 2022). The main question that remains is: How low can we go in existing dwellings during design conditions?

Aim of the study

This paper addresses the following knowledge gaps: a) direct measurement of heat flows in conjunction with supply and return temperatures towards the heating elements which enables b) experimental validation of lower supply and return temperatures in the existing building stock. Since we aim for a representative sample of the Dutch residential building stock, including at least 200 dwellings, we aim to draw conclusions on the LT-readiness of the entire residential building stock in the Netherlands.

In this paper we will focus on the minimum required supply temperature during design conditions in existing residential buildings with existing radiators and no further measures to the building envelope. The experimental set-up will be detailed in section 2. Section 3 details the fully data-driven approach to determine the minimum required supply temperature for each dwelling in the field experiment. Section 4 discusses results of the field experiment. In section 5 we summarize the main findings and provide recommendations.

Materials and methods

We address the selection of buildings for the experimental campaign and the measurement set-up. The original planning is summarized in Figure 1. We set up a collaboration with a large installation company, Feenstra BV, that monitors and maintains around 20000 Intergas individual gas boilers. The relevant monitoring data, acquired via the existing monitoring system, are described in the measurement set-up section.

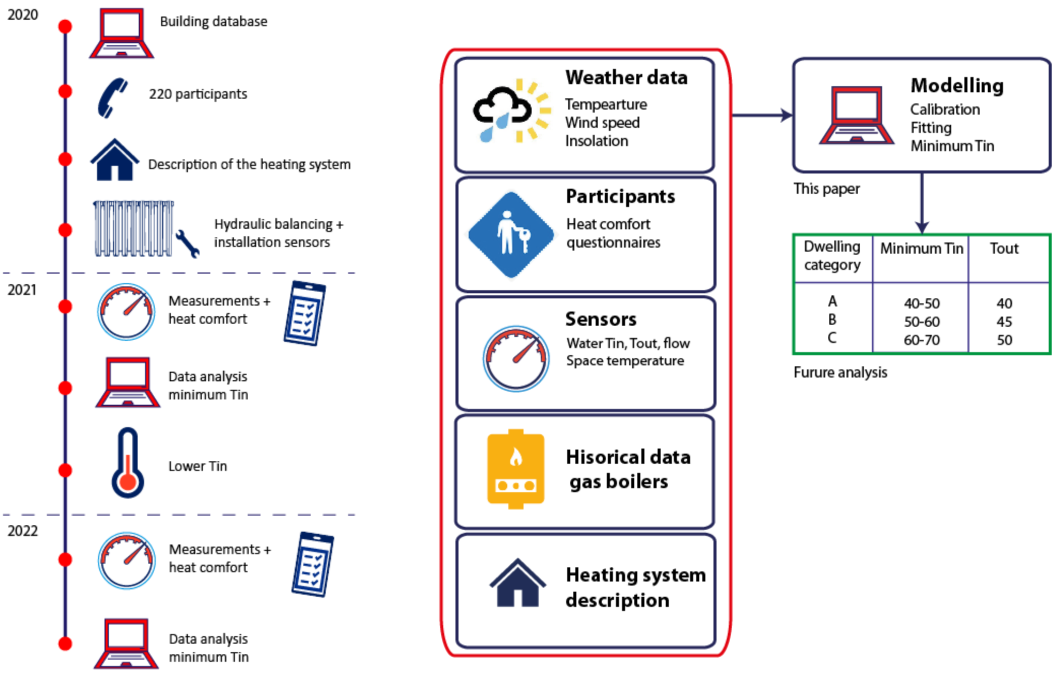

Figure 1: Original planning of the research project

Selection of buildings

We aimed for a representative sample of the Dutch residential building stock, based on building typology and construction period. The oil crisis in the early 1970s caused a significant improvement in building insulation. Therefore, the first construction period ends in 1974, which corresponds with a more detailed building classification by RVO (Netherlands Enterprise Agency (RVO), 2011). The second construction period ends in 1992, when stricter insulation regulations were imposed and computer-aided design methods were introduced, which led to the introduction of more accurately designed, smaller, heating elements. The building typologies are also aligned with the RVO-classification and include four building types, namely: apartments, terraced dwellings, corner dwellings and detached dwellings.

Common design supply and return temperatures for heating systems were 90/70 °C, 80/60 or 75/65 °C in the previous century. Most heating systems in Dutch dwellings are designed at 75/65 °C and 20 °C indoor temperature (Coenen, 2019) .

A sample of 220 dwellings distributed over building and age categories is selected based on national statistics as proposed by (Coenen, 2019). Dwellings were excluded from our sample if they had an additional heat source, hydraulically unbalanced floor heating, or lacked a plug connection near the gas boiler for our monitoring equipment. Table 1 shows the target distribution in the Netherlands and the distribution of the sample set. The sample distribution deviates from the target distribution because of the exclusion criteria mentioned above. Old apartments (before 1974) are underrepresented and terraced and corners dwellings from the construction period 1974 – 1991 are over-represented.

Table 1 Percentages of Dutch building stock per type and construction period (Top: CBS data 2016; Bottom: Sample)

Category	Detached	Corner	Terraced	Appartement	Total
Before 1974	7.3	10.9	12.6	24.1	**54.9**
1974–1991	2.5	5.9	9.5	6.3	**24.2**
After 1991	3.6	4.7	7.1	5.5	**20.9**
Total target	**13.4**	**21.5**	**29.2**	**35.9**	**100**

Before 1974	8.6 (+1.3)	12.7 (+1.8)	14.5 (+1.9)	14.5% (-9.6)	**50.4 (-4.5)**
1974–1991	2.7 (+0.2)	9.1 (+3.2)	11.4 (+1.9)	6.4% (+0.1)	**29.5(+5.3)**
After 1991	3.2 (-0.4)	5.0 (+0.3)	7.7 (+0.6)	4.1% (-1.4)	**20.0 (-0.9)**
Total realised	**14.5 (+1.1)**	**26.8 (+5.3)**	**33.6 (+4.4)**	**25.0 (-10.9)**	**100**

Measurement set-up

The measurement set-up is based on the energy meter method or integrated co-heating test as proposed by (Farmer et al., 2016), including most of the recommendations by (Bauwens & Roels, 2014) on the acquisition of environmental data (Figure 2). The purpose of these methods is to assess the overall thermal performance of a building, and the total heat emission from the heating system. We have extended the integrated co-heating test to a dynamic test to reveal the building heat loss coefficient in conjunction with the thermal inertia of the building envelope and internal thermal inertia. Prior to the start of the measurements, the heating systems were hydraulically balanced using thermostatic radiator valves in all rooms of each dwelling to obtain similar supply and return temperatures at all open radiators. The complete data acquisition set-up includes new instrumentation, available monitoring data from the monitoring system of Feenstra and climatic data from nearby weather stations.

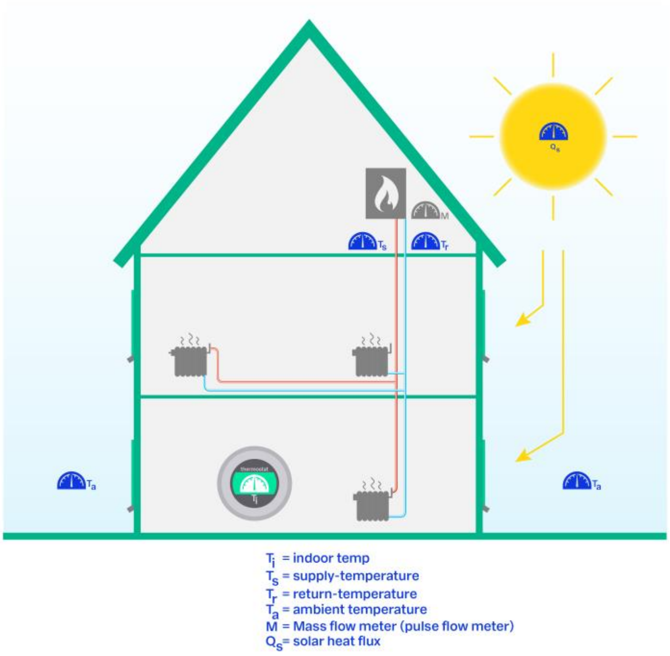

Figure 2: Schematic data acquisition set-up in individual buildings

We have installed two temperature sensors and a pulse flow meter to accurately measure the heat flow to the heating elements. The temperature sensors have been installed on supply and return pipes towards the heating elements near the gas boiler to ensure that these measurements do not interfere with the domestic hot water preparation. The measured data is transferred daily via a GSM connection. We rely on the Feenstra monitoring of the thermostat-temperature sensor in the living room for the internal building temperature. This measurement is non-equidistant and based on a minimum deviation with an unknown minimum interval. We also get temperature setpoint data and approximate gas consumption data for space heating from this monitoring system. The gas consumption is derived internally by the gas boiler from the measured ventilator frequency. With many starts and stops it is therefore possible for this gas usage to be less accurate. The gas consumption data are used only to characterize the annual gas demand and specific annual gas demand for space heating.

Table 2 Overview of data acquisition frequency of the raw data and after processing

Data type	Frequency measure	Processed frequency (averages)
Flow	Pulse per liter	10 minutes (average)
Tin and Tout	Minute	10 minutes (average)
T air inside	Non-equidistant	10 minutes (average + linear interpolation)
Weather (temperature, solar influx)	Hourly	10 minutes (linear interpolation)
Historical gas use	Daily	Daily

Monitoring data from Dutch Meteorological institute (KNMI) for station "Deelen" was collected for the outside temperature and solar influx. This station is geographically closest to most studied buildings. The data-acquisition frequencies are listed in Table 2. The dwellings were hydraulically balanced and fitted with new instrumentation between January 2021 and November 2021. This installation period took a long time, due to the COVID pandemic.

Modelling approach, calibration, and optimization

The measured data enables the calibration of an appropriate grey box model for each dwelling in our sample. A grey box model is calibrated with the measurement data for each dwelling in our sample. The grey box model is used to determine the varying indoor temperature of each dwelling during winter conditions. The grey box model also predicts the heat demand by the heating system during design conditions. The measured temperatures and heat flows will be used to determine the minimum required supply temperature to deliver the design heat demand. Additionally, we get information on the corresponding return temperature in these design conditions. This section substantiates the grey-box model choice , the next section details the data-driven method to determine the reduced supply temperature.

Bacher and Madsen have formulated a hierarchy of grey box models (xRyC) with increasing complexity and one indoor temperature as the observed variable (Bacher & Madsen, 2011), like our measurement set-up. The parameter estimation is complicated by identifiability issues as the number of state variables increases. In Bacher's third order model with the indoor temperature T_i, wall temperature T_e and radiator temperature T_h as the state variables, the parameter estimation resulted in an extremely high thermal resistance between radiator and indoor space of 93.4 °C/kW compared to 0.639 °C/kW in the 2nd order model and an extremely low radiator heat capacity of $1.39 \cdot 10^{-3}$ kWh/°C compared to 0.309 kWh/°C in the 2nd order model, leading to a realistic radiator time constant of 0.129 h (compared to 0.2 h). These extreme parameter values are a clear indication that third order building models become difficult to identify with only 1 observed variable.

Reynders et al performed several numerical tests with ideal inputs to assess the quality of lumped grey-box model calibrations(Reynders et al., 2014). They found that the parameter uncertainty increases if the model order is increased from 2 to 3 when the indoor temperature is the only observed variable. Reynders had to extend the observation vector with heat flux data from the detailed simulation model to properly identify the system parameters for the 3rd, 4th, and 5th order models. Reynders also concluded that the total solar irradiation on the vertical plane along the cardinal direction is a useful alternative input signal for the parameter identification.

Since we want to automate the grey box model identification for 200 dwellings, we have applied a NLP solver to calibrate both 1st order and 2nd order models; equations (1) and (2) show the 2nd order model equations.

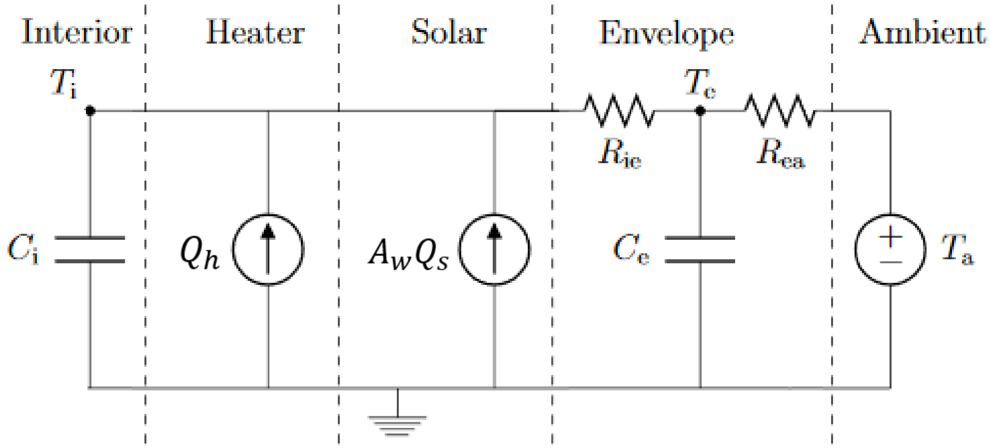

Figure 3: Schematic representation of the 2R2C building model, following the electric analogy (source: Bacher and Madsen, 2012)

In ODE form:

$$\frac{dT_i}{dt} = \frac{1}{R_{ie}C_i}(T_e - T_i) + \frac{Q_h}{C_i} + \frac{A_wQ_s}{C_i} \quad (1)$$

$$\frac{dT_e}{dt} = \frac{1}{R_{ie}C_e}(T_i - T_e) + \frac{1}{R_{ea}C_e}(T_a - T_e) \quad (2)$$

The 2nd order model has five parameters: R_{ie} and R_{ea} represent the thermal resistances between the indoor space, the building envelope, and the ambient condition; C_i and C_e represent the effective indoor respectively envelope thermal storages; A_w represents the effective window area for solar gains. We select the three coldest 10-day periods from the available data. Two of these are used for the training of the model. One period is used for validation, to check how the model behaves on unseen data and prevent overfitting. Looking at the performance on the validation periods, the prediction error of the 2R2C model was still better than that of the 1R1C model. The calibration result on the indoor temperature of one dwelling is shown in Figure 4 as an example.

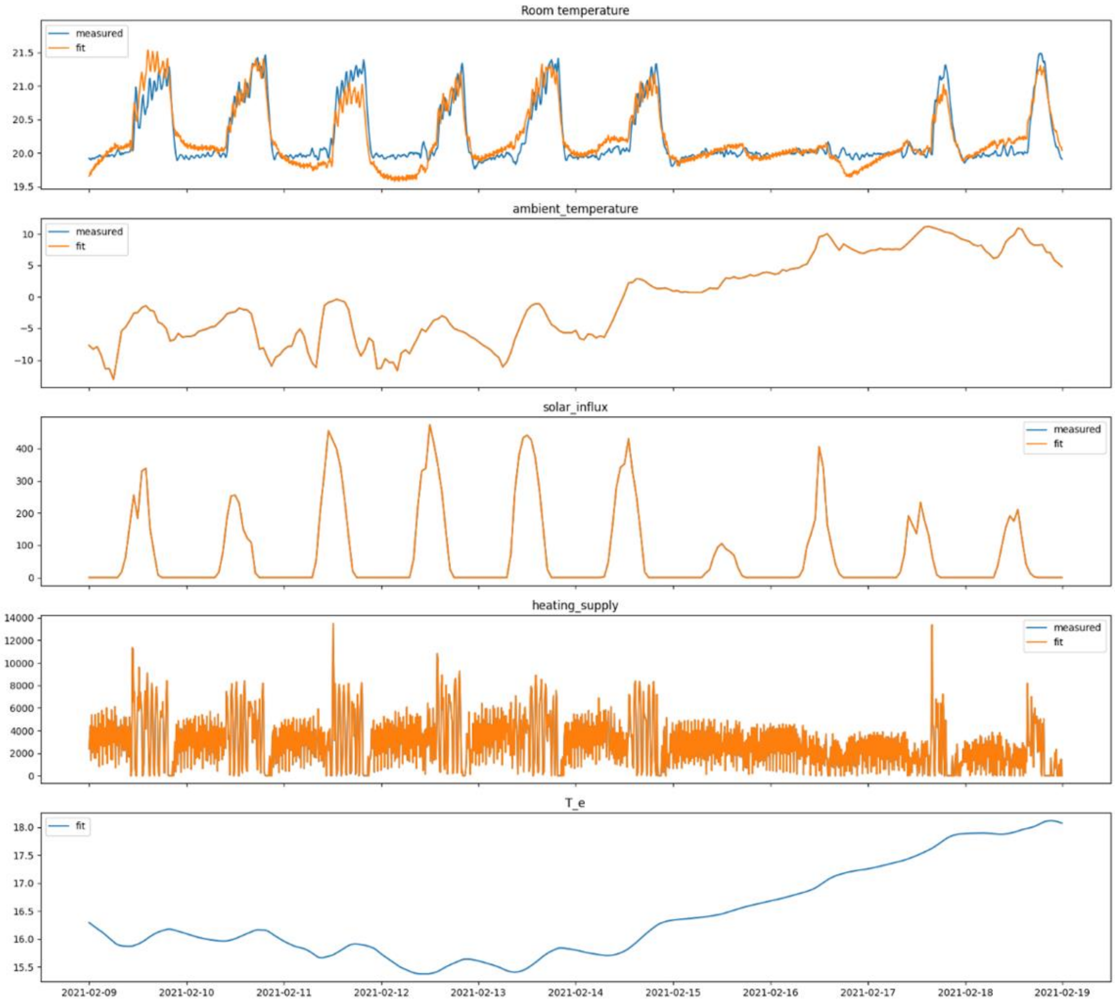

Figure 4: Typical calibration result of one dwelling

Supply temperature reduction method

The data analysis consists of two main steps:

1. Determine design heat output, Q_d.
2. Determine the minimum supply temperature to deliver this design heat output

The method to determine the design heat output is straightforward, given the successful grey box model tuning. The design weather condition in the Netherlands is a daily average ambient temperature T_a = -10°C without solar radiation and an indoor temperature of +20°C. The steady design heat output is directly derived from the calibrated RC-model, resulting in a daily average heat output. Then we make an important assumption on the future-proof design heat output: the required heat output during design conditions can be delivered in 18 hr, resulting in the design heat output Q_d [W]. The choice to deliver the spatial heat demand in 18 hr during the design day is to account for modelling uncertainties and possible domestic hot water (DHW) supply to a daily buffer from the same installation.

This section focuses on the supply temperature reduction, using a minimum set of assumptions on radiator coefficient, differential temperature or return temperature. Our objective is to determine the minimum supply temperature to emit the design heat output Q_d into the building. The heat emitted from the radiators is theoretically determined by the radiator area *A*, the heat transfer coefficient h(T_s) which depends on temperature levels in the radiator and the log-mean temperature difference (LMTD) of the radiator ΔT_{LMTD} for quasi-steady conditions; see e.g. (Østergaard & Svendsen, 2016).

$$Q = h(T_s)A\Delta T_{LMTD} = \dot{m} \cdot c_p \cdot \Delta T_{sys} \quad (3)$$

$$\Delta T_{LMTD} = \frac{\Delta T_s - \Delta T_r}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} = \frac{T_s - T_i - (T_r - T_i)}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} = \frac{T_s - T_r}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \quad (4)$$

where:
Q [W] heat output from the radiators
T_s [°C] radiator supply temperature
T_r [°C] radiator return temperature
T_i [°C] internal temperature in the main living room, recorded at the thermostat.
ΔT_{sys} [°C] heating system temperature difference. $\Delta T_{sys} \equiv T_s - T_r$

Since we measure all three temperatures T_s, T_r and T_i, we can determine the radiator ΔT_{LMTD} and system ΔT_{sys} directly. Combining the measured supply and return temperature with the measured flow rate, we also determine the heat output Q directly. Hence, we can plot the experimental heat outputs as a function of the radiator ΔT_{LMTD} or system ΔT_{sys} (Figure 5). The horizontal line denotes the design heat output Q_d . The green dots are the 1% data slice that are the closest to the design heat output.

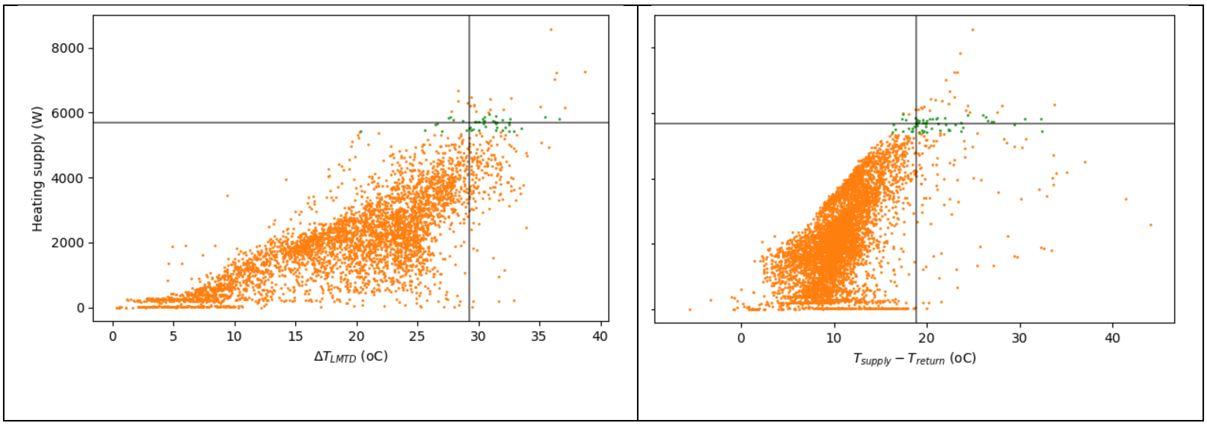

Figure 5: Method to determine the design radiator $\Delta T_{LMTD,d}$ (left) and the required system ΔT_{sys} (right). The horizontal line denotes the design heat output Q_d . The 25-percentile value of the selected (green) data points around the design heat output define $\Delta T_{LMTD,d}$ and $\Delta T_{sys,d}$ respectively, indicated with the vertical lines.

Each data point in Figure 5 shows an hourly average value of heat output to the building and flow-weighted average radiator ΔT_{LMTD} respectively system ΔT_{sys}. Each heat output can be delivered at a wide range of temperature differences, where large temperature differences refer to part-time operation. Since the smallest average radiator ΔT_{LMTD} and system ΔT_{sys} occur at full-hour operation and the largest pump flow rates, we select the 25% percentile value of the experimental radiator ΔT_{LMTD} respectively system ΔT_{sys} values that delivers the design heat output, indicated by the green datapoints and vertical lines in Figure 5. These radiator $\Delta T_{LMTD,d}$ and system $\Delta T_{sys,d}$ represent the performance at the design condition.

Now we can use these fully experimental radiator $\Delta T_{LMTD,d}$ and system $\Delta T_{sys,d}$ to determine the minimum supply temperature to deliver the design heat output. The minimum required supply temperature can be computed after some algebraic manipulations with equations (3) and (4) at the experimental design conditions:

$$T_{s,d} - T_i = \frac{\Delta T_{sys,d}}{1 - e^{-\left(\frac{\Delta T_{sys,d}}{\Delta T_{LMTD,d}}\right)}} \tag{5}$$

$$T_{r,d} = T_{s,d} - \Delta T_{sys,d} \tag{6}$$

In this way we do not need to make any assumption on the return temperature, the radiator coefficient, or the heating system temperature difference. This approach leads to the following design values for the example dwelling, illustrated in Figure 5. $\Delta T_{LMTD,d} = 29.3\ °C$; $\Delta T_{sys,d} = 18.9\ °C$; $T_{s,d} = 59.7\ °C$; $T_{r,d} = 40.8\ °C$.

Theoretical performance of heating system

During the site visits to the individual dwellings the radiator types and dimensions (length, width, and height) were recorded; these include 4 different radiator types as listed in Table 3. The dwellings in this project have 8.5 radiators or heating elements on average.

Table 3 Radiator types in participating dwellings

Radiator type	Percentage of radiator type in participating buildings [%]	Remarks
Panel	87,4	Type is recorded. Observed types include 10, 11, 20, 21, 22, 33. Design is standardized with similar performance for different manufacturers.
Column	3,5	Number of columns is specified, but recorded info seems to include multiple errors (many radiators with 1 column only). This data seems less reliable.
Design	7,8	Brand or type is not specified. Data from manufacturers shows wide range in heat output in W/m^2 . This type includes towel and bathroom radiators.
Convector	1,4	Number of flow paths is provided (2, 3, 4, 6, 8). Performance data is variable.

To determine the theoretical heating system performance in terms of heat output we have applied the following rules to estimate the available, installed design output Q_a:

1. The design radiator performance is based on supply, return and indoor temperatures of 75/65/20, typical design conditions in the Netherlands.
2. Since convectors were hardly present in the participating dwellings, we have ignored the heat output of these heating elements. Convectors were assigned 0 kW/m^2 heat output.
3. We have used conservative parameters for the heat output of Design radiators (Table 4).
4. We have used a conservative value for the heat output of Column radiators of 0,65 kW/m^2, based on 1 face of the columns (N_{col} x height x width).

5. We have approximated the heat output of panel radiators with the following correlation in panel height H and length L with parameters A and B in Table 4.

$$Q_a = (A + B \cdot H) \cdot L \tag{7}$$

Table 4 Panel and design radiator correlations

Panel type	Parameter A [kW/m]	Parameter B [kW/m²]
10	0.08	0.88
11	0.10	1.43
20	0.15	1.45
21	0.20	1.81
22	0.30	2.16
33	0.45	3.07
Design	0.06	0.51

We define the dimensionless design heat output as the ratio of the required design heat output Q_d and available, installed heat output Q_a.

$$\eta = \frac{Q_d}{Q_a} \tag{8}$$

This dimensionless design heat output is the inverse of the oversizing factor, used by (Reguis et al., 2021).

Results

First, we will assess how representative our sample of 220 dwellings is in terms of the specific heat demand. Secondly, we present results on the reduced design supply temperature in our sample. Finally, we present a couple of analyses to find simple parameters that can predict the reduced design supply temperature without the effort of the detailed measurement campaign.

Representativity of dwelling sample

We compare the specific heat demand for space heating (kWh/m^{2}yr) in our sample with available data from the province of North Holland (Servicepunt Duurzame Energie) and the Dutch national statistics agency (CBS), summarized in Table 5 and Table 6 respectively. Data on the specific heat demand is available only for single family homes and multi-family homes. Therefore, we have aggregated the detached, corner, and terraced dwellings.

Table 5 Average specific heat demand for space heating in Dutch residential buildings. Data from (Servicepunt Duurzame Energie, 2019) and national statistics. Data is reworked to the three construction periods in our field campaign.

	Average floor area [m^2]	Average gas consumption for SH [m^3]	Average specific heat demand SH [kWh/m^{2}yr]
Single family home			
before 1974	166	1729	97
1974 - 1991	130	1390	75
after 1991	149	1108	54
Multifamily residential			
before 1974	79	1164	92
1974 - 1991	70	840	70
after 1991	90	726	45

Table 6 Average specific heat demand for space heating in our field measurement in 2021. The last column includes in brackets the percentual difference with the values in Table 5.

	Average floor area [m^2]	Average gas consumption SH 2021 [m^3]	Average specific heat demand SH 2021 [kWh/m^{2}yr]
Single family home			
before 1974	135	1596	110 (+12%)
1974 - 1991	142	1332	87 (+28%)
after 1991	129	1222	88 (+59%)
Multifamily residential			
before 1974	83	974	109 (+19%)
1974 - 1991	73	756	96 (+25%)
after 1991	93	856	86 (+96%)

We make the following observations from the tables above. First, the average specific heat demand in our sample is 12% to almost 100% larger in the different building categories and construction periods. The largest deviations occur in the most recent construction period, because appartements and single-family homes in our sample are relatively old with an average construction year of 2000 respectively 1998; the newest appartement and single-family home in our sample were built in 2009. Secondly, the specific heat demand in our sample is based on gas consumption data from 2021. This year was a bit colder than average with approximately 5% more heating degree days than the average of the last 3 decades (2800 HDD). The 2021 data could lead to a correction of at most 5% in the specific heat demand. Main conclusion is that the specific heat demand of our sample is on average larger than that of typical Dutch residential dwellings.

How low can we go?

The proposed model calibration was successfully performed for 187 dwellings. Since we applied a strict calibration method using three 10-day periods, too few complete 10-day periods were available to both calibrate and validate the other models. In a few dwellings the data acquisition system was disconnected such that no data became available. The calibration proved unreliable in 2 buildings. Some statistics on the reduced design supply temperatures are summarized in Table 7.

Table 7 Statistics on the resulting supply temperature, return temperature and temperature differences during design conditions in 187 buildings

	Mean value [°C]	Standard deviation [°C]	Percentiles				
			20th	40th	60th	80th	95th
Reduced design supply temperature ($T_{s,d}$)	53.1	8.7	45.3	49.6	55.3	59.5	69.7
Corresponding return temperature ($T_{r,d}$)	38.5	6.8	32.6	36.5	40.2	43.3	50.4
System temperature difference ($\Delta T_{sys,d}$)	14.6	5.1	10.5	12.9	15.2	18.1	23.9
Log-mean temperature difference ($\Delta T_{LMTD,d}$)	25.0	7.4	18.3	22.5	26.5	30.8	37.5

We see that 40% of the building stock is already capable of supply temperatures lower than 50 °C, and 60% when extending this to 55 °C. Following Dutch definitions of low-temperature heating (Ts < 55 °C), these results suggest that 60% of the existing residential homes in the Netherlands is LT-ready. Following the international definitions for low-temperature heating (Ts < 70 °C), even 95% of the Dutch building stock is suitable for heat supply with Ts < 70 °C. It should be noted that we have excluded buildings with additional heat sources like fireplaces and buildings with underfloor heating, which would result in an even larger percentage of LT-ready buildings. The second main conclusion is backed-up by practical experiences at Dutch district heating companies. District heating company HVC has performed successful tests during a cold winter period (Feb 2021) in a neighbourhood with around 500 dwellings. Their measurements showed average supply temperatures in the dwellings of 67 °C and average return temperatures around 42 °C; the heat curve with reduced temperatures has been adopted after these tests.

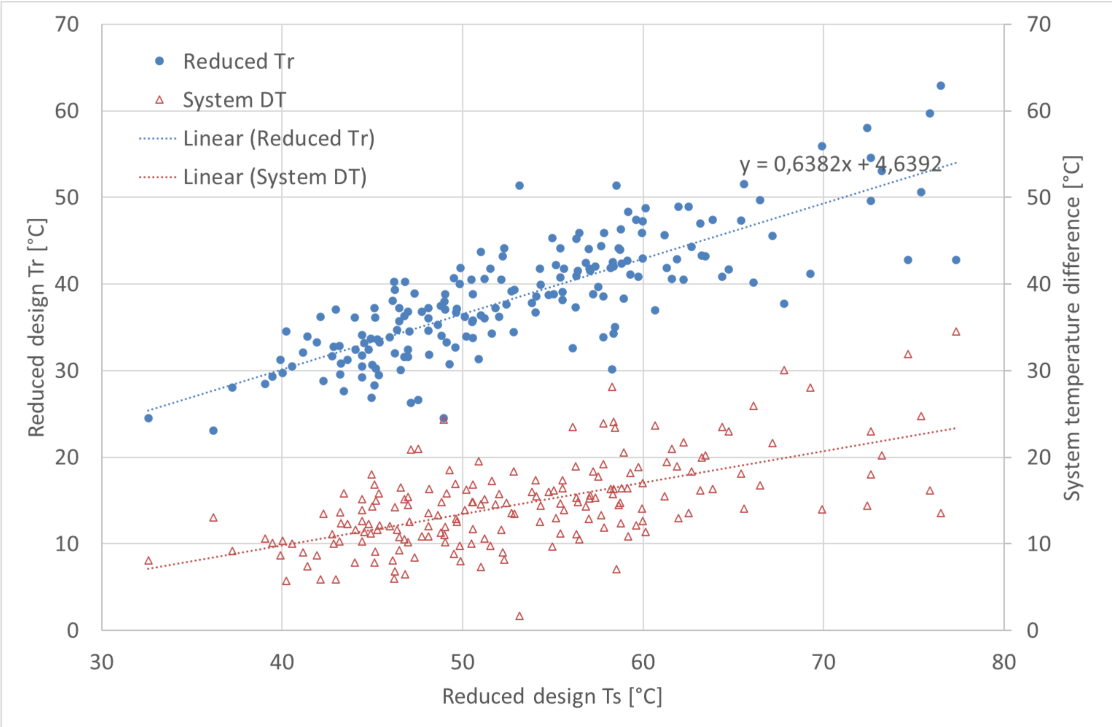

Figure 6: Correlation between reduced design supply temperature and corresponding return temperature (blue dots) and system ∆T (red triangles) for different building types.

Results show 60% of the return temperatures are below 40 °C and 95% are below 50 °C (Table 7). Figure 6 shows the linear fit of the reduced design supply temperature and corresponding return temperature. Since the slope is smaller than unity, the temperature difference increases in the design supply temperature. The reduced return temperature is partially affected by the control system of the gas boiler, which has not been optimized to minimize the return temperature.

Another interesting result from the experimental data is the relation between the annual gas consumption for space heating and the steady design heat supply (Figure 7). The linear relation confirms that the design heat demand of an existing building can be derived from the annual heat supply for space heating. This correlation suggests that a (weighted) heating degree day approach can be adopted to determine the future-proof design heat demand. It should be emphasized that the data points in Figure 7 have been extracted from independent data sources. The design heat supply is based on the model calibrations, using the temperature and pulse flow data and the future-proof assumption of 18 full load hours on the design day. The annual space heating demand is based on the estimated gas boiler consumption for space heating, derived from the gas boiler ventilator frequency.

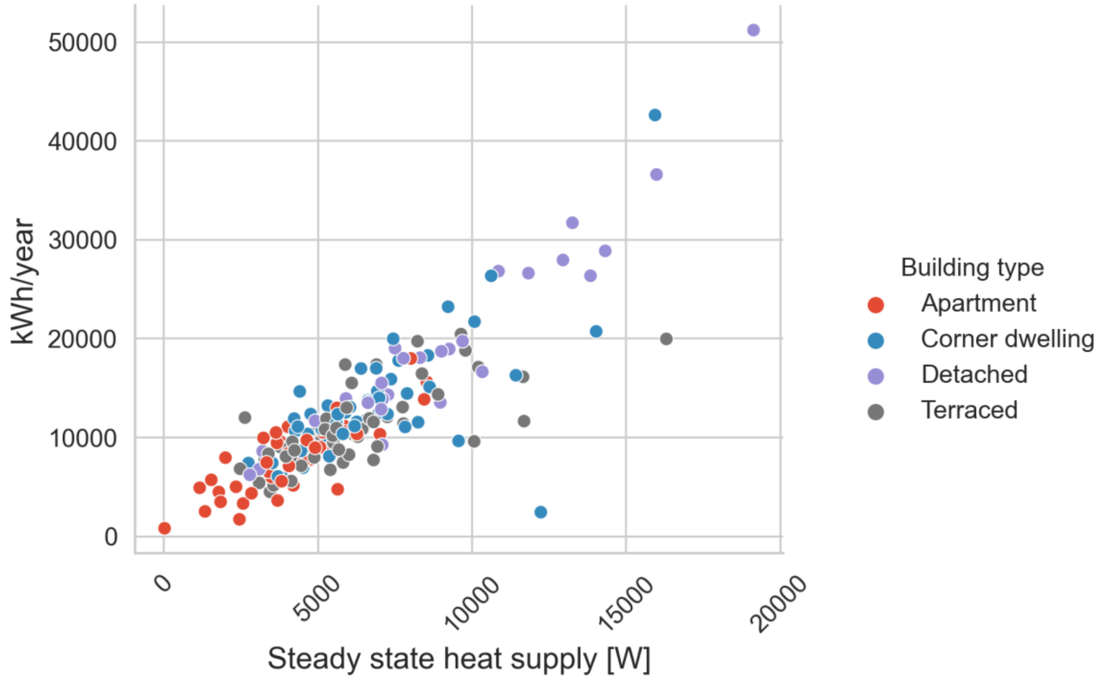

Figure 7: Relation between annual heat demand for space heating and the steady heat supply during design conditions.

Exploratory analysis to predict the reduced supply temperature

Given the result that 60% of the Dutch residential building stock is LT-ready, it would be of great value to home owners, housing corporations, installation companies and district heating companies to determine which buildings are LT-ready. Such a check on LT-readiness is preferably based on easily accessible or computable properties, like the building type, construction period or specific heat demand for space heating. Another parameter that may predict the reduced supply temperature is the dimensionless design heat output, although this parameter is more difficult to determine for an arbitrary building. Figure 7 has shown that the annual heat demand for space heating can predict the future-proof design heat demand, but it is not clear which supply temperature is required to deliver the design heat demand.

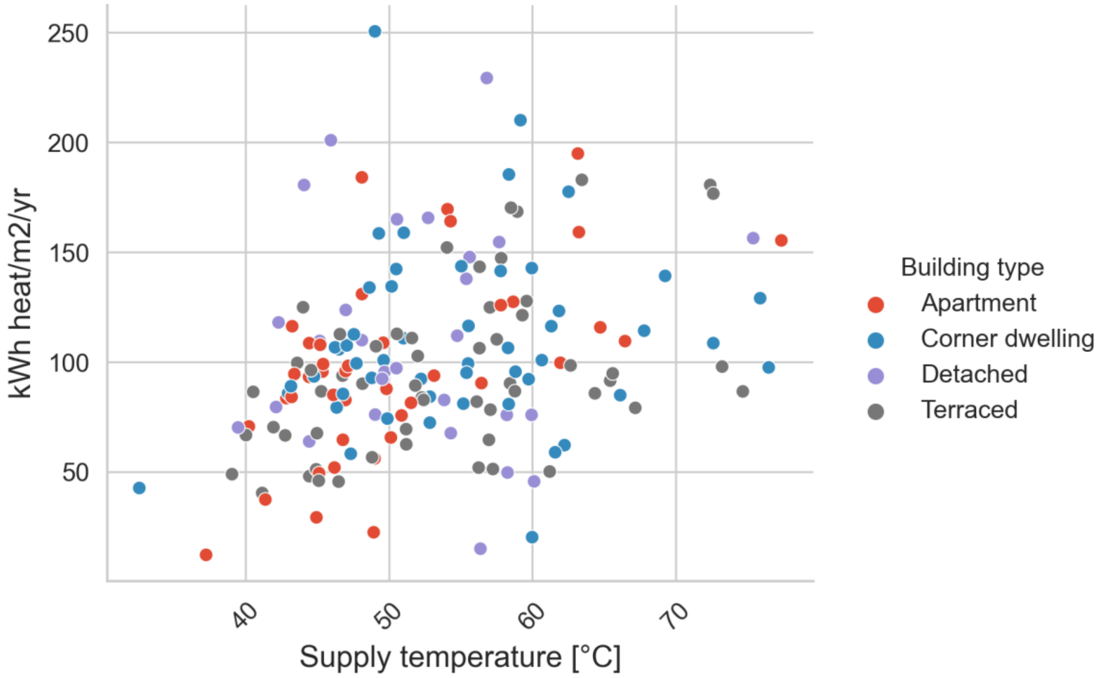

Figure 8: Specific heat demand for space heating versus design supply temperature, where colors indicate building types.

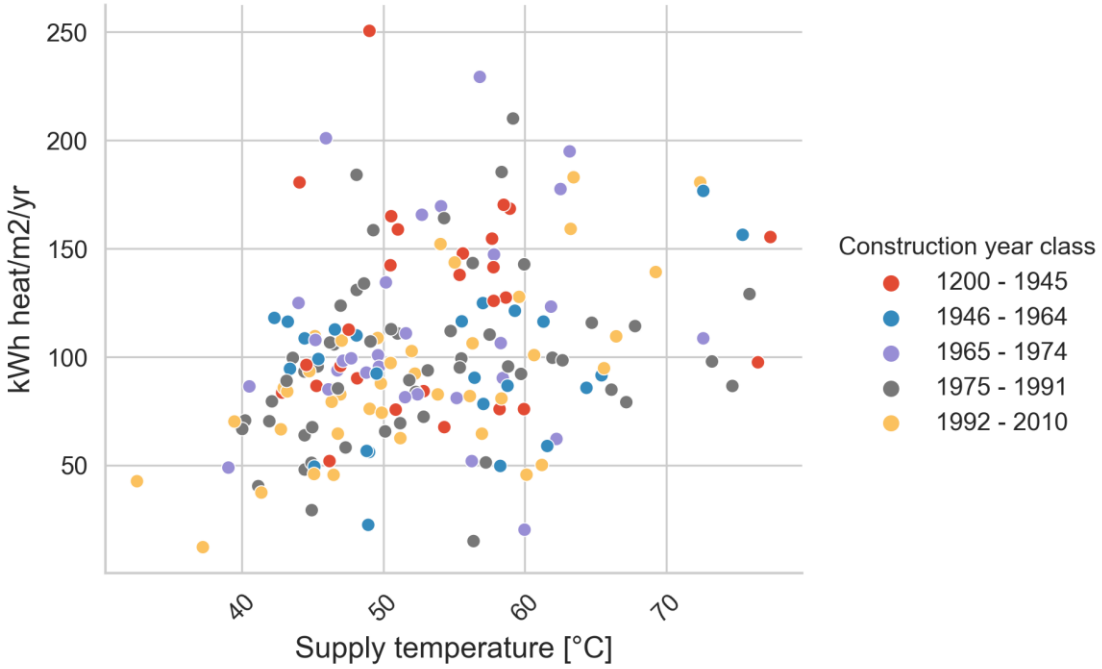

Figure 9: Specific heat demand for space heating versus design supply temperature, where colors indicate construction period.

Figure 8 and Figure 9 show the design supply temperature and the specific heat demand for the different building types and construction periods. It is immediately clear from visual inspection that the reduced supply temperature is poorly correlated to any of these simple parameters. However, some interesting observations from these figures can be made. One might expect that apartments have a smaller specific heat demand than single family homes, but this is not confirmed by Figure 8, nor by Table 6. The smaller annual heat demand in apartments is mainly due to the smaller floor area. The spread in specific heat demand and reduced supply temperature is large for all building types and construction periods. We can identify quite a few pre-war buildings with reduced design supply temperatures below 50 °C and specific heat demands varying between 50 and 250 (!) kWh/m^{2}yr. Buildings in the most recent construction period have specific heat demands between 40 and 180 kWh/m^{2}yr and reduced design heat supply temperatures below 40 °C up to 72 °C. If we focus on this construction period only, a very weak correlation between reduced supply temperature and specific heat demand could be identified. Two possible reasons may contribute to the large spread in reduced supply temperature and specific heat demand: occupant behaviour and improvements of the building envelope over time, such as cavity wall insulation, double glass windows or other upgrades.

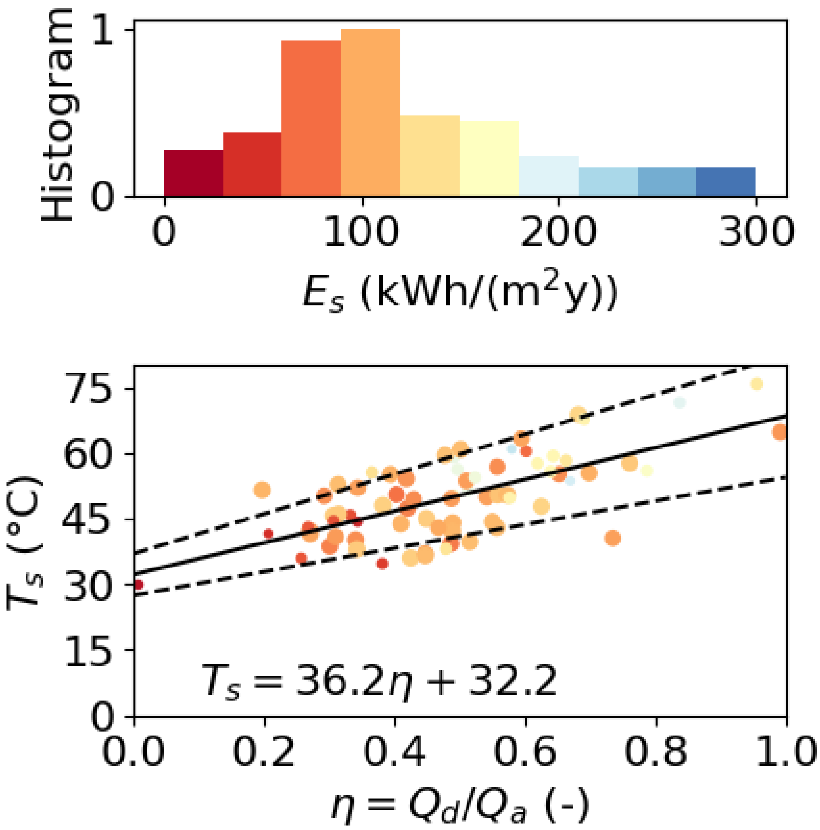

Figure 10: Relation between reduced design supply temperature and the dimensionless design heat output

The dimensionless design heat output, defined in equation (8), is much better correlated with the reduced design supply temperature T_s than the building type or construction year, as illustrated in Figure 10. The available data suggests that the reduced design supply temperature is 55 °C (or lower) if the design heat output is at most 63% of the installed radiator capacity.

Discussion

First, we will reflect on the model calibration. Secondly, we will suggest a method to determine "How low we can go" in other dwellings without the availability of the high-frequency temperature and flow data.

The wind speed, as measured by the weather station, has not been used for the model calibration. It would be possible and possibly more accurate to compensate the "raw" outside temperature with the wind chill.
It is recommended to observe the maximum possible variation of the indoor temperature and heat supply to make accurate parameter estimates, especially the thermal inertia terms (C_i, C_e). Such variation could be realized by stimulating the participants to apply night setback during cold periods. This results in more accurate estimates of the thermal inertia parameters. Furthermore, the morning peak heat output more frequently exceeds the future-proof design heat output, which is required for the reliable determination of the minimum supply temperature at design conditions.
Other possible processes, that may affect the model calibration, include a large window close to the temperature sensor in the living room or direct solar radiation on the indoor temperature sensor during certain hours.
An alternative calibration method might be Interesting for follow-up research. First, use daily average values of indoor and outdoor variables to estimate the resistance parameters and solar gains; then use the high frequency dataset to estimate the thermal inertia parameters.
The calibrated building models include parameters on the building thermal inertia. These results may be further analyzed to use the flexibility of existing buildings for demand response strategies. Such demand response strategies are required in a future-proof affordable smart energy system to match production from renewable sources with the heat demand.

Figure 7 and Figure 10 can be used in future research to develop and validate a method for the reduced supply temperature of arbitrary residential dwellings. Such a method would use the annual gas consumption for space heating and the installed radiator capacity as key parameters:

1. The annual gas consumption for space heating (kWh/yr) and the corresponding (weighted) heating degree days (HDD) determine the design heat output (kW).
2. The ratio of design heat output and installed radiator capacity determines the reduced supply temperature, following Figure 10.

This method gives a first indication which reduced design supply temperature would be sufficient for an arbitrary residential building, which is valuable input for home owners, housing corporations, installation companies and district heating companies A more refined version of this method may be developed using other parameters and multiple regression techniques.

Conclusions

We have set up a large-scale measurement campaign in 220 representative dwellings in the Netherlands, including high-frequency data of the radiator supply temperature, return temperature and flow rate to the heating elements. The available data enabled us to fit a basic 2R-2C model and to establish a fully data-driven method to assess the minimum required supply temperature during design conditions for each individual building.

The analysis of the reduced design supply temperature shows that design supply temperatures can be lowered to 55 °C or lower in 60% of the dwellings. Another important conclusion for district heating developers is that nearly all dwellings (95%) are suitable for a supply temperature of 70 °C, which implies that district heating grid temperatures in the Netherlands could be reduced to medium temperature levels all year round. Furthermore, the reduced supply temperature is poorly correlated with the building typology, construction period or specific annual space heating demand (kWh/m^2). A key parameter to determine the reduced supply temperature during design conditions proved to be the ratio of the design heating power and installed capacity of the radiators.

Future research would be recommended to determine to which the extent the return temperature can be further reduced during design conditions and normal operations.

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