

# Heating the Dutch housing stock without natural gas

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**Abstract.** This paper studies the level of improvement of building envelopes required to heat the Dutch housing stock using an energy supply without natural gas, such as a district heating network at lower supply temperature or a heat pump. We identified 35 building types to represent the Dutch housing stock of single-family dwellings. A 4R2C building model was used to assess whether the dwellings could be heated at lower supply temperatures after they were renovated according to six renovation packages of different ambition level.

## 1. Introduction

In the coming years, the Dutch housing stock will have to improve its energy efficiency in order to meet national climate targets. In addition, the Dutch government aims to make the energy supply entirely free of natural gas by 2050, to further reduce the dependency on fossil fuels.

A natural gas-free energy supply generally involves either a district heating (DH) network, preferably fed by a sustainable source, such as geothermal energy or industrial waste heat, or an all-electric energy supply, generally involving heat pumps. All have the consequence that supply temperatures of the heating system in the dwelling are lower than in the case of a conventional gas-fired boiler. The question then remains to what extent the building envelope of existing dwellings needs to be improved so that they dwellings can be comfortably heated at these lower supply temperatures.

In the Netherlands, several criteria for such an improvement are being proposed as a result of the Dutch climate agreement ('Klimaatakkoord'). Startanalyse [1], intending to introduce recommended national envelope standards, proposes that dwellings be improved to at least the level of (envelope) label B (typical U-value of opaque parts of the envelope  $0,4\text{W/m}^2\text{K}$ ). Nieman [2] conducted a study into different types of natural gas-free infrastructures, calculating the thermal power required to heat renovated dwellings. Target heat demand values (the so called 'Standaard') are being proposed depending on the 'compactness' parameter of the dwelling (envelope area over floor area) as well as recommended thermal insulation values (the so called 'Streefwaarden').

The current study focusses on single-family dwellings and considers only the heat demand for space heating since domestic hot water (DHW) supply is primarily an installation issue. Any possible cooling demand of the dwelling is also excluded in this study.

## 2. Methods

In this study, we calculate the thermal power that a renovated dwelling requires in order to stay warm throughout the year. This will be compared to the thermal power that the heat distribution system in a dwelling can deliver when operated at lower supply temperatures. Thermal powers required for DHW supply are not included in the analysis.

### 2.1. Inventory of Dutch building stock of single-family dwellings

We started by making an inventory of the types of single-family dwellings, both pre-WWII and post-WWII, that are commonly found in the Netherlands. The main criterion for the classification was that the building physics properties per class are largely uniform, as this determines the possibilities and limitations of certain renovation measures. As an example, the presence or absence of a cavity wall is an important characteristic for defining the various housing types. In addition, the vast majority of pre-war dwellings have a wooden roof and floor structures with low or no crawl spaces. For post-war dwellings, the tightening of building regulations, in particular after 1982, are important determinants for the various types of dwellings. The second criterion was that collectively, the types are an adequate representation of the Dutch housing stock of single-family dwellings. The exercise led to 35 types of pre-war and post-war single-family dwellings, summarized in table 1 below.

**Table 1.** 35 Types of common single-family dwellings in The Netherlands.

| Year of construction | type of wall | terraced  | semi-detached | detached  | specials |
|----------------------|--------------|-----------|---------------|-----------|----------|
| <1920                | single stone | 1         | 1             | 1         | 1        |
| 1921 - 1930          | single stone | 1         | 1             | 1         |          |
| 1921 - 1945          | cavity       | 1         | 1             | 1         |          |
| 1946 - 1965          | cavity       | 1         | 1             | 1         |          |
| 1966 - 1974          | cavity       | 2         | 1             | 1         | 2        |
| 1975 - 1981          | cavity       | 2         | 1             | 1         |          |
| 1982 - 1986          | cavity       | 1         | 1             | 1         |          |
| 1987 - 1991          | cavity       | 1         | 1             | 1         |          |
| 1991 - 2012          | cavity       | 1         | 1             | 1         |          |
| >2012                | cavity       | 1         | 1             | 1         |          |
| <b>Total</b>         | <b>35</b>    | <b>12</b> | <b>10</b>     | <b>10</b> | <b>3</b> |

For each of the 35 types, an existing dwelling was visited by an advisor from Duurzaam Bouwloket for a home survey (Duurzaam Bouwloket and Regionaal Energieloket man the energy desks of approx. 180 Dutch municipalities). Characteristics of the dwelling such as the area of roof, windows, facades and their U-values were determined and residents were questioned about their (energy-related) behaviour, such as thermostat settings, which rooms were heated, use of ventilation grills and fans (if present) and opening of windows in different rooms during the heating season. In the process, the possibilities and limitations regarding the application of renovation measures were also mapped out.

### 2.2. Building model

The dwellings and the behaviour of their occupants were modelled using a dynamic 4R2C-model. It calculates the hourly heat demand for space heating, taking into account hourly variations in ambient temperature and solar irradiation. The electrical equivalent of the model is shown in figure 1 (left).

The thermal resistance  $R_{cond}$  represents conduction losses through the façade and roof,  $R_{floor}$  represents conduction losses through the floor and  $R_{vent+infil}$  represents ventilation plus infiltration losses (all in K/W). Heat gains include solar gains through the windows  $Q_{solar}$ , internal heat gains from occupants and appliances  $Q_{internal}$  and heat from the heating system  $Q_{heating}$  (all in W).

The thermal mass of the dwelling is represented by two masses, with the smaller one  $C_{mass,in}$ , (typically 25% of the total thermal mass) representing the thermal mass of a few cm of the inner layer of walls, floor and roof plus the furniture and indoor air. It responds fairly rapidly to heat gains and heat losses, resulting in diurnal variations in indoor temperature.  $C_{mass,out}$ , represents the remaining part of the thermal mass. It is linked to  $C_{mass,in}$  through a thermal resistance which is a fraction ( $f_r$ , typically 40%) of the conduction losses  $R_{cond}$  (see figure 1). This link dampens the variation in indoor temperature.

The heating system will only switch on when the calculated indoor temperature falls below the setpoint temperature for that hour of the day. The 4R2C model, which is described in more detail in [3], is a one-zone model, which means that the whole building is assumed to be at a uniform temperature.

However, when surveying the 35 dwellings, it was found that generally, occupants heat only part of their dwelling, usually the ground floor, some rooms on the first floor but none on the second floor. As a result, the average temperature in the dwelling is lower than the setpoint temperature in the living room - where the thermostat is located. To compensate for this effect, a correction is made to the setpoint temperature when calculating the heat demand. This correction is described in more detail in [4].

In the surveys it appeared that occupants open their windows substantially more than anticipated, in particular setting windows ajar in bedrooms for an average of 16 hours a day. The combined effect of air tightness of the envelope, opening of ventilation grills, opening of windows and position of exhaust fan on ventilation flowrates was modelled and taken into account in the calculation of  $R_{vent+infil}$ .

An important parameter is the air tightness of the envelope. We used an equation describing a trend of decreasing infiltration with the year of construction, based on blower door test measurements with a pivotal year of 1967 [5], [6].

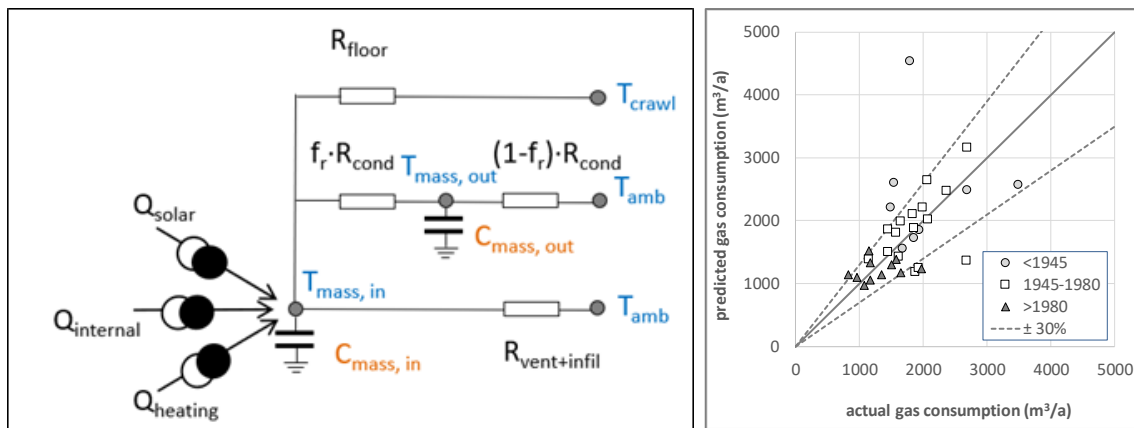
$$q_{v10} = (30 + 370 e^{[(1967 - yr)/16]}) \cdot (V/100)^{1/3}, \text{ for } yr > 1967, \quad (1)$$

$$q_{v10} = 400 \cdot (V/100)^{1/3}, \text{ for } yr \leq 1967 \quad (2)$$

In this equation,  $q_{v10}$  is the infiltration flow rate in l/s at a pressure difference between indoor and outdoor of 10 Pa, yr the year of construction and V the volume of the dwelling, in m<sup>3</sup>. The latter is used to account for the size of the dwelling, assuming that  $q_{v10}$  scales with the length of connections between building elements, i.e. according to the volume of the dwelling to the power of <sup>1</sup>/<sub>3</sub>.

### 2.3. Prediction of gas consumption of 35 dwellings

The annual gas consumption of each of the 35 dwellings was predicted, taking the self-reported occupant behaviour into account, and compared to the actual gas consumption. In calculating the gas consumption, we considered heat demand for space heating, DHW and cooking. The heat demand for space heating was calculated using the 4R2C model. Weather data (in particular hourly values of ambient temperature and solar irradiation) were used for the year in which the actual gas consumption was recorded. Heat demand was converted to gas consumption, setting the efficiency of the boiler to values between 90-95% (on HHV), depending on the age of the boiler. The heat demand for DHW was calculated from the self-reported shower duration, taking an efficiency of the boiler for DHW generation of typically 50-70%. The latter depended on the age of the boiler and the average duration of a shower (i.e. higher when showers are longer). Since, on average, 80% of the total DHW demand in The Netherlands is due to showering, we multiplied DHW demand for showering by a factor of 1/80% to arrive at the total DHW demand. Finally, when occupants reported to cook on gas, another 60m<sup>3</sup>/a of natural gas was added to the annual gas consumption. Figure 1 compares the predicted annual gas consumption to the actual gas consumption for each of the 35 dwellings. The graph distinguishes between three building periods: before 1945, between 1945 and 1980, and after 1980.



**Figure 1:** Electrical equivalent of the 4R2C-model (left) and predicted versus actual gas consumption of the 35 dwellings (right). Different symbols denote different building periods.

Ideally, all points should be on the 45-degree line, where predicted gas consumption equals actual consumption. This appears not to be the case. However, figure 1 shows that most points do fall within a margin of error of  $\pm 30\%$  (the dotted lines), although there are a number of 'outliers'. The data point at the top of the graph represents a large, renovated farmhouse built in 1650 with a floor area of 800m<sup>2</sup> and anomalous characteristics that make it difficult to even approximately calculate the gas consumption.

The observed differences between prediction and measurement can be caused by various factors, such as simplifications in the models used, errors in the building characteristics (e.g. insulation levels), and self-reported user behaviour differing from actual behaviour. A sensitivity analysis using the same 4R2C model showed that incorrectly reported occupant behaviour has a much larger effect on predicted energy consumption than errors in building characteristics. It is therefore not illogical to assume that a large contributor to the differences between prediction and measurement is incorrectly reported occupant behaviour. This is confirmed by findings from the home surveys, where residents themselves indicated that they found it difficult to give solid answers to questions about space heating and ventilation behaviour during the heating season, and shower duration.

Simplification of physical processes in the models used is also a likely cause of differences between measurement and prediction. Correctly modelling ventilation flow rates as a result of opening windows is particularly difficult. It depends on a multitude of (largely unknown) factors, such as the location and layout of the rooms relative to the prevailing wind direction, the degree of shelter from the wind, the number of opened windows, whether or not interior doors are opened, etc.

Although we had no data available to validate model predictions of hourly thermal powers required to keep the dwellings heated during the year, the fair agreement between calculated and actual annual gas consumption gives some confidence that the model yields plausible results. In the next stage, it is used to assess the effect of renovation packages on the required thermal power of the heating system.

#### *2.4. Renovation packages*

When surveying the 35 dwellings, it appeared that a number of energy saving measures had already been taken. From the current state, all dwellings were 'virtually' converted back to their original state ('as built'). If, for example, a 1920 dwelling was found to have double-glazed windows, it is assumed that the dwelling had single-glazed windows when built. Using the 4R2C model, the dwellings were then 'virtually' renovated according to six renovation packages and energy savings were calculated relative to the original state.

The renovation packages consist of three levels of thermal insulation of the building envelope, taking into account the structural possibilities and limitations of the various types of dwellings. The generic packages are the following:

- Package 1: Limited insulation. In this package, only part of the building envelope is improved at limited insulation levels. This package discards high impact renovations requiring considerable investments. These measures are often referred to as 'low-hanging fruit'.
- Package 2: Good insulation. A larger part of the building envelope is addressed at higher insulation levels, typically 0,4-0,7W/m<sup>2</sup>K for the façade and roof and 1,3W/m<sup>2</sup>K for windows.
- Package 3: Very good insulation. The complete building envelope is addressed at insulation levels equal to or exceeding the current (2020) building code for new build, typically U-values of 0,16-0,22W/m<sup>2</sup>K for the opaque façade and roof and 0,9-1,3W/m<sup>2</sup>K for windows. Often this involves a partial or complete replacement or reconstruction of the building envelope.

Each of these three packages has also been investigated with the additional application of a ventilation system with heat recovery combined with improved air tightness of the building envelope. This brings the total number of renovation packages to six.

#### *2.5. Heating a dwelling at lower temperatures of the heat delivery system*

When applying a DH network aiming to include sustainable heat sources, the supply temperature of the DH network should be as low as possible. Likewise, with (electrically driven) heat pumps, the lower the temperature of the heat delivered, the higher the efficiency or Coefficient Of Performance (COP) of the

heat pump. Consequently, with DH networks at lower temperature or heat pumps, temperatures of the central heating system in the dwelling will be lower than in the case of a gas fired boiler (i.e. 90°C supply, 70°C return). For a medium-temperature level DH network (MT), we assume a supply/return temperature of 70°C/55°C and for a low-temperature level DH network (LT) 50°C/40°C. A supply temperature of 50°C is also an upper limit for temperatures that can be achieved with a standard heat pump, although heat pumps prefer to supply heat at temperatures below 50°C. As a result of the lower supply temperatures, the heat delivery system in the dwelling can provide less thermal power. Assuming radiators in all dwellings, and neglecting the temperature drop in the heat exchanger between DH and central heating system in the dwelling, the relation between the heat delivered by a radiator  $Q_{rad}$  and the temperature difference between the average radiator temperature  $T_{rad}$  and indoor temperature  $T_{indoor}$  is:

$$Q_{rad} = C \cdot (T_{rad} - T_{indoor})^n \quad (3)$$

$C$  is a constant depending on the type and size of the radiator and  $n$  is the dimensionless radiator exponent, for which we used a value of 1.3. Using equation (3), we can calculate the reduction in thermal power of the heat delivery system when operated at a lower radiator temperature. Assuming an indoor temperature of 20°C, and an average radiator temperature of 62.5°C in the case of a MT network, the reduction in thermal power compared to the use of a boiler (radiator temperature 80°C) is 36%. In the case of an LT network (or heat pump), the reduction in thermal power is 68%. By applying renovation packages, the dwelling has lower heat losses and therefore requires less thermal power to keep the house warm. The reduction in thermal power due to the renovation packages must be greater than 36% to be able to apply an MT network and greater than 68% to apply an LT network (or a heat pump).

## 2.6. Occupant behaviour in renovation scenarios

In our earlier calculations of the annual gas consumption of the 35 dwellings, we accounted for the self-reported occupant behaviour, such as temperature setpoints and ventilation behaviour. Contrary to that, in the scenarios of dwellings renovated according to the renovation packages discussed, we used ‘standard’ behaviour, i.e. we assumed that the entire dwelling is heated to 20°C and no night setback is applied. After all, night setback leads to a peak in heating power in the morning. This peak is lower the less night setback is applied, and the more time the heating system is allowed to heat up the house in the morning. The lower limit for the required heating power is determined by the heat losses of the house in a scenario without night setback. We also assumed ‘standard’ ventilation behaviour, i.e. ventilation grills (when present) fully open, the exhaust fan in the ‘high’ position and no opening of windows.

## 2.7. Thermal power of existing heat delivery system

To be able to assess whether or not the (renovated) dwelling can be heated at lower supply temperatures, the missing parameter is the thermal power of the existing heat delivery system. When two equally sized dwellings are renovated to a similar insulation level (and therefore similar heat losses), the dwelling with the larger heat delivery system can provide more thermal power, also at lower water temperatures, than the dwelling with the smaller heat delivery system.

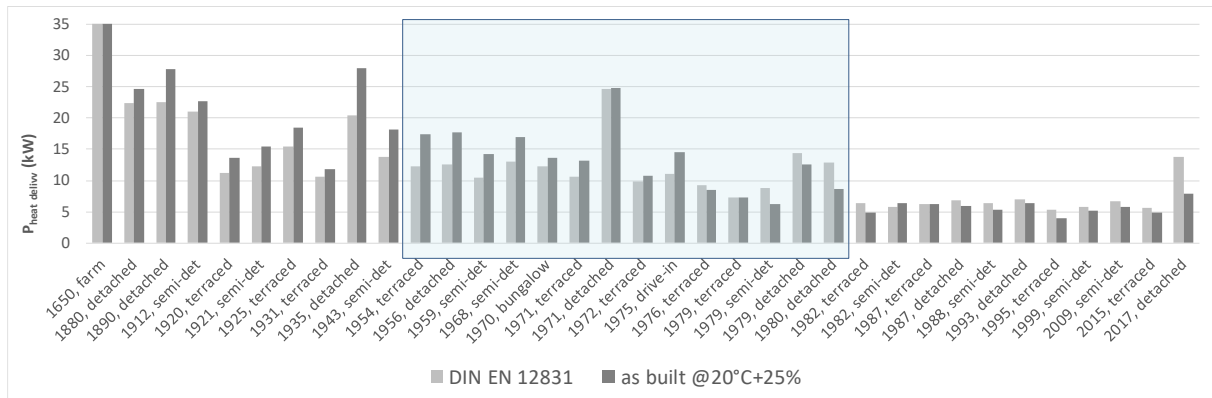
The thermal power of the heating system in the 35 dwellings was determined in two ways:

- We converted the 35 dwellings back to their original state and used the 4R2C model to calculate the maximum thermal power in the test reference year. The latter represents the typical Dutch weather, including ambient temperatures as low as -10°C in January. In the calculations, we assumed a constant indoor temperature of 20°C without night setback. In the end, we added 25% of ‘spare’ power to allow for heating up the dwelling after a night setback. Adding spare power is also a feature of the official heat loss calculation following ISSO51 that is used to dimension the size of a heating system for residential buildings [7].
- A calculation according to the German DIN EN 12831 [8]. This method is similar to the heat loss calculation according to ISSO51, but it requires less input data because the calculations are carried out at dwelling level and not at room level as in ISSO51. Parameters used include middle thermal weight construction, 1 hour of allowable time for reheating after night set-back, temperature drop during night setback: 4°C for pre-war and 2°C for post-war dwellings.

### 3. Results

#### 3.1. Thermal power of the existing heat delivery system

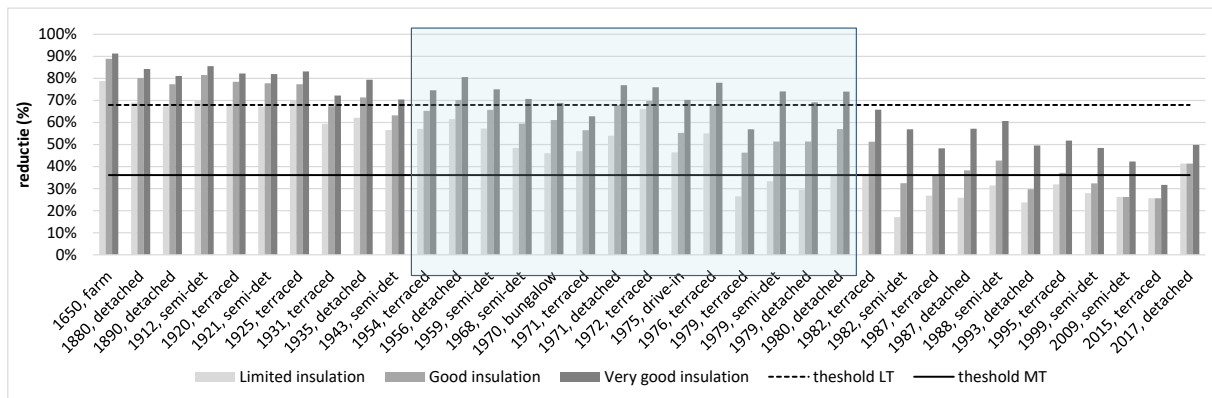
The results of the two calculations are shown in figure 2 below. It shows that, with a few exceptions, there is reasonable agreement between the two methods within about 30%. The DIN EN 12831 generally yields somewhat lower values for dwellings up to about 1980 and somewhat higher values for post 1980 dwellings. In subsequent calculations, we used the average of the values obtained with the two methods.



**Figure 2:** Estimated thermal power of the existing heat delivery system of 35 dwellings, calculated using two methods. Results for dwellings built between 1945 and 1980 are shown in the shaded area.

#### 3.2. Applicability of networks at lower supply temperatures

For each renovation package, the 4R2C-model was used to calculate the (maximum) thermal power required to keep the dwelling heated at 20°C throughout the year and subsequently, the reduction relative to the thermal power of the heat delivery system (from figure 2). The results of the calculations are shown in figure 3 for the three renovation packages without heat recovery and improved airtightness. The threshold value for the application of an MT network (36% reduction) is shown as a horizontal solid line, that for an LT network (68% reduction) as a dashed line.



**Figure 3:** Reduction in heating power after renovation (vertical bars) compared to the decrease in thermal power of the heat delivery system at lower temperatures (horizontal lines). The renovation packages do not include heat recovery and improved air tightness.

Figure 3 shows that the reduction for dwellings before 1980 is generally higher than for dwellings built after 1980. This can be explained by the thermal power of the existing heating system. At the time of construction, the less stringent insulation standards applicable to pre-1980 dwellings resulted in higher heat losses and therefore in a larger heat delivery system than in post-1980 dwellings. Therefore, compared to a renovated post-1980 dwelling with similar heat losses, a renovated pre-1980 dwelling is better able to cope with lower supply temperatures.

Figure 3 shows that application of an MT network (solid line) is possible for the majority of the pre-1980 dwellings for all three packages studied. This is less so for post-1980 dwellings: an MT network can be applied in 10 out of 11 houses in the case of 'very good insulation', in 6 out of 11 dwellings in the case of 'good insulation' but only in 2 out of 11 dwellings in the case of 'limited insulation'. The issue with post-1980 dwellings applies all the more to an LT network or a heat pump. In the most ambitious renovation scenario, an LT network (dashed line) can be applied in all pre-war dwellings, but only in 12 out of 14 dwellings built from 1945 to 1980 (shaded area), and in none built after 1980.

In the scenarios with application of heat recovery and improved air tightness, with single exception, application of an MT network is possible for all dwellings in the three renovation packages considered. Application of an LT-network or a heat pump is possible for all pre-war dwellings with all three packages, and for all dwellings between 1945 and 1980 renovated according to the package of 'very good insulation' (plus heat recovery and improved air tightness). Only in 9 out of 11 post-1980 dwellings renovated according to the package of 'very good insulation' (plus heat recovery and improved air tightness), an LT network can be applied.

### *3.3. Modification of the heat delivery system*

The above scenarios assume that the heat delivery system in the dwellings is not modified in the renovation process. However, the thermal power of the heat delivery system can be increased by adding radiators, by replacing them with a variant of higher thermal output or by installing an underfloor heating system. Replacing a single-plate radiator without slats (type 10) with a two-plate radiator without slats (type 20) yields a factor of 1,7 gain in thermal output, while replacing the latter with a two-plate radiator with slats (type 22) yields another factor of 1,6.

We therefore considered a scenario in which the thermal power of the heat delivery system is increased by a factor of 1,5. In this case, application of an MT network is possible for all dwellings, even in their original state. However, from an energy savings point of view, increasing the thermal power of the heat delivery system without investing in better insulation is not a recommended way to make dwellings ready for an energy supply that is free of natural gas. An LT network can be applied in all pre-1980 dwellings considered with the packages of 'good insulation' and 'very good insulation', both in combination with heat recovery and improved air-tightness. Post-1980 dwellings require a 'very good insulation' package in combination with heat recovery and improved air-tightness.

## **4. Discussion**

Some reservations should be made about the results. First of all, they are based on a number of assumptions, such as a potential improvement in air tightness of the envelope of 60% and an efficiency of heat recovery of 70%. These values may vary in practice. Furthermore, the results depend on the magnitude of the thermal power of the heat delivery system in the dwellings. Despite the fact that the two methods used give comparable results, the actual value can be quite different in individual cases.

The results are based on the criterion of a minimum required thermal power of the heat delivery system, in a scenario without night setback. Thus, in limiting cases, residents will not be able to use night setback on the coldest days in the year because there is no 'spare' thermal power available to heat up the house in the morning. On the other hand, in most of the heating season, ambient temperatures are higher and therefore heat losses are lower than on the coldest days, so that sufficient 'spare' heating power is available and night setback can be applied on most days.

In heating scenarios without night setback, the annual heat demand for space heating can be up to 10% higher than in scenarios with night setback, depending on how well the house is thermally insulated and therefore how much it cools down during the night. Not being able to apply a night setback therefore costs extra energy. However, there are several arguments for not applying any night setback in a natural gas-free energy supply. In the case of DH, peak thermal power (e.g. to heat up dwellings in the morning) is often provided by gas fired boilers, creating a demand for natural gas after all. Heat pumps, when forced to supply peak powers in the morning, may run at unfavourable operating conditions, resulting in a significantly lower efficiency (COP) than under nominal conditions. In addition, a large electricity demand in the morning to run the heat pumps will result in a large load on the electricity grid.

In our modelling, the entire house is assumed to be at one and the same temperature, and the heating of individual rooms is not assessed. In limiting cases therefore, it is possible that the heating power in some of the rooms is too low to fully cover the heat losses, which may result in local discomfort on the coldest days in those rooms.

## 5. Conclusion

We assessed the potential of six renovation packages for keeping a dwelling warm in a natural gas-free energy supply with lower supply temperatures. The results lead to the following conclusions.

Based on the existing heat delivery system in the dwellings, with single exception, an MT heat network can be applied in all dwellings studied when renovated according to the three renovation packages when combined with heat recovery and improved air tightness of the building envelope.

Based on the existing heat delivery system in the dwelling, the application of an LT heating network requires more drastic measures, especially for post-1980 dwellings. Even with the most ambitious package of 'very good insulation' with heat recovery and improved air tightness, an LT heat network can be implemented in only 9 out of 11 post-1980 dwellings considered.

It follows from our methodology that pre-1980 dwellings are easier to prepare for a natural gas-free energy supply than post-1980 dwellings, the reason being higher heat losses when built and therefore a larger heat delivery system. Consequently, for similar sized dwellings and the same renovation package (and therefore similar thermal power required), pre-1980- dwellings have less difficulty in coping with lower supply temperature than post-1980 dwellings do. Research in the field is to demonstrate that this is actually the case.

An important parameter appeared to be the thermal power of the heat delivery system in the dwelling. If it is possible to increase the thermal power of the heat delivery system, for example by replacing existing radiators with a variant of higher thermal output, the application of an MT or LT network will come within reach of a larger number of dwellings. However, the annual heat demand of the dwelling does not decrease when enlarging the heat delivery system. Therefore, from an energy-savings point of view it is better to (further) insulate the dwelling rather than to simply enlarge the heat delivery system as a measure to make a dwelling ready for a natural gas-free energy supply.

The option of increasing the thermal power of the heat delivery system also means that the annual heat demand (in kWh/m<sup>2</sup>a) of a dwelling is not the only parameter determining whether or not a dwelling can be comfortably heated by an MT or LT network.

A ventilation system with heat recovery in combination with improved air tightness of the envelope appears to be an effective measure to reduce both the annual heat demand (for space heating) and the thermal power required, facilitating the application of MT and LT networks.

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