# Towards Lower Temperature Heating

## A framework to support decision-making for energy renovations of existing Dutch dwellings

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**DOI**
10.37190/PLEA_2024

**Publication date**
2024

**Document Version**
Final published version

**Published in**
PLEA 2024: (Re)Thinking Resilience

Proceedings of 37th PLEA Conference,
26-28 June 2024 Wrocław, Poland

# PLEA 2024: (RE)THINKING RESILIENCE

## The book of proceedings

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Proceedings of 37th PLEA Conference, Sustainable Architecture and Urban Design

26-28 June 2024 Wrocław, Poland
Wrocław University of Science and Technology

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Organised by: PLEA, Fundacja PLEA 2024 Conference

Honorary Patronage: Rector of Wrocław University of Science and Technology,
Prof. Arkadiusz Wójs, DSc, PhD, Eng.

Scientific Patronage: The Committee for Architecture and Town Planning of the Wrocław Branch of the Polish Academy of Sciences

PAN



Wrocław University of Science and Technology Publishing House
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław
http://www.oficyna.pwr.edu.pl
e-mail: oficwyd@pwr.edu.pl
zamawianie.ksiazek@pwr.edu.pl

ISBN 978-83-7493-275-2
https://doi.org/10.37190/PLEA_2024

# Towards Lower Temperature Heating:
## A framework to support decision-making for energy renovations of existing Dutch dwellings

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*ABSTRACT: This study introduces a systematic framework to facilitate decision-making in selecting renovation options for preparing existing Dutch dwellings for utilising lower temperature heat (LTH) supplied by district heating (DH) systems. The framework was applied to an archetype terraced intermediate house built between 1945 and 1975 to identify the renovation options required for transitioning from existing High-Temperature (90/70℃) supply from gas-boilers to Medium Temperature (70/50℃) supply from DH systems. The framework's effectiveness was demonstrated by systematically assessing the readiness of the archetype dwelling for LTH use, reducing the number of viable renovation options, evaluating the financial feasibility using a life cycle costing approach and generating decision support insights through comparative analysis. The framework identified an optimised solution involving cavity wall insulation, exhaust ventilation and switching to low-temperature radiators. This solution incurs low initial investment and global costs while significantly reducing space heating and underheated hours. As a result, the framework provides tangible solutions for the specific use case and can serve as a valuable tool for dialogue among stakeholders during the decision-making process.*
*KEYWORDS: Energy Transition, Thermal Comfort, Heating Demands, Cost-Benefits, District Heating*

### 1. INTRODUCTION

Lower temperature district heating systems offer a natural gas-free alternative for heating our dwellings. Compared to traditional district heating (DH), these systems supply heat at temperature below 75℃ [1]. This allows for integrating sustainable heating sources [2], reduces network heat losses and improves distribution efficiencies [2]. For dwellings, heating with lower temperature heat (LTH) can improve thermal comfort and indoor air quality [3,4].

Currently, only 6.4% of households in the Netherlands are connected to a DH system, although by 2050, it is expected that 50% of the sustainable heat will be supplied through them [5]. Consequently, the DH system with a lower temperature supply will be crucial in decarbonising the residential heating sector. However, with LTH, existing dwellings with higher heating demands may encounter thermal discomfort due to the reduced heating capacity of original heat distribution systems (e.g., radiators) and high heat losses [6,7]. Moreover, higher peak loads from these dwellings can create bottlenecks for reducing the supply temperature at the district level and designing future networks with sustainable heating sources [8]. As a result, existing dwellings might require energy renovations before connecting them to a DH system with a lower temperature supply.

In this study, energy renovations refer to modifications at the building level to decrease heating needs, making it suitable for LTH with sustainable heat sources [9,10]. However, stakeholders, including municipalities, private individuals and professional parties such as developers or housing associations, encounter decision-making challenges in selecting the appropriate renovation options specific to their context [10]. The heterogeneity of the existing dwelling stock, with variations in types and characteristics [11], makes it difficult for stakeholders with extensive portfolios to identify and prioritise dwellings that require renovations to enable using LTH. Additionally, the availability of numerous renovation options [11–13] and limited decision support further hinder the selection of suitable renovation options [10], impeding the renovation rates in the Netherlands. Therefore, a systematic approach is needed to support the stakeholders in preparing the existing dwellings for LTH from DH systems.

This paper introduces a comprehensive framework that aids decision-making in selecting renovation options for existing dwellings in the Netherlands to enable using LTH from DH systems. Through its application to archetype dwelling, the study aims to illustrate its advantage in 1) assessing the readiness of the dwelling for LTH use, 2) reducing the number of viable renovation options, 3) evaluating the financial feasibility of these options using a life cycle costing approach, and 4) preparing decision support insights through comparative analysis. The findings from the framework's application have the potential to impact the decision-making process and mitigate challenges for the stakeholders involved.

## 2. MATERIALS AND METHODS

A systematic framework is crucial when choosing appropriate renovation options for LTH supplied by DH systems. Figure 1 presents a concise six-stage decision support framework that can be adapted to various dwelling types. It addresses both the preliminary investigation and actual decision-making aspects.

### 2.1 Identification and Diagnosis

The initial stage of the framework focuses on identifying the target dwellings and establishing the benchmark performance metrics to assess their readiness for LTH. For this study, an archetype representing a terraced intermediate house built between 1946-1975 is selected. The terraced house constitutes around 42% of the entire dwelling stock of the Netherlands. Of these, 40-50% were constructed between 1945-1985 [14]. A calibrated parametric model developed in Rhino Grasshopper, with Ladybug and Honeybee plugins for energy analysis, is employed to establish the benchmark performance of the archetype in the existing high-temperature (HT) supply.

### 2.2 Evaluate suitability for LTH

In this study, a dwelling case is deemed ready for LTH if it either maintains or improves the space heating demand and reduces underheated hours in lower temperatures compared to the benchmark performance in HT supply [15]. Key performance indicators (KPIs) encompass annual space heating demand (kWh/m$^2$) and occupied hours below the threshold of 20% PPD or percentage of people dissatisfied [16].

This stage first involves establishing the transition goals for lowering the supply temperature, such as reducing the existing supply temperature from HT(90/70℃) to medium temperature (MT) level of 70/50℃ as accepted in the Netherlands [15] but may vary internationally. Once defined, the dwelling's performance at lower temperatures is compared to HT benchmark performance through KPIs to evaluate its LTH readiness. If the dwelling is not ready, the next step involves developing a solution space of potential renovation options to prepare the dwelling for the lower supply temperature transition goal defined earlier.

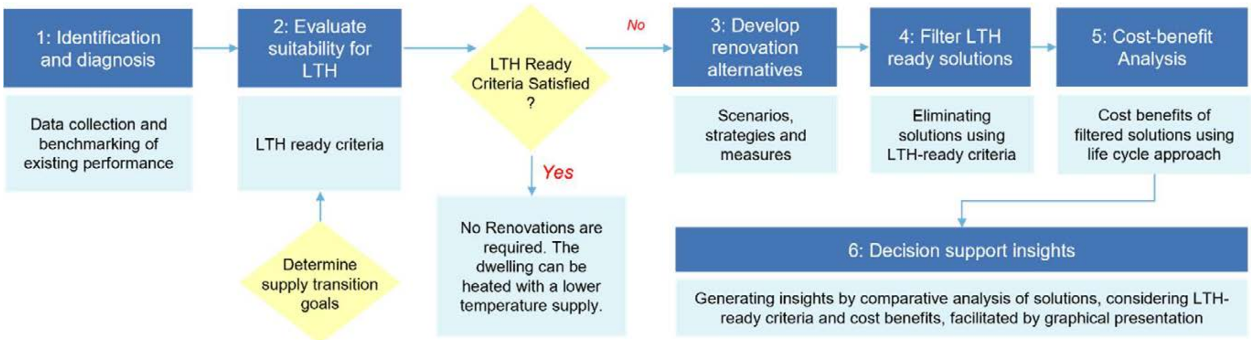


*Figure 1: Proposed framework to support decision-making in selecting renovation solutions for using LTH from DH systems.*

### 2.3 Develop Renovation Alternatives

Given the availability of various renovation options often leading to decision paralysis, this stage utilises a sub-framework designed to systematically identify and organise the available renovation options into scenarios, strategies and measures. Scenarios represent the diverse situations to achieve the renovation objectives. In this study, the renovation objective is to prepare the dwelling for heating with lower supply temperature transition goals set in stage 2 of the framework. Three different levels of renovation interventions—basic, moderate and deep—are considered to achieve the objective. Once scenarios are established, various strategies, or application-level alternatives, are identified to address each renovation scenario. Finally, product-level measures are outlined for implementing the renovation strategies. For a detailed explanation of the sub-framework, readers are referred to the study by Wahi et al., 2023 [15].

### 2.4 Filter LTH-ready solutions

The renovation options identified in Stage 3 undergo an evaluation to filter out the solutions that can prepare the dwelling for the transition goals identified in Stage 2. For the same, the solutions are dynamically simulated using the parametric model, and their performance is compared against the benchmark performance of the dwelling in the HT supply. Solutions that fail to improve space heating demand or reduce underheated hours are excluded. This results in a filtered set of desirable solutions that can prepare the dwelling for LTH.

### 2.5 Cost-Benefit Analysis

Assessing costs and benefits is paramount for stakeholders in decision-making. Given the importance of evaluating the trade-offs between initial renovation investments and the ensuing benefits, such as operational cost savings or improved thermal comfort, this stage focuses on conducting a cost-benefit analysis for the desirable LTH-ready solutions. A life cycle costing methodology is adopted for calculating global costs over a 30-year time frame. The global costs (GC) are calculated as the sum of initial investment costs for renovation and the net future costs of operation, maintenance and replacement discounted to present value or Net present value (NPV). This study uses a real interest rate of 2.8% and an inflation rate of 2 % for calculating NPV.

**2.6 Decision-support insights**

The purpose of the framework is to provide support for decision-making and facilitate the selection of appropriate solutions. Consequently, it becomes imperative to consolidate and communicate the results clearly and insightfully. As a result, a graphical representation is generated to depict the performance evaluation outcomes of LTH-ready solutions and their cost-benefit analyses. This graph serves as a vital tool for communicating the performance of various solutions, enabling stakeholders to navigate trade-offs effectively and gain insights into selecting the appropriate solutions tailored to their specific contexts.

**3. RESULTS**

The study aims to demonstrate the application of the framework on existing dwellings in the Netherlands. It showcases its utilisation in addressing decision-making challenges associated with transitioning from HT supply to LTH. The framework is applied to an archetype terraced intermediate dwelling constructed between 1945-1975 to demonstrate the same. Table 1 outlines the typical characteristics of the archetype dwelling.

These characteristics were used to establish the benchmark performance of the archetype dwelling under the existing HT supply. Annual simulations, following the Test reference year (TRY) specified by NEN 5060 [17], were conducted to determine the KPIs, including space heating demand (kWh/m$^2$) and underheated hours, acting as benchmarks in the HT supply context. The underheated hours were only evaluated for the living room, as it can be used as a proxy for evaluating the thermal comfort of the entire dwelling [15].

Subsequently, the readiness of the archetype dwelling for a lower temperature supply goal was evaluated, focusing on the transition towards MT supply (70/50 °C). Table 2 illustrates the performance of the dwelling in HT and MT supply. The space heating demand in MT decreases as the radiator capacity also decreases with the reduction in supply temperature. Consequently, the space heating system's reduced capacity (radiators) is insufficient to compensate for the heat losses, thus resulting in a higher number of underheated hours. Therefore, the archetype dwelling in its existing condition is not ready to be heated with an MT supply and requires renovation before being connected to the DH system with an MT supply.

*Table 1: Typical characteristics and assumptions of selected archetype terraced house from 1945-1975* [18]

| | Properties | Units |
|---|---|---|
| Compactness Ratio | 1.22 | - |
| Usable floor area | 142 | m$^2$ |
| Window-Wall Ratio of facades | 0.38 | - |
| Ground floor, *U* | 1.75 | W/m$^2$K |
| External Wall, *U* | 1.19 | W/m$^2$K |
| Roof, *U* | 0.82 | W/m$^2$K |
| Windows, *U* | 2.73 | W/m$^2$K |
| Doors, *U* | 3.31 | W/m$^2$K |
| Infiltration rate | 3 | dm$^3$/s.m$^2$ |
| Ventilation System | System A: Natural supply and exhaust | - |
| Temperature Setpoint | Living Room and Kitchen: 20<br>Other spaces: 16 | °C |
| Number of occupants | 3 | - |
| Lighting and Equipment density | 4 | W/m$^2$ |

*Table 2: Benchmark performance of the archetype dwelling in HT supply compared to the MT supply.*

| Supply Temperature | Annual space heating demand [kWh/m$^2$] | Occupied underheated hours[1] |
|---|---|---|
| HT Supply (90/70) | 163 | 1630 |
| MT supply (70/50) | 130 | 2123 |

*[1]Out of 5840 occupied hours in a year.*

Three scenarios based on the level of renovation intervention—basic, moderate, and deep—were employed to achieve the renovation objective of preparing the dwelling for MT supply. The basic intervention level, entailing no changes to the building envelope, involves strategies such as increasing the capacity of the heating system to compensate for increased underheated hours or lowering the setpoint temperature to reduce the space heating demand. The moderate intervention level focuses on selected improvements to the building envelope, such as changing windows, cavity insulation or improving the ventilation system. In contrast, deep renovation encompasses holistic changes to the dwelling to exploit the combined effect of improvements at the building envelope, system, and control levels. Table 3 provides an overview of the renovation scenarios indicating the intervention level required for MT supply along with corresponding strategies. The measures aligned with each strategy are derived from the RVO platform, indicating energy-efficient renovation measures at the product level, including investment costs [19].

*Table 3: Organisation of the solution space in the form of renovation scenarios, strategies and measures* [15,19].

| Scenario | Strategy | Measure |
|---|---|---|
| Basic | Increasing heating capacity | Existing HT Radiators[1], Radiators with extra convectors |
| | Reducing setpoint temperature | 20[1], 19 [°C] |
| Moderate | Improving ventilation system | System A: Natural Ventilation[1], System C: Mechanical exhaust ventilation |
| | Cavity wall insulation *(U)* + infiltration rate | 1.19[1], 0.63, 0.56, 0.48 [W/m²K] |
| | Improving window insulation *(U)* + infiltration rate | 2.73[1], 1.6, 1.5, 1.2 [W/m²K] |
| | Infiltration rate due to improvement in envelope | 3[1], 2 [dm³/s.m²] |
| | Basic + Moderate combinations | - |
| Deep | Replacing existing radiators | Radiators with extra convectors |
| | Reducing setpoint temperature | 20[1], 19 [°C] |
| | Replacing ventilation system | System D: Balanced mechanical ventilation with heat recovery (MVHR) |
| | Airtight envelope | 0.4 dm³/s.m² |
| | External Wall insulation *(U)* | 0.26, 0.21, 0.17 [W/m²K] |
| | Replacing windows *(U)* | 1 [W/m²K] |
| | Internal roof insulation *(U)* | 0.27, 0.15, 0.14 [W/m²K] |
| | Underneath ground floor insulation *(U)* | 0.48, 0.27, 0.24 [W/m²K] |
| | Replacing external door *(U)* | 1.4 [W/m²K] |

*[1] Existing condition of the dwelling.*

As indicated in Table 3, the basic intervention level leads to three measures, excluding the base case involving the existing radiators and setpoint temperature. On the other hand, the moderate intervention level includes individual as well as combinations of strategies, leading to 124 combinations of measures. The deep intervention level involves 54 measures combining explicitly fixed measures while varying four strategies. Consequently, these 182 measures are simulated parametrically in MT supply, and their performances were assessed against the benchmark performance of the dwelling in HT supply to identify solutions suitable for MT supply.

In addition, Figure 2 illustrates the solutions that do not meet the LTH-ready criteria for improving space heating demand and reducing the underheated hours compared to benchmark performance in HT supply. Notably, it is observed that the basic intervention level cannot prepare the dwelling, whereas only 46 moderate measures prove effective in preparing the dwelling for MT supply. In contrast, all the deep renovation solutions demonstrate the capability of preparing the dwelling for MT supply.

The subsequent step involves a comprehensive cost-benefit analysis of the filtered solutions. As outlined in section 2.5, GC was calculated using the NPV for each measure combination over a 30-year timeframe. The investment costs were sourced from the RVO platform [19], including components, labour, and installation costs for the filtered measures. Operating costs were based on the fixed and variable rates for gas, electricity and DH as of 2022. A baseline for comparison of GC was established using a base case scenario with no renovation while only considering gas boiler maintenance and replacement through its lifetime. Once the GC was calculated for all desirable LTH-ready options, it was plotted against the thermal comfort benefits of LTH-ready solutions, forming the graphical representation to support decision-making.

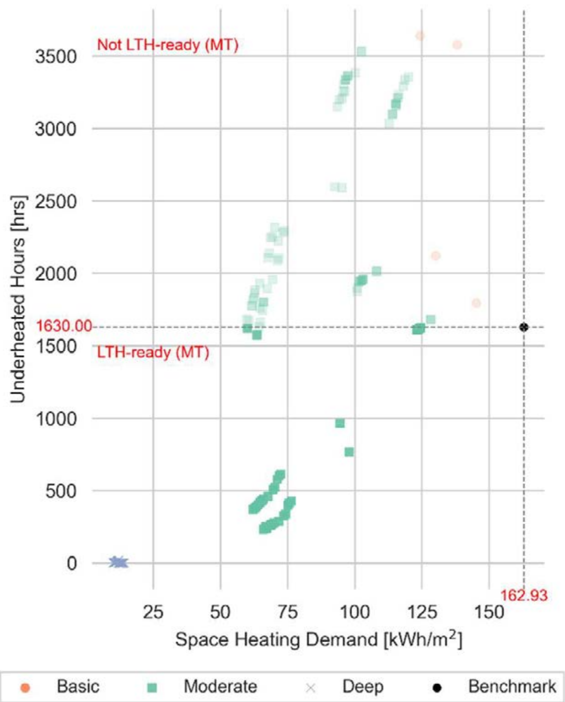


*Figure 2 Filtered solutions for LTH-readiness. Out of 182 measures, only 100 can prepare the dwelling for MT supply.*

Figure 3 shows the life cycle costs, as GC (includes investments, maintenance, and operation costs) and the associated benefits stemming from the reduction of underheated hours (thermal discomfort) due to the renovations. The graph visually depicts the range of space heating demand for each measure, with the base case (no renovation, existing condition with HT supply with gas-boiler) serving as the benchmark for visual comparison of the performance of LTH-ready measures.

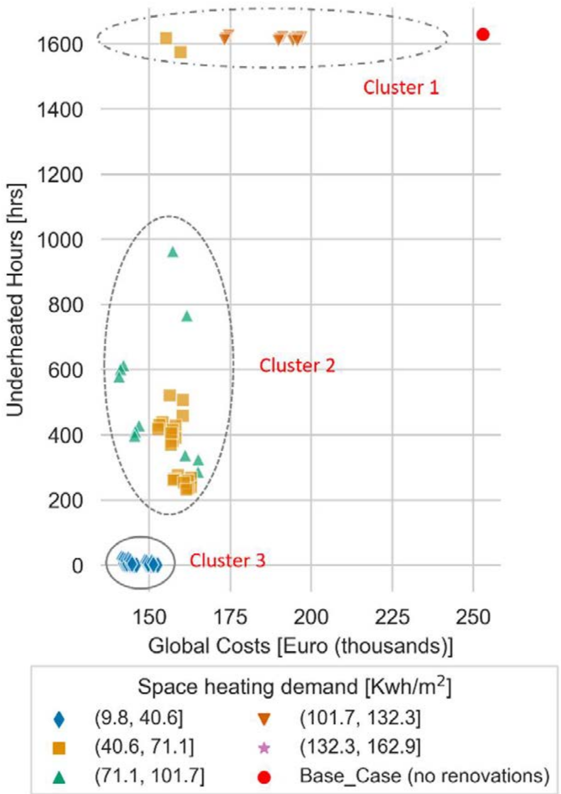


*Figure 3 Decision Support Insights: Evaluating the cost-benefits of the LTH-ready solutions.*

Upon observing Figure 3, the measures can be categorised into three clusters. Cluster 1 comprises 14 renovation measures that are on the cusp concerning the LTH-ready criteria compared to the base case scenario. These solutions can improve the space heating demand by 20-60% and reduce GC by 22-38% from the base case. However, thermal comfort improvements are marginal, with an average reduction in discomfort hours of only 1%. As a result, it can be argued that the measures within cluster 1 can correspond to the minimum renovation intervention required for heating the dwelling with MT supply. Given the limited impact of these measures on improving thermal comfort, it is imperative to analyse the trade-offs only between initial investment and global costs.

The options with the lowest investment costs are the measures with cavity wall insulation of 0.56, 0.48, or 0.63 W/m$^2$K with LT radiators (refer to Table 3). These solutions incur initial investment costs ranging from 2.3k to 2.8k euros, with an average 24% reduction in space heating demand and a 31% reduction in global costs. In contrast, the solution with a cavity wall insulation of 0.48 W/m$^2$K, glazing insulation of 1.2 W/m$^2$K, mechanical exhaust ventilation (type C) and a temperature setpoint of 19°C achieves a 38% reduction in the GC. Even though this measure can reduce the space heating demand by 63%, it entails a higher initial cost of 26k euros. Consequently, if the preference is to minimise renovation intervention and changes to the dwelling, thus reducing overall hassle, the option for cavity wall insulation with a switch to LT radiators can be considered the minimal renovation solution required by the archetype dwelling for heating with MT supply from DH systems.

Cluster 2 encompasses 32 moderate-level measures that can reduce the space heating demand and the number of underheated hours by 40-60% and 40-85%, respectively, compared to the base case. Simultaneously, these measures can reduce GC within the 35-45 % range. Among these, the solution with minimal investment costs (3k euros) involves only replacing the ventilation system with type C (mechanical exhaust , natural supply), which leads to a 42%, 41% and 37% reduction in the space heating demand, the number of discomfort hours, and GC, respectively. Moreover, the solution with the lowest GC at 140k euros achieves a 44% reduction in GC from the base case. This is attained by replacing the ventilation system with type C and adding cavity wall insulation of 0.48 W/m$^2$K. With an investment of only 3.5k euros, this solution reduces the space heating by 56% and the number of discomfort hours by 64%. Finally, the solution with the highest thermal comfort, providing an 85% reduction in discomfort hours, integrates a ventilation system type C with cavity wall insulation of 0.48 W/m$^2$K, glazing with a U-value of 1.2 W/m$^2$K and LT radiators. While this measure results in a 60% reduction in space heating demand and a 36% reduction in global costs, it does require a higher initial investment of 28k euros.

Finally, the third cluster comprises deep renovation solutions that can reduce the number of discomfort hours with considerable energy savings by around 90%. Furthermore, these solutions exhibit a reduction in global costs by around 44%. Even though these measures can have the highest benefits, they also account for the highest initial investment, between 40-55k euros.

Examining Figure 3 and the insights it provides, the measure incorporating the cavity wall insulation of 0.48 W/m$^2$K for the archetype dwelling, paired with exhaust ventilation system type C and a switch to LT radiators, emerges as the optimised solution for preparing the dwelling for MT supply. This measure requires a comparatively lower investment of 3.5k euros, just a thousand euros more than the minimum suggested in cluster 1, and substantially reduces discomfort hours and space heating demand. However, an additional factor of future readiness could be considered: whether the solution remains effective in satisfying LTH-ready criteria if the supply temperature is further reduced to a Low-Temperature (LT) supply of 55/35℃ while contributing to the lowest GC.

## 4. CONCLUSION

This study presents a systematic framework to facilitate decision-making in selecting renovation options to prepare existing Dutch dwellings for heating with LTH supplied through DH systems. By applying the framework to a typical terraced intermediate dwelling from 1945-1975, the study showcases its effectiveness in evaluating its readiness for LTH in its existing condition and identifying necessary renovations for a transition to MT supply. The framework organises the available renovation options and aids in effectively filtering out the solutions that cannot prepare the dwelling for LTH. Thus, it offers a curated solution space tailored to the specific context of the dwelling. Moreover, the study employs a life cycle costing approach and conducts a cost-benefit analysis to assess the financial feasibility of the filtered solutions. The results are presented graphically to provide insights on prioritising measures based on their impact on LTH readiness and global costs. Through the framework's application, an optimised solution with a cavity wall insulation of 0.48 W/m$^2$K, mechanical exhaust ventilation type C and a switch to LT radiators is identified for MT supply. This solution leads to the lowest investment and global costs while substantially reducing space heating demand and underheating hours. However, due to space limitations, this study only describes renovations required for transitioning to MT supply. Future studies will explore Low-Temperature (LT) supply scenarios, particularly at 55/35°C, to identify solutions satisfying LTH-ready criteria while contributing to the lowest GC. In conclusion, the framework provides tangible solutions for a specific use case and serves as a valuable tool for dialogue among stakeholders in the decision-making process. Nevertheless, validating the framework through real cases and associated stakeholders is vital to refining its utilisation in the decision-making process.

## ACKNOWLEDGEMENTS

This study was carried out with the support from the MMIP 3&4 scheme of the Dutch Ministry of Economic Affairs & Climate Change and the Ministry of the Interior & Kingdom Relations.

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ISBN 978-83-7493-275-2