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Lower-Temperature-Ready Renovation: An Approach to Identify the Extent of Renovation Interventions for Lower-Temperature District Heating in Existing Dutch Homes

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Abstract: This study presents an approach to determine the extent of renovation interventions required for existing Dutch dwellings aiming to transition to lower-temperature district heating (DH) systems. The proposed method is applied to a typical intermediate terraced house built before 1945 in the Netherlands, and it consists of two steps: first, assessing the potential of a dwelling to be heated with a lower temperature supply from DH systems and subsequently developing and evaluating alternative renovation solutions if necessary. This study defines a set of criteria for evaluating the readiness of a dwelling for lower-temperature heating (LTH), considering energy efficiency and thermal comfort as non-compensatory criteria. The application of the approach reveals that the case study dwelling is presently unsuitable for a medium-temperature (70/50 °C) and low-temperature (55/35 °C) supply compared to a high-temperature supply (90/70 °C), thus requiring energy renovations. Furthermore, this study indicates that moderate intervention levels are required for the dwelling to be lower-temperature-ready in both supply temperature goals. These interventions include strategies and measures that upgrade the building envelope to the minimum insulation levels stipulated by the Dutch Building Decree, improve airtightness, and replace existing radiators with low-temperature radiators. By systematically narrowing down renovation options, this approach aids in simplifying the decision-making process for selecting renovations for heating dwellings with LTH through DH systems, which could reduce stakeholders' decision paralysis.

Keywords: district heating systems; lower-temperature heating; energy renovations; existing dwellings; decision-making process

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1. Introduction

The Netherlands is on the cusp of an energy transition from natural gas to sustainable sources in order to meet residential heating demands. The built environment accounted for 15% of The Netherlands' total greenhouse gas emissions in 2021, of which 73.5% was attributed to the demands of residential heating [1]. These demands correspond to space heating, hot water preparation, and cooking; for these, approximately 90% of Dutch homes continue to rely on natural gas [2]. The impact of carbon emissions from fossil fuels on climate change, in conjunction with earthquakes resulting from the natural gas extraction from underground reservoirs and recent geopolitical events, has prompted the Dutch government to reconsider its reliance on natural gas or fossil fuels in general to tackle climate change and secure an affordable heat supply to combat energy poverty [3]. As a result, the Dutch climate agreement focuses on gradually removing natural gas for 1.5 million homes in an effort to reduce 3.4 Mton of $CO_{2;eq}$ emissions by 2030 [4].

To achieve this transition, the investigation of a variety of available heating supply systems, including collective (district heating), electric (heat pumps), hybrid (collective in combination with electric), or sustainable gases [5,6] is central for replacing natural gas with a viable alternative for residential heating. The district heating (DH) systems in the Netherlands currently supply high-temperature (HT) heat, between 70 and 90 °C, with high-value fossil fuels such as coal or natural gas as primary energy sources [7,8]. Nevertheless, there is a shift towards reducing the supply temperatures in the heat networks from HT (>75 °C) to lower temperatures (<75 °C) for meeting residential heating demands. Table 1 illustrates the DH temperature levels distinguished in the Netherlands based on the direct use of heat for space heating and hot tap water, along with their corresponding heat sources. In this study, the temperature levels "Medium", "Low", and "Very/Ultra Low" are collectively considered lower-supply temperature levels.

Table 1. District heating supply temperatures based on heat use and its subsequent sources available in The Netherlands. T_a corresponds to the supply temperatures. Source: [7–9].

Temperature Level	Supply Temperature	Use of Heat		Heat Source
		Space Heating	Hot Tap Water	
HT: High Temperature	$T_a > 75$ °C	• Direct use	• Direct use	• Combined heat and power (CHP) fired with coal, natural gas, solid waste, or biomass. • Heat plants fired with biomass and natural gas. • Ultra deep geothermal energy. • Residual heat from industry, power plants, and waste incineration.
MT: Medium/Middle Temperature	55 °C ≤ T_a ≤ 75 °C	• Direct use.	• Direct use. • Heating of tap water ≥ 65 °C to prevent the risk of legionella	• Geothermal energy. • Biomass boilers. • Residual heat from industry, power plants, and waste incineration. • Solar thermal and heat pumps.
LT: Low Temperature	30 °C ≤ T_a ≤ 55 °C	• Direct use of heat only with LT delivery systems	• Upgrading heat for hot tap water	• Shallow geothermal energy. • Low-temperature residual heat from the cooling process of data centres, ice rinks, and cold storage. • Solar thermal plants and heat pumps with ULT sources.
ULT: Very/Ultra Low Temperature	T_a ≤ 30 °C	• No direct use of heat • Upgrading heat for both space heating and hot tap water		• Aquathermal from sewage and surface water. • ULT residual heat from the cooling process of data centres and supermarkets. • Solar thermal systems.

The use of the DH system has the potential to provide cost-effective heat to densely populated areas [10–12]. Currently, only 6.4% of households in the Netherlands are connected to a DH system [13], although it is projected that by 2050, the share of DH systems will increase to 50% [6]. Given the vital role DH systems will play in achieving the Netherlands' energy transition goals when combined with lower supply temperatures, it is necessary to examine the integration of lower temperature DH into the existing built environment.

On the heating supply side, reducing the supply temperature in the DH network enables the integration of sustainable heat sources [12,14,15], reduces heat losses in the network, and improves distribution efficiencies [12,15,16]. Meanwhile, on the demand side (i.e., *dwellings*), the use of lower-temperature heat (LTH) improves thermal comfort and indoor air quality [17–19]. Potential reduction in DH supply temperatures depends on the dwelling's space-heating and hot water demands [20]. Space-heating demands are determined according to the transmission, infiltration, and ventilation heat losses combined with solar and internal heat gains, while the hot water demand is related to cooking and bathroom use [21]. Regarding space heating, newly constructed dwellings with improved energy efficiency can address the lower demands for space heating through supply temperatures closer to ambient temperatures [22]. Nevertheless, challenges arise in the case of existing dwellings with high space-heating demands. As the supply temperature is reduced, the heating output of the existing heat emission systems, such as radiators, also diminishes [23,24]. Consequently, the reduced heating output may not compensate for the high heat losses, resulting in thermal discomfort for the occupants. Therefore, to ensure adequate thermal comfort, existing dwellings would require an HT supply from DH, which would limit reduction in the supply temperature in the DH system. Furthermore, the higher heating loads associated with existing dwellings could create bottlenecks in designing future lower temperature DH systems based on sustainable heating sources [11]. As a result, existing dwellings with high heating demands may require energy renovations prior to connecting to a DH system with a lower temperature supply [25]. In this study, energy renovations correspond to modifications at the building level to reduce the heating demands of a dwelling, thus preparing them for LTH through supply systems using sustainable heat sources [26–28].

Recent studies in the Netherlands indicate a growing interest towards integrating LTH from DH systems in the existing residential dwelling stock. Existing research focuses on LTH network design [29], sustainable energy concepts at the neighbourhood level [30], or maximum reduction in supply temperatures in existing heating systems under design conditions [31]. However, little attention is paid towards assessing the readiness of existing dwellings to be heated with a lower temperature supply from DH systems. Furthermore, identifying the level of renovation intervention required for preparing existing dwellings for LTH integration remains unexplored. This research gap is critical for private individuals and professional parties, such as developers or housing associations, who encounter decision-making challenges when selecting suitable renovation measures specific to their context [28]. The decision-making landscape surrounding the selection of renovation interventions for buildings is often complex [32,33], as it involves multiple, often conflicting objectives and criteria [34–36] alongside diverse stakeholder preferences [32,37]. To facilitate the evaluation of trade-offs among these conflicting factors, the structured approach of multi-criteria decision making (MCDM) has been well documented in the literature on building renovations [33,38–42]. This approach aids in streamlining the decision-making process by accounting for conflicting criteria and stakeholder preferences [43]. However, the application of MCDA methods is often complex and requires the integration of multiple techniques to ensure reliable decision making.

Furthermore, several studies emphasise the challenges arising from the availability of various renovation options and the assessment of possible combinations resulting in many alternatives, leading to decision paralysis [44–48]. Numerous studies have focused on generating alternative renovation solutions based on intervention levels derived from investment cost or construction limitations [33,49,50], literature and empirical studies [40,51], and digital databases [52] combined with algorithms [42]. However, it is still unclear how these approaches for generating alternatives can be applied to mitigate the decision paralysis caused by numerous renovation options for making existing dwellings suitable for lower temperature supply from DH systems. In addition to that, insufficient knowledge regarding available renovation options, high costs and limited customisability [53], the lack of time and expertise to appraise the available renovation options properly [54], and limited decision support based on individual preferences [28,55] further contribute to the decision-making struggle towards selecting appropriate renovation solutions. Consequently, to alleviate this decision-making struggle, it is essential to eliminate the solutions that are not technically desirable to comfortably heat dwellings with LTH from DH systems, given the dwelling's context. As a result, this paper aims to address these research gaps by evaluating the suitability of an existing dwelling in the Netherlands and identifying appropriate renovation options for using LTH from DH systems.

The primary objective of this study is to test an approach for determining the extent of the renovation intervention necessary for preparing existing dwellings in the Netherlands to be connected to DH systems with lower temperature supply. To accomplish this, the study proposes a two-step approach. The initial step involves evaluating the suitability of utilising LTH by establishing criteria to determine the readiness of the existing dwellings. Subsequently, if the dwellings are found unsuitable for using LTH, then the lower-temperature-ready criteria can be employed to filter out potential solutions from various available options depending on the context of the dwelling. The proposed approach was applied to a typical terraced house built before 1945 to assess the readiness of the dwelling to be heated with lower temperature supplies of MT (70/50 °C) and LT (55/35 °C) from DH systems, compared to the original HT (90/70 °C) from a natural gas boiler. Additionally, if applicable, the study aims to identify and compare the renovation interventions required for preparing the case study dwelling for the two supply temperature transition goals. This study argues that the proposed approach facilitates the narrowing down of possible renovation solutions from a diverse range of solutions, thus limiting the solution space and reducing the decision-making struggles in selecting appropriate renovation solutions for gas-free heating with LTH from DH systems.

Following the introduction, Section 2 provides an overview of the two-step approach, its application to the case study dwelling, an exploration of various applicable renovation options, and the utilisation of the dynamic simulations for analysing them. Subsequently, Sections 3 and 4 illustrate both the intervention level required for the case study to be comfortably heated with LTH using the two-step approach and the broader implication of the study's findings. Finally, Section 5 summarises the main findings, acknowledges its limitations, and suggests future research directions.

2. Materials and Methods

This study proposes a two-step approach to determine the extent of renovations required by existing dwellings in the Netherlands when transitioning from an HT heating supply to an LTH supply from DH systems. First, lower-temperature-ready criteria are introduced, which serve as the guiding principle for evaluating the readiness of the dwelling for LTH, followed by the proposed two-step approach. Additionally, the case study and the dynamic simulation methods utilised by the study to implement the proposed approach are described in detail.

2.1. Lower-Temperature-Ready Criteria

As discussed in the Section 1, reducing the supply temperature also reduces the capacity of the heat emission systems initially designed for HT supply. Consequently, the inability of the heating systems to compensate for the high heat losses of existing dwellings may result in thermal discomfort for the occupants. One strategy to address this could be by increasing the heating system's output by, for instance, adding radiator fans, although this has minimal potential for energy saving, which is counterintuitive for energy renovations [14,56]. Additionally, our recent review on integrating LTH in existing dwellings revealed that despite lacking a standard set of criteria, a dwelling's performance or renovation options for using LTH were widely assessed based on energy efficiency and thermal comfort criteria [57]. As a result, this study proposes a definition of readiness for a dwelling to be heated with LTH from DH, which corresponds to an improvement in both the thermal comfort and energy efficiency of the dwelling compared to its existing conditions with HT supply. This definition is based on the non-compensatory decision-making model in the multi-criteria decision-making (MCDM) approach, where trade-offs between criteria are not allowed [58,59]. As a result, in the context of the proposed approach, different options must simultaneously satisfy the energy efficiency and thermal comfort improvement criteria to be considered technically desirable solutions for the preparation of a dwelling with an LTH supply from DH systems. This study used annual space-heating demands and occupied cold hours as key performance indicators (KPIs) for evaluating the energy efficiency and thermal comfort criteria, as elaborated in Section 2.4.2.

2.2. The Proposed Two-Step Approach

The two-step approach presented in this study focuses on assessing the readiness or potential of the existing dwelling to be heated with LTH and suggests renovation options that could prepare the dwelling for the same by filtering out options that are not technically desirable. As previously discussed, the technically undesirable options correspond to renovation solutions that do not meet the criteria set by the lower-temperature-ready definition (Section 2.1). Figure 1 illustrates the overall framework of the proposed approach.

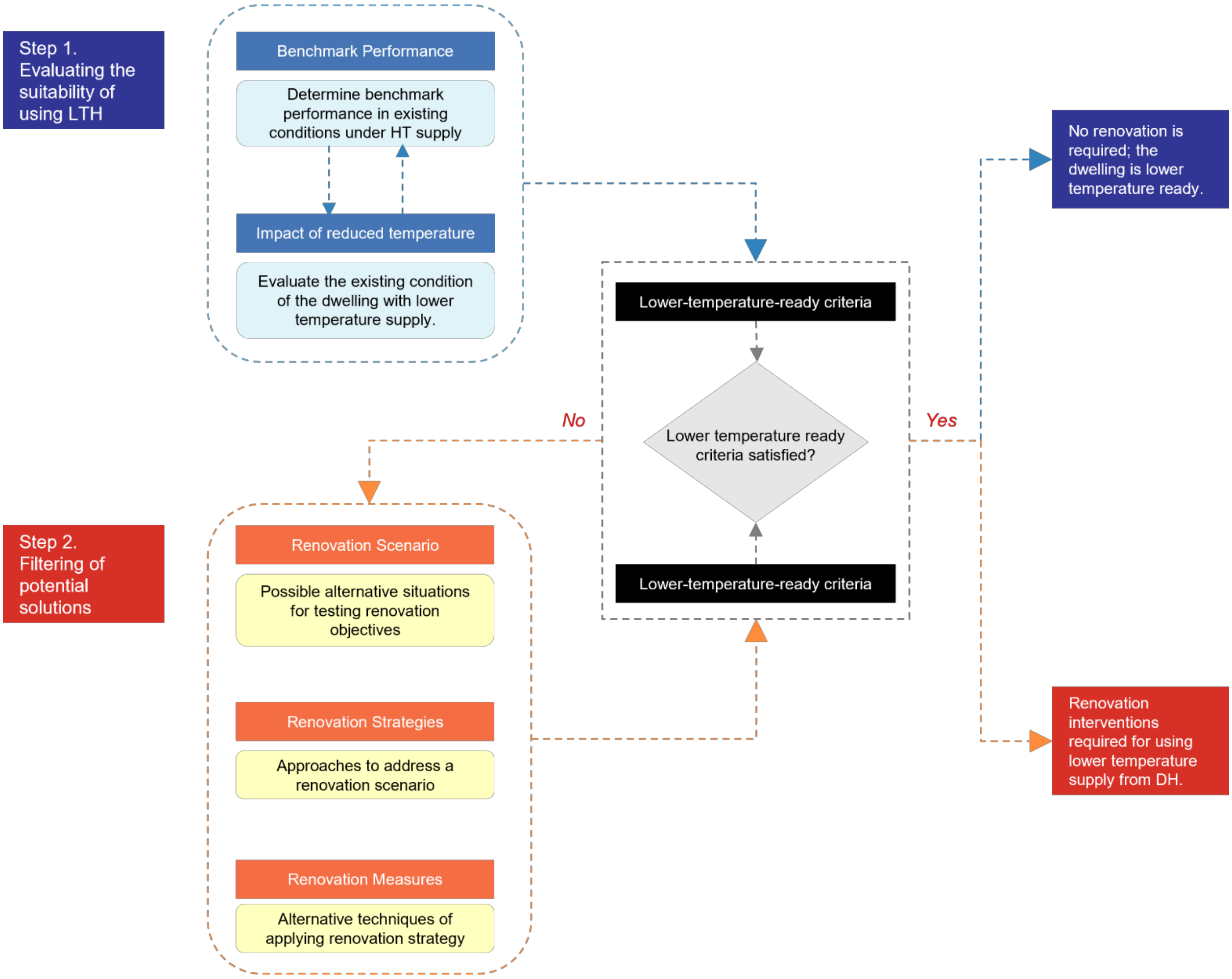

Figure 1. The proposed two-step approach.

2.2.1. Step 1: Evaluating the Suitability of Using LTH

For evaluating the readiness of a dwelling to be heated with a lower supply temperature from DH systems, it is imperative to first establish the benchmark performance of the dwelling's current performance with the original HT supply in terms of annual space-heating demand and occupied cold hours. For the same, building diagnostics can be performed by utilising simulation models, which can be steady-state or dynamic calculation models [34,42,45,60].

Next, the two KPIs are recalculated for the existing dwelling condition with lower supply temperatures of MT and LT and are compared with the benchmark performance of the dwelling with an HT supply. According to the lower-temperature-ready criteria described in Section 2.1, if the dwelling's performance in lower temperatures does not satisfy the benchmark performance, the dwelling can be considered not ready for LTH. In such a case, the next step would involve developing a renovation solution space based on the dwelling context.

2.2.2. Step 2: The Filtering of Potential Solutions

The renovation solution space, including all potential renovation options given the dwelling's context, is developed in this step. This study employs a scenario-based approach, in which scenarios represent alternative situations for addressing single or multiple renovation objectives [38,42]. A renovation scenario can be decomposed into different renovation strategies followed by subsequent measures [42], where a renovation strategy comprises either an individual or a combination of distinct renovation approaches. Alternatively, renovation measures correspond to various techniques within a strategy [42,61]. Furthermore, renovation measures can be broadened to encompass available products with specific attributes such as cost, thermal properties, and environmental product declarations, thereby streamlining the process of selecting renovation options.

In this study, the objective of renovations is to prepare existing dwellings for transitioning from an existing HT supply to lower (MT and LT) supply temperatures from DH systems. As a result, renovation scenarios are developed depending on the depth or extent of the renovation interventions required to achieve the renovation objective [62]. Since every dwelling in a neighbourhood has different renovation potentials and limitations due to varied building characteristics, envelope properties, and construction styles, three intervention levels were defined that cover different possibilities for preparing dwellings for lower supply temperatures from DH systems.

- **Basic renovation.** At this level of intervention, the primary focus of the renovation is to increase the space-heating system's heat output with no modification to the building envelope.
- **Moderate renovation.** As is defined by the Dutch Building Decree [63], partial or moderate intervention constitutes renovations lower than 25% of the building envelope's surface area. Some research studies [11,14,64] also describe this intervention level as "light renovations", which involve specific upgrades at the building envelope level. These improvements include window replacements, the post cavity insulation of walls, and insulating floors or roofs. These improvements can be applied either individually or in combination.
- **Deep renovation.** In contrast to moderate renovations, the Dutch Building Decree [63] defines deep renovation as interventions that address more than 25% of the building envelope's surface area. This involves the comprehensive renovation of the dwelling, involving essential changes such as a complete replacement of an existing roof. Additionally, studies [11,14,64,65] indicate that deep renovations typically entail a higher insulation of the envelope, the mitigation of thermal bridges, improved airtightness, and upgraded ventilation systems.

Depending on the definition of intervention levels, single or multiple renovation strategies can be identified, followed by specific techniques or measures to implement these strategies, depending on the context of the dwelling in question. Figure 2 illustrates the different renovation strategies and measures that can be applied at the building envelope, building system, and control level for preparing dwellings for LTH [57,61]; while Figure 3 illustrates the process of developing the renovation solution space in relation to renovation scenarios, strategies, and measures.

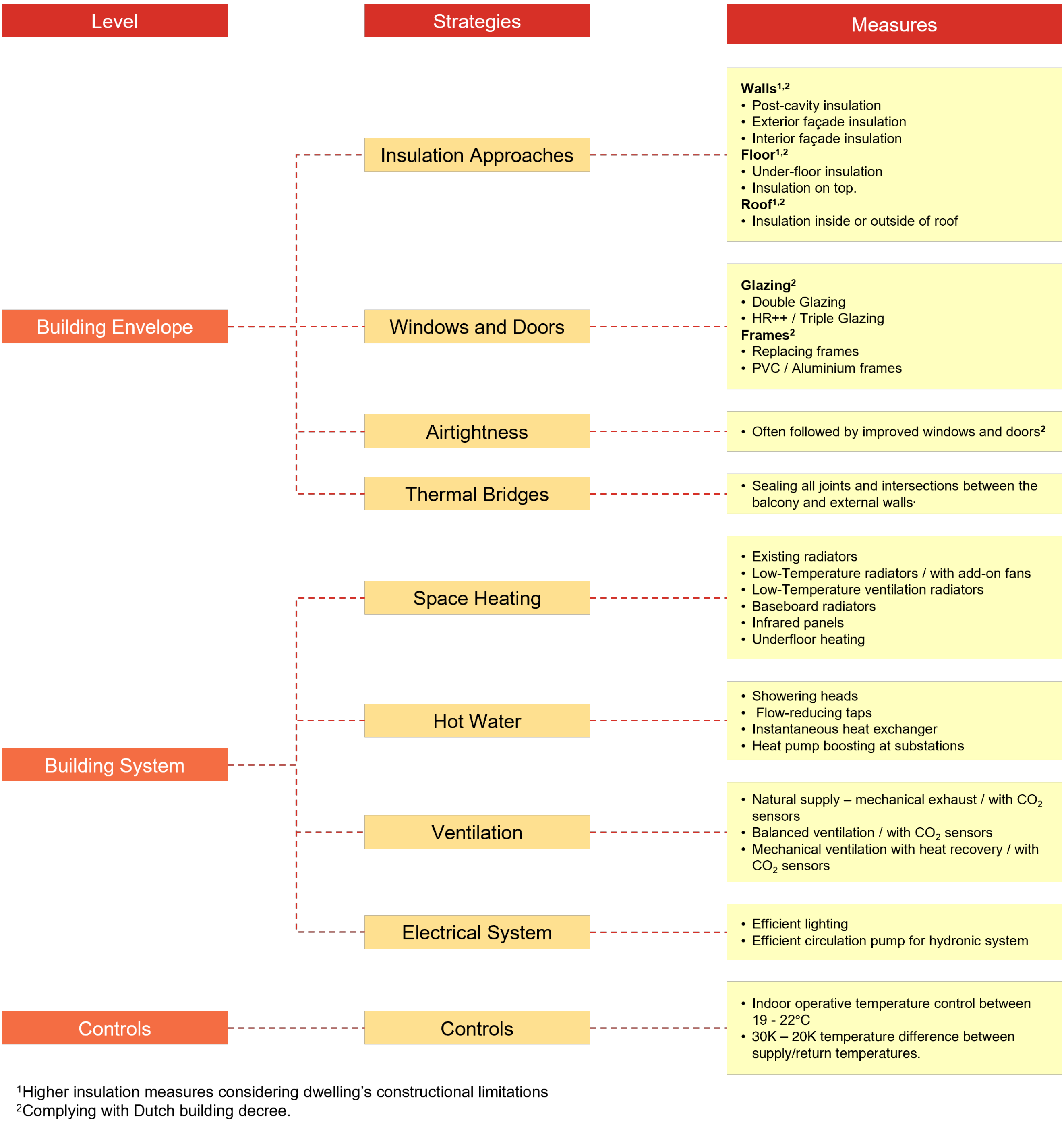

Figure 2. The selection of renovation strategies and measures applicable at the building envelope, building system, and control level [57,61].

Once the renovation solution space is developed, the performance of different measures stemming from the renovation scenarios and strategies are quantified using the two KPIs and compared with the benchmark performances calculated in Step 1. Only those solutions or measures that demonstrate a reduction in space-heating demand and occupied cold hours compared to the benchmark performance were considered technically desirable solutions for preparing a dwelling for a lower MT or LT temperature level when supplied from DH systems.

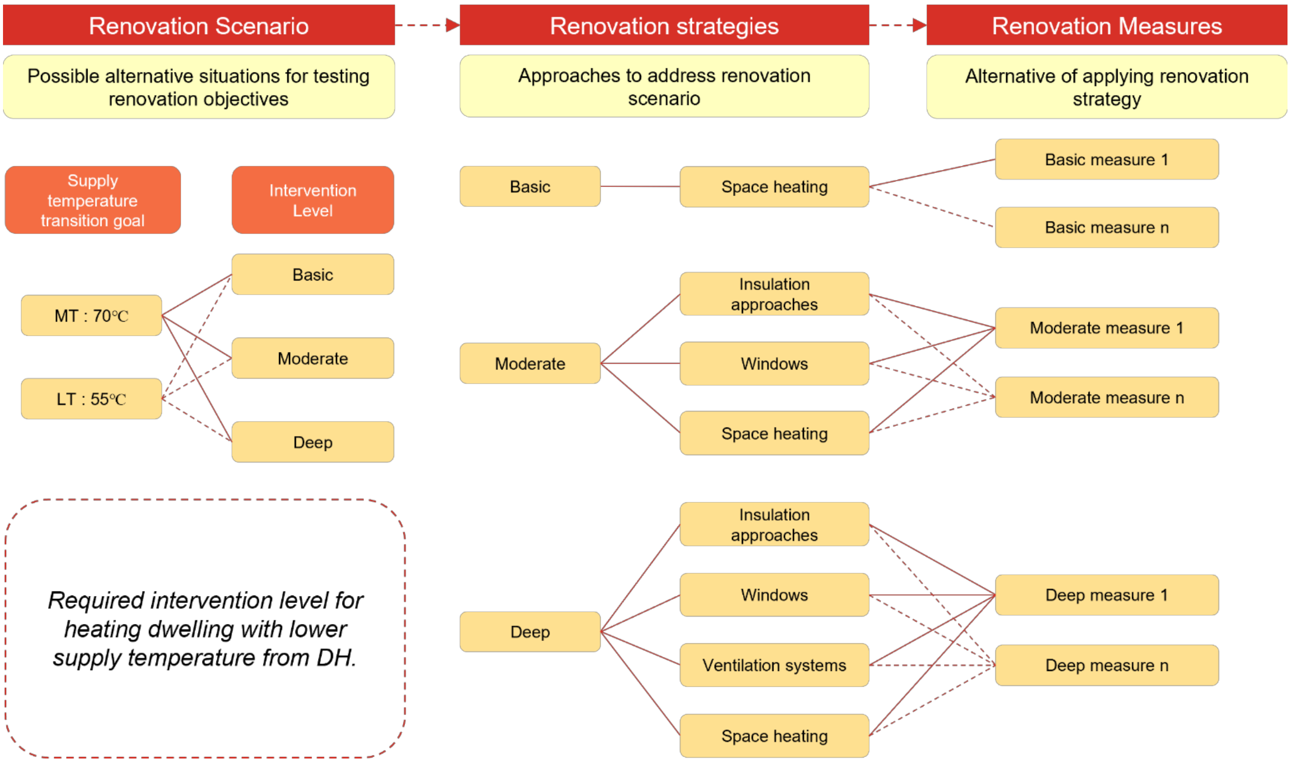

Figure 3. The process of developing the renovation solution space in relation to the renovation scenarios, strategies, and measures.

2.3. Case Study Dwelling

Dwellings with high heating demands connected to the DH system can affect the maximum reduction in the supply temperatures of the DH system. Such dwellings can negatively impact the energy and economic performance of the DH system and may also lead to higher investment costs in designing future lower-temperature DH systems using renewable energy sources [11,66]. Consequently, this study selected a case study dwelling of a typical Dutch intermediate terraced house constructed in 1938. Terraced houses, or “rijwoningen” in Dutch, account for 42% of the total residential dwelling stock in the Netherlands [67,68]. As illustrated in Figure 4, 30% of these terraced dwellings were built before 1945 [68] with an average energy label of “G” [69], exhibiting high heating demands. As a result, it is argued that these dwellings would require energy renovations in order to utilise a lower temperature supply from DH systems. Additionally, analysing them under different lower-supply temperature transition goals will provide insights into the minimum renovation requirements necessary for the worst-performing dwellings in the neighbourhood in order to prepare them for heating with LTH supplied from DH systems.

Figure 4. A typical terraced house constructed prior to 1945. The red box illustrates the dwelling’s intermediate (in-between) position within the adjoining row houses [67].

2.4. Dynamic Simulation Models

Dynamic simulations were performed to analyse the impact of lower supply temperatures on the dwelling case, using DesignBuilder® V7.0 bundled with EnergyPlus® V9.4 as simulation tools. The building profile data of the case study dwelling was acquired from the "LT Ready" research project by TU Delft, where the case study dwelling was renovated in 2020 as part of the project [70]. Therefore, calibrated models (calibrated using the statistical index recommended by ASHRAE guidelines [71]) were prepared with the renovated conditions of the dwelling and later reverted to illustrate the characteristics before renovations. The dwelling characteristics before and after the renovation (Table S1), the input parameters used to create the simulation model (Table S2), and calibration results (Section S3) can be found in the supplementary material in the appendix. Figure 5 depicts the spatial characteristics, heating conditions, size, and type of radiators for each thermal zone.

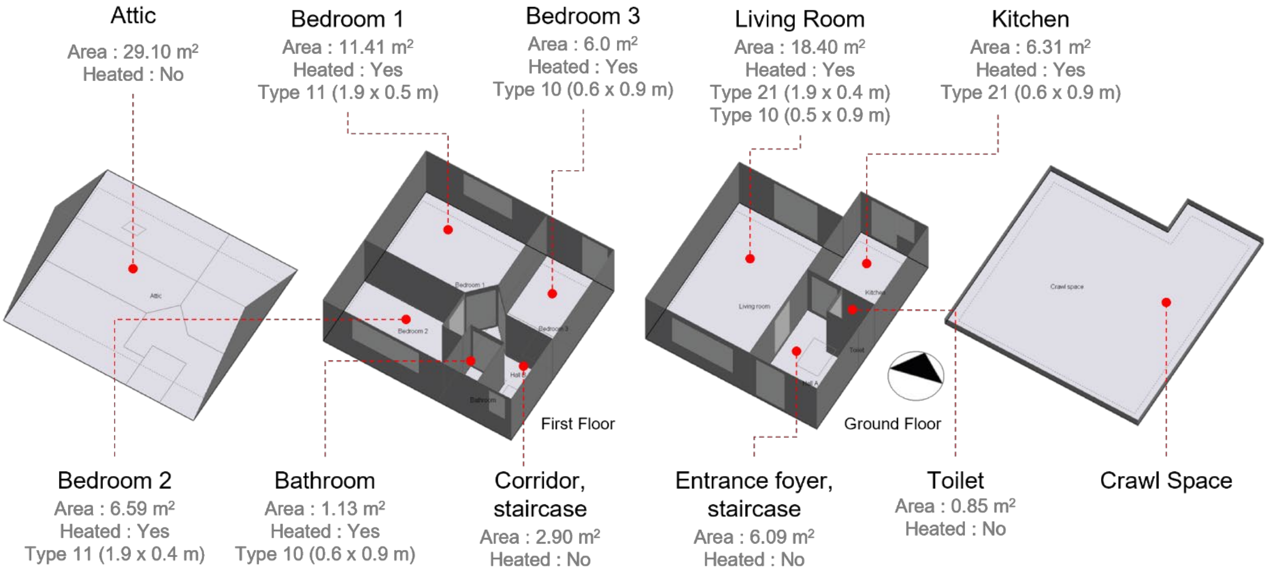

Figure 5. The figure illustrates the case study dwelling's surface area, heating condition, radiator type, and size in meters (length × height).

The existing radiators were positioned beneath the windows to counteract the cold draught due to window glazing. During the LT-ready project, interviews were conducted with the occupants, although it is to be noted that the interview results are not made public at this time. According to the interviews, the heating system was scheduled to operate between 8:00–23:00, with an indoor set-point temperature of 20 °C, and a night set-back of 18 °C between 23:00 and 8:00. According to the study conducted by Guerra-Santin and Silvester [72] on the development of the occupancy and heating profiles of Dutch households for building simulations, the heating schedule can be kept constant for the entire week to simplify the simulation process. The interviews also revealed that occupants heated all the rooms except "bedroom 3" on the first floor. Since the thermostat controlling the heating system is located in the living room, the study considered the same heating set-point and set-back for all the heated spaces with individual heating capacities of the installed radiator identified in the LT-ready project. The original heating capacities of the radiator HT (90/70 °C) for each heated space can be found in Table S2 of the Supplementary Material.

2.4.1. Modelling Lower-Supply Temperature from the DH System

The simulation model developed in this study is an aggregate or lump model, thus limiting the dynamic modelling of return temperatures or advanced ventilation air loops.

For modelling lower supply temperatures, this study utilised the reduced heating capacities of the existing radiator in both MT and LT supply scenarios, which were calculated using Equations (1) and (2) [73]:

$$\emptyset = \emptyset_0 \times \left(\frac{\Delta T}{\Delta T_0}\right)^n \tag{1}$$

where Ø and $Ø_0$ represent the radiator heating power in watts at the new and original temperature set, respectively, ΔT and ΔT_0 are the logarithmic mean temperature differences at the new and original temperature set, and n is the radiator exponent with a fixed value of 1.33.

$$\Delta T = (T_s - T_r)\left[\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)\right]^{-1} \tag{2}$$

where ΔT is the logarithmic mean temperature difference; T_s and T_r are the supply and return temperature in °C, respectively. T_i is the indoor design temperature of 20 °C [74].

The heating capacities of the radiators were calculated with a temperature differential of 20 K between supply and return temperatures to maintain the mass flow rate of the existing distribution pipes of the DH system. In other words, if the supply temperature were lowered, the mass flow rate could not be increased to achieve the same heating power [11] as the original HT supply. As a result, the lower temperature DH system would be unable to satisfy the peak heating demand of the dwelling, resulting in thermally uncomfortable hours or increased cold hours.

2.4.2. Key Performance Indicators (KPIs)

The KPIs associated with the energy efficiency and thermal comfort criteria were annual space-heating demand and occupied cold hours (underheated hours), respectively. The annual space-heating demand, simulated using DesignBuilder, was normalised based on the usable area of the dwelling, as calculated following the NEN 2580:2007 standard [75] and reported in kWh/m^2/year. This area-weighted space-heating demand reflects the energy utilised by the space-heating system to counteract heat losses caused by transmission, infiltration, and ventilation while also considering heat gains from solar radiation and internal heat sources [21,56].

Additionally, this study employed the adaptive thermal limit (ATL) method to analyse thermal comfort to determine occupied cold hours. The ATL method, as outlined by Peeters et al. [76], takes into consideration the adaptive behaviour of occupants by establishing a comfort temperature and defining the comfort ranges with upper and lower limits to achieve a 90% (10% PPD) and 80% (20% PPD) acceptability of indoor operative temperatures. Peeters et al. proposed the division of a dwelling into three zones with different thermal comfort requirements, such as living room, bathrooms, and bedrooms (The equation proposed by Peeters et al. [76] for calculating the lower thresholds of the comfort range for bedroom spaces yielded temperatures above neutral or comfort temperature. This is counterproductive, as it implies that occupied hours at a comfort temperature would be perceived as cold hours. Therefore, in this study, the equation from Peeters et al. for calculating the lower bounds of thermal comfort was adapted as $T_{lower} = max\,(16\,℃, T_n + (1 - w) \times \alpha)$.) and provided algorithms for computing the comfort temperatures and comfort ranges for these spaces. In this study, the thermal comfort analysis excludes short presence spaces like corridors and bathrooms [72]. Consequently, the analysis focuses on living rooms, considered occupied during the day, and bedrooms, which are occupied during the night [72]. For calculating the occupied cold hours using the ATL method, the operative temperatures during the occupied hours were compared to the running mean outdoor temperature over the preceding three days. Subsequently, the occupied hours during which the operative temperature fell below the lower limit of 20% PPD were identified as underheated or occupied cold hours.

3. Results

This study aimed to evaluate the effectiveness of the two-step approach outlined in Section 2.2 on a case study dwelling to determine the level of renovation intervention required to heat the house using LTH from the DH system. The proposed approach was designed to alleviate the decision-making struggle of selecting suitable renovation solutions by narrowing down the technically desirable solutions for using LTH. Accordingly, this section follows the structure of the proposed two-step approach. First, the case study dwelling was assessed in its existing condition for its readiness to be heated with LTH. Subsequently, a renovation solution space was developed, guided by current guidelines in the Netherlands, and finally evaluated to narrow down possible options to make the dwelling lower-temperature ready.

3.1. Evaluating the Suitability of Using LTH

To assess the existing condition of the case study dwelling for lower-temperature-supply heating from the DH system, it is necessary to establish the benchmark performance of the dwelling under the original HT (90/70 °C) supply. Therefore, the calibrated simulation model was simulated annually using the test reference year specified by NEN 5060 [75]. Table 2 provides the area-weighted annual space-heating demand and the occupied cold hours for the existing condition, with HT (90/70 °C) supply as the benchmark performance. The case study dwelling was estimated to require an annual space-heating demand of 172 kWh/m^2/year. Throughout the year, the living room was occupied for 5840 h at 8:00–23:00, of which nearly 13% (743 h) were below the 20% PPD lower limit, while the bedroom spaces were occupied for 3650 h at 23:00–8:00, with very few occupied cold hours. For analysing the readiness of the case study for a lower temperature supply, the heating capacities of the radiators were calculated for an MT (70/50 °C) and LT (55/35 °C) supply using Equations (1) and (2). As illustrated in Figure 6, the heating capacities of the existing HT radiators in the living room and bedrooms were significantly reduced by 42% under the MT supply and 70% under the LT supply.

Table 2. The annual simulation results of the dwelling in existing conditions under the MT and LT supply, compared to the benchmark performance under HT supply.

Supply Temperature	Annual Space-Heating Demand [kWh/m^2/Year]	Occupied Cold Hours below 20% PPD [h]			
		Living Room	Bedroom 1	Bedroom 2	Bedroom 3
Benchmark Performance: HT supply (90/70 °C)	172	743	1	1	4
MT Supply (70/50 °C)	165	879	1	2	9
LT Supply (55/35 °C)	143	2376	137	94	653

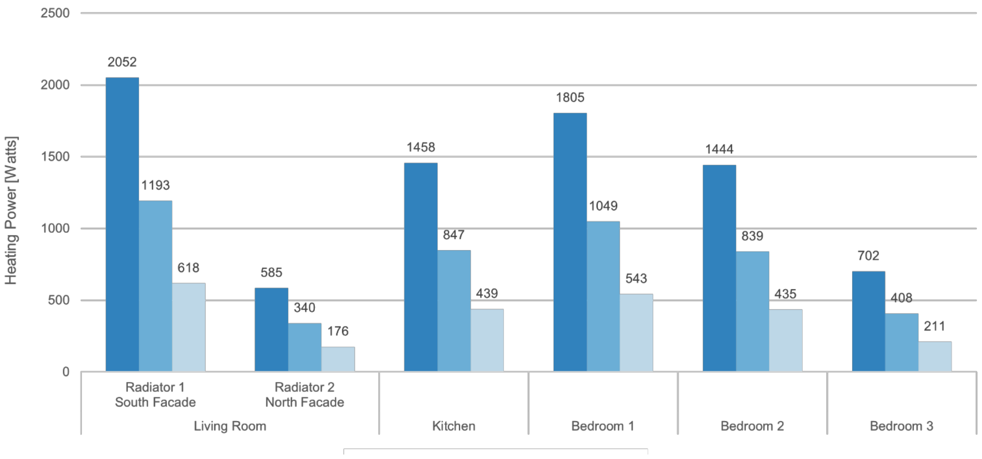

Figure 6. The heating capacities of existing radiators under the MT (70/50 °C) and LT (55/35 °C) supply compared to the existing HT (90/70 °C) supply.

As depicted in Table 2, the reduced heating capacities had a noticeable effect on the performance of the dwelling. The heating delivered by the existing radiators proved insufficient for the offsetting of heat losses, resulting in increased occupied cold hours and consequent thermal discomfort for the occupants when compared to the HT supply. This is particularly pronounced in the living room, where, in contrast to the HT supply, the occupied cold hours increased to 15% (879 h) and 40% (2376 h) under MT and LT supply conditions, respectively. The bedrooms faced significant discomfort under LT supply. Thus, it can be argued that compared to the bedrooms, the living room exhibits a higher risk of discomfort. Consequently, if the living room is prioritised to improve thermal comfort, the other spaces might inherently become comfortable. Therefore, the living room can serve as a proxy for evaluating the impact of renovation strategies in improving the thermal comfort of the dwelling under different lower supply temperatures in subsequent steps.

Additionally, these findings indicate that compared to the benchmark performance of the case study dwelling under the HT supply, the dwelling could not be comfortably heated with lower supply temperatures in its current condition. As a result, the dwelling requires renovations before using MT or LT supply levels from the DH system.

3.2. Evaluating the Performance of Alternative Renovation Options

3.2.1. Developing Alternative Renovation Options

As described in Section 2.2.2, three renovation intervention levels (basic, moderate, and deep) were tested on two supply transition goals (MT and LT), thus giving rise to six renovation scenarios. Moreover, depending on the definition of the intervention level, each renovation scenario could be approached with a combination of renovation strategies and related renovation measures (Figure 3).

The basic renovation level strategy corresponds to increasing the heat output of existing heat emission systems. In this study, the chosen measure involved replacing existing radiators with LT radiators, which included additional plates and convectors. For example, in the living room (Figure 5), type 21 and 10 radiators were replaced by type 33 and type 20, respectively. Consequently, LT radiators maintained the length and height of the original radiators while only increasing the depth to accommodate the added plates and convectors. Moreover, in this way, the original radiators could be easily replaced without any changes made to the piping system [14].

Next, for moderate renovations, selected improvements to the building envelope with three different measures were chosen: (1) improving window insulation due to its potential for significantly reducing heating demands [57,77], (2) minimum insulation levels for the building envelope, as recommended by the Dutch Building Decree [63], and (3) energy-saving measures (besparingspakket), as recommended by studies on reference homes by the Dutch government [78]. Finally, higher insulation values, similar to new construction, as suggested by the Dutch Building Decree, and the latest study on reference homes in the Netherlands [67] were considered for deep renovations along with improvements to infiltration and ventilation systems. Furthermore, as existing radiators might become over dimensioned after renovations due to reduced heating demands, measures from moderate and deep intervention levels were also simulated as a result, with or without changing existing radiators. As the next step, the strategies and measures described in Table 3 were tested for MT and LT supply transition goals against the benchmark performance of the dwelling using a HT supply, as indicated in Table 2.

Table 3. Renovation measures are categorised into three distinct intervention levels, with no renovation level representing the existing condition of the case study dwelling. MD1, MD2, and MD3 denote moderate renovation measures, while DP1 and DP2 signify deep renovation measures. The U-value of window insulation in MD1 and the envelope insulation, as well as infiltration values in MD2 and DP2, adhere to the Dutch Building Decree [63]. By contrast, MD3 and DP1 derive their values from [77] and [67], respectively.

Component	**No Renovation**	**Basic**	**Moderate**			**Deep**	
			MD1	**MD2**	**MD3**	**DP1**	**DP2**
Space-heating System	Existing Radiators	LT Radiators	Existing or LT Radiators			Existing or LT Radiators	
External Wall (U-Value in W/m^{2}K)	1.45	1.45	1.45	0.71	0.40	0.58	0.21
Floor (U-Value in W/m^{2}K)	1.45	1.45	1.45	0.38	0.40	0.28	0.27
Roof (U-Value in W/m^{2}K)	0.58	0.58	0.58	0.47	0.40	0.28	0.16
Glazing (U-Value in W/m^{2}K)	2.40	2.40	1.9	1.9	1.8	1.4	1.1
Internal Partition (U-value in W/m^{2}K)	2.40	2.40	2.40	2.40	2.40	0.40	0.21
Infiltration (Air change rate in h^{-1})	0.4	0.4	0.4	0.3	0.3	0.2	0.2
Ventilation System	Natural Ventilation					Exhaust ventilation with CO_2 sensors	Balanced mechanical ventilation with heat recovery

3.2.2. Renovation Scenarios for Using a Medium-Temperature (MT: 70/50 °C) Supply

The renovation measure only involved substituting existing radiators with LT radiators for the basic intervention level. As mentioned in Section 3.2.1, the LT radiators maintained the dimensions of the original radiators (length and height) due to space limitations preventing the installation of bigger radiators in the dwelling.

Figure 7 illustrates that the basic intervention level involving LT radiators had only a limited effect on lowering space-heating demands and occupied cold hours when compared to the benchmark performance with the HT supply. The replacement of existing radiators with higher capacity LT radiators can provide a quick and cost-effective approach for utilising LTH. However, it is essential to note that these solutions offer minimal potential for energy savings. Therefore, the emphasis should be placed on prioritising improvements to the building envelope to reduce heat losses, as this is considerably more crucial than increasing the heating capacity of the space-heating systems.

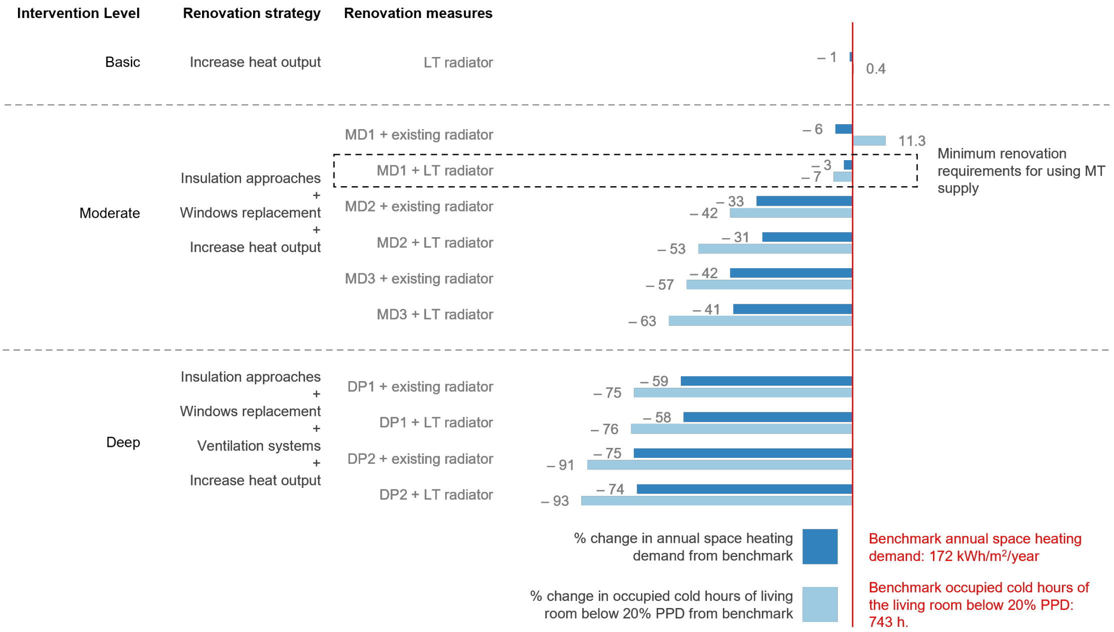

Figure 7. The annual space-heating demand of the dwelling and occupied cold hours of the living room with different renovation measures under the MT supply.

In the context of moderate renovations, implementing measure MD1 alongside existing radiators resulted in a 6% reduction in the space-heating demand. However, applying this measure does not lead to an improvement in the occupied discomfort hours compared to the benchmark performance. It was only when this measure was combined with LT radiators that a 6.5% reduction was achieved in occupied cold hours compared to the benchmark performance, with a slight increase in energy demand (decrease in % change) due to higher heating power (larger heating surface area). For measures MD2 and MD3 with existing radiators, measure MD2, in accordance with the recommended minimum insulation levels according to the Dutch Building Decree, contributed to a 33% reduction in the space-heating demand and a 42% decrease in the occupied cold hours. Similarly, measure MD3, in conjunction with existing radiators, demonstrated a substantial 42% and 57% reduction in the space-heating demand and occupied cold hours, respectively. Additionally, combining MD2 and MD3 with LT radiators could extend their impact by reducing the occupied cold hours by 53% and 63%, respectively.

Moreover, deep renovation strategies involving holistic improvements to the building envelope, heating systems, and ventilation systems resulted in substantial reductions in both space-heating demand and occupied cold hours. For example, measure DP1 alongside existing radiators achieved a significant 59% reduction in the space-heating demand and 75% in the occupied cold hours. On the other hand, compared to the benchmark, measure DP2 with existing radiators resulted in a 75% and 91% reduction in the space-heating demand and occupied cold hours, respectively. While existing radiators provide adequate heating power to offset heat losses in deep renovation, they could also be replaced with LT radiators during deep renovations, in practice. This could further reduce the occupied cold hours, although with a minor increase in energy consumption. Nevertheless, it is essential to note that deep renovations might result in the risk of overheating during the summer period. Therefore, additional strategies might be required for preventing and controlling heat gain to avoid overheating in summer. Therefore, a comprehensive evaluation of renovation measures for utilising LTH at a deep intervention level should include a thorough analysis of potential summer overheating.

The results indicate that improving existing windows and radiators could be regarded as the minimum intervention required for comfortably heating the case study dwelling with an MT (70/50 °C) supply. Nevertheless, it is essential to evaluate whether the specific MD1 measure with LT radiators would be adequate to ensure the comfortable heating of the dwelling, even with an LT (55/35 °C) supply.

3.2.3. Renovation Scenarios for Using a Low-Temperature (LT: 55/35 °C) Supply

The highest level of discomfort was observed when the supply temperature was further reduced to the LT supply (Figure 8). In the case of basic renovations, the occupied cold hours remained above the benchmark performance. While the three moderate renovation measures (MD1, MD2, MD3) could reduce the space-heating demand, they failed to improve the thermal comfort of the living room compared to benchmark conditions. However, when MD2 and MD3 were implemented in conjunction with LT radiators, there was a notable reduction of 37% and 52%, respectively, in the occupied cold hours. This suggests that MD2, combined with LT radiators, can be considered the minimum renovation required for the transition to an LT supply. Deep renovation measures can further reduce the space-heating demand by 60–75% and occupied cold hours by 65–90%.

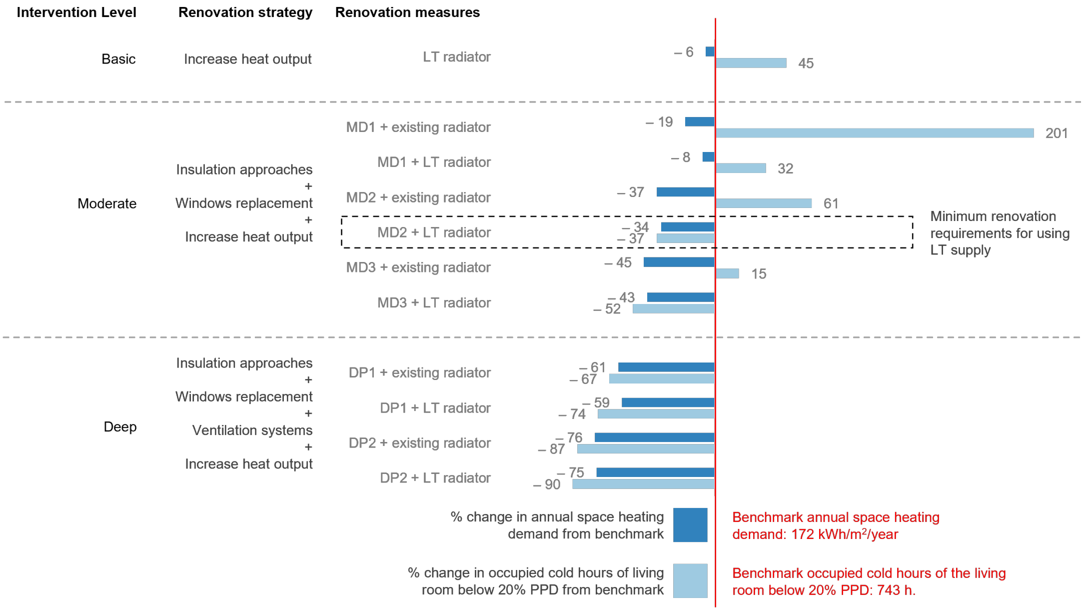

Figure 8. The annual space-heating demand of the dwelling and occupied cold hours of the living room with different renovation measures under an LT supply.

4. Discussion

4.1. Case Study: Renovation Interventions for Using LTH

Applying the two-step approach to the case study revealed that the intermediate terraced house built before 1945 cannot be heated comfortably with the reduced supply levels of MT and LT. As a result, the dwelling would require energy renovations before being connected to a DH system with a lower temperature supply. Upon evaluating specific renovation options derived from Dutch reference homes studies [67,78] and the Building Decree [63], it became evident that utilising LTH from DH systems requires at least moderate renovation interventions. Implementing measure MD1 with LT radiators could prepare the dwelling for heating with an MT supply. However, insulating the closed part of the envelope in addition to MD1—resulting in measure MD2 with LT radiators could prepare the dwelling for an LT supply.

These findings align with recent standards and target values for home insulation in the context of gas-free heating in the Netherlands [79]. According to the study, if a dwelling meets the standard value of net heat demand, derived based on its compactness ratio (the ratio of envelope heat loss area to usable area), type (single or multi-family), and construction year (>1945 or <1945), then the dwelling can be considered prepared for future gas-free heat networks or individual solutions with a lower temperature supply. For the case study dwelling, which was an intermediate terraced house built before 1945 with a compactness ratio of approximately 2.0, the standard for the net heating demand was calculated at 164 kWh/m^2/year. Compared to the benchmark performance of the dwelling at 172 kWh/m^2/year, only a 5% reduction in the heating demand would suffice for the dwelling to use an MT supply. This implies that measure MD1 with a 6% (161 kWh/m^2/year) reduction in the net heating demand (Figure 7) without changing the radiator is an MT-ready solution. However, according to the lower-temperature-ready criteria, this solution is insufficient for improving thermal comfort compared to the benchmark performance. Consequently, LT radiators with measure MD1 reduced occupied discomfort hours. This increased the heating energy consumption to 167 kWh/m^2/year, exceeding the standard net heating demand of 164 kWh/m^2/year. As a result, the subsequent moderate renovation measure MD2 should be considered as the minimum renovation required for an MT supply, as it satisfies both the net heating demand standard and lower-temperature-ready criteria.

Additionally, deep renovation measures yielded the most substantial reduction in the space-heating demand and occupied cold hours. However, it is worth noting that deep renovations may introduce the potential risk of overheating during the summer months. Furthermore, when deep renovations are combined with other systems to prevent legionella growth in domestic hot water systems, they can lead to expensive solutions for property owners. Consequently, it is imperative to assess the financial and environmental implications of these measures during the decision-making stage.

Furthermore, for evaluating thermal comfort criteria, only the living room was analysed under the assumption that improving the living room's occupied cold hours could also solve the thermal comfort problems in bedroom spaces. This assumption is crucial for transitioning to an LT supply, as seen in Table 2, where the bedroom spaces had higher occupied cold hours with the LT supply than the MT supply. Therefore, measure MD2 with LT radiators was also evaluated for bedroom comfort. As shown in Table 4, the findings reveal a complete reduction in the occupied cold hours below 20% PPD compared to the benchmark performance and with the LT supply without renovations. Consequently, it can be concluded that the living room can be utilised as a proxy to evaluate the thermal comfort criteria of the dwelling.

Table 4. Improvement in space-heating demand and thermal comfort hours in the living room and bedroom spaces under an LT supply due to moderate renovation measure MD1 with LT radiators.

	Annual Space-heating Demand [kWh/m^2/Year]	**Occupied Cold Hours below 20% PPD [h]**			
		Living Room	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Benchmark Performance: HT supply (90/70 °C)	172	743	1	1	4
Existing condition: LT Supply (55/35 °C)	143	2376	137	94	653
MD2 + LT radiators: LT Supply (55/35 °C)	114	467	0	0	0

In conclusion, it can be ascertained that the MD2 measure or, in other words, the minimum renovation requirements mandated by the Dutch Building Decree, prove to be sufficient for a terraced house built before 1945 to transition to lower supply temperatures (MT and LT levels) from a DH system, considering energy efficiency and thermal comfort criteria. These findings can be qualitatively extrapolated to recommend minimum renovation interventions for intermediate terraced houses built after 1945 when connected to a DH system with a lower temperature supply.

The study on reference dwellings in the Netherlands [67] provides the current insulation levels of such dwellings across various construction years, as illustrated in Table 5. It can be observed that the case study dwelling's insulation levels before renovations

(Table 3) closely align with the median insulation values of terraced houses built before 1945. Moreover, by implementing moderate renovation measures, MD2 could upgrade the houses to an insulation level closer to dwellings constructed in 1975–1991. Therefore, it can be inferred that dwellings built before 1975 may require MD2 measures without changing their radiators for an MT supply; by changing to LT radiators, they can also be prepared for an LT supply. On the other hand, dwellings built after 1975 may already have a certain level of readiness for an MT supply, although basic intervention would be required for an LT supply.

Table 5. Renovation recommendations for intermediate terraced houses in different construction years. The table also includes median insulation values and the state of the dwellings in five construction periods [67].

Component	<1945	1946–1964	1965–1974	1975–1991	>1991
External Wall	1.92	1.92	1.67	0.68	0.37–0.21
	Uninsulated: 70% of the homes	Uninsulated: 62% of the homes	Uninsulated: 35% of the homes	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Ground Floor	2.4	2.4	2.3	1.28	0.36–0.27
	Uninsulated: 70% of the homes	Uninsulated: 85% of the homes	Uninsulated: 62% of the homes	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Roof	0.84	1.12	0.97	0.68	0.37–0.16
	Uninsulated: 30% sloping roof, 50% flat roof	Uninsulated: 48% sloping roof, 68% flat roof	Uninsulated: 31% sloping roof, 68% flat roof	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Windows	2.9	2.9	2.9	2.9	1.8
	16%: single glazing, 59%: double glazing, 16% HR++ glass	16%: single glazing, 54%: double glazing, 23% HR++ glass	56%: double glazing, 29% HR++ glass	8%: single glazing, 64%: double glazing, 21% HR++ glass	Mostly HR++
Ventilation system	Natural ventilation: 89% homes, Mechanical ventilation:11% homes	Natural ventilation: 89% homes, Mechanical ventilation:11% homes	Natural ventilation: 73% homes, Mechanical ventilation:27% homes	Natural ventilation: 41% homes, Mechanical ventilation:57% homes, Balanced: 2% homes	Mostly mechanical ventilation and balanced ventilation
Infiltration	Some houses are airtight	Some houses are airtight	Some houses are airtight	All houses are airtight	All houses are airtight
Recommendations for a minimum level of renovation intervention required					
MT supply (70/50 °C)	Moderate renovations with MD2 measure without changing existing radiators			Could be ready for MT supply	
LT Supply (55/35 °C)	Moderate renovations with MD2 measure with LT radiators			Basic: LT radiators	Basic: LT radiators

4.2. Implications and Limitations of the Proposed Approach

The proposed two-step approach developed in this study has implications and limitations that must be considered when used to select renovations for heating dwellings with LTH through DH systems. This approach aims to identify technically desirable solutions from a diverse renovation solution space that can potentially prepare a dwelling for utilising LTH supplied by DH systems. Even though this study analysed a limited number of measures, this method could still help filter out suitable solutions when the solution space is extensive. This approach provides stakeholders with a systematic method to assess the necessity of renovations for using LTH and reduces the number of viable solutions to select from, thus alleviating decision paralysis. However, a comprehensive validation through stakeholders involved in the decision-making process is required to validate this theory.

The novelty of this method lies in its criteria for testing the readiness of a dwelling for LTH, which is essential in narrowing down the renovation options before the decision-making stage. Energy efficiency and thermal comfort were identified as essential non-compensatory criteria, serving as filtering criteria for reducing renovation options.

Nevertheless, for actual decision making, it is essential to evaluate the feasibility and environmental impact of narrowed renovation options, which was beyond the scope of this study.

Additionally, for developing relevant renovation scenarios, it is essential to consider the feasibility and practicality of alternative solutions based on the constructional limitations of the dwelling in context. For instance, the selection of post-cavity insulation as a renovation measure would depend on the cavity's presence and width, based on the construction year of the dwelling.

Since this study focused on intermediate terraced houses, the recommendations may not directly apply to other dwelling types in the Netherlands. However, a recent study by Cornelisse et al. [79] determined that houses with similar building characteristics and compactness ratios can be grouped. As a result, other housing types with compactness ratios and characteristics similar to the case study dwelling might have a similar energy performance and recommendations for renovation options for being lower temperature ready. However, a comprehensive study is necessary to test this hypothesis. Finally, it is essential to mention that the proposed two-step approach works well for analysing one or a few houses. Consequently, additional adjustments to the method might be required for analysing a large number of dwellings at a district level or housing corporations with a considerable portfolio, thus suggesting future research opportunities.

5. Conclusions

This study presented a two-step approach for identifying the renovation intervention required for existing dwellings in the Netherlands to enable them to use LTH from DH systems. The approach was structured to assess the dwelling's potential to be heated in its existing condition with lower supply temperatures from DH systems. On the other hand, if this was not possible, the objective was then to develop and evaluate alternative renovation solutions to make the dwelling lower temperature ready.

The approach was applied to a typical intermediate terraced house built before 1945 to test its applicability. The renovation problem entailed determining minimum renovation requirements for utilising LTH from the DH system. The objective of the renovation was to prepare the dwelling for an MT (70/50 °C) and LT (55/35 °C) supply compared to existing HT (90/70 °C) from DH systems. This study proposed a definition for evaluating the readiness of a dwelling to be heated with a lower supply temperature that corresponds to an improvement in thermal comfort and energy efficiency relative to the current situation of the dwelling with an HT supply. As a result, energy efficiency and thermal comfort were considered as non-compensatory criteria, meaning that both criteria must be satisfied without any trade-offs. The KPI used to evaluate energy efficiency was the annual space-heating demand, while for thermal comfort, occupied hours below the lower limit of 20% PPD was used as an indication of thermal discomfort and was calculated according to the ATL method. A calibrated simulation model was developed and used to evaluate the performances of the dwelling in its existing condition with an HT supply and under MT and LT supply levels.

Consequently, the approach proposed six renovation scenarios based on different intervention levels (basic, moderate, and deep) for MT and LT supply temperature transition goals. Depending on the definition of the intervention level, each scenario consisted of renovation strategies and subsequent renovation measures. The main findings from the application of the two-step approach on the selected case study dwelling are as follows:

1. Intermediate terraced houses constructed before 1945 require energy renovations to enable heating with an MT and LT supply.
2. The basic renovation strategy, which involved the replacement of existing radiator systems with ones that provide higher heat output, was insufficient for preparing the case study dwelling to be heated with a lower temperature supply from the DH system.

3. The moderate intervention level, with the measure that upgrades the building envelope to meet the minimum insulation levels mandated by the Dutch Building Decree (Wall: 0.71 W/m²K, Floor: 0.38 W/m²K, Roof: 0.47 W/m²K, and Windows: 1.5 W/m²K), along with reduced infiltration and LT radiators, served a dual purpose of preparing the dwelling for both MT (70/50 °C) and LT (55/35 °C) supply transition goals.
4. When applied with the MT supply, this measure achieved a 33% reduction in the space-heating demand and a 42% decrease in occupied cold hours. Conversely, when an LT supply was utilised, the same measure resulted in a 34% reduction in the space-heating demand and a 37% reduction in occupied cold hours.
5. Deep renovation strategies can further reduce the space-heating demand and occupied cold hours, although it is essential to note that these deep renovation measures may introduce a risk of summer overheating, which must be included in future analyses.

Finally, the proposed two-step approach has significant implications, as it has the potential to systematically streamline the decision-making process for selecting renovations for heating dwellings with LTH through DH systems by reducing the number of renovation options. These reduced options can then be further analysed in the decision-making stage by evaluating their performances on economic and environmental criteria with a life cycle perspective. In this manner, the method could reduce stakeholders' decision paralysis, although it must be thoroughly confirmed through stakeholder analysis. Additionally, this study is limited to only a single dwelling type, and further research is essential for evaluating and analysing its application in different types of dwellings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13102524/s1, Section S1: Characteristics of the case study dwelling before and after renovations; Section S2: Input parameters for creating the simulation model; Section S3: Calibration of the simulation model; Figure S1: Comparison between simulated and monitored indoor air temperature of the living room after calibration; Table S1: Building characteristics data of the case study dwelling before and after renovations. The case study dwelling was renovated as a part of the LT-ready project.; Table S2: Overview of input parameters for making simulation model for the renovated condition of the case study dwelling.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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Nomenclature

ATL	Adaptive Thermal Limit
DH	District Heating
HT	High Temperature
KPI	Key Performance Indicator

LT	Low Temperature
LTH	Lower-Temperature Heating
MCDM	Multi-Criteria Decision Making
MT	Medium Temperature
PPD	Percentage of People Dissatisfied
ULT	Very/Ultra Low Temperature
Ø	Radiator heating power at new temperature set [W]
$Ø_0$	Radiator heating power at original design temperature set [W]
ΔT	Logarithmic mean temperature difference at new temperature set [°C]
ΔT_0	Logarithmic mean temperature difference at original design temperature set [°C]
n	Radiator exponent [-]
T_s	Radiator supply temperature [°C]
T_r	Radiator return temperature [°C]
T_i	Design indoor temperature [°C]

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