Towards low flow temperatures: Making buildings ready for heat pumps and modern district heating

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Summary

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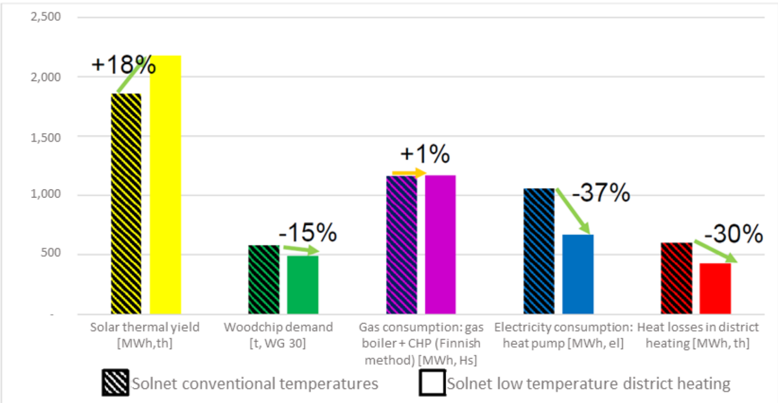
Following the fossil gas crisis, saving energy used for heating has become a priority for many households, companies, and governments. At the same time, many European countries are in the process of introducing policies to shift from heating oil and gas as well as fossil fuel-based district heating to clean and renewable heat as part of their decarbonisation agendas.

Why do we need low flow temperatures?

A key element in saving energy from heating and facilitating the introduction of clean heat sources is to increase the use of low flow temperatures in heating systems. Typically, heating systems in Europe use water flowing through pipes and emitters (radiators) heated to high temperatures (70-90°C). This is the flow temperature. Reducing this flow temperature, while ensuring required internal temperatures can still be met, enables heat pumps, solar thermal collectors, condensing boilers, and district heating systems to run more efficiently and on renewable energy.

- **Low flow temperatures support heat pump deployment and enables building owners to decarbonise buildings with lowest cost for the consumers:** Flow temperature is a decisive factor in heat pump efficiency. Lower flow temperatures significantly reduce electricity consumption, and thus operating costs.
- **Low flow temperatures reduce the load on the power grid:** At the power system level, winter loads are reduced, decreasing stress on the system and lowering future investment needs for grid expansion.
- **Low flow temperatures enable district heat with excess, ambient, and renewable heat:** Low flow temperatures significantly broaden the scope of potential heat sources, as many excess and renewable heat sources and all ambient heat sources are of lower temperatures. Also, renewable sources such as solar thermal, geothermal, and biomass/biofuels have higher yields at lower temperatures. In our case study of the Steinheim low flow temperature district heating system, the grid losses are 30% lower, the efficiency of the solar collectors is 18% higher, and electricity demand of the heat pump is down by 37% compared to conventional systems run at 90°C.

Figure 1: Benefits of switching to low temperature district heat (Source: Wärmenetz Steinheim GmbH)



- **Low flow temperatures reduce gas and oil use in condensing boilers:** Condensing boilers only reach their advertised efficiency levels if the water vapour in the exhaust gas condenses fully. The lower the flow temperature, the more efficient a condensing boiler will be. For a gas boiler, a flow temperature of at least 50°C is required to operate at above 90% efficiency.
- **Low-temperature readiness contributes to climate targets.** With low-temperature readiness, the heat supply is gradually decarbonised. The higher share of renewable energy leads to lower CO_2 emissions, which means that climate targets can be met.

What is a 'low flow temperature ready' building?

In many cases, buildings and heating systems need to undergo some changes in order for the building to be comfortably heated to the required temperature using low flow temperatures. To reduce flow temperatures in heating, two variables can be optimised:

1. **The heat load of the building can be reduced** by improving the energy performance of the building envelope through, for example, insulation, window replacement, and airtightness.
2. **The heating capacity of the heat distribution system can be increased**, for example by enlarging radiators and/or pipes, replacing radiators with models of the same size but higher surface area and more efficient design, or installing large area heating systems like underfloor, wall, or ceiling heating.

In the case of district heating or heating systems that also supply domestic hot water from the same heat generator, extra investments in legionella prevention measures or temperature boosters might be necessary as the flow temperature for heating can often not be regulated separately from the flow temperature for domestic hot water.

How can we define and measure if a building is 'low flow temperature ready'?

Defining 'low flow temperature readiness' (LT readiness) in buildings is highly country-specific as it depends on a range of factors: amongst others, the predominant heating technologies used in the country or region, especially whether individual or district heating systems are most common; the building stock, including age and dominant building typologies; the share of energy use for space heating compared to domestic hot water production; energy costs, particularly the ratio of electricity prices to gas/heating oil prices; the climate zone; and the condition of the electricity grid.

There are three key approaches which could be used to define and measure LT readiness in buildings:

1. **Define a maximum flow temperature to give building owners, operators, and users a simple guiding indicator**. For example, the case study for Germany (chapter 6.5) suggests 55°C as the maximum temperature that can be considered 'low'. While this approach is simple to communicate, it could be wrongly seen to present a binary choice (LT ready/not LT ready): for example, it would be a mistake to assume that with an LT ready temperature set at 55°C, a system at 56°C would not work with heat pumps or low flow temperature district heating.
2. **Define a building standard adjusted to the state of the building stock and other constraints** (see chapter 6.3).
3. Based on the principle 'the lower the flow temperature, the better', a **continuous scale for LT readiness could be defined** (the exact values would need to be defined for each country).

What policies can drive uptake of low(er) flow temperatures in Europe?

To implement the low flow temperature concept, an integrated policy framework could include:

- Raising awareness of existing heating settings for both building owners and the industry
- Integrating low temperature testing or readiness into inspections, advice, audits, and assessments
- Communicating a readiness indicator and measures to move towards LT readiness through Energy Performance Certificates and Building Renovation Passports
- Supporting the achievement of LT readiness through funding programmes
- Normalising low temperature heating through product standards
- Enabling LT readiness through building standards.

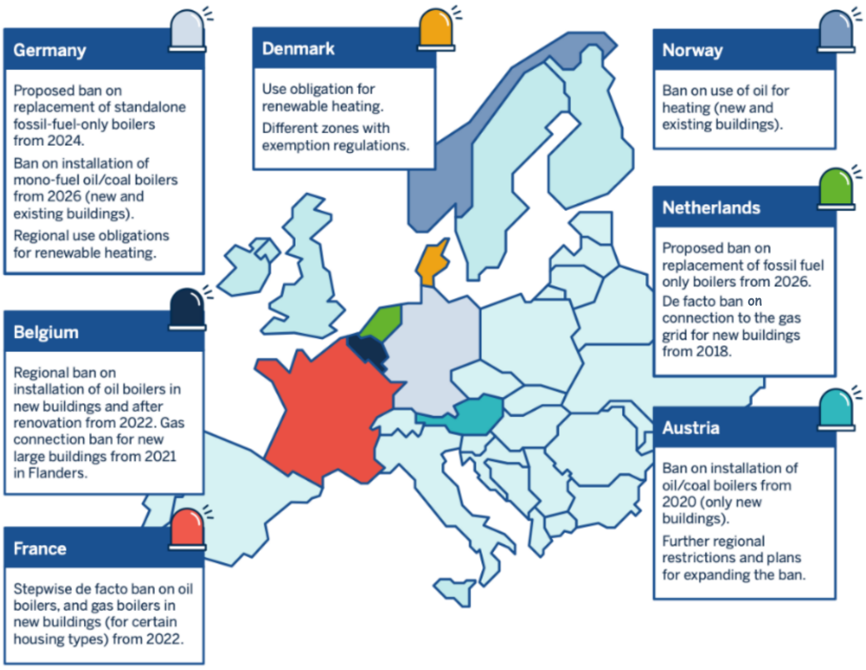
1 Introduction and context

The 2020s must be the decade in which the transition to clean heat is radically scaled up. The European Union (EU) is still heavily reliant on fossil fuels when it comes to space heating, with over 80% of the energy used coming from fossil sources.[1] To meet the EU's climate target of a 55% reduction in greenhouse gas emissions by 2030, one in four homes will need to replace its heating system by the end of the decade (European Commission, 2020).

The energy crisis in 2022 made it even more urgent that we drastically reduce our reliance on fossil fuels. Moreover, in its crisis response the European Commission (the Commission) stated its wish to become independent from Russian energy (European Commission, 2022). As space heating represents the single largest use of gas in the EU, switching to clean heat is key. To this end, European governments have introduced a variety of policies aimed at phasing out the use of fossil fuels in heat for buildings and replacing fossil boilers (see Figure 2).

In this study, we describe how a 'low flow temperature ready' (LT ready) concept can be an important tool to ensure buildings can be heated efficiently, particularly with clean heat. Hydronic or central heating systems heat buildings more efficiently when water at low(er) temperatures is used to deliver heat through the pipes and emitters compared to water at high(er) temperatures. This is particularly true when it comes to heat pumps and district heating.

Figure 2: National fossil fuel heating restrictions in EU Member States and Norway



Source: Based on Figure 4 from: Braungardt, S. et al. (2021). *Phase-out regulations for fossil fuel boilers at EU and national level.*

[1] In 2017, 83% of EU space heating capacity was fossil-fuel-fired (66% gas, 15% oil, 2% coal) (Bagheri et al., 2022).

First (Chapter 1), we explore the benefits of heating with low(er) flow temperature water for different heating technologies, focussing on heat pumps and district heating. **Chapter 2 analyses barriers to reducing flow temperatures in heating systems.**

Next**, in Chapter 3, we examine the concept of LT readiness** and its limitations by discussing how to make a building LT ready. We then explore this concept in two case studies.

The first case study, in **Chapter 4, looks at LT readiness from the perspective of individual buildings**. For four typical German buildings, we calculate the required steps to make them LT ready and propose a 'procedure' to renovate them.

In Chapter 5, we look at a German city that plans to develop a low temperature district heating system and make 400 buildings LT ready.

Chapter 6 explores how LT readiness can be implemented through a range of policy tools and provides a short inventory of policies that address low temperature heating and LT readiness.

Limitations of the study: This report focusses on the advantages of the concept of LT readiness, which can be achieved by making the building envelope more energy efficient, by improving the radiators and heat emitters, or by a combination of both of these approaches. It does not, however, address other aspects of improved efficiency of the building. Of particular importance are the effects of the heat pump on the power grid, and the benefits a good efficiency level can have for power consumption, resilience, and demand-side flexibility. These aspects are investigated in other studies; see for instance FIW and ifeu (2023).

Neither does this report investigate hybrid heat pumps, which can offer grid benefits and allow the heat pump to reduce heat production on very cold days. To set against these advantages, hybrid heat pumps require at least two heat generators, with associated maintenance costs. Often the heat pump will be coupled with a gas boiler, with the risk of locking the building in to perpetuated gas demand. Hybrid heat pumps therefore deserve more attention in a separate study.

Finally, this report is not intended as a ready-to-implement recipe for building owners: rather it explains the technical background of the LT readiness concept and aims to derive actionable and effective policy recommendations.

2 Why low flow temperatures?

2.1 Summary

High flow temperatures in heating systems are inefficient, whatever the heating source. They also impede the efficient use of renewable energy carriers, waste heat, and fossil energy. Low flow temperatures significantly increase the efficiency of heat pumps, leading to a significant reduction of greenhouse gas emissions, a reduction in electricity consumption, operating cost, and winter loads on the electricity grid. In district heating networks, low flow temperatures reduce losses and enable (additional) use of waste heat, geothermal energy, biomass, and cost-effective solar thermal energy. Condensing boilers also benefit from lower flow temperatures through increased heat recovery from the flue gasses.

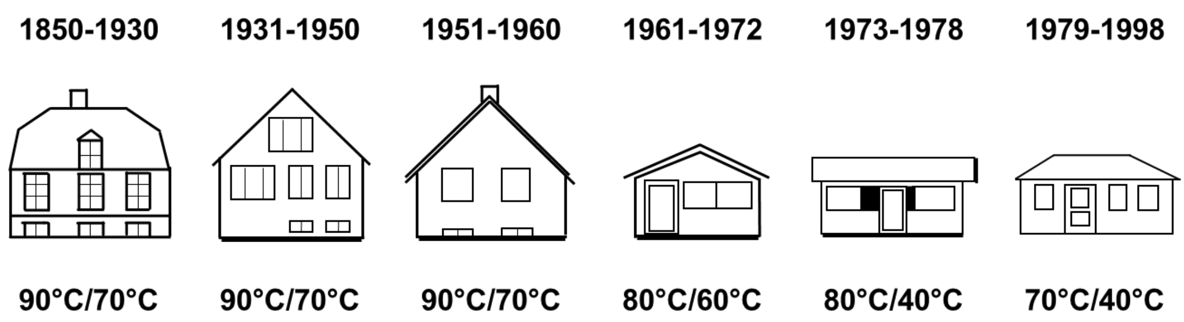
2.2 Flow temperatures today

In buildings with central heating, hot water is pumped from the heat generator (boiler, heat pump, solar storage tank, district heating substation) to the heating emitters (radiators, underfloor or other surface heating), then is returned to the heat generator having transferred much of its useful heat content to the space. The temperature of the heating water on its way to the heating emitters is called the **flow temperature**. On its way back it is called the **return temperature**. The flow temperature is usually regulated by sensors and controls in modern central heating systems. In some systems, the temperature is adjusted according to a heating curve that depends on the outside temperature (weather compensation).

Historically, heating systems were designed to operate at high temperatures. Heat was supplied by burning fuels to produce hot water, and the thermal insulation of buildings was poor. A high flow temperature was therefore required. In addition, high flue gas temperatures were required to prevent the risk of damage to the boiler and/or chimney due to condensing water (Østergaard, 2018).

Since then, building regulations as well as fuels have changed, and modern heating systems are designed for lower temperatures. For example, Figure 3 shows how the flow and return temperatures of Danish buildings have changed over time.

Figure 3: Typical flow and return temperatures of buildings at the time of their construction (own presentation, according to Østergaard, 2018)



Although there is limited evidence on actual flow temperatures in buildings, some studies indicate that older buildings could be heated comfortably with lower flow temperatures than expected. According to a Danish study of 1,645 buildings, most of the buildings in each of the construction year categories in Figure 3 can operate with flow temperatures below 70°C. If all of these buildings were renovated to the common Danish level of 60W/m², typical Danish flow/return temperatures of 70°C/40°C would be insufficient for heating in only 8% of the buildings (Østergaard, 2018). The data shown in the study allow a conversion to other temperature values. At the flow/return temperatures of 55°C/45°C of interest in this paper, 14% of the buildings would no longer be sufficiently heated on the coldest winter days. In these cases, more efficient radiators or improved insulation would also be needed.

A recent study based on 200 homes from the Netherlands found that 60% of Dutch houses can use a flow temperature of 55°C without adaptations (Pothof et al., 2022). However, a study from the UK reports much lower numbers, finding that only 10% of UK dwellings are already able to operate a heat pump on a peak winter day with a maximum flow temperature of 55°C (BEIS, 2021). Both these studies calculated maximum necessary flow temperatures based on the heat demand of the buildings and the performance of the installed radiators. Unfortunately, studies based on flow temperatures measured on site are rare. In Geneva (Switzerland), measurements were carried out in 62 larger old buildings (IEA, 2017). For radiator heating systems, a mean flow temperature of 62°C was found at an outdoor temperature of -10°C. The associated return temperatures were on average 9°C lower. The values calculated in Denmark for the mean temperature of the radiators (average of flow and return temperatures) on the coldest days are thus close to the values measured in Switzerland. This indicates that in different European countries, despite different climatic conditions, heating systems are operated at similar temperatures.

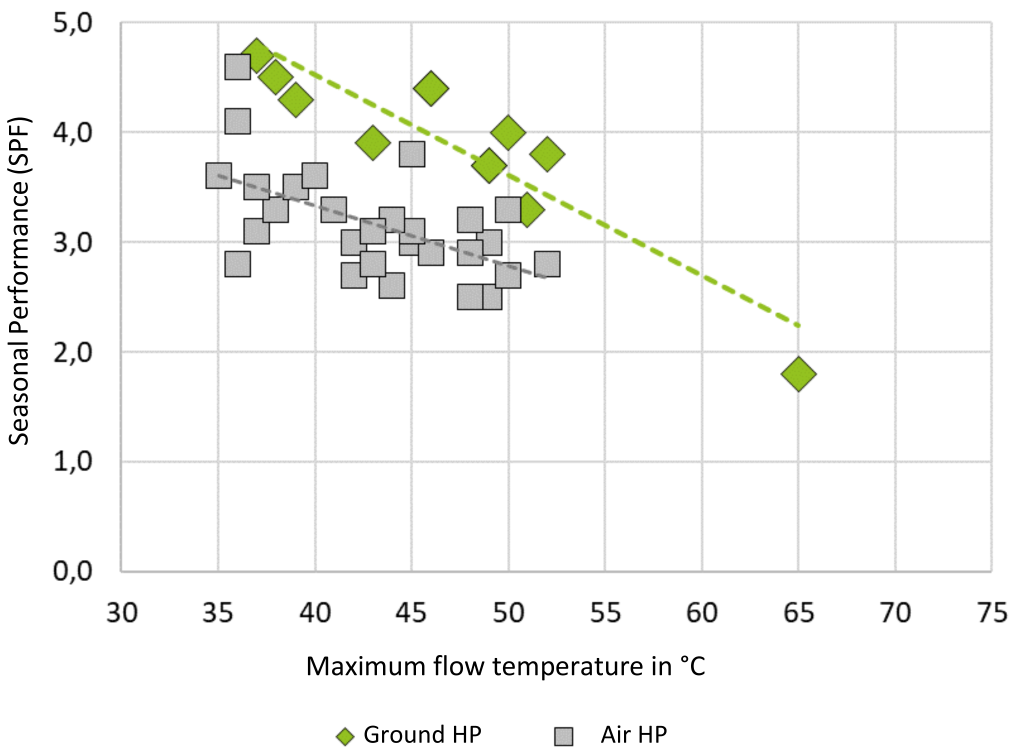
2.3 Benefits of low flow temperatures for different heating technologies

2.3.1 Heat pumps

The lower the flow temperature, the more efficiently a heat pump operates. Measurements taken in test conditions show that lowering the flow temperature by 10°C to 45°C leads to an improvement in efficiency[1] of about 25% (Buchs, 2018). In other words: for each degree of flow temperature reduction, the efficiency of the heat pump increases by 2-3%. If the flow temperature required on the coldest winter day can be reduced, electricity consumption improves significantly. Figure 4 shows the overall yearly efficiency of heat pumps as a function of the flow temperature on the coldest days.

[1] Mostly called COP (Coefficient of Performance)

Figure 4: Effect of temperature on efficiency of heat pumps (Source: own presentation, based on Fraunhofer ISE, 2021)



In winter, heat pumps will have relatively high electricity usage due to the lower coefficient of performance on cold days and the higher heat demand. As electricity demand is already generally higher in winter, this could lead to capacity issues on the electricity grid. Operating heat pumps at lower flow temperatures reduces electricity demand, especially on colder days, and thus reduces pressure on the electricity grid. This effect will be stronger for air source heat pumps than for ground or water source heat pumps, as air temperatures fluctuate to a greater degree. While older heat pumps had difficulties in providing temperatures of 55°C and above, modern heat pumps use refrigerants that enable higher temperatures. However, even for these high-temperature heat pumps, the fact remains that higher flow temperatures result in lower efficiency.

2.3.2 Condensing boilers

Condensing boilers achieve higher efficiencies than non-condensing boilers because they recoup part of the heat contained in the water vapour of the exhaust gas. If the flow and return temperatures in a heating system are sufficiently low, the flue gases in condensing boilers can be cooled down to such an extent that the vapour condenses in the boiler, releasing additional heat to the system. A gas boiler that properly condenses can ideally generate up to 11% more heat than a non-condensing boiler with the same amount of gas. Condensation only starts at temperatures below 56°C. In a typical building, reducing the flow temperature from 80°C to 55°C improves boiler efficiency by 6% (Farmer et al., 2022).

Condensing technology can also be used with other fuels, although usually with lower efficiency gains. In the case of fuel oil, low flow temperatures improve efficiency by up to 5%. When burning biomass, the efficiency gains of condensation depend on the chemical composition and water content. Freshly harvested biomass contains more water, meaning more condensation can take place (as more water will be released during combustion). Therefore, when burning wood chips, the advantage of using condensing technology can be even greater than with natural gas.

2.3.3 Solar thermal collectors

The hotter a solar thermal collector, the more heat it loses to the (colder) surrounding air. The efficiency of using heat from solar thermal collectors increases with every degree by which the flow temperature, and thus the temperature of the collectors, can be lowered, as less heat is lost to the air. For example, well-designed flat-plate collectors achieve a yield of 437 kWh/(m²*a) under typical German weather conditions with constant collector temperatures of 75°C all year round. If these temperature requirements can be reduced to 55°C, the collector yield increases by 35% to 590 kWh/(m²*a) (Wagner, 2015).[1] In addition, lower return temperatures lead to an increased amount of heat that can be stored in the tank.

The efficiency gains mentioned above provide an indication of the benefits of lower flow and return temperatures in a system that is predominantly used to provide space heating. This also applies to solar heating networks where solar heat from large collector arrays can be fed into district heat at a quarter of the heat generation price that would be charged for collector systems on the roofs of single-family homes (Pehnt et al., 2017).

2.3.4 District heating

Lowering flow temperatures in district heating offers several benefits:

- **Reduced transport losses**. In district heating, the pipes that distribute the water from the heating plant to the buildings lose heat during transport. The higher the temperature in these pipes, the higher the distribution losses.[2] In addition, lower flow temperatures and the associated lower distribution losses also support making district heating economically viable in rural and suburban areas with low(er) energy density, as illustrated by the case study on Steinheim (see Chapter 5).
- **Enables the use of excess, ambient, and renewable heat sources** and increases the efficiency with which they can be used. As many of these sources are of low(er) temperatures, they can be used more economically with lower flow temperatures as less additional heating – from e.g., heat pumps or boilers – is required. As there is a high unused potential of excess, ambient, and renewable heat in Europe (Paardekooper et al., 2018), lowering flow temperatures in district heating systems can contribute significantly to decarbonising space heating.
- **Lower investment costs**: At lower temperatures, cheaper components such as plastic pipes can be used, and materials will experience lower wear and tear. This reduces investments for both new district heating and the maintenance of existing district heating.
- In so-called **cold district heating systems,** the very low temperatures used allow for **even lower investment costs** (less pipe insulation required) and for the **flow temperature to be varied per building.** In very low temperature district heating, each building uses an individual water source heat pump to heat the water provided by the network to the flow temperature required in the building. Although this increases costs compared to using a centralised heat pump, it has the advantage that each building can adapt the flow temperature exactly to its needs, and distribution losses are low. By contrast, in district heating systems that use centralised heat production, the flow temperature is determined by the building with the highest temperature and pressure demands. A combination of centralised and individual heat production can also be used, for example, by feeding geothermal heat and excess heat into the network, which is then heated further using the heat pump present in each building.

[1] It should be noted however that when the collectors are installed in a real heat supply system, the flow temperatures will not be constant but will vary during the year, so these efficiencies cannot be directly assumed. In addition, the hot water preparation has to be taken into account as well as the heating.

[2] This also applies to the heating pipes inside buildings that connect the heat generator to the heating emitters.

3 The concept of low flow temperature readiness

3.1 Summary

To enable lower flow temperatures in buildings, either the required heat load of the rooms can be reduced through building envelope improvements, or the capacity of the heat emitters can be increased by adding radiators, replacing them with radiators with higher surface or higher efficiency, or by installing systems with high surface areas such as underfloor, wall, or ceiling heating. In cases where buildings have been renovated over time, making them more energy-efficient, emitter sizes might already be sufficient to allow the reduction of flow temperatures.

Balancing efficiency improvements and ease of implementation, low temperature readiness could either be defined by a given flow temperature required to heat a building to comfortable (country-specific) temperatures on the coldest winter day or could be evaluated with a continuous scale from green to red to demonstrate that the lower the flow temperature that can be achieved, the better.

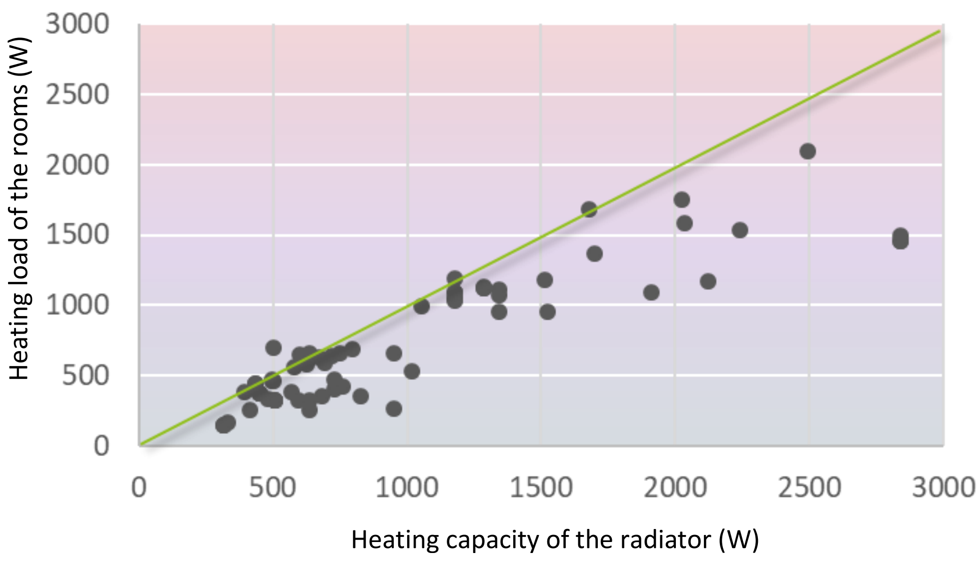
3.2 How to achieve low flow temperatures in buildings

The flow temperature of a heating system depends on two variables:

- **The heat load of the building**. This is the power required to keep the building warm on the coldest day of the year. It depends on the area and the insulation and airtightness of the outside surface of the building (the envelope). The better the energy performance of the envelope of the building, the better an existing radiator or other heat emitter will be able to cover its needs. When for instance a wall is insulated or a window exchanged in a building, the required heat load goes down and lower temperatures are sufficient to supply the room with heat.
- **The capacity of the radiators**. This is the amount of heat that the radiators or panel heaters can deliver to the room, and for a given flow temperature it depends on the active surface of the emitter. It can also be increased by other means, e. g., through fans that increase the heat transfer from the emitter to the room.

Figure 5 shows the heating load and heating capacity for the rooms of an apartment building (ifeu, 2021). In an ideal building, all radiators would have an output corresponding exactly to the heating load of the room (in the diagram this would be shown as a dot lying on the green line). However, in practice, radiators are often oversized (in which cases the dot lies below the line in the diagram), meaning that they could also operate well with lower flow temperatures. Radiators that are slightly undersized can act as a bottleneck, determining the temperature requirements for the entire system.

Figure 5: Heating load of the rooms versus heating capacity of the radiators in a multi-family house (ifeu, 2021)



Assuming that the temperatures of the heating system are set correctly (in many buildings the heating systems incorrectly operate on too high temperatures that could be reduced without compromises regarding comfort), there are two main approaches to reduce the flow temperature:

- Reduce the required heat load of the building by improving the energy performance of the building envelope through e.g., insulation, window replacement, and airtightness.
- Increase the capacity of the heat emitters by adding radiators, replacing them with radiators with higher surface or better efficiency, or by installing systems with high surface areas such as underfloor, wall, or ceiling heating.[1]

The flow temperature strongly depends on the conditions of the specific building. The decisive factors are whether the installed heating surfaces are over- or under-dimensioned, and the state of modernisation of the envelope. In general, in apartments external wall insulation is of high importance for LT readiness (as a single apartment is surrounded by other heated apartments), while in single-family houses other insulation measures such as ceiling, basement, and roof insulation also play key roles.

It is not usually obvious whether an existing building is LT ready or what measures would be required to make it so. There are two possible approaches to take:

1. A first approach is to measure the actual flow and return temperatures on a cold winter day. This establishes whether the house would also manage with a low flow temperature on such a day and still be comfortable.
2. The second, more precise approach would be to calculate the required flow temperature with a heat load calculation for each room. This can identify rooms where the radiator/emitter size needs to be adjusted.

[1] Underfloor heating brings many advantages, such as greater living comfort, but also disadvantages because the renovation effort is fairly high and there are restrictions because of the need to lift and replace floor finishes. This could result in the room volume becoming smaller, the door height having to be changed, the door thresholds having to be adjusted, fitted furniture (e.g. kitchen) needing to be adjusted, and water and wastewater connections no longer fitting. Wall heating also has some restraints with respect to the usability of the wall.

3.3 Considerations that may limit the reduction of flow temperatures

In addition to heat load and emitter capacity, there are other factors that can limit the potential for lowering flow temperatures:

Comfort. If the flow temperature in the heating system of a building is lowered, the maximum heat output of the radiators decreases. This means that the time needed for the building to heat up increases. Heating schedules may therefore need to be changed from periodic heating at higher temperatures (for example to heat up the building in the morning and evening) to longer periods or constant heating at lower temperatures. While occupying buildings that are heated to a more constant temperature can be more comfortable and beneficial to health, behavioural adjustments are needed. A heating system that takes longer to warm up rooms could lower comfort for some building users.

Domestic hot water. Even though domestic hot water is only a small part of a household's heating needs (Eurostat, 2023), domestic hot water production can influence the required flow temperatures, particularly in district heating systems. Hot water must be provided at the same temperature all year round. For space heating, in contrast, relatively low temperatures in the heating circuit are sufficient to keep a building warm during spring and autumn – the flow temperature required in the heating system can be below the temperature required for domestic hot water. In district heating systems that also provide domestic hot water, this could limit temperature reductions to the minimum temperature necessary for the domestic hot water (unless adaptations are made such as an electric water heater).

Legionella is a bacterium that multiplies in lukewarm water and can become a health risk when inhaled. Many countries therefore have regulations in place to reduce this risk. For example, in Germany the outlet of large hot water tanks (common in apartment buildings) must be at least 60°C.[1] As a result, the heat generator must provide temperatures of at least 65°C. If the individual or district heating system does not have specific measures in place to ensure adherence to the required legionella alleviation – for example, an automated heating cycle to temperatures that kill legionella or membrane filters to eliminate legionella – this limits flow temperature reductions in domestic hot water.

The legionella problem does not occur if the domestic hot water is produced in stations within individual apartments using instantaneous water heaters. With this method, the comfort requirements for domestic hot water can be met with flow temperatures between 50°C and 55°C without violating legionella prevention regulations.

In single family houses and multi-family homes with individual hot water systems, the hot water pipes are shorter than in multi-family homes with communal hot water systems, so the risk of legionella multiplication is significantly lower. Accordingly, both the temperature requirements and the control regulations are significantly lower.

Existing pipe diameters. The maximum heat output that can be transported through pipes depends both on the diameter of the pipes (and the maximum flow rate they allow) and on the flow and return temperatures. The higher the difference between the flow and return temperatures, the more heat can be supplied. If the flow temperature is lowered, the return temperature will likely not decrease to the same extent. Consequently, the difference between the flow and return temperatures decreases. The heat capacity that can still be transported at this temperature difference may then no longer be adequate to sufficiently heat the connected radiator or building with the installed pipe diameter.

[1] In German multi-family houses, for instance, the temperature of the water fed into the circulation line must never drop below 60°C and the entire contents of the hot water tank must be heated at least once per day to a temperature of at least 60°C.

Often, both the heating pipes inside the buildings and the district heating pipes in the streets are oversized. A study shows that the diameters of 80% of the district heating pipes in Switzerland are larger than necessary (Nussbaumer et al., 2017). The volume flow through the pipes can be increased to compensate for the lower temperatures. However, this leads to an increase in the energy consumption of the pumps because the flow resistance increases with flow velocity. In addition, disturbing noise occurs in the pipes at high flow velocities. Maximum flow rates must be checked in each individual case (FIW and ifeu, 2023).

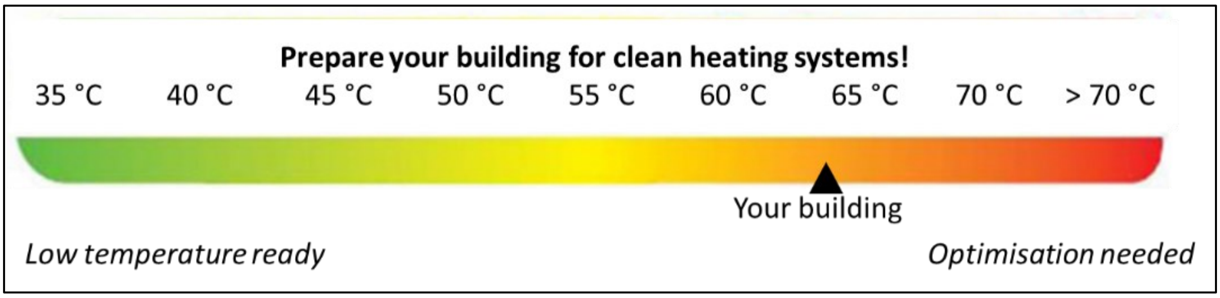
3.4 Operationalising low flow temperature ready

It would be helpful to have a more precise definition of LT readiness; however, defining LT readiness is highly country specific. Among other factors, it depends on the predominant heating technologies (particularly whether heat is delivered through individual or district systems),[1] the nature of the existing building stock, the share of energy for space heating compared to domestic hot water production, as well as energy costs (especially the ratio of electricity to gas/heating oil) and climate.

Different national approaches to defining the standard are also emerging. Some countries may choose to define a maximum flow temperature to present a simple orientation for homeowners (see, for instance, chapter 6.5). Although this approach has the advantage of being easy to communicate, it could be wrongly conceived as a binary approach (heat pumps possible/not possible). As with efficiency requirements (e.g., "seasonal COP > 3.0"), one might mistakenly assume that with an LT ready temperature set at 55°C, a system at 56°C would not allow heat pumps. Other countries may translate the potential for a building to be heated at a low flow temperature into a building standard that takes into consideration the building archetypes and other constraints (see, for instance, Chapter 6.3).

In addition, following the approach **'the lower the flow temperature, the better'**, a continuous scale for LT readiness could be created – the exact values would need to be defined for each country.

Figure 6: Draft of an LT readiness scale. The numbers are indicative only and need to be adapted to each country. (Source: ifeu)



An 'LT readiness' indicator illustrates the benefits of lowering flow temperatures. It is a useful concept for **preparing buildings** for a change of heating system from conventional boilers to heat pumps or low-temperature district heat. However, it is important to note that:

- LT readiness is **not a black or white decision** for or against heat pumps or low-temperature district heating. It serves instead as a guide, while reflecting the importance of lowering temperatures.
- LT readiness **does not guarantee** an efficient operation of heat pumps and other systems, as this depends on other variables beyond flow temperatures. LT readiness is a necessary condition for efficient heating, but not the only one.

[1] District heating systems usually require higher flow temperatures than can be achieved in buildings with individual heating systems, so temperature standards designed for individual and district systems may be different.

- Beyond LT readiness, a further **reduction in demand** is useful and necessary, e. g., to reduce the strain on the electricity grid and the demand for (renewable and non-renewable) electricity as well as to enable heating to be operated flexibly to optimise the use of abundant renewable generation (Rosenow and Lowes, 2020; Yule, Bennett and Sunderland, 2022).
- To make a building fit for renewable heating, there are other aspects which need to be considered as well as the flow temperature. For instance, it might be necessary to check the potential for installing a heat pump.

4 Case study I: Achieving low flow temperatures in German buildings

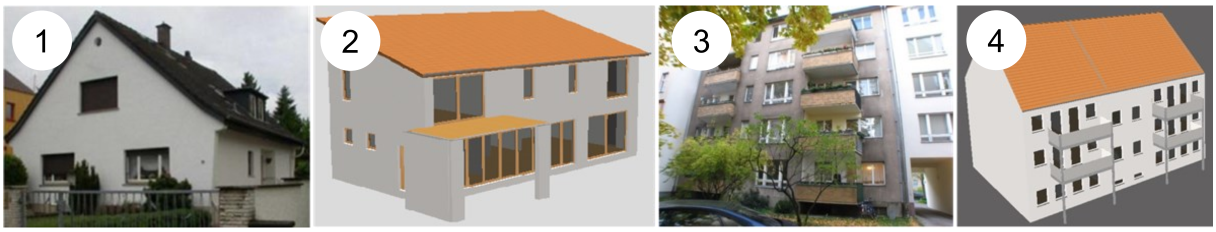
4.1 Summary

Modelling based on representative German building types allows to develop a ‘feeling’ for the temperature reductions that can be achieved by renovation measures and radiator upgrades. The analysis shows that LT readiness is achievable for all buildings, sometimes easily and sometimes with more effort required. The calculations also show that buildings must be investigated individually, because the many potential combinations of efficiency, building layout, radiator/emitter structure and user patterns can lead to a range of different outcomes.

4.2 A modelling approach based on the German housing stock

To gain insight into how buildings can be made LT ready, this case study looks at modelling carried out for four ‘real’ buildings (two single-family and two multi-family homes) (Pehnt et al., 2022). The four archetypes (Figure 7) represent typical German buildings. The model looks at the effects of envelope insulation measures and adaptations to the heat distribution system (pipes/emitters) on the flow temperature of the heating system.

Figure 7: Four buildings that are modelled to quantify LT ready measures (two single-family houses and two multi-family houses). Figure sources: Building 1: IWU, 2015; Building 2: EEI/ifeu; Building 3: ifeu; Building 4: EEI/ifeu.



Building 1: This single-family house was built in 1978 and has not been modernised since. An oil boiler provides space heating via panel radiators, and hot water. This building type represents about 6% of the living area in Germany.

Building 2: This single-family house was built in 1995. The building has an insulated monopitch roof and plastered exterior walls. The south-facing façade is extensively glazed. A condensing gas boiler provides space heating via panel radiators, and hot water. This building type represents about 4% of the living area in Germany.

Building 3: This multi-family residence was built in 1955. Heating is provided by a centralised (for all apartments) constant-temperature boiler using oil. Domestic hot water is heated in each apartment using electric water heaters. The burner in the boiler has been replaced once. This building type represents about 4% of the living area in Germany.

Building 4: This multi-family residence was built in 1995. It is a free-standing building with windows and door openings to the east and west. A gas condensing boiler provides space heating and domestic hot water. This building type represents about 3% of the living area in Germany.

For the model calculations, the building envelope of each building is renovated step by step and the heat distribution measured to determine the effects on the flow temperature. The energy demand is also calculated to show the impact of LT readiness.

4.2.1 Example: Making a single-family house low temperature ready

For each building, four envelope insulation measures are defined: insulation of the exterior wall, replacement of the windows, basement ceiling insulation, and insulation of the top floor ceiling (loft insulation). Then the effects on the heating demand of the building, the heating load of the room, and the required flow temperature level on cold winter days (-10°C) of the existing radiators are calculated. The individual envelope insulation measures are combined in different ways. All measures are calculated using two different insulation standards: 1) the U-values of the building components corresponding to the values required in the national German building code ('Building code quality'); and 2) the higher requirements of the financial support scheme 'Bundesförderung für effiziente Gebäude' (Federal Efficient Buildings Programme), e.g., an external wall U-value of 0.2 W/m^2K, which represents a 'deep renovation quality'[1] (Pehnt et al., 2022).

Based on these calculations, a package of insulation measures and upgrades to the heating distribution (floor/wall heating is excluded) that would make the building LT ready is then defined.

As an example, let's explore what the journey of Building 1 – a typical German single-family home – towards low flow heating temperatures could look like (Figure 8).

Figure 8: Building 1 and the installed radiators. Figure sources: Building: IWU, 2015; radiators: ifeu.

Building envelope

Radiators

[1] The two standards correspond to the following example U-values:
German building code: External wall 0.28 $W/(m^2K)$; windows 1.3 $W/(m^2K)$; roof 0.2 $W/(m^2K)$; floor areas against ground 0.35 $W/(m^2K)$. BEG: External wall 0.2 $W/(m^2K)$; windows 0.95 $W/(m^2K)$; roof 0.14 $W/(m^2K)$; floor areas against ground 0.25 $W/(m^2K)$.

Table 1: Effect of efficiency measures and optimised heat distribution on flow temperatures on a cold winter day. Example is based on a single-family house. (ifeu, 2021)

Options	Efficiency level	Wall, windows, doors	Roof, roof windows	Basement	Only wall	No changes to the heating system	Replacing the most critical radiator	Replacing the five most critical radiators
		Renovation packages				Flow temperature [°C]		
Status quo	not renovated					63	59	55
1	Building code quality	x				54	53	48
2			x			59	57	51
3				x		63	58	54
4		x	x			48	47	44
5			x	x		55	54	51
6		x		x		54	53	48
7		x	x	x		47	42	42
8					x	57	54	51
9	Deep renovation quality	x				53	53	47
10			x			58	56	51
11				x		63	58	54
12		x	x			46	45	41
13			x	x		54	54	50
14		x		x		53	53	45
15		x	x	x		45	41	41
16					x	56	54	51

The starting point for the flow temperature is a moderate 70°C. Built in the 1970s, the top floor ceiling inside the building was insulated in 2010. In the basement ceiling there is an old and thin layer of insulation. The radiators are generously dimensioned; a flow temperature of 63°C would be sufficient, but no one has calculated this in detail so far, so the heating runs at 70°C. The façade is no longer in good shape and should be renewed. Making use of this opportunity, a thermal insulation system is applied as part of the façade renovation. Afterwards, hydraulic balancing of the heating system is carried out. A flow temperature of 57°C is now sufficient to heat the home to comfortable levels. Even better insulation according to the deep renovation standard lowers the temperature to 56°C. A combination of the modernisation measures on external walls, windows and doors plus the insulation of the roof lowers the temperature even further to 46-48°C. The greatest effect is achieved by insulating the entire envelope to the deep renovation standard: in this case, the temperature drops to 45°C.

The flow temperature also depends on the size and design of the radiators. Modern radiators emit more heat while sharing similar dimensions and flow temperatures with older radiators. To reduce the flow temperature, old radiators can be replaced with more powerful ones. This requires less investment than improving the building envelope, but it does not reduce the heat demand.

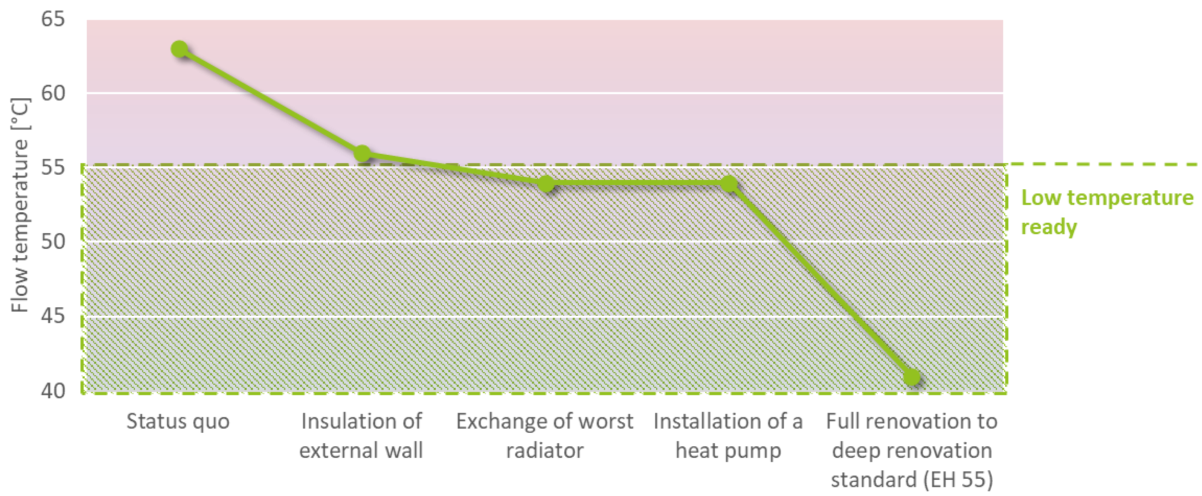
In the example of Building 1, the heat output of five radiators in the 12 rooms is not sufficient to lower the flow temperature. The radiator(s) which requires the highest flow temperature sets the flow temperature for the entire building. All radiators need to be checked to determine if there are ‘critical radiators’ that block lower flow temperatures. In the example, if these five radiators are replaced, a flow temperature of 55°C is sufficient to heat the entire building without insulation measures. The building would then already be LT ready (if we assume 55°C as an adequate LT ready temperature for Germany). If only the most unfavourable radiator (which is in the bathroom) is replaced, the flow temperature can already drop to 59°C. This assumes that 20°C in every room is comfortable – in real life, users could accept lower temperatures in certain rooms (or require higher temperatures), so the flow temperature required would also depend on behaviour.

If the insulation of the external wall and the replacement of the ‘critical’ radiator in the bathroom are combined, the flow temperature can be lowered to 54°C.

At the next opportunity, the household installs a heat pump. For now, the heat pump runs with a seasonal performance factor of 2.8, but already emits 30% less CO_2 than a gas condensing boiler. As the share of renewable electricity on the grid continues to grow, emissions will come down further.

In the remaining years, further insulation measures will be integrated in the natural renovation cycle. The flow temperature can be lowered to 41°C, and the heat pump's seasonal performance factor rises to a very efficient 3.4.

Figure 9: The pathway to a low flow temperature: Example one-family house (ifeu, 2021)



Even after reaching LT readiness, buildings must continue to be improved. LT ready in and of itself is not a climate-neutral state. However, it is the minimum requirement – the entry threshold – to support the swift switch to renewable energy in the building sector that is necessary to stay in line with climate targets. Through future improvements to the buildings, it should become possible to lower the flow temperature even further, so that the renewable heat generators can then be operated optimally.

4.2.2 Modelling results for the other building types

The flow temperature of the single-family house from 1995 (Building 2) is 81°C in its current state (see Table 4 in the Appendix). This means that the calculated flow temperature is about 20°C higher than that of the older Building 1, despite its year of construction and corresponding insulation standard. This is because the radiators in Building 2 are very tightly dimensioned, and there is a 'critical' radiator in the bathroom that blocks the possibility of lowering the flow temperature.

By insulating the exterior wall to the deep renovation standard, the flow temperature is reduced by 10°C to 71°C. With further insulation measures (deep renovation standard), the temperature falls to 63°C. Finally, by replacing five radiators and the 'critical' radiator in the bathroom, the flow temperature can be reduced to 53°C.

In the multi-family houses (Buildings 3 and 4), there are around 70 radiators of different designs, mostly from the year of construction. Usually, they are over-dimensioned or under-dimensioned. With so many radiators across different apartments, the least favourable radiator is more difficult to identify. In Building 3, the calculated flow temperature is 79°C – and is probably even higher when measured, because the system has not yet been hydraulically balanced and the heating curve has not been adjusted for a long time. Building 4 also has a high flow temperature of 76°C.

In both multi-family buildings, the external wall represents the largest part of the envelope area, so that insulation of the external wall reduces the temperature significantly to around 60°C (deep renovation standard). Insulating the roof in the multi-family houses reduces the flow temperature by only a few degrees.

If 30% of the radiators in Building 3 are replaced in addition to the external wall being insulated, the building reaches a flow temperature of 54°C and is thus LT ready. For Building 4 to become LT ready, it must be fully insulated and one-third of its radiators must be replaced. The flow temperature then reaches 55°C.

Overall, the modelling shows that the buildings must be investigated individually, because the combination of efficiency, shape of the building, radiators/emitter structure and use patterns can lead to a wide variety of potential results.

5 Case study II: A city goes 'low flow temperature' for district heating

5.1 Summary

Steinheim is a German town that wants to phase out oil and gas for heating. To do this, decision-makers have opted to expand the existing small district heating system and modify it to deliver heat at low flow temperatures. Reducing temperatures and adjusting connected buildings as required will enable the town to integrate heat from clean sources and achieve huge efficiency gains across the system. Steinheim's experience can be seen as a case study for communities across Germany and Europe.

Given its relatively low urban density, and thus lower heat density, high efficiency and low flow temperatures are essential to ensure the heat delivered to the buildings remains affordable. Initially the system will run at 64°C, and it will drop over time to 58°C. Compared to conventional district heating systems, which run at 90°C, the low temperatures reduce heat losses by 30%, increase the efficiency and yield of the solar collectors through a higher usable temperature difference by 18%, and reduce the electricity demand of the heat pump by 37%. The system will be digitised using smart meters to gradually optimise the efficiency of the distribution network and buildings. In the future, seasonal thermal energy storage will be added to the system, further increasing its efficiency and reducing dependency on biomass and gas for fuel.

To ensure all connected buildings are 'low flow ready,' energy audits including heat load calculations will be performed. Where relevant, the heating surface (radiators) will be increased and/or building envelope improvements such as insulation and airtightness will be undertaken.

5.2 Steinheim on the way to low flow temperature

Steinheim an der Murr is a small town on the edge of the Stuttgart metropolitan region in Germany. It is not only home to the *Homo steinheimensis*, one of the oldest prehistoric skulls found in Europe, but also to 12,000 current inhabitants. Winegrowing and service industries are the main local economic activities. Steinheim is a town like many others in Germany and across Europe more widely: a small, older village centre surrounded by spacious terraced housing settlements, single-family houses, and a few larger multi-family houses.

Currently, buildings in Steinheim are mainly heated with oil and gas boilers, while a small district heating system using woodchip boilers supplies a school and some surrounding buildings. If you were to look down on Steinheim from above, this small rural town with relatively low building and energy density would not strike you as an area suitable for district heating.

But the energy managers from the Ludwigsburg Energy Agency – Anselm Lauber, Raphael Gruseck, and Florian Kamp – had a different view. Their basic idea: a municipal heating supply company would offer building owners heat from a district heating system, delivered at a low temperature but providing comfortable indoor environments, at favourable rates, and with high shares of renewables.

Three reasons were decisive in gaining support for this approach:

Climate protection requirements and the Russian war in Ukraine both meant that a new heat supply was urgently needed. The climate protection goals of the state of Baden-Württemberg and the federal government, as well as the constantly rising price of CO_2 (until 2026, there is a defined CO_2 price path leading to annually increasing CO_2 prices) were the immediate triggers to plan for a new decarbonised heat supply in Steinheim. The enormous energy price spikes of 2022 confirmed that this was the right approach.

Only with low flow temperatures can losses be kept low and clean heat generators be used. The potential for solid biomass and biogas is limited; and Steinheim has no attractive waste heat or geothermal options. The choice of clean heat source therefore falls on heat pumps and solar thermal energy. For district heating to be economically feasible in a town with comparatively low heat density such as Steinheim, and for heat pumps and solar thermal energy to be operated with high efficiency, low flow temperatures are crucial.

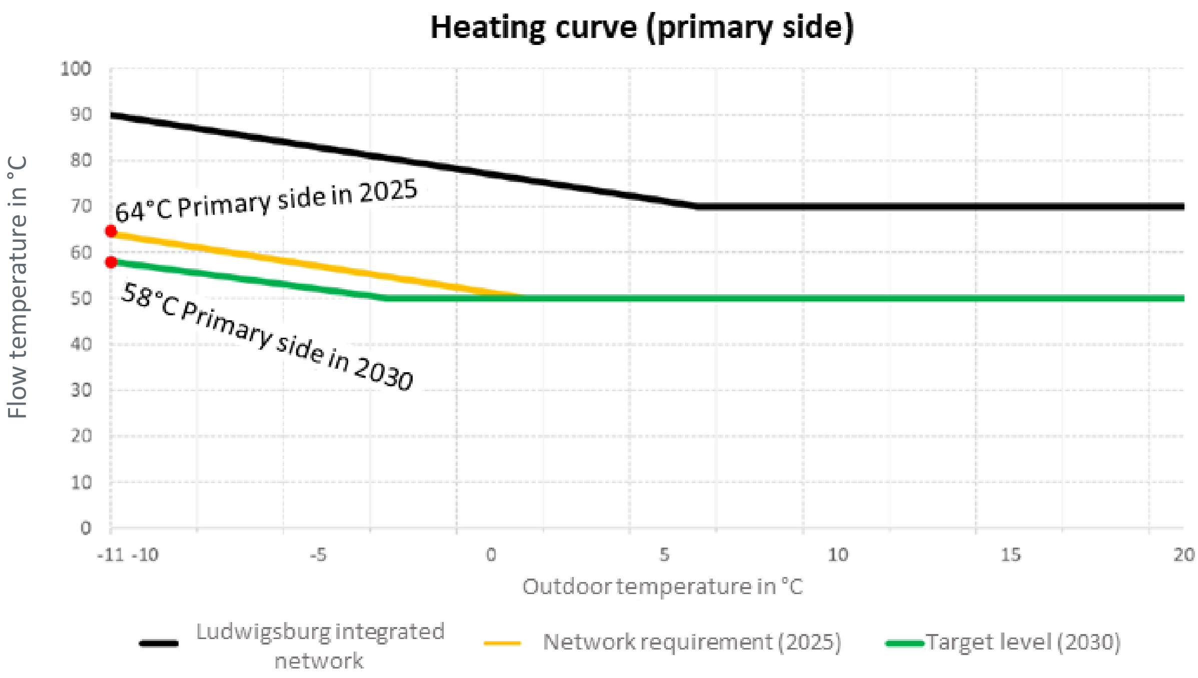
The required speed of the transition to clean heat. By 2045, all buildings in Steinheim must be supplied with renewable and climate-neutral heat in accordance with federal law. The 65% renewable energy rule, which will come into force in Germany in 2024 (see Chapter 6.5), requires that all new heating systems use 65% renewable energy. This could involve, for example, a heat pump or a wood pellet heating system. The rule creates a sense of urgency in Steinheim, and also raises questions: Should each building owner make an individual decision? Should the 400 buildings in the heat network planning area be supplied with individual heat pumps? For most of the row-houses in Steinheim, this is not spatially possible, as the noise and distance regulations do not allow it. On the other hand, a collective heat supply takes the burden away from the residents and allows all buildings to switch to clean heat in one go.

The planned low-temperature district heating in Steinheim could become a flagship project in Germany for a new approach to the heat transition: combining temperature reduction in individual buildings with district heating supplied by heat pumps.

Figure 10: The Homo Steinheimensis and a view of Steinheim from the community centre (Source: ifeu)

The idea for the Steinheim heating plan is to install a new district heating system that is initially operated with a maximum flow temperature of 64°C. This temperature will then be gradually reduced to 58°C. The planned temperature reduction will be known to building owners from the beginning, so they can take steps as needed to prepare their building for low flow temperatures.

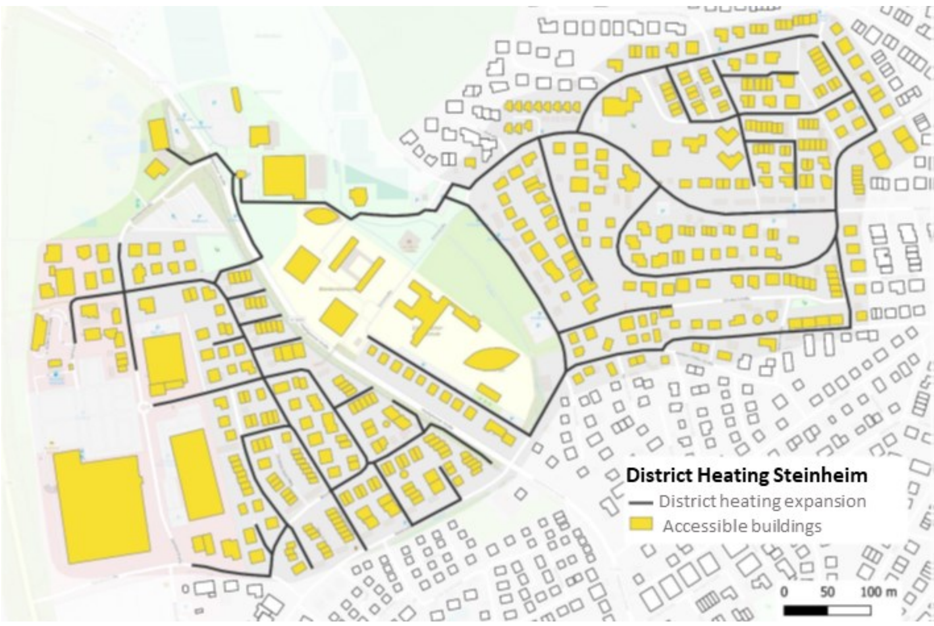
Figure 11: Flow temperature of Steinheim district heat network (primary side at the house energy transfer station) as a function of the outdoor temperature (Source: Wärmenetz Steinheim GmbH)



5.2.1 The building stock in Steinheim

The planned target area of the new district heating network comprises around 400 buildings. The new system will supply around 4.5GWh of heat per year over a pipe length of 5 kilometres, assuming a connection rate of 50%. The corresponding heat density of 900kWh/m line is low by urban standards. The fabric of the buildings is average. No precise data is available on the renovation rate.

Figure 12: District heat for Steinheim: potentially connected buildings (Source: Wärmenetz Steinheim GmbH)



There are a significant number of row houses in the target area, which are not far enough from their neighbours to (legally) allow the use of heat pumps. Multi-family houses with up to nine floors are also located in the supply area.

Figure 13: Buildings in Steinheim (Source: ifeu)

A comparatively high proportion of buildings have **single-pipe heating systems**. Single-pipe heating systems are much more difficult to convert to low temperatures than two-pipe heating systems.[1] An energy audit of each building is therefore needed to determine the measures required for conversion to low flow temperatures.

There are a **wide variety of heating systems** in operation in Steinheim, including less common systems such as 'bathtub heaters', baseboard heaters and radiant band heaters. This makes it more complicated to assess, in the energy audit, whether measures are required to make the buildings in question suitable for low temperatures – and if so, which ones.

Idea: Development of 'communicating radiators' that do not open their valves simultaneously, but alternately. This would make it easier to implement low temperature **concepts** in single-pipe heating systems.

Regarding **domestic hot water supply**, a distinction must be made between single-family and multi-family houses. In single-family houses, a so-called freshwater station that heats water using heat from the network or storage is usually sufficient to avoid problems with legionella. If necessary, additional electric water heaters can be installed at the outlets to ensure direct availability of hot water.

In multi-family houses with central domestic hot water supply, the water in the tank and pipes must be regularly heated to over 60°C to avoid legionella growth. Alternatively, membrane filters can be used. In Steinheim, domestic hot water will be supplied either through decentralised booster heat pumps in each building, direct electric reheating at the tap, or floor-by-floor freshwater stations (the latter mainly in buildings that previously had gas flow heaters).

Idea: Development of a home station with a 'booster button': the building owners can activate a booster button – via an app or at the touch of a button – which briefly raises the heating temperature electrically in very cold temperatures. Since it involves actively having to operate the booster button, this increase is targeted and deliberate.

5.2.2 Heat sources for the Steinheim district heating system

The Steinheim district heating system will use a mix of heat sources to optimise emissions reductions and economic viability:

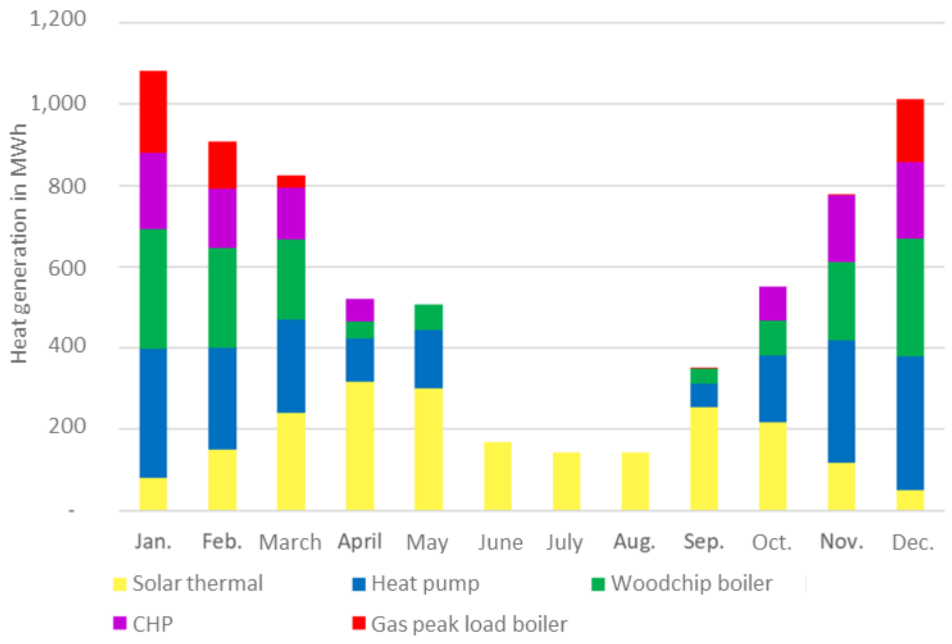
- **Solar thermal:** Even though space is scarce in Steinheim, it was possible to identify suitable areas for a solar thermal system: the roof of the car park of a public pool, and open spaces close to the town that are not suitable for agriculture.
- **Heat pump:** A large air-to-water heat pump will be at the core of the heat supply.
- **Solid biomass:** The existing woodchip boilers will continue to operate but will be retrofitted with filters to further reduce pollutant emissions, particularly particle emissions.

[1] Single-pipe heating systems connect all radiators, in line, to the same pipe, which acts as both flow and return. In a two-pipe system, radiators are connected to both a supply pipe and a separate return pipe. In a one-pipe system heat output can reduce in radiators further down the line.

- **Biomethane**: A biomethane combined heat and power (CHP) unit will supplement the heat production. However, in accordance with regulations (Renewable Energy Act), it will only be used flexibly, running for a maximum of 15% of the year.
- A **gas boiler** serves as a peak-load and reserve boiler.
- In the future, the use of a **seasonal water storage tank** is planned, connected to a possible expansion of the solar thermal system.

Figure 14 shows the projected contribution of each source to the overall heat production. The project aims for a solar thermal share of over 30%. The heat pump has a projected share of around 27%, and is not used in the summer. The construction of seasonal storage could further increase the share of solar thermal energy by making summer surpluses usable in winter. To fully replace the gas-fired CHP, the heat pump could also be made larger.

Figure 14: Projected contributions of energy carriers to the heat supply (Source: Wärmenetz Steinheim GmbH)

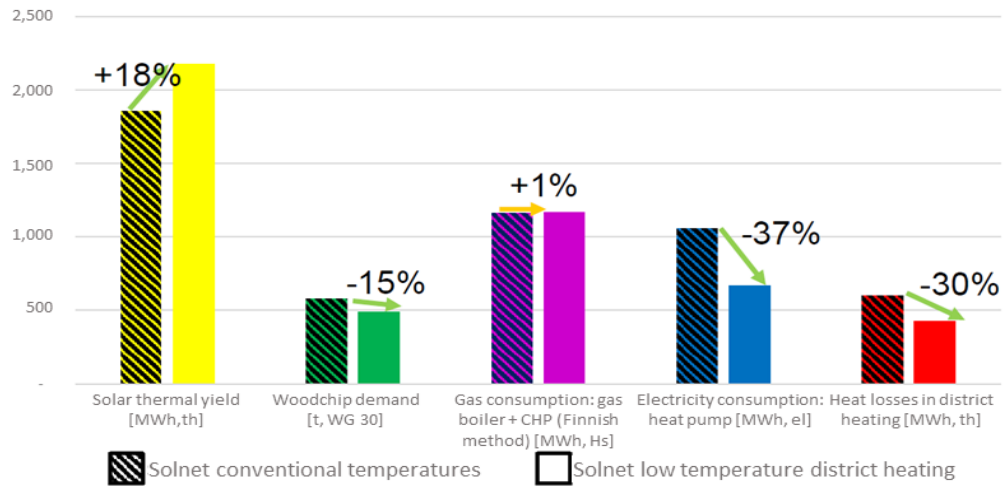


5.2.3 Advantages of flow temperature reduction in district heating

Compared to a conventional district heating system with a flow temperature of 90°C, the low flow temperature system in Steinheim has several advantages (see Figure 15):

- The **grid losses** are reduced by 30% due to the lower temperature.
- The **solar collector yield** increases by 18% as the usable temperature difference is increased.
- The **heat pump** can be operated using 37% less electricity, as the **coefficient of performance** is significantly higher due to the lower temperature range. The efficiency of the woodchip boiler can also be increased.

Figure 15: Calculated benefits of a reduction to low flow temperature district heating (Source: Wärmenetz Steinheim GmbH)



5.2.4 Cost of connection

It is expected that it will typically cost around €13,500 to connect a single-family house to the district heating system. This includes costs of around €12,000 for the actual house connection, and €1,500 for the connection of the house energy transfer station to the heating circuit system and the domestic hot water supply. Depending on the local circumstances, e. g. the hydraulic balancing, and, if necessary, the removal of the old heating system and the oil tank, the latter cost can rise to max. €6,000. For a multi-family building of eight apartments, costs will be around €35,000. This does not include the costs of additional improvements to the individual heating system, such as replacing radiators. A 30% subsidy for every building owner is available from the federal government. In the future, the federal BEW programme[1] will offer additional support for investments in new district heating systems and for building connections.

It is expected that end users will pay less for their heat through the district heating system than they would by getting it through an individual gas or oil boiler. This is mainly due to the significant price increases for oil and gas in 2021-2022, and which are expected to remain high in the future due to carbon pricing. In addition, when using the district heating system, the costs for chimney-sweeping, tank-cleaning, and maintenance for individual heating systems are almost eliminated.

Table 2: Operating costs for supplying a single-family house (heat consumption 12,800 kWh p.a.)

		District heating	Gas condensing boiler	Oil condensing boiler
Efficiency of transfer station/ heat generator		*100%*	*92.5%*	*85.3%*
Fuel/heat price	*Ct/kWh*	*9.90*	*12*	*14*
Fuel, annual	€ p.a.	1,270	1,660	2,100
Basic price/maintenance	€ p.a.	285	120	200
Service price (DH) or chimney sweep	€ p.a.	95*	70	70
Electricity	€ p.a.	30	120	120
Total	€ p.a.	**1,680**	**1,970**	**2,490**

[1] https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html

5.3 Enabling conditions for the clean heat transition in Steinheim and lessons learned

There are several useful lessons which can be drawn from the Steinheim case study for communities and policymakers looking to drive the development of clean temperature district heating.

5.3.1 Benefits of a non-profit district heating owner

The most important requirement for a transformation to a district heating-based system is that a **reliable, professional player** builds and operates the heating network.

Municipal utilities can be well placed to take up this role. In Steinheim, a somewhat different approach has been taken with the foundation of Wärmenetz Steinheim GmbH, a company owned 100% by the town of Steinheim which owns the district heating, manages the heat supply contracts, and commissions an experienced operator to run and maintain the heating network.

The big advantage of this set-up is that the heating network company **does not have to make a profit**. Therefore, it can offer attractive heat prices. Moreover, it can adopt a different economic perspective: as a rule, companies with a profit-oriented perspective make decisions based on marginal cost considerations. For example, the question of whether to insulate the heat pipes with very good or medium insulation is decided by a profitability calculation, namely whether the additional investment for very good compared to medium insulation will be amortised in a comparatively short time (e.g., 10 years). Neither the focus on marginal costs nor the short consideration period (the district heating system has a lifetime of more than 50 years) is helpful for long-term investments.

Idea: Nationwide start-up funding for the establishment of non-profit district heating companies that are structured as cooperatives or limited liability companies and can offer end customers an attractive heating price.

The heating network operator takes on another important role too. By installing intelligent metering technology in the heat transfer station, the operator can highlight optimisation potential for customers in real time, e.g., if excessive return temperatures are detected. In this way, the efficiency of the district heating and the buildings can be **continuously optimised**.

In the **heat supply contracts**, the temperatures offered are fixed over time. This gives the customers a long-term perspective on how they need to develop their building to ensure comfort and satisfy demand with the temperature supply.

5.3.2 Importance of energy audits for every building

In Steinheim, every building receives a consultation during which its low-temperature suitability is checked. This service is organised and carried out by the local energy agency. The procedure takes place in stages:

First step: Initial information. The building owners receive a letter in which they are made aware of the project. A municipal-wide event informs residents about the basic concept.

Second step: Each individual building is the subject of a **detailed on-site consultation** on the potential for lowering the temperature. Steps to increase the heating surface and to improve efficiency – from low-investment measures to full renovations – are considered. Experience shows that many recipients of advice initially focus on low-investment improvements to radiators. This is also due to the above-average proportion of older building owners in Steinheim, who may be reluctant to make long-term investments. Only around 10% of the building owners are also planning measures to improve the building envelope.

Figure 16: Screenshot of the room-by-room heating load calculation containing a detailed analysis of all of a building’s emitters (translated to English) (Source: Wärmenetz Steinheim GmbH)

Variant: District heating connection with radiator replacement

The following is an overview of which radiators are recommended to be replaced in order to supply the residential units with the appropriate heat according to the standard. The dimensions of the radiator have been adjusted so that it meets the underlying heating load of the room. For implementation, it must be checked in each individual case whether the conditions in the room are suitable. This may result in a deviation from the dimensions given here. These serve solely to illustrate what is to be expected.

Legend		
	100	Radiator output too low
	100	Size of radiators changed
	-100	Heating load covered by adjoining room

			Existing building	Radiator exchange				District heating connection with enlarged radiators		
Flow temperature / Return temperature [°C]								55/35		
Floor	**Apartment type**	**Room**	**Heating load [W]**	**Radiator type**	**Number of elements / length [mm]**	**Height [mm]**	**Type / Depth [mm]**	**Radiator output [W]**	**Radiator replaced?**	**Standard output of radiator [W]**
3	I	Storage	-350						No	
3	I	Bathroom	483	Plate	1.100	530	Typ 22	489	Yes	1.675
3	I	Hall	-942						No	
3	I	Child	505	Plate	1.000	600	Typ 21	530	Yes	1.398
3	I	Kitchen	464						No	
3	I	Bedroom	1.775	Plate	1.700	610	Typ 33	1.570	Yes	4.144
3	I	WC	122						No	
3	I	Living/dining	1.048	Plate	1.200	600	Typ 33	1.094	Yes	2.887
3	II	Storage	-245						No	
3	II	Bathroom	514	Plate	750	600	Typ 33	526	Yes	1.804
3	II	Hall	-661						No	
3	II	Child	604	Plate	1.000	600	Typ 22	637	No	
3	II	Kitchen	479						No	
3	II	Bedroom	1.609	Plate	1.800	600	Typ 33	1.641	Yes	4.331
3	II	WC	178						No	
3	II	Living/dining	2.511	Plate	800	600	Typ 33	2.552	Yes	1.925
3	II	Living/dining	0	Plate	2.000	600	Typ 33		Yes	4.812
5	III	Storage	-216						No	
5	III	Bathroom	1.247	Plate	1.400	900	Typ 33	1.368	Yes	4.690
5	III	Hall	-570						No	
5	III	Hall	-617						No	
5	III	Child	584	Plate	1.000	600	Typ 22	637	Yes	1.682
5	III	Child 2	486	Rib	20	600	160	560	No	
5	III	Kitchen	479						No	

Third step: The energy agency also offers interested owners the option to develop a **renovation roadmap** for their building. The renovation roadmap shows the short-term measures needed to make the building LT ready, while also outlining further measures that need to be taken to reach climate neutrality by 2045. This also has benefits if the owners apply for government support: measures taken as part of a renovation roadmap can receive a 5% bonus on their funding.

Idea: Further development of the renovation roadmap to make buildings LT ready by means of room-by-room heating load calculation.

5.3.3 Communication is vital to long-term heat planning

In the Steinheim case study it was found to be important to start communication with the building owners early to synchronize the planning of the district heat and the renovations of the buildings. It was found that many building owners plan renovation measures only around two years in advance, while the planning horizon of the district heating extends many decades into the future.

Moreover, building owners often only wanted to implement the least expensive measures to lower the flow temperature (i.e., replacing radiators). However, in the longer term, these measures are insufficient and could even prove unnecessary. If the buildings are insulated, the existing radiators may be able to be kept. With lower heat demand, the district heating system will be able to supply more buildings in the area with clean heat. It therefore makes sense to stimulate insulation measures from the beginning of the planning process. While it is desirable to avoid an obligation to renovate as a prerequisite for connection to the district heating system, the long-term benefits of insulation measures, their eligibility for subsidies, and the prevention of 'stranded assets' should be emphasised to building owners. The building renovation roadmap was found to be an effective tool to communicate the long planning horizons.

In addition, it was found that secondary, non-technical advantages contributed to the acceptance of the project. For example, the solar thermal plant, which is planned as a roof over the public swimming pool's car park, was very well received by the community because it shades parked cars and prevents them from overheating in summer. While in many cities heat network operators come as 'supplicants', in Steinheim it becomes a privilege to be connected to the district heating.

5.3.4 The national framework should support the transformation

Further general conditions at the federal level are necessary – and have already been implemented in part – to successfully shape the heat transition in Steinheim. The following conditions were already in place in Steinheim and support the implementation of a low-temperature transformation:

- The **long-term perspective** for building owners is clear. According to the Buildings Energy Act, every newly installed heating system must be operated on 65% renewables. This makes it very attractive for customers to connect to the district heating.
- **Financial support:** The development of Steinheim's district heating is funded by two federal funding schemes. Without this support, district heating might have been economically unattractive compared to other options.
- **Availability of planners and energy consultants with know-how.** Planners must have a sound knowledge of both the optimisation of district heating and the adaptation of individual buildings. In Steinheim, trained energy experts are available and have a high level of knowledge in this area. Where such experts are not yet available, training is required.
- **Individual building roadmap** (individueller Sanierungsfahrplan (iSFP)). The LT ready standard should ideally be part of a broader perspective on the modernisation needs of individual buildings. In Germany, individual building roadmaps are available and provide a good framework to address LT readiness. However, in the future, the topic of flow temperatures and heat pump readiness could be introduced more systematically into the iSFP, as is already the case in Steinheim.

Communities across Europe that want to take collective approaches to clean heating can learn from the Steinheim experience, as can area-based heat planners who are considering district heating as a future solution, and managers of existing district heating who must modernise and decarbonise their systems.

The work in Steinheim shows that taking a holistic approach to a district heating system and the buildings connected to it, and focussing on delivering heat at lower flow temperatures, opens up new sources of renewable heat and enables them to be used efficiently. It's a small town with big plans.

6 Policies supporting low-temperature heating in buildings

6.1 Summary

The concept of a low flow temperature ready building is a relatively new one, but it's one that is increasing in visibility. Ensuring buildings can be heated efficiently and cost-effectively at lower temperatures will become increasingly important as countries and regions begin to phase out the use of fossil fuels for heating.

Several policy tools are emerging at the national and EU level that aim to either require heating systems to run on lower temperatures or to improve the building fabric to enable heating at lower temperatures. The design of these policies can inform the next generation of initiatives.

6.2 Types of policy mechanisms to address LT readiness

The concept of 'low flow temperature ready' is relatively new. Nevertheless, several European countries and regions have already put in place policies related, directly or indirectly, to lowering flow temperatures in heating systems and/or working towards making buildings low temperature ready. Policy measures used to promote lower flow temperatures include:

- Standards for heating system installation
- Renovation standards for existing buildings
- Preconditions for financial support of renewable heat
- Inspections, audits, and energy performance assessments
- Product regulation
- Public information and engagement campaigns.

Table 3 below presents an overview of policy mechanisms currently in use that can be used to drive low flow temperatures in heating and low flow temperature readiness in buildings. The later sections of this chapter present in more detail the policies in place in the Netherlands, the United Kingdom (UK), and Germany.

In addition to the national approaches, the recast Energy Performance of Buildings Directive (EPBD) proposes to introduce requirements for Member States to integrate low temperature readiness into building assessment and inspection regimes (European Commission, 2021). The relevant proposals include:

- Requirements for the recommendations in national Energy Performance Certificate (EPC) frameworks to include an assessment of whether the heating or air-conditioning system can be adapted to operate at more efficient temperature settings, such as by using low temperature emitters for water-based heating systems, including the required design of thermal power output and temperature/flow requirements (Article 16).
- Inspections required for large heating installations to include an assessment of the feasibility of the system to operate under different and more efficient temperature settings (Article 20).

Table 3: Overview of national policy tools promoting low temperature heating and low temperature readiness

Building codes	**Example**
Building codes can be used to require the readiness of new buildings to operate heating at low flow temperatures, and/or new or renovated heating systems in existing buildings to be designed to run on low temperatures.	In the UK, newly installed or fully replaced wet heating systems should be designed for a maximum flow temperature of 55°C (see section 6.4).
Renovation standards or regulations	**Example**
Minimum energy performance standards require existing buildings to meet a performance standard by a date or trigger point in their lifecycle. The proposal for the recast EPBD includes such standards. Although these proposals (and existing national examples) do not specifically target low temperature ready buildings, one Member State, the Netherlands, has already designed such a standard.	The Dutch National Insulation Standard introduced in 2021 is an energy demand standard designed to ready buildings for heating provided at low flow temperatures (see section 6.3).
Funding programmes: requirement for access to funding	**Example**
Low temperature readiness can be required as a condition for accessing funding for heating systems. An alternative is to make low temperature readiness a quality standard for renovations and renovation funding. This ensures that no sunk costs occur when renovating buildings with subsequent exchanges of the heating system.	Requirements for buildings to meet standards related to flow temperatures are included in funding schemes in Austria (Government of Austria, 2022), Luxembourg (Government of Luxemburg, 2022), Flanders (Belgium) (Government of Flanders, 2022), and Germany (see section 6.5).
Energy audits, inspections and Energy Performance Certificates	**Example**
An assessment of low temperature readiness can be included in: • The (mandatory) inspection of chimneys, heating systems, and boilers. A standardised checklist on how to achieve low temperature readiness could be included. • Home energy audits and consultations, renovation passports and renovation advice given to building owners, including through the one-stop shops and (digital) decision-making tools. • Energy Performance Certificates, either as an indicator or in the recommendations.	In Germany the mandatory gas heating inspection also includes information provision and advice on the reduction of flow temperatures (see section 6.5). In the Netherlands, an indicator showing the 'National Insulation Standard' for each building assessed is included in the EPC label (see section 6.3).
Public information, awareness, and engagement campaigns	**Example**
Public awareness and engagement campaigns on the benefits of low flow temperatures can stimulate building users to lower the flow temperature of their boilers where possible. Increased awareness can also encourage building owners to consider measures to improve the low flow temperature readiness of buildings.	Public campaigns and guides on how to reduce the flow temperature have been implemented in several countries by both governments and civil society including the UK (Government of the UK, 2022; Nesta, 2023), The Netherlands (Urgenda, 2022), and Germany (see section 6.5).
Product regulation	**Example**
Include low flow temperatures in product requirements and EU ecodesign regulations.	No examples from countries were found, but this could be done through requirements on measuring devices (e. g. displays showing the flow temperature), requirements on radiator sizing, and installation.

Although the specific policy mix will depend on national conditions, it will likely be most effective to use a combination of ways to promote the use of low flow temperatures in heating systems. In the short term, public information, awareness, and engagement campaigns can increase the sense of urgency among building owners, users, and operators, as well as among heating technicians and energy auditors. This can lead to increased demand for check-ups of heating systems and LT readiness measures.

Integrating the concept of LT readiness in building audits, assessments and recommendations can be a good way of growing capacity among the relevant building professionals and expanding their knowledge of the interactions between building fabric, heating system design and heat source. Linked to this assessment and advice, criteria in funding schemes to ensure new heating systems run efficiently would help make effective use of public funds and reduce the risk of inefficient and expensive installations.

However, care should be taken that these conditions do create unnecessary barriers to the deployment of clean heating systems. For example, in Ireland it was found that grant criteria for heat pumps (based on a heat loss indicator for the building) were overly strict, meaning some installations might not have qualified for funding even though they would have led to energy and greenhouse gas emission savings (Lowes, 2022).

Mandatory standards both in building codes and in performance standards for existing buildings have a key role to play across the whole stock and go hand in hand with national and regional policies aimed at phasing out fossil fuel use in heating. Building codes are particularly effective for new building design and construction. Standards for existing buildings, coupled with monitoring and enforcement mechanisms, can drive LT readiness in all buildings, preparing buildings for a future switch in heating systems, or temperature reductions in the case of district heating. A simple way to do this would be to mandate that all newly fitted boilers and heating systems operate at a specific maximum (low flow) temperature, as is now recommended in the UK.

LT ready standards could also be a useful tool to complement other minimum energy performance standards, such as the standard discussed as part of the EPBD recast. The proposal in the EPBD uses the EPC to define the standard. EPCs are whole-building performance assessments, meaning that all building-level measures – including installing solar photovoltaics or a more efficient heating system – contribute to meeting the standard. This means that, in some cases, homes could meet the standard with minimal energy efficiency improvements (or none in the case of solar PV). A low flow temperature standard, that specifically directs activity to the building envelope and heat distribution system, could then be a useful supplement to drive energy efficiency improvements in the building stock.

6.3 The Netherlands – Home Insulation Standard

As part of its broad set of policies to shift away from natural gas-based heating, the Netherlands introduced a 'Home Insulation Standard' in 2021 (RVO, 2021). This is designed to provide homeowners and inhabitants with an indication of when their home's energy performance is sufficient to be able to switch to sustainable and low(er) temperature heating sources. The standard considers envelope insulation, airtightness, and ventilation, and gives an indication of the net heat demand of the home.

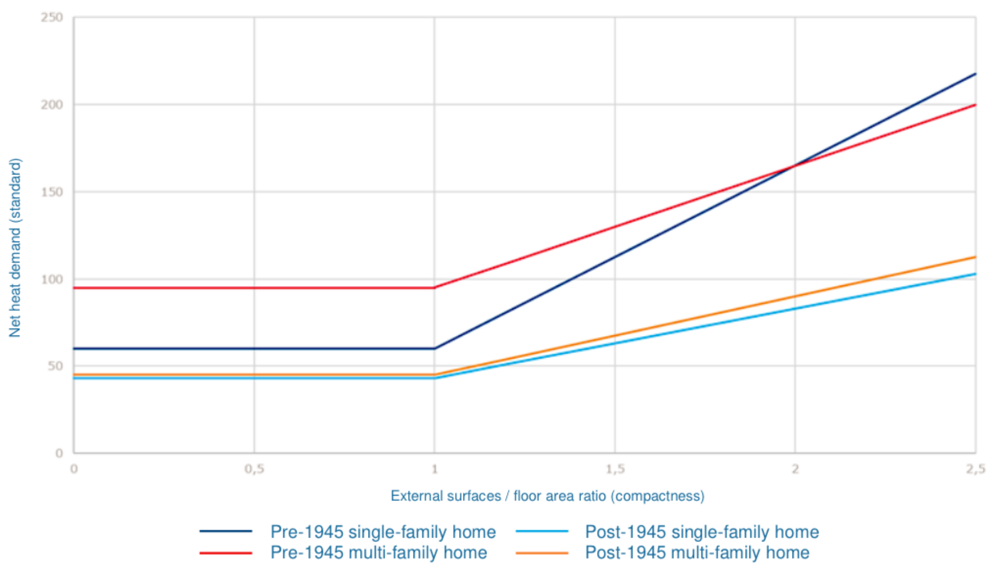
The standard aims to strike a balance between affordability and a lower net heat demand. It is designed so that homes improved to meet it will not have to be insulated again to meet national 2050 emission targets and will be ready for whichever future sustainable heat solution their local authority chooses to employ. This links the standard with the neighbourhood and municipal heat planning approach taken in the Netherlands (Sunderland, 2021). The standard is not currently obligatory, but it serves as a reference for the energy performance level the housing stock should achieve by 2050. The standard is also indicated on all new Energy Performance Certificates.

The Home Insulation Standard is based on the following principles. All measures must:

- Be possible within the existing construction to minimise construction changes to the home
- Maximise usable space within the construction
- Be equivalent to or better than current high-standard renovations undertaken by social housing providers
- Prevent adaptations to the radiators as much as possible
- Be 'future proof': homes built after 1945 should be able to be heated using 50°C to ensure flexibility with regards to the future heating source.

The level of standard that a home needs to achieve varies depending on its age and type, as well as on a measure of 'compactness', i.e., the ratio between its floor surface and its envelope surface (see Figure 17). As guidance for staged renovations, the standard is supplemented with more ambitious target values to achieve for each separate building element (if fully implemented the staged renovation would thus lead to higher energy efficiency levels than the standard). Homes built after 1995 already largely meet the standard when it comes to insulation, but may nevertheless require improved windows, airtightness, and ventilation.

Figure 17: Dutch Home Insulation Standard (reprinted with permission from Sunderland, 2021)



To ensure flexibility in the choice of future heating sources, the levels of the standard are chosen so that they enable heating with low(er) temperatures, but the standard itself does not directly regulate flow temperatures. The lower flow temperatures are made possible by the reduced net heat demand. The assumption is that, with a lower heat demand, the existing radiators in the home will have over-capacity, allowing the flow temperatures to be lowered. It is projected that, of the homes insulated to the standard, only 5% will need significant changes to their radiator systems, and up to 20% minor changes, to lower the flow temperatures.

The expectation is that homes built before 1945 renovated to the standard will achieve an EPC of 'D', which would only allow for a lowering of the flow temperature to 70°C. By contrast, for post-1945 homes, the standard will be comparable to an EPC of A or B, allowing for a lowering of the flow temperature to 50°C in most cases. However, with more significant changes to the radiator systems, flow temperatures could be reduced further. For pre-1945 homes in particular, this will be necessary to make them low flow temperature ready.

6.4 United Kingdom – Building code and Future Homes Standard

In 2021, the UK government changed the building regulations (part L) to include a recommendation for all new heating systems in England and Wales to run on lower flow temperatures (Government of the United Kingdom, 2021). This applies both to new-build homes and to homes undergoing renovation. The obligation is meant to bridge the gap between current standards and the 'Future Homes Standard' for new-build homes, which is expected to be introduced in 2025. This standard is aimed at reducing greenhouse gas emissions from new homes by 75-80% in support of the UK's 2050 net-zero target and will likely include both stringent fabric efficiency standards and the requirement to instal low-carbon heating systems (Government of the United Kingdom, 2019).

The building code directly regulates the maximum flow temperatures of heating systems in homes. Newly installed and/or fully replaced (heating appliance, emitters, and pipework) wet central heating systems in existing buildings need to be sized for a maximum flow temperature of 55°C (down from 80°C in the previous standard). For existing homes where systems cannot be sized to achieve 55°C, the system should be designed for the lowest achievable flow temperature. The low temperature requirements apply only to space heating, not to hot water production.

6.5 Germany – Heating Inspection and Subsidy Schemes

Germany is in the process of introducing a new regulation called 'the 65% renewables rule' (BMWK, 2023). This regulation will require heating systems installed after 2024 to operate with 65% renewable energy input. This will lead to a huge shift from gas and oil boilers to renewable heating systems, especially heat pumps and district heating.

As part of general energy savings efforts and to enable low flow temperatures, many buildings in Germany will need to undergo envelope insulation measures and/or adaptations to their heat emitters. To support this several measures have been implemented or are under discussion.

As part of the emergency response to the energy crisis caused by the Russian war in Ukraine, the 'EnSimiMaV' ordinance was set up. It requires owners of gas boilers to have a boiler check-up and have their heating system optimised, which includes:

- Checking if flow temperatures (hot water and heating) can be reduced
- Checking if hydraulic balancing is needed, whether efficient circulation pumps are used, and to what extent insulation measures on pipes and fittings are needed
- Optimising the operation of the heating system in line with the usage profile and climate
- Informing the building owner or user about further savings measures.

The EnSimiMaV requires owners and operators of heating systems to undertake measures identified through this check-up to reduce the flow temperature. As part of a general revision of the German building code, one of the measures being discussed is to apply the EnSimiMaV to all heating systems that are more than 15 years old.

Another measure is the introduction of LT readiness into Germany's main building efficiency funding scheme, which is known as the 'BEG' (Bundesförderung für effiziente Gebäude). The BEG funds both single renovation measures and deep renovations. From 2023 on, it requires all new funded renovations (except in heritage buildings) to be LT ready.

The BEG defines LT ready as follows: "Buildings are low-temperature-ready if they do not exceed a heating circuit flow temperature of 55°C in the design case and in operation" (BMWK, 2022). This will ensure that buildings are prepared for the installation of heating systems in line with the 65% rule and can be heated comfortably and efficiently with heat pumps and lower-temperature district heating.

In the national discussion on LT ready, a more precise definition was proposed in the context of the building code (ifeu, 2021). It reads:

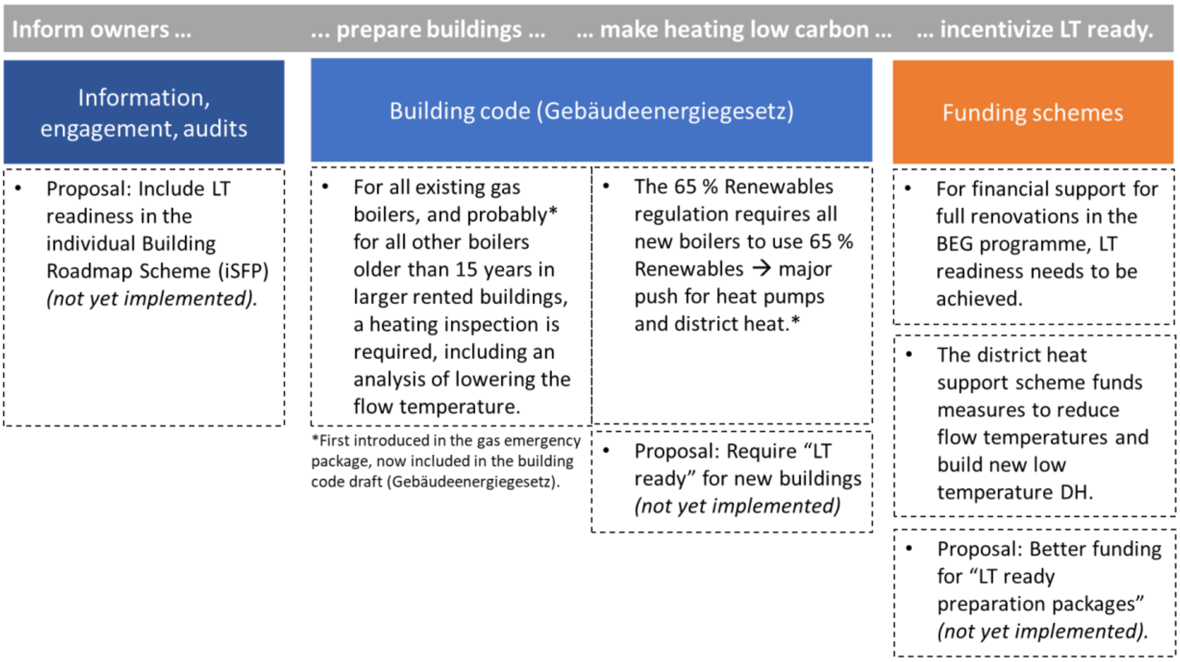
"A building is ready for clean heating systems through low flow temperatures if

1. measures for thermal insulation or heating circuit optimisation have been implemented to such an extent that the room temperature required by the users is guaranteed with a maximum heating water flow temperature of 55°C[1] and
2. the hot water preparation is technically arranged in such a way that it functions at a flow-temperature of 55°C. For hygienic reasons, a further increase in temperature is permissible in circulation pipes if this increase is implemented independently of the central heat generator."

The reasoning behind this definition is that, at maximum temperatures of 55°C, air to water heat pumps achieve a seasonal efficiency of about 2.7, according to the onsite measurements carried out by Fraunhofer ISE (2021). At this SCOP, a heat pump would be competitive with respect to the operating costs at typical gas and electricity prices in Germany. Above 55°C, the efficiency typically drops below 2.5-2.7 for air heat pumps. With an annual performance factor below 2.5, the operating costs typically start to rise above levels for conventional heating.

The definition of LT readiness is only one piece in the policy package. Germany's will possibly include different elements which inform owners about the potential for LT readiness, prepare the buildings through an analysis of the temperature level, support or require the installation of renewable heating, and financially support LT readiness.

Figure 18: Elements of a future LT ready policy package (Source: ifeu)



a heat pump would be competitive with respect to the operating costs at typical gas and electricity prices in Germany. Above 55°C, the efficiency typically drops below 2.5-2.7 for air heat pumps. With an annual performance factor below 2.5, the operating costs typically start to rise above levels for conventional heating.

7 Conclusions

The benefits of focusing on buildings' LT readiness are well established. Lowering the flow temperatures of heating systems is important for heating efficiency, whatever the heat source. It is particularly important for clean heat, leading to a decarbonised, climate friendly heat supply: lower flow temperatures enable heat pumps to operate more efficiently and enable a more diverse range of clean heat sources to be integrated into the heating mix. For building owners and occupiers, ensuring heat can be provided at low flow temperatures is a key safeguard for affordable heating. Enabling lower-flow-temperature heating is thus a no-regrets option.

The concept of an LT ready building brings a new perspective to the design of polices and strategies for building decarbonisation, namely one that focuses on the interactions between the building fabric, the heat distribution system and performance of the heat source. Understanding this interaction is important for decisions on best-placed investments. The concept, therefore, fills a gap in the European buildings and heating policy framework, and in most national frameworks.

A picture is emerging of an integrated policy framework to implement the low flow temperature concept, influenced by front-running countries like Germany and the Netherlands. This includes:

- Defining a long-term vision of a climate-neutral building stock, where LT readiness is the first and important step towards the use of renewable energies
- Awareness raising over existing heating settings for both building owners and the industry
- Integrating low temperature testing or readiness into inspections, advice, audits, and assessments
- Creating an LT readiness indicator and measures to move towards LT readiness through Energy Performance Certificates and Building Renovation Passports
- Supporting LT readiness through funding programmes
- Normalising low temperature heating through product standards
- Mandating LT readiness through building standards.

Readying a building for low temperature heat does not, however, guarantee that it will be heated at a low flow temperature or that its heating installations will perform efficiently. Alongside the LT readiness of the building, a range of other measures are essential to ensure that heating industry norms and standards drive high performance, and that systems are commissioned and building owners are empowered to operate them effectively. Designing a low temperature standard from the perspective of an individual building also fails to consider the interaction of that building with the energy system. Local grid constraints, the availability of distributed energy resources and grid investment needs are particularly relevant considerations for the electrification of heat. These circumstances might create additional incentives for extra investment in energy efficiency, which is also key to enabling the flexible use of heating systems at individual building level.

In the development of a lower flow temperature standard, individual countries or regions will take different approaches in response to local conditions and priorities. In defining what 'low' temperature is, a maximum flow temperature of 55°C on the coldest day can be considered to be at the higher end of the range, with the lower end at around 35°C. However, the lower the flow temperature, the better. Target temperatures may be different for district heating and individual systems, as district heating usually needs higher temperatures than individual systems.

Policymakers also have choices to make on the approach they take to defining the standard. A standard can be communicated as a maximum flow temperature to be measured in operation or achieved through as-designed building and heating system parameters (as per the UK building code), or as a building thermal performance standard as a proxy, or both. If designing a building standard, the balance between prioritising minimum improvements to radiators and prioritising building envelope improvements (as per the Dutch standard) is also to be considered. Improvements to the thermal performance of a building bring additional benefits to heat demand and energy bill reduction, enabling new electrified heat loads to be integrated flexibly into electricity grids, and reducing the impact (and related need for investment) on electricity systems.

A range of contextual factors will therefore affect the design of individual policies. These include dominant building typologies and significant barriers to either heat distribution or building fabric changes; predominant heating technologies, especially whether individual or district heating systems are being used; energy costs, particularly the ratio of electricity prices to gas/heating oil prices that affect the cost-effectiveness of investments; climate zone; and the condition of the electricity grid.

8 References

Bagheri, M., Mandel, T., Fleiter, T. et al. (2022). Renewable space heating under the revised Renewable Energy Directive: Description of the heat supply sectors of EU Member States space heating market summary 2017. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/256437

BEIS. (2021). Domestic heat distribution systems: Evidence gathering. Final Report BEIS Research Paper Number: 2021/015. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/976021/beis-dhds-final-report__1_.pdf

Benakopoulos, T., Vergo, W., Tunzi, M., Salenbien, R., & Svendsen, S. (2021). Overview of Solutions for the Low-Temperature Operation of Domestic Hot-Water Systems with a Circulation Loop. Energies **2021**, 14, 3350. https://doi.org/10.3390/en14113350

BMWK. (2022). Richtliniefür die Bundesförderung für effiziente Gebäude– Wohngebäude (BEG WG). https://www.bundesanzeiger.de/pub/publication/RQnsxjil5J2GBTH5sAC?0

BMWK. (2023). Wärmewende: BMWK leitet Umstieg aufs Heizen mit Erneuerbaren ein. https://www.bmwk.de/Redaktion/DE/Schlaglichter-der-Wirtschaftspolitik/2023/03/05-waermewende.html#:~:text=Umstieg%20auf%20heizen%20mit%20Erneuerbaren&text=gibt.,65%20Prozent%20erneuerbare%20Energie%20nutzen

Buchs. (2018). Wärmepumpen-Testzentrum: Prüfresultate Sole/Wasser-Wärmepumpen basierend auf der EN 14511:2013 und EN 14825:2013/ EN 14825:2016, Status 29.01.2018. https://www.ost.ch/fileadmin/dateiliste/3_forschung_dienstleistung/institute/ies/wpz/sole-wasser-waermepumpen/pruefresultate_sw.pdf

Danfoss. (n.d.). Termix One-B, Typ 3, 16 bar, 100°C, Reglertyp TWE: AVTB. https://store.danfoss.com/de/de/Climate-Solutions-W%C3%A4rmetechnik/Stationen/Durchlauferhitzer-mit-W%C3%A4rme%C3%BCbertrager/Termix-One-B%2C-Typ-3%2C-16-bar%2C-100-%C2%B0C%2C-Reglertyp-TWE%3A-AVTB/p/004U3051 [accessed 17.02.2023]

European Environment Agency. (2015). Household energy consumption for space heating per m^2. https://www.eea.europa.eu/data-and-maps/daviz/unit-consumption-of-space-heating#tab-chart_1

Entranze. (2014). Breakdown of dwellings according to heating systems. https://www.entranze.eu/

European Commission. (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. Stepping up Europe's 2030 climate ambition. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2020:176:FIN

European Commission. (2021). Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

European Commission. (2022). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic And Social Committee and the Committee of the Regions. REPowerEU Plan. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230

European Heat Pump Association. (2023). Heat pump record: 3 million units sold in 2022, contributing to REPowerEU targets [Press release]. https://www.ehpa.org/press_releases/heat-pump-record-3-million-units-sold-in-2022-contributing-to-repowereu-targets/

Eurostat. (2023). Energy Consumption in households. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households

Farmer, D., Henshaw, G., Roberts, B., Fitton, R., Swan, W., & Burrows, R. (2022). Salford Energy House Boiler Flow Temperature Testing. Initial report. https://media.nesta.org.uk/documents/UoS_Nesta_Energy_House_Initial_Report_-_FINAL_2022-10-08.pdf

FIW, ifeu. (2023). Wärmedämmung und Wärmepumpen – Warum beides zusammengehört (Insulation and heat pumps – why both belong together). https://www.ifeu.de/publikation/waermeschutz-und-waermepumpe-warum-beides-zusammengehoert/

Fraunhofer-Institut für solare Energiesysteme (Fraunhofer ISE). (2021). Wärmepumpen in Bestandsgebäuden: Ergebnisse aus dem Forschungsprojekt "WPsmart im Bestand".

Government of Austria. (2022). Raus aus öl und gas [Factsheet]. https://www.umweltfoerderung.at/fileadmin/user_upload/umweltfoerderung/b triebe/Raus_aus_Oel_Erneuerbare_Waermeerzeugung_100_kW/UFI_Infoblatt_WAERMERZEUGER_PAU.pdf

Government of Flanders. (2022). Mijn VerbouwPremie voor warmtepomp. https://www.vlaanderen.be/bouwen-wonen-en-energie/bouwen-en-verbouwen/premies-en-belastingvoordelen/mijn-verbouwpremie/mijn-verbouwpremie-voor-warmtepomp

Government of Luxembourg. (2022). Certificat de conformité concernant la pompe à chaleur. https://environnement.public.lu/dam-assets/documents/emweltprozeduren/personnes_prives/energie/rgb-2022/certificats-conformite/cc-poch-2022.pdf

Government of the United Kingdom. (2019). The Future Homes Standard. Consultation on Changes to Part L (Conservation of Fuel and Power) and Part F (Ventilation) of the Building Regulations for New Dwellings. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/852605/Future_Homes_Standard_2019_Consultation.pdf

Government of the United Kingdom. (2021). The Building Regulations. Part L of Schedule 1 Conservation of Fuel and Power (2021 Edition). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1099626/ADL1.pdf

Government of the United Kingdom. (2022). Small changes mean energy advice campaign adds up to big savings [Press release]. https://www.gov.uk/government/news/small-changes-mean-energy-advice-campaign-adds-up-to-big-savings

ifeu. (2021). Energieeffizienz als Türöffner für erneuerbare Energien im Gebäudebereich. https://www.ifeu.de/fileadmin/uploads/Publikationen/Biomasse/Landwirtschaft/_ifeu_2021__Energieeffizienz_als_T%C3%BCr%C3%B6ffner_f%C3%BCr_erneuerbare_Energien_im_Geb%C3%A4udebereich_Endbericht.pdf

ifeu et al. (2019). EnEff:Wärme – netzgebundene Nutzung industrieller Abwärme (NENIA), kombinierte räumlich-zeitliche Modellierung von Wärmebedarf und Abwärmeangebot in Deutschland (Modelling the spatial waste heat potential in Germany). Institut für Energie- und Umweltforschung Heidelberg (ifeu), GEF Ingenieur AG, Indevo GmbH, geomer GmbH

International Energy Agency (IEA). (2017). Transformation Roadmap from High to Low Temperature District Heating Systems: Annex XI final report. https://orbit.dtu.dk/en/publications/transformation-roadmap-from-high-to-low-temperature-district-heat

ifeu, ITG et al. (2023). Heizen mit 65% erneuerbaren Energien – Begleitende Analysen zur Ausgestaltung der Regelung aus dem Koalitionsvertrag 2021. https://www.bmwk.de/Redaktion/DE/Downloads/Energie/heizen-mit-65-prozent-erneuerbaren-energien.pdf?__blob=publicationFile&v=8

IWU. (2015). Deutsche Wohngebäudetypologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden. https://www.iwu.de/fileadmin/publikationen/gebaeudebestand/episcope/2015_IWU_LogaEtAl_Deutsche-Wohngeb%C3%A4udetypologie.pdf

Lowes, R. (2022). Good COP/Bad COP: Balancing fabric efficiency, flow temperature, and heat pumps – A case study of the Irish HLI requirements. https://www.raponline.org/wp-content/uploads/2022/11/RAP-Lowes-Ireland-HLI-Requirements-2022-Nov-29-FINAL-properties.pdf

Nesta. (2023). Lowering boiler flow temperature to reduce emissions. https://www.nesta.org.uk/project/lowering-boiler-flow-temperature-reduce-emissions/

Nussbaumer, T., Thalmann, S., Jenni, A., & Ködel, J. (2017). Planungshandbuch Fern-wärme. https://www.verenum.ch/Dokumente/PLH-FW_V1.2.pdf

Østergaard, D. S. (2018). Heating of existing buildings by low-temperature district heating. Technical University of Denmark, Department of Civil Engineering. https://backend.orbit.dtu.dk/ws/portalfiles/portal/161127842/Untitled.pdf

Østergaard, D. S., Smith, K. M., Tunzi, M., & Svendsen, B. (2022). Low-temperature operation of heating systems to enable 4th generation district heating: A review. Energy (Volume 248). https://doi.org/10.1016/j.energy.2022.123529

Paardekooper, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L., David, A., Dahlbæk,J., Kapetanakis, I. A., Lund, H., Bertelsen, N., Hansen, K., Drysdale, D. W., & Persson, U. (2018). Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Aalborg Universitetsforlag. https://vbn.aau.dk/ws/portalfiles/portal/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps..pdf

Pehnt, M. et al. (2017). Wärmenetzsysteme 4.0 Endbericht – Kurzstudie zur Umsetzung der Maßnahme "Modellvorhaben erneuerbare Energien in hocheffizienten Niedertemperaturwärmenetzen" ("District Heat 4th Generation"). https://www.ifeu.de/fileadmin/uploads/W%C3%A4rmenetze-4.0-Endbericht-final.pdf

Pehnt, M., Mellwig, P., Lempik, J., Schul-ze-Darup, B., Schöffel, W., & Drusche, V. (2021). Neukonzeption des Gebäudeenergiegesetzes (GEG 2.0) zur Erreichung eines klimaneutralen Gebäudebestandes. https://www.ifeu.de/publikation/neukonzeption-des-gebaeude- energiegesetzes-geg-20-zur-erreichung-eines-klimaneu-tralen-gebaeudebestandes/

Pehnt, M., Mellwig, P., & Lempik, J. (2022). Fit for Renewables through "low temperature readiness" of buildings. https://www.eceee.org/static/media/uploads/site-2/summerstudy2022/pdfs_docs/abstracts_2022_rev4june.pdf

Pothof, I., Vreeken, T., & van Meerkerk, M. (2022). Field measurements on lower radiator temperatures in existing buildings, Manuscript for Energy and Buildings. WarmingUp Project. https://www.warmingup.info/documenten/11205149-hye-001_field-measurements-on-lower-radiator-temperatures-in-existing-buildings_def.pdf

Urgenda. (2022). In een handomdraai geld besparen: Zet 'm op 60!. https://www.urgenda.nl/in-een-handomdraai-geld-besparen-zet-m-op-60/

Rijksdienst voor Ondernemend Nederland (RVO). (2021). Standaard en streefwaarden voor woningisolatie. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/standaard-streefwaarden-woningisolatie

Rosenow, J. & Lowes, R. (2020). Heating without the hot air: Principles for smart heat electrification. Regulatory Assistance Project. https://www.raponline.org/knowledge-center/heating-without-hot-air-principles-smart-heat-electrification-2/

Sunderland, L. (2022). How Much Insulation Is Needed? A Low Consumption, Smart Comfort Standard for Existing Buildings. Regulatory Assistance Project. https://www.raponline.org/wp-content/uploads/2022/05/rap-sunderland-insulation-standard-2022-may-4.pdf

Wagner. (2015). Summary of EN 12975 Test results. https://www.dincertco.de/logos/011-7S2596%20F.pdf

Yule-Bennett, S. & Sunderland, L. (2022). The joy of flex: Embracing household demand-side flexibility as a power system resource for Europe. Regulatory Assistance Project. https://www.raponline.org/knowledge-center/joy-flex-embracing-household-demand-side-flexibility-power-system-resource-europe/

9 Appendix

Table 4: Effect of efficiency measures and optimised heat distribution on flow temperature for Buildings 1 to 4 from Chapter 4 (ifeu, 2021)

Building 1:

Options	Efficiency level	Wall, windows, doors	Roof, roof windows	Basement	Only wall	No changes to the heating system	Replacing the most critical radiator	Replacing the five most critical radiators
		Renovation packages				Flow temperature [°C]		
Status quo	not renovated					63	59	55
1	Building code quality	x				54	53	48
2			x			59	57	51
3				x		63	58	54
4		x	x			48	47	44
5			x	x		55	54	51
6		x		x		54	53	48
7		x	x	x		47	42	42
8					x	57	54	51
9	Deep renovation quality	x				53	53	47
10			x			58	56	51
11				x		63	58	54
12		x	x			46	45	41
13			x	x		54	54	50
14		x		x		53	53	45
15		x	x	x		45	41	41
16					x	56	54	51

Building 2:

Options	Efficiency level	Wall, windows, doors	Roof, roof windows	Basement	Only wall	No changes to the heating system	Replacing the most critical radiator	Replacing the five most critical radiators
		Renovation packages				Flow temperature [°C]		
Status quo	not renovated					81	75	72
1	Building code quality	x				71	65	61
2			x			80	73	66
3				x		81	75	67
4		x	x			69	63	61
5			x	x		80	73	66
6		x		x		71	65	61
7		x	x	x		69	63	60
8					x	72	69	64
9	Deep renovation quality	x				68	62	56
10			x			77	72	64
11				x		81	75	67
12		x	x			63	58	53
13			x	x		77	71	64
14		x		x		68	62	56
15		x	x	x		63	58	53
16					x	71	69	63

Building 3:

Options	Efficiency level	Wall, windows, doors	Roof, roof windows	Basement	Only wall	No changes to the heating system	Replacing the most critical radiator	Replacing the five most critical radiators	Replacing 30 % of all radiators
		Renovation packages				Flow temperature [°C]			
Status quo	not renovated					79	77	77	73
1	Building code quality	x				64	63	60	55
2			x			77	77	76	69
3				x		79	77	77	71
4		x	x			64	62	57	52
5			x	x		77	77	74	69
6		x		x		64	63	60	53
7		x	x	x		64	62	56	52
8					x	68	67	64	58
9	Deep renovation quality	x				63	61	60	54
10			x			77	77	76	69
11				x		79	77	77	71
12		x	x			63	61	56	51
13			x	x		77	77	74	69
14		x		x		63	61	58	51
15		x	x	x		63	61	55	51
16					x	67	67	64	57

Building 4:

Options	Efficiency level	Wall, windows, doors	Roof, roof windows	Basement	Only wall	No changes to the heating system	Replacing the most critical radiator	Replacing the five most critical radiators	Replacing 30 % of all radiators
		Renovation packages				Flow temperature [°C]			
Status quo	not renovated					76	74	71	67
1	Building code quality	x				69	64	62	59
2			x			76	74	70	67
3				x		74	74	70	67
4		x	x			69	64	61	58
5			x	x		74	74	70	67
6		x		x		68	64	61	58
7		x	x	x		68	63	61	58
8					x	72	67	65	62
9	Deep renovation quality	x				67	62	59	57
10			x			76	73	70	66
11				x		74	74	70	66
12		x	x			67	62	59	55
13			x	x		74	74	70	66
14		x		x		65	60	58	57
15		x	x	x		65	60	57	55
16					x	72	66	64	61