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The Contradictions between District and Individual Heating towards Green Deal Targets

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Abstract: The blind spot can be defined as the area around the vehicle where the driver cannot see through the mirrors without turning their head or taking their eyes off the road. Similar blind spots occur in energy policy. Blind spots can occur in forecasting economic development and creating policy documents. This study uncovers potential blind spots and controversies in the sustainability assessment of energy supply technologies. A composite sustainability index was constructed to compare district heating with four individual heating technologies—wood pellet boilers, natural gas boilers, solar collectors, and heat pumps. A total of 19 indicators were selected and grouped into four dimensions of sustainability—technical, environmental, economic, and social. The results reveal that district heating can compete with individual heating technologies in all dimensions of sustainability; however, a possible blind spot lies in evaluating environmental performance indicators of the different heating technologies. This study provides a novel decision-making tool that policy-makers could use to identify and avoid potential blind spots and uncertainties in energy policy at an early stage.

Keywords: energy policy; contradictions; composite sustainability index; sustainability dimensions; heating technologies

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1. Introduction

The transition to a low-carbon economy is one of the most pressing challenges on the global policy agenda. Five years after the Paris agreement came into force, the European Union has committed itself to taking on a leading role in the global fight against climate change [1]. Only a year after launching the European Green Deal, in December 2020, EU leaders have agreed on a common target to decrease greenhouse gas emissions by at least 55% by the year 2030, compared to levels in 1990, thereby significantly surpassing its initial goal of 40% [1]. This political commitment forces the EU and its Member States to reassess current energy policies and legislation to reach the ambitiously raised climate change mitigation goals [2].

Over the last decade, numerous strategies, regulations, and policies have been enforced to drive decarbonization, increase energy efficiency, and accelerate and advance the adaptation of green energy solutions [3]. National regulatory authorities have their own responsibility to launch policy instruments that meet the transition objectives for a low carbon economy. However, the policies pursued and the enforcement mechanisms used are not always highly effective and often fall short of the necessary climate targets set by policy-makers [4]. Therefore, one of the most essential cornerstones of energy policy is to understand the main drivers of the policy ambiguities and controversies that hinder the achievement of the climate goals. There are situations when the government can not overlook existing blind spots in policy-making. They tend to treat climate change issues solely as technical matters while most of the challenges are highly reliant on social and political aspects [5]. Lack of understanding and ignorance of all the underlying forces of

sustainability create systematic risks and contradictions of the intended goals [6], which can lead to costly consequences that affect the entire economy.

The ongoing debates among policymakers over the most optimal, cost-efficient and sustainable energy infrastructure outlines a number of controversial issues, such as: choice of distributed electricity generation versus centralized electricity generation, renewable energy as opposed to fossil fuels, centralized compared to decentralized production of electricity and heat supply, and many others. These are just a few examples of the issues that require careful investigation to preliminarily identify possible blind spots in energy policy and avoid decision-making biases.

It is estimated that heat supply is the most carbon and energy-intensive sector in the European Union, accounting for about 50% of the total demand of the European Union [7]. Sustainable heating systems focus on mitigating climate change by replacing fossil fuels with renewable energy solutions and residual heat, and reducing fuel intensity and improving energy efficiency while reducing energy consumption. Sustainable heating systems are categorized by the temperature at which heat is supplied, the heat source, and whether it is a central or individual heating system. Sustainable heating systems are categorized according to the temperature at which the heat is delivered, the heat source and whether it is a collective system that includes district heating or individual heating solutions [8].

Most studies comparing district heating and individual heating focus primarily on one perspective: analysing either the cost-effectiveness, technical performance, or environmental impact of the different heating technologies. Looking at only one dimension and neglecting other sustainability dimensions can create unexpected blind spots in energy policy. Since each of these sustainability indicators is composed of different measures, it is necessary to develop a comprehensive methodology that allows for a full-fledged sustainability assessment that includes a unified consideration of all aspects together. This study demonstrates the composite index methodology's application to create a sustainability index for district heating and four different individual heating technologies. The composite index methodology has gained acceptance as an innovative tool that allows the inclusion of an unlimited number of indicators to measure different aspects of complex and controversial issues, such as sustainability, prosperity, innovation potential, competitiveness and many others [9,10]. Therefore, this study provides a novel decision-making tool that policy designers could use in order to identify and avoid potential blind spots and uncertainties in energy policy at an early stage.

The aim of this study is to design a methodology to analyze contradictions and validate the methodology by revealing some of the controversies of the energy sector. This study's main objective is to compare the sustainability of district heating with different individual heating solutions. The subject of the study is not individual heating and district heating solutions in a particular country, but the study aims to highlight the existing trends in the sustainability of heating solutions. Sustainability is assessed in terms of the compatibility of the technology with the goals of a low-carbon economy.

1.1. Literature Review

A number of factors influence household energy consumption behaviour and it is estimated that changing household behaviour patterns and learning to use energy more efficiently can reduce existing energy consumption by up to 10–30%. Evidence shows that the greatest energy savings can be achieved by combining sustainable technological solutions with consumer behaviour change. Therefore, it is essential also to consider the dimension of social sustainability when pursuing more efficient energy use [11]. Objective and subjective factors influence energy consumer behaviour. Objective factors are characterized, for example, by energy prices, income levels, housing characteristics, energy policies, or climatic conditions. Subjective factors, in turn, are related to consumers' own choices and understanding of energy use [11].

Similarly, it is estimated that certain consumer behaviours could reduce carbon dioxide emissions by 25% in the case of the European Union [12]. It is recognized that one of the biggest obstacles to changing the behaviour of electricity and heat consumers is consumer habits, which are difficult to change. In households, economic incentives to save heating or electricity are one of the reasons for changing consumer behaviour [12].

It is estimated that domestic heating generates significant energy demand [13,14]. Although significant amounts of fossil fuels are still used for heat supply, in recent years, biomass and heat pumps have been increasingly used alongside fossil resources [14]. The energy consumption is determined by a number of factors, such as the energy required for heating, which is determined by the house's construction and location. The consumption required for heating depends on average winter temperatures. It is estimated that in climates with lower temperatures, the energy consumption is two thirds [14].

In order to meet the decarbonisation goals set in Europe, heating and cooling have been identified as priorities in the energy sector, accounting for almost half of total energy consumption. The largest heating consumption takes place mainly in the household sector and in the industrial and tertiary sectors [15]. Several factors need to be considered in the transition to a sustainable heat supply, including social and consumer behavioural barriers. A sustainable heat supply is characterised by the efficient use of renewable energy sources for heat supply, both through the use of renewable energy sources in individual heat supply and through their integration into district heating systems [16]. Although global heat supply accounts for one third of total carbon emissions, energy policy is more concerned with electricity generation, which could be explained by the fact that both district heating systems and technological plants of different sizes, temperatures and types are used for heat supply, which complicates decision-making processes [17,18]. It is estimated that 53% of total household energy consumption is used for heating and 16% for hot water [18]. For private households, there are a number of factors that can influence the type of heat supply. Important factors that determine the type of heat supply include safety, cost and comfort. District heating, which uses renewable energy sources as fuel, has been assessed as the most suitable heating solution for households. Other common solutions include district heating that uses fossil fuels and heating with gas boilers or heat pump technologies [19].

The availability of fuel also influences the choice of fuel for heat supply. Countries that did not have access to natural gas for space heating in the recent past, e.g., Germany, Austria, switched from fossil energy to renewable energy relatively early. Due to the taxation of fossil fuels, for example in countries like Denmark, Sweden and Finland, automated wood pellet boilers are increasingly used for heating [14]. Since space heating is one of the main consumers of energy, renewable energy sources are increasingly being used for district heating in Sweden, for example [14]. It is estimated that the transition to net zero CO_2 will only be possible if the transition to a more sustainable heat supply is secured [16].

1.2. Impact on Energy Consumption Change Due to COVID-19 Crisis

As a result of the COVID-19 pandemic, energy demand has changed significantly, and the changes in energy consumption and demand in 2020 are expected to be the largest in the last 70 years. Compared to 2019, total energy consumption has decreased by 6%. [20]. It is estimated that total energy consumption in some parts of Europe decreased during the pandemic COVID-19, but the household sector shows different trends. It is acknowledged that more renewable energy than fossil energy was used for heating during the constraints, which is partly explained by the limited availability of fossil fuels. The pandemic's timing constraints also had a significant impact on changes in energy users' consumption patterns and the household sector saw a significant increase in energy consumption in contrast to other sectors [21].

In the first half of 2020, the global coal market is estimated to have declined by 8% compared to the first months of 2019, which is partly explained by the decline in economic activity. The coal market is not expected to recover from the pandemic fully and

will not return to pre-pandemic levels. As a result, other, more environmentally friendly solutions will be more widely used in the future energy sector. It is estimated that the world experienced a significant drop in natural gas demand in the first months of 2020—natural gas demand dropped by 2%. It is estimated that most demands for natural gas fell in the United States, China, as well as Europe. In contrast, the opposite trend was observed in renewable energy demand. It is estimated that in the first months of 2020, demand for the use of renewable energy for electricity and heat increased by 1.5%. This was partly due to the increasing capacity of solar and wind power plants. However, the demand for renewables varied significantly from country to country over the period of COVID-19 and depended on national policies [22]. The COVID-19 pandemic is expected to increase uncertainty about global energy demand and user consumption. However, it is recognized that the impact of pandemic restrictions on energy consumption and user behaviour will vary from country to country, and will be highly dependent on country-specific COVID-19 restrictions and measures taken [23].

The study predicted that compared to energy consumption in February 2019, heating and cooling consumption will increase by 60% between January and February 2020 due to COVID-19 restrictions. With a longer stay in households during a pandemic, electricity and heating are expected to increase significantly. In the case of electricity, it is estimated that at the beginning of the restrictions, in March 2020, electricity costs are projected to increase by 95%, in April by 35% and in May by 22%. During pandemic restrictions, household consumers are more active in the use of household electrical appliances and there is more need for heat supply for heating or hot water. It can be concluded that household energy consumption and energy costs are significantly affected by the various national pandemic restrictions and implemented national mitigation measures [24].

The main changes during a pandemic are related to the need to stabilize and restore energy demand, as it is variable during the pandemic and depends on the implemented and different national policies to reduce the pandemic. Only by stabilizing energy consumption will it be possible to achieve economic sustainability. Economic sustainability is characterised by ensuring economic growth without compromising social, environmental or cultural aspects [17]. Consequently, trends in changes in energy demand need to be monitored at the national level. Rationalisation of energy needs and regular energy consumption are among the main tasks to stabilise energy consumption Local and national incentives are needed to stabilise energy demand. It is projected that after the end of the pandemic, if economies and energy consumption return to previous levels, by using environmentally friendly energy solutions, it may be possible to reduce global warming by 0.3 °C by 2050. Thus, renewable energy is becoming an increasingly important solution for economic recovery and sustainable energy [20].

The literature review shows that there have been several attempts to compare centralised and decentralised energy supply solutions outlining the advantages and disadvantages of both options. A decentralised energy system's benefits relate to the autonomy of the end-user and sustainability [25].

1.3. Individual Heating

Decentralised energy systems often use renewable energy sources, promoting the development of decentralised energy systems and carbon-neutral energy production. Decentralised energy can be more expensive than centralised energy in some cases, so it is not available to everyone for financial reasons; statistically, decentralised energy supply to residential buildings is chosen by more financially stable residents [25]. Decentralised heating solutions include a variety of different technologies such as gas/oil boilers, air/ground source heat pumps, solar thermal, wood pellet boilers, and electrical panel/radiators [26,27].

Individual natural gas boilers, which use natural gas as fuel which is a type of fossil fuel [28], are common in the industrial sector as well as in households. Despite its widespread use, the use of natural gas is influenced by environmental aspects, such as the

proportion of carbon and hydrogen in natural gas [16]. Another major disadvantage of individual gas boilers is the increased risk of fire [26].

Heat pumps are electrically powered thermal technologies that use solar energy stored in natural heat sources such as air, water or soil to generate heat. They are increasingly used in residential heating and cooling, influenced by heat pumps' high energy efficiency [29,30]. Heat pumps can be described as technological devices where, using mechanical or electrical energy, heat is transferred using refrigerant circulation. The thermal energy produced can be used to provide space heating or hot water. Heat pump technologies can be used in commercial buildings and factories, as well as in households. Heat pumps are considered environmentally friendly and highly energy efficient, and can be integrated into existing systems [7].

Heat pump systems can use a variety of heat sources, such as surface water, ground heat or air, which are the most commonly used heat sources. Depending on the heat source used, heat pumps are classified as ground source heat pumps, hydrothermal heat pumps, or aerothermal heat pumps [7]. Depending on the type of heat pump, the efficiency and operating parameters of the heat pump also change [31].

One type of heat pump is the air-source heat pump, the basic principle of which is based on the use of air as a heat source. Low-grade heat is extracted from the air, which is raised to such a level that the extracted heat can be used, for example, to supply heat to households. It is estimated that the amount of electricity consumed by this type of heat pump to operate the system is less than the amount of heat produced [7]. Air-source heat pumps are divided into two types, depending on the source used—they can be either air-to-air or air-to-water [7].

Air-to-air heat pump systems generate hot air that is circulated by fans; in contrast, air-to-water heat pumps produce heat through wet central heating systems. In combination with underfloor heating, air source heat pumps are considered an efficient solution for hot water supply and space heating [7].

Another type of heat pump is water source heat pump technology that uses water, such as water bodies or groundwater, as a heat source. The operation of these heat pumps is based on the conversion of low-value heat from water into usable heat. One of the advantages of water source heat pumps over air source heat pumps is lower carbon emissions during operation and greater cost savings. Although water source heat pumps have been evaluated as effective technological solutions, their disadvantages are related to the applicability of limiters because, in addition to heat pumps, there must be a heat source—water bodies or the possibility of installing water storage tanks. Consequently, the wider application of this type of heat pump may be affected by climatic and geographical conditions [7].

Ground source heat pumps use the heat stored in the ground as a heat source, which is converted into usable heat energy for further use. Ground source heat pumps have been evaluated as the most environmentally friendly technological solutions with the highest efficiency due to the relatively stable underground temperature. This type of heat pump can be used regardless of climatic conditions. [7,31].

Heat pumps have been evaluated as one of the heat supply technologies on the way to sustainable heat supply, both for use in individual heat supply solutions and in district heating systems [31]. Regardless of whether heat pumps are used as individual heat supply solutions or integrated into district heating networks, they play an important role in decarbonisation [7]. Evidence shows that the use of heat pump systems reduces energy consumption and increases efficiency. One of the advantages of heat pump technology is that heat pumps can be used to convert the excess energy into heat. Another advantage of using heat pump technologies in buildings is that it is possible to ensure the required temperature conditions throughout the year, providing heat in winter but cooling in warm weather conditions. [7].

The Danish energy system analysis estimated that by 2035 the integration of heat pumps into the heat supply system could reduce system costs by 16% and reduce biomass consumption by up to 70% [7].

Despite the high efficiency and sustainability of these technologies, it is estimated that only 3% use heat pumps as a heating solution for heating buildings; however, there are recent increasing trends in the use of heat pumps. In recent years, policy-makers have identified heat pump technologies as one of the most important possible solutions for a more sustainable energy supply, which is reflected in various measures for the installation and diffusion of heat pumps [7].

With the exception of Switzerland and Sweden, the use of geothermal energy sources to reduce greenhouse gas emissions is still low, mainly because heat pumps have higher installation costs compared to other technological solutions [31]. It is estimated that smaller heat pump technologies may incur higher operating costs, but the introduction of large heat pumps may require additional capital investment, such as building modernisation or boiler replacement [7].

Solar collectors are individual heat supply technologies that use solar energy as a heat source which converts solar irradiation into solar thermal energy [28]. During the solar collector operation, solar irradiation is absorbed, then the absorbed heat is transferred to a working fluid, which may be, for example, oil, air or water. The heat generated can be used for heating water, as well as solar energy storage [32].

There are several possible types of solar collectors; the most commonly used solar collectors include both evacuated tube collectors and flat plate collectors. Out of the mentioned solar collector types, flat plate collectors are chosen as the most preferred heating solution. It is influenced by the lower prices of these solar collectors, the simple design and the desired achievable heating temperatures [33].

With the increasing use of solar collectors, it is possible to significantly reduce the demand for fossil energy resources and use solar energy instead. In recent years, solar collectors have been increasingly used in the construction of buildings to reduce carbon emissions. By using solar collectors, it is possible not only to provide space heating, but also to meet the demand for hot water [20] efficiently. The disadvantages of solar collectors are related to the periodicity of solar energy and the need to combine solar collectors with other heat supply solutions in case of insufficient heat energy [26].

Wood pellet boilers are individual technological devices for the production of thermal energy, in which wood pellets, obtained by granulating wood fibres, are used as fuel. Wood pellets are one of the forms of renewable energy that can be used to achieve climate goals. The heating system of pellet boilers consists of such elements as a heat accumulator, boiler and building, which is a unit of energy consumption [28].

Electrical panels/radiators such as an office or household electrical appliances for space heating, are widely used and are capable of converting electrical energy into heat using heating elements [34].

1.4. District Heating

In district heating, heat is delivered centrally to the end user by transporting hot water or steam through a network of pipes. Centralised heating systems use high-capacity combustion plants with higher energy efficiency and improved air pollution control. District heating is considered to be environmentally friendly for heating buildings and is recognized as one of the solutions to mitigate climate change [22].

One of the advantages of district heating is that the heat source can be any process that generates heat. The heat source can be a geothermal process, solar collectors, biomass boilers or heat generated in industrial production. The possibility of using different energy sources also offers financial advantages, as the possibility of optimising costs also depends on the price of the energy source used. This also contributes to the stability of the supply system [26].

Another advantage in favour of district heating is the possibility of using low-grade energy. Thus, district heating offers the possibility of using energy sources that are difficult or impossible to use in individual heating solutions. If district heating is to use renewable energy, such as solar thermal, then seasonal storage of the generated energy is possible through storage systems [12]. District heating technologies can be used to prevent the inefficient use of individual heat supply solutions for heating or hot water supply [35].

District heating is easily accessible, specific sources do not limit its use, and district heating is assessed as an essential element for achieving the European Union's climate goals in the future [26]. It is estimated that in Europe, district heating systems can reduce emissions by 113 million tonnes of CO_2 per year, which is 2.6% of total CO_2 emissions [36]. Several countries have implemented various policies to promote the district heating infrastructure since it is an essential element of a low carbon energy system. It is particularly true for colder climate countries that have higher average space heating and hot water consumption [37]. Cold climatic conditions strongly influence the share of district heating use; in the Baltic States, Nordic countries, as well as in the countries of Eastern Europe, district heating systems have a share of 36–92% of the total heat supply [38]. The competitiveness of district heating systems in residential buildings depends on factors such as the heating system's price, the price of fuel or electricity, the efficiency used, and the expected price increase [36,39]. District heating is positively recognised for its ability to effectively use waste, excess heat and low-grade heat sources to produce heat for household demand [27]. In several countries, district heating systems are positioned as one of the key elements in national strategic plans [26]. It has been assessed that district heating will become more profitable and cost-effective in the future, and district heating using renewable energy sources is estimated as one of the most important solutions on the way to the decarbonisation of the energy sector [19]. However, district heating is often criticised by policy-makers for its high capital intensity, arguing about its lower cost efficiency against decentralized heating solutions [13].

Although district heating systems have several advantages, there may be some obstacles. One of the disadvantages is, for example, the possible heat loss along the pipe-lines in cases of inadequate design of distribution networks [26,35]. Heat losses in district heating systems are affected by linear heat density. High heat losses up to 25% occur at low linear heat densities, while at high linear heat densities, heat losses can be below 5%. In the case of new and upgraded district heating networks, heat losses are up to 10% [40]. One of the major uncertainties in district heating is related to the initial investment in district heating. The distribution network cost depends on several factors, including the heat demand, such as the ratio of building to the area. [12].

1.5. District Heating versus Individual Heating

District heating systems and individual heating solutions, which differ in the way they generate heat, meet hot water needs, and the particular type of heat supply, have different management. Individual and district heating differ in the degree of comfort they provide to the consumer. Compared to district heating systems, where the hot water can be used immediately with individual heating technologies, it takes time for the water to heat up to the appropriate temperatures [41].

It is estimated that heat consumers with a higher level of education as well as a higher income choose the district heating system, while other consumers prefer individual heat supply solutions [29]. Studies show that, due to the ability of heat source diversification, cheaper fuels, and high technology efficiency, the new district heating system is the most cost-efficient and competitive solution compared to different individual heating technologies [8,9].

It is believed that district heating costs are more expensive than individual heating costs, with the necessity of generating extra investments related to pipeline damage or steam leakage as one of the reasons [41]. In fact, district heating systems are cost-effective and competitive systems that can be used in both cities and outside urban areas [26].

The United Kingdom, in a study, estimated that heat pumps could reduce costs and emissions even by 37%. Another study estimates that the use of heat pumps can reduce the consumption required for heating by 72% compared to individual natural gas boilers [42].

Although different information on district heating costs can be found in the literature, individual solutions for the initial supply of heat generally require higher initial investments compared to district heating [7]. It is estimated that, for example, installing district heating networks in a household has a lower cost than investing in a household by installing a single boiler. It is estimated that district heating's annual cost is 19% lower than individual natural gas boilers and 30–31% lower than individual water source heat pumps and individual biomass boilers. For district heating, efficiency is strongly influenced by a new or existing district heating system. It is estimated that new district heating systems have a more competitive heating price than individual heating solutions [43].

It is proven that by integrating individual renewable energy technologies into the district heating supply, higher efficiency, lower energy consumption and a more environmentally friendly heat supply can be achieved. Therefore, in order to achieve the set climate goals, district heating and individual heating solutions must be considered in their interaction and not separately. In Northern California, a study was conducted to analyse the benefits of district heating in low-energy buildings. It found that the highest efficiency was achieved by integrating geothermal heat pumps into a district heating system [28]. District heating's high efficiency was evaluated in the new district heating system with an electric compression heat pump or a wood chip boiler [43].

2. Data and Methodology

Assessment of sustainability requires an integrated approach and structure that is composed of several interlinked steps. As illustrated in Figure 1, the methodology of this study is constructed based on the three main pillars: (1) the identification of internal and external context influencing heat supply system sustainability, (2) the calculation of the composite sustainability index, and (3) the result analysis and decision-making procedure.

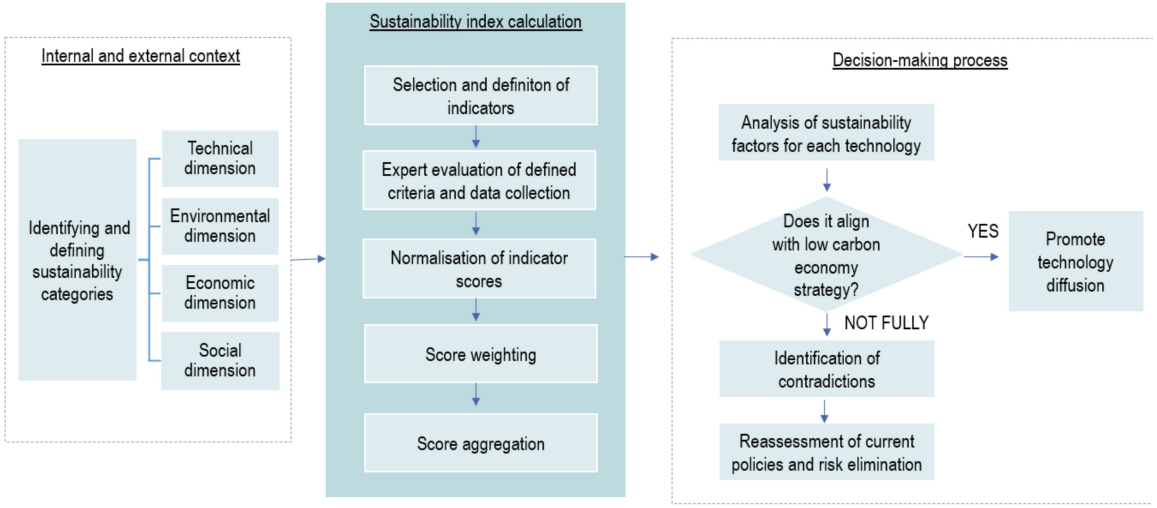


Figure 1. Model for the sustainability index construction and decision-making algorithm.

Identifying the internal and external context includes a literature review on the common practices of sustainability assessment of energy supply technologies to identify the main sustainability aspects and design a comprehensive research methodology.

The core element for the sustainability assessment is the construction of the composite sustainability index. In this study, the composite sustainability index is calculated for district heating (based on the natural gas) and four different technological solutions of decentralised (individual) heating such as: (1) the wood pellet boiler, (2) the natural gas boiler, (3) solar collectors, and (4) the heat pump. The choice of the heat supply

technological solutions was determined by the ability of the technology to ensure the necessary heat demand of a medium-sized household. The selection of individual heat supply solutions was based (1) on a Danish study on individual heat supply solutions, (2) on the availability of the data to create a complex index, and (3) on the sustainability of the heat supply solution. Among the individual heat supply solutions using a biomass source, the study evaluated wood pellet heating as a sustainable individual heat supply solution [43]. It was necessary to select individual heat supply solutions that are used at the household level and for which relevant and reliable data can be obtained. The study excluded consideration of the electrical heater since this application is usually used as an additional heating element and not as a primary heating supply source.

The sustainability index in the context of this study is defined as a tool that is composed of different indicators that measure the long-term sustainability of a heat supply system. The heat supply system is considered to be sustainable when the constructed heat production infrastructure and installed technologies are balanced with environmental, economic and social aspects of the economy [44].

The sustainability index calculation outcomes could be further utilised to make more constructive and reasonable decisions related to the achievement of long-term targets for a low carbon economy. The sustainability index results permit preliminary due-diligence of technology sustainability and identify possible controversies requiring immediate governmental intervention to eliminate risks associated with sustainability, and reassess current policies that govern the heat production sector.

2.1. Determination of Sustainability Dimensions and Selection of Indicators

Although there is no consensus amongst scientists and policy-makers on the main aspects that should be included in the sustainability assessment of energy supply technologies, the general sustainability framework suggests that different technological solutions should be evaluated with regard to their effects on three main dimensions of sustainability: environmental, economic, and social [45]. The sustainability framework is applied in this study, where general sustainability dimensions are combined with a technical dimension that represents the analysed technology's main performance parameters. As a result, the model includes four main dimensions: technical, environmental, economic, and social. Each dimension is composed of various descriptive indicators that are summarised in Table 1.

In total, 19 indicators were selected and grouped into representative dimensions. The indicators were selected and reassessed carefully to avoid the unnecessary bias of correlations among indicators.

The technical dimension represents the technology competitiveness, technical feasibility of district heating and different individual heating technologies. The technical dimension incorporates seven different indicators, such as heat production efficiency, complexity of technology maintenance, availability of necessary energy resources, opportunities for the diversification of utilised energy resources, possibilities for heat load optimisation, operational stability, and opportunities for utilisation of low-quality energy resources.

The environmental dimension outlines emission damage that heat supply technologies produce depending on their utilised energy resources and technical capacity to minimize the environmental impacts from production processes. Two main indicators are utilised to characterise the performance of environmental dimensions of technology such as specific CO_2 emissions and the complexity of flue gas cleaning.

The economic dimension includes all of the relevant cost positions that are associated with the specific heat production technology, such as the initial capital expenditure, service and maintenance costs, technology lifetime, energy resource costs, as well as the possibility to utilise surplus heat and opportunities for cost optimisation (e.g., the choice of the energy resource based on the most economically advantageous price in the market, opportunities for the economies of scale).

The social dimension represents both socioeconomic impacts of technology and consumer satisfaction levels with certain technology characteristics. The socioeconomic aspects are measured by technology's ability to create positive socioeconomic impact by promoting utilisation of local resources. The consumer satisfaction level is measured for overall comfort level, safety level (reduced risks of ignition, leakage, etc.) and to control over heat consumption.

Table 1. Selected sustainability indicators and classification into dimensions [9,23].

Dimension	Notation	Indicator Description	Source	Impact
Technical	tech1	Efficiency	Data	+
	tech2	Complexity of service and maintenance (availability of specialists on site, immediate prevention of risk situations)	Expert evaluation	-
	tech3	Stable availability of energy resources for sufficient heat production	Expert evaluation	+
	tech4	Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply)	Expert evaluation	+
	tech5	Possibility to balance the produced heat load (ability to respond to rapid seasonal and short-term changes in demand)	Expert evaluation	+
	tech6	Operational stability (stable heat supply to the grid, no or reduced heat disruptions)	Expert evaluation	+
	tech7	Opportunities for the utilisation of low-quality energy resources	Expert evaluation	+
Environmental	env1	Specific CO_2 emissions	Data	-
	env2	Complexity of flue gas cleaning	Expert evaluation	-
Economic	econ1	Capital investments (CAPEX)	Data	-
	econ2	Service and maintenance costs (OPEX)	Data	-
	econ3	Technology lifetime	Data	+
	econ4	Specific energy costs	Data	-
	econ5	Possibility to utilise surplus heat for optimisation of heat production and maximisation of resource efficiency	Expert evaluation	+
	econ6	Opportunities for cost optimisation (choice of energy resource based on most economically advantageous price in the market, opportunities for the economies of scale)	Expert evaluation	+
Social	soc1	Consumer comfort level	Expert evaluation	+
	soc2	Consumer safety level (reduced risks of ignition, leakage, etc.)	Expert evaluation	+
	soc3	Impact on the promotion of local resources (reduction of energy imports)	Expert evaluation	+
	soc4	Consumer control level over heat consumption	Expert evaluation	+

2.2. Data Collection and Expert Evaluation

Quantitative indicator values for each technology were determined based on two main approaches: quantitative and qualitative assessment. For the indicators where the specific values could be found from publicly available databases, scientific papers, research and reports, legislation, and technology data sheets, data were collected from relevant sources of information. These indicators were the following: technology efficiency (tech1), specific CO_2 emissions (env1), specific capital investments (econ1), specific service and maintenance costs (econ2), technology lifetime (econ3), and specific energy costs (econ4). All the utilised data inputs and data sources for quantitative indicators are listed in Table 2.

Table 2. Data and assumptions for district heating and individual heating technologies.

Indicator	Notation	Unit	Data Source	District Heating	Wood Pellet Boiler	Natural Gas Boiler	Solar Collectors	Heat Pump
Efficiency	tech1	%	[26,43]	100	80	92	82 *	257
Specific CO_2 emissions	env1	g/kWh	[46,47]	202	0	202	0 *	42 *
Capital investments	econ1	EUR		6175	10,740	6440	23,980 *	16,243
Service and maintenance costs	econ2	EUR/year	[27]	0 *	605	255	300 *	360
Technology lifetime	econ3	years	[27,48]	25	20	19	30	20
Specific energy costs	econ4	EUR/kWh	[27,48–51]	0.036	0.038	0.04	0 *	0.058 *

* authors' calculations.

Most of the data inputs for district heating, wood pellet boilers, natural gas boilers and heat pumps were taken from the Danish study [27,43] on the cost effectiveness of district heating compared to individual heating technological solutions. Due to limited data, the performance data in Table 2 were taken from the Danish Technology Catalogue and various sources in research [23]. This was the most reliable data for determining specific values for district heating technologies and for achieving the current research objectives.

Economic data on initial capital investments and yearly service and maintenance costs represent the average household expenditures with an annual heat demand of 13,800 kWh. Data for the heat pump represent the average values for ground and air heat pump parameters.

Data on solar collector nominal efficiency and technology lifetime were assumed based on average values observed from solar collector technology manufacturers' technical data sheets.

The efficiency of solar collectors was calculated using the following formula:

$$\eta = \eta_0 - \alpha_1 \frac{T_1 - T_2}{G} - \alpha_2 \frac{(T_1 - T_2)^2}{G}, \quad (1)$$

where η is solar collector efficiency [%], η_0 is zero heat loss efficiency of the solar collector [%], α_1 is the heat loss coefficient [W/m^2 K], T_1 is the average temperature of the solar collector [°C], T_2 is the air temperature [°C], G is the solar radiation intensity [W/m^2], and α_2 is the temperature-dependent heat loss coefficient [W/m^2 K^2]. The values for the coefficients η_0, α_1, α_2 were taken from data sheets of high performance plate solar collectors which correspond to the values from the study by [33]. Plate collectors are more widespread and used in the EU and Latvia. Table 3 summarizes the input data used to calculate the efficiency of solar collectors. To estimate the maximum potential of the solar collectors, the values for T_2 and G were determined for May, since solar radiation is highest in this month.

The solar collector absorption area was calculated by deriving the following equation:

$$\mathrm{Q\ (kWh)} = \mathrm{S} \cdot \eta \cdot \mathrm{R} \cdot \mathrm{PR} \quad (2)$$

where S is the solar collector absorption area [m^2], η is the solar collector efficiency [%], R is the average solar radiation intensity [kWh/m^2], and PR is the solar system heat loss factor (coefficient in a range from 0.9 to 0.95) (Table 4).

Table 3. Input data for the solar collector efficiency calculation.

Parameter	Value	Justification
η_0	81.7	According to technical specification in [33]
α_1	2.741	According to technical specification in [33]
α_2	0.0147	According to technical specification in [33]
T_1	70	Assumed average temperature value of solar collector in a range of (60–80) °C
T_2	12.4	Average temperature in Riga, Latvia in May according to Cabinet of Ministers Construction Standard LBN 003-19 "Construction Climatology" (entered into force on 21 September 2019)
G	172,540	Average solar radiation in May in Riga Latvia in the time period from 2015 to 2017

Table 4. Input data for the solar collector absorption area calculation.

Parameter	Value	Justification
Q	13,800	Assumed heat demand of an average household according to [27,43]
η	82	According to calculated solar collector efficiency based on technical specification of flat plate solar collectors in [33]
R	173	Average solar radiation in May in Riga Latvia in the time period from 2015 to 2017
PR	0.9	Assumed solar system heat loss factor (coefficient in a range from 0.9 to 0.95)

The investment costs for solar collectors were calculated for households with an average heat demand of 138,000 kWh, based on the average solar radiation in Latvia and assuming that the solar system's specific cost is 220 EUR per m^2 of the absorption area of the solar collector. For a heat demand of 13,800 kWh, the solar collector's calculated absorption area is 109 m^2.

Specific CO_2 emissions for wood pellet boilers and natural gas boilers were assumed based on the Latvian Cabinet of Ministers Regulation No. 42 on the methodology for Calculating Greenhouse Gas Emissions [47]. For the district heating unit, specific CO_2 emissions were determined assuming that all energy is produced by natural gas. For heat pumps, specific CO_2 emissions were calculated based on the specific electricity emission factor of 109 g/kWh [46], taking into account Coefficient of Performance (COP) of 2.57. Similarly, specific energy costs for heat pumps were calculated assuming the average electricity price is equal to 0.15 EUR/kWh [51] considering COP of 2.57. Therefore, both indicators—specific electricity emission factor and specific energy cost for heat pumps—were calculated by dividing the representative values of electricity price and emission factors with COP.

Specific energy costs for district heating and natural gas boilers were taken from the Central Statistical Bureau of Latvia and Eurostat databases given the average values for the year 2019. Specific energy costs for wood pellets were taken from price surveys of energy producers.

For the part of indicators that represented particular technologies' qualitative characteristics, the values were determined through an expert evaluation survey. Indicators were evaluated according to an 8-point impact scale as summarized in Table 5.

Table 5. Evaluation scales for the indicator assessment.

Score	Impact
1	None
2	Very low
3	Low
4	Relatively low
5	Moderate
6	Relatively high
7	High
8	Very high

In total, the assessment of qualitative indicators was carried out by a selected group of high-level industry experts who have gained extensive professional and scientific experience and knowledge in heat generation, heat supply, and the energy sector. The experts evaluated indicators based on the observations and knowledge obtained over several years of working on heat supply systems, energy-related projects and on-site objects. Each expert was asked to assign a score for each indicator based on the given impact scale. The final score for each technology was calculated as the mean of all the surveyed experts' assigned scores.

2.3. Data Normalisation

Results were normalised using a min–max normalisation technique. The min–max normalisation standardises the indicator values in the range (0–1) which allows comprehensive comparison of indicators that have different units of measurement [52]. The min–max normalisation is the most suitable for this study since the sustainability assessment in this study includes both quantitative and qualitative indicators.

The normalisation technique for each indicator depends on its impact on the sustainability index. An indicator can either positively or negatively impact the sustainability index. Therefore, at first, each indicator was assessed with respect to its impact on the sustainability index. The indicator has a positive impact on the sustainability if its increasing value increases the sustainability [53]. For example, higher efficiency has a positive effect on the overall technological performance of the technology and therefore it also increases the sustainability of the technology. However, the indicator has a negative impact on the sustainability if its increasing value decreases the sustainability of the technology. For example, higher specific emissions from the technology produces a negative impact on the sustainability and therefore decreases the sustainability of the particular technology. Figure 1 summarises the impact assessment for each indicator. Positive impact indicators are normalised using Equation (3), and negative impact indicators are normalised according to Equation (4).

$$I^{+}_{N,ji} = \frac{I^{+}_{act,ji} - I^{+}_{min,ji}}{I^{+}_{max,ji} - I^{+}_{min,ji}} \tag{3}$$

$$I^{-}_{N,ji} = 1 - \frac{I^{-}_{act,ji} - I^{-}_{min,ji}}{I^{-}_{max,ji} - I^{-}_{min,ji}} \tag{4}$$

where

$I^{+}_{N,ji}$ is the normalised value of positive impact indicator,
$I^{-}_{N,ji}$ is the normalised value of negative impact indicator,
$I^{+}_{act,ji}$ is the actual value of an indicator,
$I^{-}_{min,i}$ is the minimal value of an indicator among all the technologies,
$I^{+}_{max,i}$ is the maximum value of an indicator among all the technologies,
j denotes the specific sub-dimension,
i denotes the specific indicator in a particular sub-dimension.

Since the assessment of qualitative indicators has the specifically defined scale from 1 to 8 as indicated in the expert evaluation Table 1, then these values are taken as minimum and maximum values in the calculation during the normalisation procedure.

2.4. Weighting and Indicator Aggregation into Sustainability Index

Weighting is performed in order to proceed with indicator aggregation into representative sub-indices and the final composite sustainability index. After data normalisation, weights are assessed by a two-step procedure. At first, equal weighting is applied to calculate sustainability dimension sub-index scores using Equation (5). Then the analytical hierarchy process (AHP) method is utilised to account for the different impact scales of each dimension to the overall sustainability index using Equation (6).

$$I_{S,j} = \sum_{i}^{n} W_{ji} \times I_{N,ji}^{\pm}, \; W_{ji} = \frac{1}{n_{ji}} \tag{5}$$

where

$I_{S,j}$ is the dimension's sub-index value,
W_{ji} is the impact weight of indicators on the dimension sub-index (application of equal weighting),
n_{ji} is the number of indicators in a particular dimension.

$$I_{CSI} = \sum_{j}^{n} W_j \times I_{S,j} \tag{6}$$

where

I_{CSI} is the composite sustainability index,
W_j is the impact weight of the dimension sub-index on the composite sustainability index (determined from AHP).

The application of equal weights into dimension sub-index scores represents each indicator's equal contribution and importance on the overall performance of the representative dimension [54]; however, the method of analytical hierarchy process (AHP) was chosen when selecting weight values for sustainability index aggregation. Using the AHP method, it is possible to quantify the weight or significance of the relevant criteria. In the AHP method, the assessment is based on the pairwise comparison, evaluating the significance of the criterion in comparison with another criterion. The AHP consists of a formulation phase, a hierarchy structure, comparison of criteria pairs, weighting criteria, consistency checks and an analysis of the results obtained. Criteria are first defined, followed by a comparison of the significance of the criteria across the criteria pairs, assigning them values on a scale of 1 to 9 according to the Saaty rating scale that is summarized in Table 6. The weighting of the criteria is essential in further process to allow ranking alternatives [55]. Using the AHP method, it is possible to evaluate nine criteria at the same time [56].

Table 6. Saaty rating scale.

Score	Explanation
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

The AHP method was used to collect expert opinion on each dimension's impact on the overall sustainability. Experts were asked to compare four different dimensions according to which sustainability of technologies was compared. A calculations matrix

was created based on Equation (7) where all four criteria were supplemented with the raw data obtained from the expert surveys.

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \end{bmatrix} \quad (7)$$

According to expert opinion and after performing the AHP calculation procedure, the following weights were obtained for each dimension: technical is 0.38, environmental is 0.36, economic is 0.16, and social is 0.10. The obtained weighting values were validated by calculating the consistency ratio where the obtained results reached the necessary threshold of 0.1.

The application of different weighting methods was experimented with during the model development process and calculation procedures to check for the robustness of the obtained results. No significant changes in the overall distribution of results were observed when equal weights for the dimensions were given.

Figure 2 outlines the overall hierarchy of the developed composite sustainability index for the district and individual heating comparison.

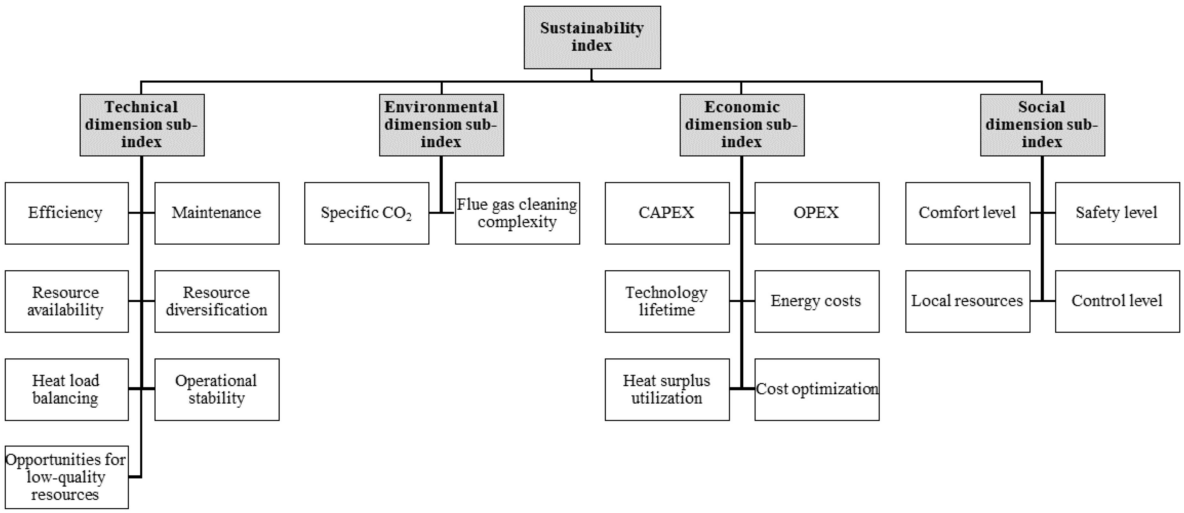


Figure 2. Basic hierarchy of the composite sustainability index [26,43].

3. Results

3.1. Technical Dimension Sub-Index

The highest technical dimension sub-index was obtained for district heating (0.64), followed by heat pumps (0.51), wood pellet boilers (0.50), and solar collectors (0.26), as illustrated in Figure 3. The absolute leader in the technical dimension was district heating which reached the highest values in indicators, such as opportunities for diversification of utilised energy resources (tech4), operational stability (tech6), and opportunities for the utilisation of low-quality energy resources (tech6). These results are consistent with the study by [27] and argues that opportunities for excess, low quality and waste heat utilisation are essential factors and benefits of district heating systems, raising their efficiency and competitiveness above other competing individual heating solutions.

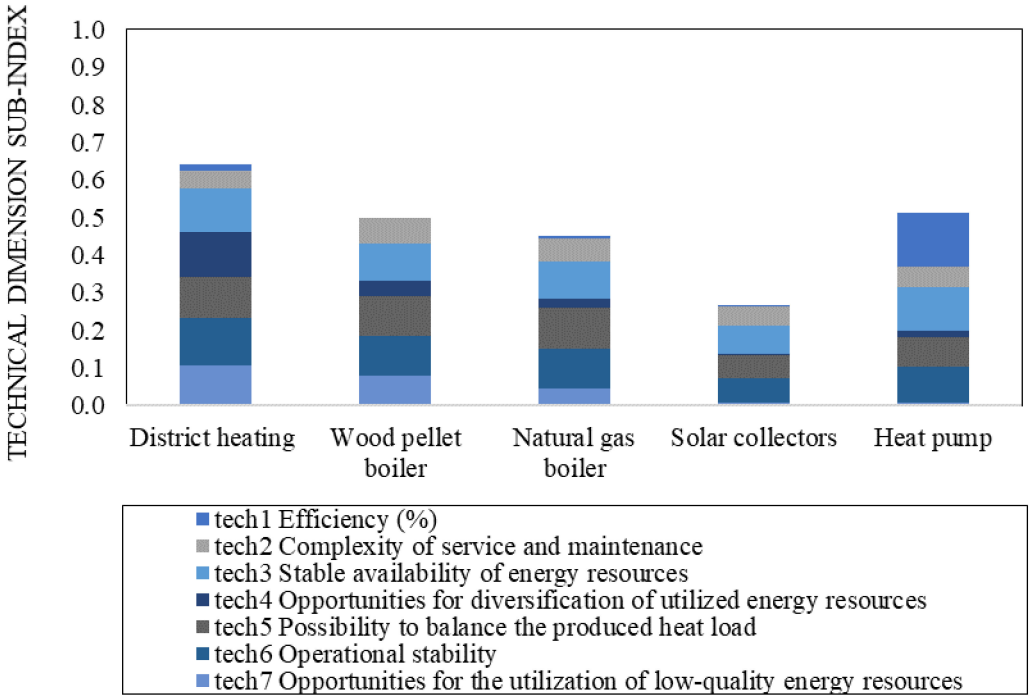


Figure 3. Technical dimension sub-index values [26,43].

Heat pumps reached the second-highest score in the technical dimension due to their highest efficiency ratio and equally high score for both stable availability of energy resources (tech3) and district heating since both technologies offer unrestricted access to energy resources. Compared to district heating, wood pellet boilers and natural gas boilers, heat pumps indicated slightly lower technical performance values for operational stability (tech6). Compared to district heating and wood pellet boilers, heat pumps indicated lower opportunities for diversification of utilised energy resources (tech4) and a lower possibility to balance the produced heat load (tech5).

The competitive advantage of both wood pellet boilers and natural gas boilers lies in their slightly lower complexity of service and maintenance (tech2) compared to district heating, solar collectors and heat pumps. Both wood pellet and natural gas boilers showed equally high scores for the possibility to balance the produced heat load (tech5) as the district heating unit.

Solar collectors reached the lowest scores in technical dimension due to their inability to diversify utilised energy resources (tech4), and lower operational stability (tech6): also, they have substantially lower constant availability of necessary energy resources (tech3) compared to other heating solutions that are particularly relevant for Nordic region countries with a colder climate.

3.2. Environmental Dimension Sub-Index

Renewable energy technologies reached the highest environmental dimension sub-index values: solar collectors with a score of 1.0, heat pumps with 0.70, and wood pellet boilers with 0.64. The lowest sustainability score in the environmental dimension was reached by natural gas boilers (0.23) and district heating units (0.16), determined by indicators such as the degree of complexity of flue gas cleaning and specific CO_2 emissions (see Figure 4).

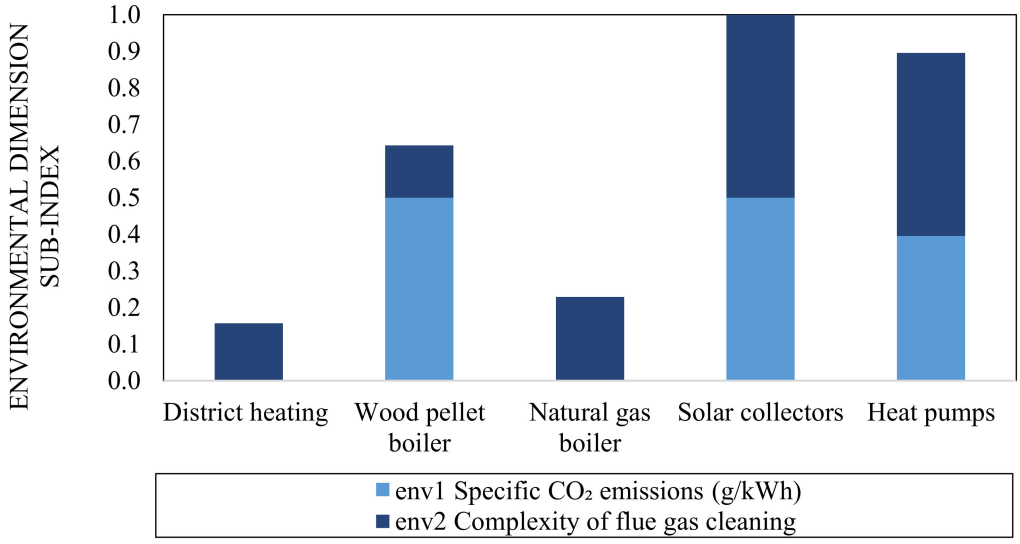


Figure 4. Environmental dimension sub-index values [26,43].

Solar collectors achieved the highest possible sustainability sub-index value in the environmental dimensions as the solar thermal system does not require flue gas cleaning in the heat supply process and does not generate CO_2 emission during the heat production processes. Similarly, the heat produced by the heat pumps does not require flue gas cleaning. However, since the heat pumps' operations consume a considerable amount of electricity, the CO_2 emission factor is applied for electricity consumed from grids, thus making heat pumps less competitive compared to solar collectors in the environmental dimension of sustainability.

Wood pellet boilers indicated lower environmental dimension sub-index values compared to other renewable technologies. Despite the CO_2 emission neutrality, wood pellet boiler operations and combustion processes produce other emissions such as exhaust particulate matter (PM) and specific NO_X emissions, therefore making higher complexity of flue gas cleaning [43]. The lowest environmental dimension sub-index values were observed for both natural gas boilers (0.23) and district heating (0.16). For both technologies, the same emission factor was used. It was assumed that natural gas is used exclusively as the main source of energy for district heating since no accurate information on the amount of renewable energy sources used in the district heating in Latvia was available. The experts evaluated the complexity of flue gas cleaning as higher for district heating than natural gas boilers, resulting in a slightly decreased overall environmental dimension sub-index value for district heating. If a more precise emission factor were used for district heating, taking into account the share of renewable energy sources used in heat production, the overall heat performance in the environmental dimension would also improve.

3.3. Economic Dimension Sub-Index

The highest economic dimension sub-index value was achieved by district heating units (0.77), as illustrated in Figure 5. Solar collectors achieved the second-highest economic dimension sub-index score (0.52), followed by natural gas boilers (0.42), and wood pellet boilers (0.34). The lowest sub-index score in economic dimension was reached by heat pumps (0.29). District heating substantially surpassed its competing technologies in indicators for capital investments (econ1), service and maintenance costs (econ2), possibility to use surplus heat (econ5), and cost optimisation options (econ6) as well as specific energy costs (econ4) that ranked district heating in the leading position of the economic dimension sub-index. Overall, district heating shows the highest economic and cost efficiency compared with individual heating technologies.

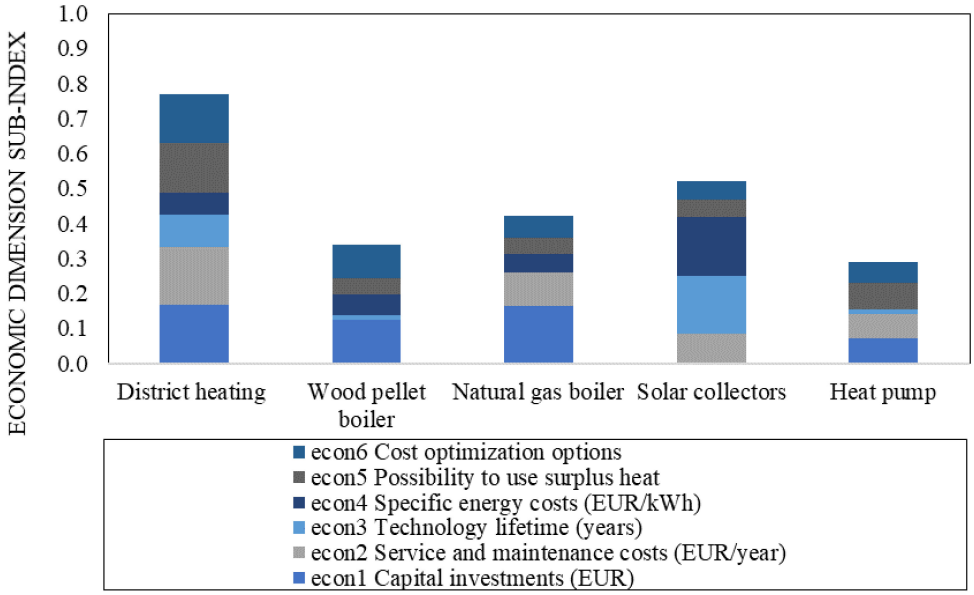


Figure 5. Economic dimension sub-index values [26,43].

Initial capital investments for natural gas boilers are significantly lower than for solar collectors to match the average household's heat demands, therefore improving the overall sub-index score for natural gas boilers. By comparison, the solar collectors reached the lowest specific energy costs since it is the only technology that does not require the purchase of external energy sources to produce heat. Heat pumps indicated the lowest score in the economic dimension sub-index mainly due to considerably higher specific energy costs (econ4), capital investments (econ1), and a lower technology lifetime (econ3).

Compared with other technologies, wood pellet boilers indicated the highest service and maintenance costs (econ2) and specific energy costs (econ4) that negatively impacted the overall economic dimension sub-index score. A lower technology lifetime (econ3) and fewer possibilities to utilise surplus heat (econ5) also hindered the overall economic dimension score for the wood pellet boilers, ranking it in the lowest position of the economic dimension sub-index overall.

3.4. Social Dimension Sub-Index

Overall social dimension sub-index scores are less distributed compared with the other sustainability dimensions (see Figure 6). The highest sustainability sub-index was reached by the solar collectors (0.8). Equally high results (0.77) were achieved by three technologies: district heating, wood pellet boilers, and heat pumps. The lowest social dimension sub-index score was obtained by the natural gas boilers (0.58).

District heating reached the highest indicator values for consumer comfort level (soc1) and consumer safety level (soc2), which can be explained by the fact that in district heating, an operator is providing consumers with a certain level of comfort and safety but for technologies with individual heating solutions, all responsibility lies with the consumer. By contrast, the indicator value for consumer control level over heat consumption (soc4) was assessed to be the lowest for the district heating. Unlike the individual heating solutions, in district heating, supplied heat amounts are controlled by the grid operators, not the end-users. In total, the social dimension sub-index scores for district heating indicated that it can offer high user convenience as an individual heating solution. These results are also supported by findings from the study by [41] that show that consumers are willing to pay more to utilise district heating instead of switching to individual heating solutions due to higher convenience and loyalty to the district heating supply system.

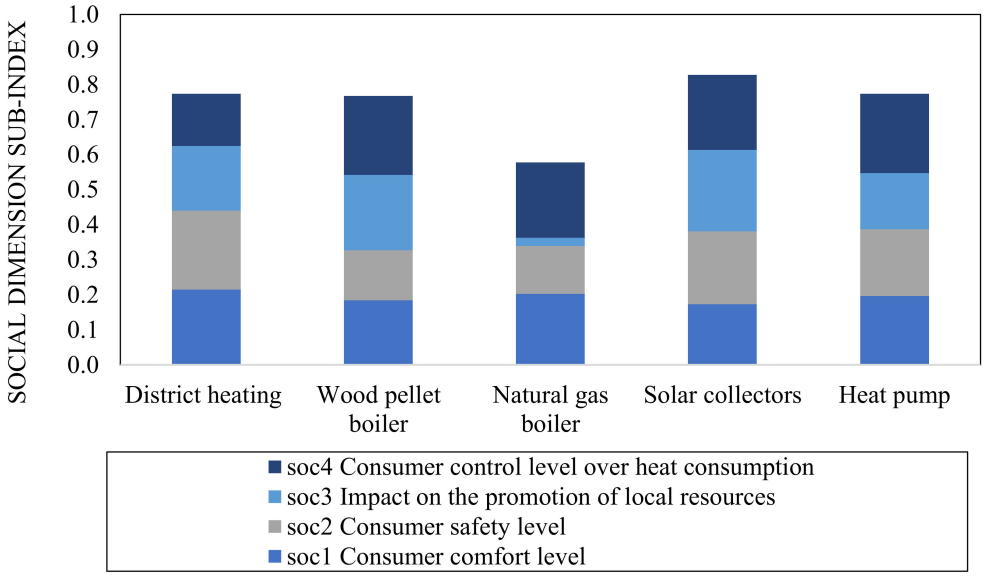


Figure 6. Social dimension sub-index values [26,43].

The total score of the social dimension sub-index for solar collectors surpassed district heating and other technologies due to their ability to combine two essential aspects: consumer satisfaction levels with safety and control over heat consumption, and promotion of local resources. Consumer comfort level (soc1) was indicated the lowest for the solar collectors compared with other technologies. That could be partly attributed to solar energy's periodicity and the necessity to compensate for the lack of solar energy with other heat supply technologies.

Both heat pump and wood pellet boiler technologies obtained the highest scores for consumer control level over heat consumption (soc4). Wood pellet boilers indicated a substantially higher score for impact on the promotion of local resources (soc3), which was the lowest for natural gas boilers. However, unlike the other technologies, the wood pellet and natural gas boiler technologies indicated the lowest scores for the consumer safety level (soc2), possibly associated with risks such as leakage or other type of accidents that could, in turn, affect the consumers' choice of these technologies.

3.5. Composite Sustainability Index

The highest composite sustainability index was rated for individual heat supply technologies which utilise renewable energy, use local resources and can be used in order to achieve the climate neutrality goals: heat pumps (0.64), solar collectors (0.63), and wood pellet boilers (0.55). A slightly lower sustainability index was estimated for district heating (0.50), but the lowest sustainability index was obtained by natural gas boilers (0.38) that utilise fossil fuels as the main energy source as opposed to a low carbon transition strategy.

Figure 7 shows the result distribution by the dimension sub-index categories for each technology. The composite sustainability index results identify the competitive advantages for each technology, as well as critical positions that currently hinder the achievement of higher sustainability.

Due to remarkably higher technical efficiencies and environmental benefits, the heat pumps represent the highest sustainability, despite having the lowest score in the economic dimension compared to district heating and the other individual heating technologies. However, the heat pump installation choice as the main heat supply technology is influenced by the higher initial investment and specific energy costs. Likewise, the wood pellet boiler's score is affected by specific energy costs and service and maintenance costs, which pose a negative impact on higher technology market diffusion.

District heating is the absolute leader in technical and economic dimensions, indicating higher technology efficiency and economic viability compared to the individual heating

solutions. District heating indicated equally competitive social dimension sub-index values by showing high indicator values for consumer safety and comfort levels.

Although the solar collector indicated the second-highest sustainability score due to its high performance in the environmental dimension, the inconsistent solar energy supply technology requires additional heating solutions to get sufficient heat coverage which is also represented in lower values of the technical dimension sub-index. Despite the widespread public perception that solar collector installation can only be afforded by high-income households, the results show that, in terms of economic dimension, solar collectors are the second most sustainable technology after district heating.

The authors argue that due to the considerably low impact of the economic dimension sub-index on the overall composite sustainability index, the lowest economic sub-index scores for the heat pump did not significantly affect its overall sustainability scores. Therefore, in further studies, it is suggested to perform a more detailed investigation and scenario analysis in applying different weights for the representative dimensions.

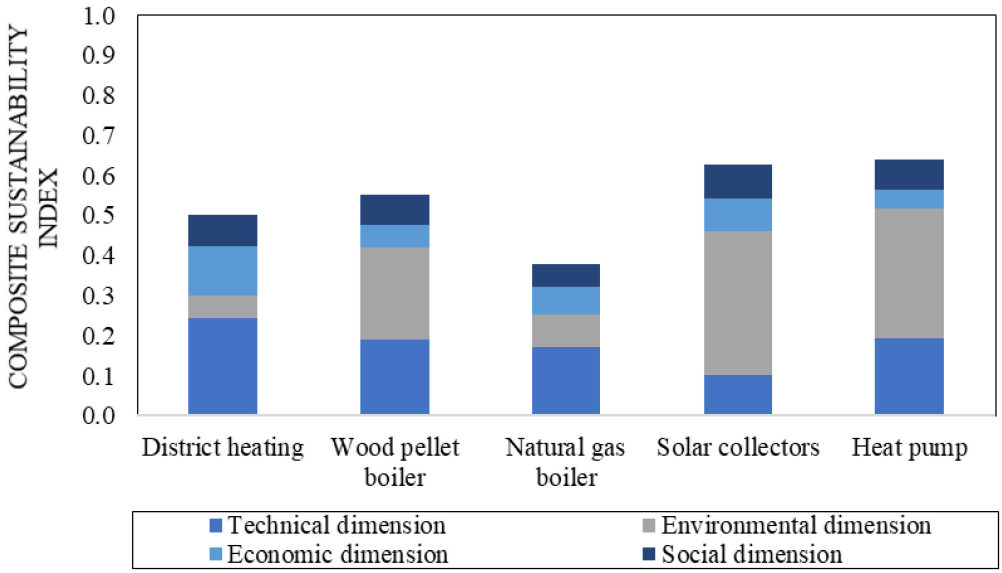


Figure 7. Composite sustainability index values [26,43].

3.6. Identification of Controversies and Blind Spots in Energy Policies

The study highlighted several potential blind spots of a sustainable energy supply system. One of the blind spots is represented in the environmental dimension of the composite sustainability index. In the calculations of the environmental dimension sub-index for district heating, a natural gas emission factor was used without considering the RES share in district heating. As a result, district heating achieved the lowest environmental dimension sub-index value. Moreover, due to higher flue gas cleaning complexity, the environmental dimension results ranked district heating lower than the individual natural gas boilers. It is essential to take into account that the actual emission factor of district heating could be achieved at a significantly lower level than it is generally portrayed in the studies or legislation if the share of RES would be increased. The results showed that district heating obtained the highest sustainability scores for all dimensions except for the environmental dimension, indicating that higher sustainability could be achieved by cutting the utilisation of fossil energy resources, such as natural gas, for combustion processes and replacing them with renewable energy sources.

District heating is proved to serve as one of the most effective solutions in energy system decarbonisation since it provides unlimited opportunities for more efficient and sustainable utilisation of energy resources. With new generation technological solutions, it is possible to diversify the district heating supply system by using cleaner technologies, such as renewable geothermal energy technologies, solar collectors, large-scale heat pumps,

and by increasing energy efficiency by utilising the surplus heat from different industrial processes [57]. Moreover, biomass such as wood and agricultural residues could be used as primary energy resources to decarbonise district heating. For example, in Sweden, the district heating mostly utilises wood, sawdust and wood chips, followed by wood pellets and briquettes. In addition, bio-oil, wood residues, and by-products from pulp production, such as tall oil, are also used as fuels. Decarbonisation of district heating has helped to significantly reduce CO_2 emissions in Sweden, which have diminished from 90 g/MJ in the 1970s to 9 g/MJ in 2014 [58].

Another controversy over the district heating environmental impact compared to individual heating solutions is outlined in a study by [37] which concludes that in countries where a large proportion of heating consists of burning local biomass resources in individual stoves, the issue of air quality and decontamination is more crucial than the decarbonisation of the heat supply system. Although high biomass consumption is considered a sustainable solution since it is a renewable energy resource, its combustion inefficiency and significantly higher PM emissions production negatively influence air quality, especially in urban areas. Therefore, district heating could serve as the most efficient solution to coordinate collective decontamination and decarbonisation of the heat supply system.

Findings from the paper by [57] therefore challenge the obtained results of this study, indicating that even though district heating performed poorly in the environmental dimension of the composite sustainability index, by looking at the perspective of created air pollution, the DH sustainability is higher compared to wood pellet boilers. Although wood pellet boilers are promoted as one of the most sustainable individual heating technologies due to its carbon neutrality, its generated PM emissions are substantially higher than those of other technologies, which is reflected in the higher complexity of flue gas cleaning. According to experts, the pellet boiler has the highest flue gas cleaning complexity among the technologies. Considering that PM particles are a significant factor influencing the environment, but are formed in small amounts or not at all (solar collectors) in other considered technological solutions of heat supply, it was not considered separately in the environmental dimension. The model includes the complexity of flue gas cleaning as an indicator, which includes the PM particles' influence. Flue gas cleaning was included as an indicator as it applies to both individual gas boilers, district heating boilers and wood pellet boilers, with PM being most relevant for pellet boilers. Another reason for not including PM particles as an indicator in the environmental dimension was that it is possible to technologically reduce PM particles from flue gases, e.g., through filters, which is considered difficult but can reduce pollution and improve the environmental dimension through treatment plants. Therefore, in the case of the pellet boiler, it would be essential to consider the various treatment methods used if the PM particles produced were used as a separate indicator in the environmental dimension.

Although the use of wood pellet boilers is considered to be environmentally friendly, the combustion of wood biomass generates a significant amount of particulate matter (PM) and the flue gases must be cleaned of PM emissions before being released into the atmosphere. The composite sustainability sub-index in the environmental dimension for the wood pellet boiler could be higher if the complexity of flue gas cleaning would be reduced. Therefore, in order to increase environmental sustainability, it would be necessary for consumers of pellet boilers to identify technologies that would be able to clean flue gases from PM as efficiently as possible. Nevertheless, efficient flue gas cleaning for the pellet boilers is influenced by the fact that flue gas cleaning and equipment maintenance is completely dependent on the consumer; therefore it would be necessary to develop certain standards to ensure higher cleaning efficiency of wood boiler equipment. For example, studies have estimated that ceramic filters can remove up to 96% of $PM_{2.5}$ and PM_{10} particulate matter from flue gases and therefore can be used effectively to clean wood boiler flue gases; moreover, the ceramic filters are assessed as effective in achieving climate goals [59]. In addition, to ensure higher efficiency of wood pellet boilers, it is

necessary to regularly clean the boilers to reduce the ash content and operate the boiler at a higher load [60].

A study by [58] outlines additional contradictions regarding the choice of the most sustainable energy policy. Current policies supporting decarbonisation of heat supply systems significantly push district heating towards a higher utilisation of biomass, thus increasing the share of renewable energy sources in heat production. However, high biomass utilisation in heat-only boilers contradicts the energy efficiency opportunities offered by district heating units that allow utilising recovered heat from primary processes. Policies that favour the use of renewable energy sources force district heating to switch to biomass instead of heat recovery, which is especially true if heat is produced from fossil energy resources. Substituting secondary heat with primary energy reduces the share of fossil energy resources by a minimal amount and therefore has a lower impact on reaching climate neutrality targets [57,58]. These findings are supported by the sustainability index results that showed the highest sustainability level for heat pumps.

There is conflicting information in the literature as to whether district heating systems are more expensive. From the perspective of policy-makers, district heating is often criticized for the system's high cost compared to individual heating solutions [41]. Using the results obtained in the study, it was found that district heating has the lowest costs among the heat supply technologies, which is reflected in the highest sustainability indicators in the economic dimension.

3.7. The Value of Research for Further Practice

The use of a sustainability index could improve the decision-making process for policy-makers when implementing energy policies. The composite sustainability index method can serve as a useful tool to determine which technologies need or should be promoted. Most importantly, it can help identify the critical aspects of each technology that need to be addressed in order to avoid potential blind spots in energy policies.

During research, a methodology was developed for evaluating a complex sustainability index using reliable data sources and weighting the dimensions using the expert survey method. The developed methodology can be adapted by assigning equal weights rather than using expert interviews, but this did not significantly change this study's result. The sustainability of the most popular heating solutions was quantified by considering four dimensions: technical, environmental, economic and social. Information on the advantages and disadvantages of each heating solution can be found in the literature, but in this study, the specific heating solutions are evaluated in four dimensions by creating several indicators that make it possible to evaluate each dimension and the overall sustainability of the heating systems and to determine whether these heating solutions will achieve the emission reduction targets set by policy-makers.

The study can serve as a potentially viable method for evaluating the specific problem, taking into account all relevant dimensions, each of which is assessed using indicators that quantify each dimension and the overall sustainability index. The study serves as a test case to analyse other identified contradictions in energy policy in this way. This method can be used to assess controversial issues and uncertainties in energy and other sectors such as bioeconomy. In this way, policy-makers can think in several dimensions and avoid the risks of unforeseen blind spots without underestimating any of the dimensions.

4. Conclusions

The composite sustainability index was constructed to compare sustainability levels of district heating with four different individual heating solutions: wood pellet boilers, natural gas boilers, solar collectors, and heat pumps. A wide range of indicators were selected, including both quantitative and qualitative assessment methods. The sustainability index was composed of 19 different indicators that were grouped in four sustainability dimensions: technical, environmental, economic, and social. Indicators were normalised using a min–max normalisation technique that scaled sub-indices and index values in a

range of [0;1], allowing comprehensive interpretation of the obtained results. The criteria were weighted using an AHP weighting technique. According to the industry experts' assessment, technical and environmental dimensions were evaluated as the most essential determinants of a heat supply system's sustainability. After the model approbation process, it was concluded that it is important to carefully select indicators to obtain an objective assessment of technological solutions and consistent calculations.

The study presented the importance of including several aspects in the analysis since the distribution of results for each dimension showed significant differences among technologies. Blind spots often arise due to solely looking at one-dimension factors; however, in the sustainability assessment, technical performance indicators must be analysed in the context of economic, environmental and social aspects, combined.

The highest sustainability index was obtained by heat pumps (0.64), followed by solar collectors (0.63), wood pellet boilers (0.55), and district heating (0.50). The lowest index value was obtained by natural gas boilers (0.38).

The results indicated that district heating is highly competitive and cost-efficient compared to individual heating solutions since it obtained the highest sustainability scores for the technical and economic dimension sub-indices. However, a potential blind spot was identified in environmental dimension sub-index values where district heating reported poor values due to higher flue gas complexity and emission factor assumptions made during the calculation procedure. The results showed that higher sustainability for the district heating could be achieved by cutting the utilisation of fossil energy resources, such as natural gas, for combustion processes and replacing them with biomass.

The discussion of the results concluded that, although there is an increase in biomass utilisation in district heating as well as the installation of wood pellet boilers, they seem to be a sustainable and environmentally friendly alternative due to their positive impact on carbon neutrality targets, and policy-makers should put more emphasis on finding sustainable ways to promote flue gas cleaning and air decontamination from biomass combustion processes.

The utilisation of a sustainability index could improve policy-makers' decision-making processes during the implementation of energy policies. The composite sustainability index method can serve as a useful tool for determining which technologies should be promoted. Above all, it can help identify the critical aspects of each technology that need to be addressed to avoid possible blind spots in energy policy.

The state of knowledge significantly influences the objectivity of the research results based on the literature about which advantages district heating systems and individual heating solutions have, which disadvantages, which current trends there are, and which blind spots in the political decision-making process can result from underestimation or evaluation based on only one aspect without joint consideration of all dimensions.

The success of the study depends mainly on which indicators are selected and which data sources are used: whether they are representative and whether they are based on the literature; whether it is possible to use them to make an objective assessment of all dimensions; whether the indicators chosen characterise the sustainability of the systems or, on the contrary, show their inefficiency; and whether it is possible to create a complex environmental sustainability index based on the selected indicators, which can be compared with each other.

The results could be influenced by the participation of industry experts who are able to objectively evaluate and compare heating solutions. In this study, only experts from the energy sector with the relevant knowledge and experience in heating supply issues participated in the expert interviews. In this study, less importance should be given to the experts' weighting, as the results obtained by additional analysis and by assigning the same weight to all dimensions did not change significantly.

Data availability was one of the major limitations of this study. The collection of reliable and relevant data in this study was limited in terms of sources. If it had been possible, the authors would have certainly selected multiple sources and then combined

them to obtain the final data. Since it was not possible to find other data sources as reliable as those used in the study, based on specific values for home heating solutions in the Danish Technology Catalog and the calculations and assumptions clearly presented in the study, the authors decided to use data from the Danish research.

The study does not consider whether it is an existing or new district heating system. According to literature, new district heating systems are evaluated as very efficient systems, so this could be one of the factors that should be considered when evaluating the sustainability of district heating systems.

The study does not take into account whether the technologies considered are used in urban areas or outside cities, as no specific cases are considered, but the sustainability of the technologies is evaluated. Nevertheless, based on the literature, technological solution choice is also significantly influenced by the geographical location and the distance to the connection possibility to district heating networks.

The results of the study are influenced by the assumption that only natural gas is used in district heating, regardless of the fact that renewable energy sources are also used in district heating. However, the results obtained show the trends and according to which indicators district heating is more sustainable compared to other heating solutions.

The drawback of the study is that no data are available to determine the sustainability of heating heat pumps, solar panels or wood pellets in district heating. National policies and incentives for district heating or individual heating solutions were not considered as this was not the aim of the study, but these factors should be considered in further studies.

This is one of several studies planned to analyse contradictions in energy policy. Further research is linked to the analysis of other contradictions in energy policies, assessing sustainability and the factors that contribute to or hinder the achievement of climate goals. Further research would be needed at the national or regional level, taking into account the share of renewable energy sources in district heating, the policies implemented in the field of renewable energy and district heating, and whether the dimensions of sustainability are taken into account in the decision-making. The role and use of renewable energy sources in district heating vary from country to country and this is a factor that has a significant impact on the sustainability of district heating.

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