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Renewable District Heating Strategies to Enhance Economic Feasibility, Efficiency, and Sustainability

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ABSTRACT

The implementation of Renewable District Heating systems (RDH) is crucial for the shift toward sustainable and low-carbon energy systems. These systems significantly enhance greenhouse gas emission reduction, and energy usage efficiency, while accomplishing these goals in urban contexts. Nonetheless, several barriers pertaining to their cost effectiveness and operational efficiency prevent universal adoption. This project sets out to find innovative methods of enhancing the economic, operational, and environmental sustainability of RDH networks.

In urban areas, changing from traditional heating systems to novel alternatives that use renewable energy sources presents both difficulties and chances. This paper examines the case for integrating solar thermal, biomass, geothermal, and recovered industrial heat into district heating systems on the basis of economic, technical, and policy feasibility. Comprehensive research focuses on examining pricing and cost structures, policy subsidization, operational models in order to find ways to make renewable district heating networks more economical, operationally effective, and environmentally sustainable.

Moreover, this study also outlines the importance of key socio-economic stakeholders, including energy providers, local governments, and consumers/prosumers, in this change. The main goal of the research is to devise strategic solutions to issues such as high upfront investment costs, infrastructure modification difficulty, and regulatory hurdles by examining new financial models, effective compliant systems, and modern technology. Using scenario modeling and detailed case studies, this research identifies practical ways through which the production, distribution, and storage of heat in cities can be greatly improved.

These findings have significant implications for carbon emission reduction in the context of providing long-term energy security for densely populated regions as it furthers the understanding of implementing renewable heating solutions. The H 2020 COMETS(Collective action Models for Energy Transition and Social Innovation)[[34](#)]

project innovations are instructive to policymakers, city planners, and energy firms that seek to improve the district heating systems in a sustainable, resilient, and cost-effective way.

Achieving these goals requires examining the biomass of agricultural and forestry residues, geothermal energy from underground heat, solar energy from novel photovoltaic and thermal systems, and waste heat from industries and municipal refuse. In essence, all these energy sources will be analyzed for their feasibility as inputs in current and prospective District Heating Systems (DHS).

The ongoing interventions adopt sophisticated optimization modeling and simulation tools with a view to demand-side management so as to achieve an equilibrium between energy supply and demand. The other research deals with several thermal storage technologies that can store surplus energy in insulated tanks in the form of heat and in various phase change materials for future use. Another aspect of this research is to look into sector coupling, which unites the heating, electricity, and transport sectors in a bid to maximize overall system efficiency and resource utilization.

The third element of the problem statement examined in this research lies in RDH viability in different countries which also includes an analysis of the economic and policy prerequisites for its feasible development in every specific case of district heating deployment. They contain targeting features such as the tariff structure which allows for demand responsiveness, investment supports for renewable energy technologies, and trading as well as balancing services markets for electricity and network stability. Using case studies of European cities which constructed RDH, we give an example of the impact of smart control, predictive maintenance, and decentralized energy management on operational efficiency and reliability.

The purpose of this research is to identify the most critical strategies that simultaneously enhance the viability and performance of renewable district heating systems while lowering carbon emissions and achieving sustainable development of urban energy systems. Achieving these goals breaks new ground in providing effective scalable solutions for modernized district heating networks and, hence, makes a notable contribution towards achieving more energy-efficient and environmentally friendly cities. As an endeavor to understand the implications of the combination of both technical and economic factors, this research intends to define steps that local government officials, energy system engineers, and other stakeholders can take in order to achieve sustainability. This is done with lots of aim to change the performance of the primary systems.

This thesis offers critical aspects of improving the competitiveness and resilience of RDH systems, decreasing carbon emissions, and attaining long-term sustainability. This work is equally efficient in solving the problem of developing scalable innovative solutions for the next generation of district heating networks and contributes to the energy efficiency and sustainability of urban infrastructures.

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1.INTRODUCTION

The adoption of energy technology has undergone a global transformation due to the growing concern with climate change, energy caps, and the scarcity of resources. Out of all the sectors that emit carbon, heating—particularly in urban centers where people greatly exceed the land available to them—is one of the largest consumers of energy. Traditionally, coal, oil, and natural gas have provided the underpinning of the urban heating infrastructure. All these, however, pose a host of environmental issues including colossal greenhouse gas (GHG) emissions, air pollution, and overdependence on fossil fuels. Due to these issues, companies around the world are turning to renewable sources to assist in the development of decarbonization targets and provide heating systems.

Renewable district heating (RDH) is much more appealing aesthetic wise than conventional heating systems. These types of heating systems draw from renewable sources such as solar, biomass, geothermal, and even capture heat from industrial sources. This results in lowered carbon emissions as well as raising energy efficiency levels simultaneously. Furthermore, the novel district integration networks tend to improve the capacity of integrating multiple energy sources and positively impact system adaptive capacity and economic efficiency. Nevertheless, while it is encouraging, the shift from traditional fossil fuel focused heating systems to renewable sources of energy is challenging, particularly in densely populated metropolitan areas. Some of the barriers include infrastructural gaps, funding constraints, regulatory hurdles, and complex stakeholder participation.

The objective of the investigation is to analyze the issues and opportunities of adoption of alternative heating technologies in the metropolitan areas. It will further analyze critical factors such as cost structure, policy, and business model and ascertain their bearing towards the success of implementation of RDH. This research will also be concerned with the role of socio-economic factors, such as energy suppliers, local authorities and citizens, in determining the course of change. This study tries to find solutions on how urban spaces could effectively preposition themselves for the deployment of renewable district heating networks by best practices and design methodologies systemically.

1.1. Problem Statement

Shifting away from fossil fueled based heating systems to renewable ones comes with various distinct technology and cost related issues. One major challenge is the required investment at the start, which is quite large for upgrading the needed infrastructure and modifying the utilization of the renewable energy. Many urban districts already possess heating systems that rely on fossil fuels so the transition is expensive and complex. In addition, the absence of reliable funding coupled with the fluctuating cost of renewable energy makes economic feasibility a lot more challenging.

Even though policy frames make these transitions easier, there remain many areas that still lack adequate policies and regulatory frameworks supporting renewable district heating. In most cases, the subsidies or incentives that come with fossil fuels are far greater than those associated with renewable energy option, creating a distortion in competition. In addition, the governance

of urban energy systems tends to be very fragmented along the multiple parties' competing interests, which makes coordination even more difficult. Thus, understanding the prevailing economic, technological, and societal conditions enabling the renewable district heating (RDH) system and formulating these obstacles is fundamental to developing adequate approaches. The goal of this research is to address this deficiency by outlining several transitions path ways, estimating the cost of each pathway, and determining the critical enabling factors for the effective implementation of RDH. Besides this, the research will develop change policies aimed at stimulating investment interest on one hand, and ensuring sustainability on the other.

1.2. Research Objectives

The assessment at hand is concerned with understanding the problems present, their economic costs and context, the legal and administrative structure, the operational context, participation, and devising implementation strategies. For this case, the focus will be on the integration of fossil fuel-based heating systems into renewable district heating (RDH) systems in large metropolitan clusters, especially the technical and economic and policy boundaries set on them.

This study will pay particular attention to the evaluation of price and cost components of the RDH which include quantitative investment, operational expenditure, as well as grant and subsidy payments. It will examine the active policies and other supports or incentives already in place which affect the use of RDH and seek policy ways to augment them. Some of the ways to enhance the efficiency of RDH, such as demand-side management, thermal energy storage, and sector coupling, will be analyzed. The local energy suppliers, the government, and consumers' contribution towards the change will be evaluated, as well as how to improve stakeholder cooperation. In the end, a few recommendations will be made so that municipalities and policymakers are better able to support an efficient and effective change to RDH.

1.3. Significance of Study

This is of great importance especially because it tackles a complex issue of decarbonization in the heating sector. This effort will be useful in analyzing the impacts on climate change by looking at how renewable district heating (RDH) systems are used. The results will be helpful for various policymakers, urban planners, energy corporations, and researchers who wish to appreciate the economics and efficiency of renewable heating systems.

Moreover, this study elaborates on the important role that cities can play in carbon mitigation while enhancing energy security and affordability for their citizens. The recommendations that are made will give directions to the relevant government departments and other stakeholders on how to develop effective policies and investment frameworks for the implementation of RDH systems. The aim here is not only to promote environmental sustainability, but also to make the process of transitioning to renewable heating sources as beneficial and seamless as possible for the community.

2. LITERATURE REVIEW

Focusing on the domestic aspect, renewable district heating systems need to be modified for each of the country's features and intricacies while attending to the economically vulnerable. For achieving energy efficiency and renewable district heating projects, incentive schemes combining partial investment grants or reimbursement payment contracts (involving subsidized and tax exempted interest rate) together with rising finance options should be provided for as the core of these schemes that are most commonly implemented through financial brokers which for the public sector include development, commercial and community banks, and in the case of the tax authorities provide tax expenditures, cuts, or reliefs. Other public sector institutions or Government declared private sector priority institutions (ecology or energy efficiency funds, energy agencies, etc.) and even private sector such as appliance and fuel suppliers or power plants.

Figure 1.1: Framework for sustainable heating

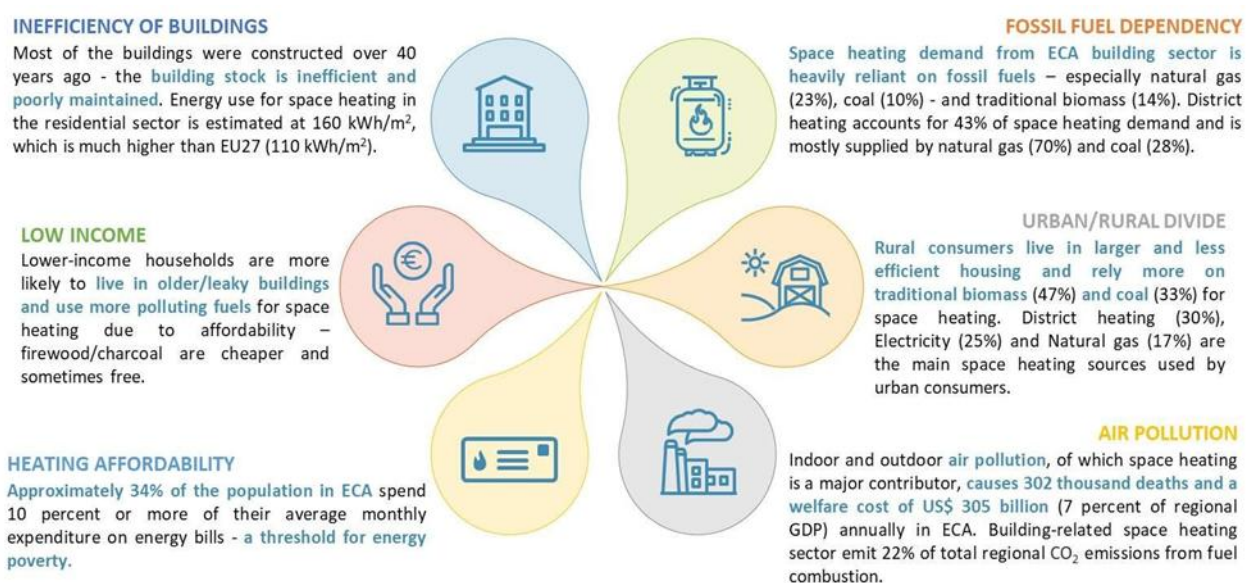


Source: <https://documents1.worldbank.org/curated/en/099092023140527206/pdf/P1777440fed3230ce089060ff8ce59c9f5e.pdf> (2023)

If funds are made available, the integrated institutional framework like renewable energy supporting a particular fund can meet its targeted objectives on time. An organization can function as a specialized centralized unit for the collection and dissemination of information, knowledge, and finances for district heating powered by renewable energy sources. Funding initiatives themselves also require additional supporting elements that will market the programs, enroll people, alter behaviors, disseminate lessons and materials, and reduce

transaction costs such as auditing, training, monitoring, and even reporting. Also, government programs must include elements to assist the poor by employing adequate financing, delivery methods, outreach, and gender. The countries need to develop certain approaches and schemes that would seamlessly shift toward sustainable heating. Without such methods, we can hardly expect developing effective policies, market structures, or even investment opportunities. Moreover, without a coordinated picture of government working together with businesses, households, utilities, and others, heating system investment choices would be less than optimal. Such approaches assume the same problems of clean heating, shifts in demographics, future demand for heating, appropriate technological capabilities, and anticipated housing forms, among other things.

Figure 1.2: Status of Space Heating in ECA



Source:

<https://documents1.worldbank.org/curated/en/099092023140527206/pdf/P1777440fed3230ce089060ff8ce59c9f5e.pdf> (2023)

In addition, there is the problem of improving data repositories at the national level to ensure these can form the basis necessary for the assessment and selection of alternative heating sources. Given such data, SHRs propose a more detailed methodology of building and infrastructure and planning low carbon heating that makes use of sophisticated analytical tools that allow for systematic data driven decision making by civil stratum.

2.0. Renewable Energy Integration

The entire environment concerning space heating in the ECA region reveals deep seated economic, environmental and social problems which make energy transition fair and sustainable. In any case, energy-inefficient, outdated buildings that rely on fossil fuels are destitute. Fuels, fossils or otherwise, coupled with increasing heat expenditure causes energy impoverishment in low income and rural families. Furthermore, these detrimental fuels cause even more air pollution, creating further health and economic problems.

Table 2.1: Characteristics of District Heating Systems, by Generation

	1 st Generation (1880–1930)	2 nd Generation (1930–1980)	3 rd Generation (1980–2020)	4 th Generation (2020–)
Heat carrier	Steam	Pressurized hot water (>100°C)	Pressurized hot water (<100°C)	Low-temperature water (30–70°C)
Pipes	Insulated steel pipes	Insulated steel pipes	Pre-insulated steel pipes	Pre-insulated flexible pipes
Circulation systems	Steam pressure	Central pumps	Central pumps	Central and individual pumps
Metering	Condensate meters to measure the amount of steam used	Heat meters with annual or monthly readings. sometimes allocation meters on radiators	Heat meters; sometimes metering of flow to compensate for high return temperatures; wireless, more frequent readings	Continuous meter reading
Radiators	High-temperature radiators (>90 °C) using steam or water	High-temperature radiators (>90 °C) using DH water	Medium-temperature radiators (70°C) using DH water	Low-temperature radiators (50°C)
Hot water	Tank heated directly with steam or from a secondary water circuit	Tank heated to 60°C and circulated at 55°C when needed	Heat exchanger heats water to 50°C; domestic water tank heated to 60°C and circulated at 55°C when needed	Efficient local heat exchanger heating water to 50°C
Heat production	Coal steam boilers and some CHP plants	Coal- and oil-based CHP and some heat-only boilers	Large-scale CHP, distributed CHP, biomass, and waste, or fossil-fuel boilers	Low-temperature heat recycling and RE sources
Integration with electricity supply	CHP as a heat source	CHP as a heat source	CHP as a heat source; some large electric boilers and heat pumps	CHP systems integrated with heat pumps and operated on regulating and reserving power markets as well as spot markets
Primary motivation	Comfort and reduced risk	Fuel savings and reduced costs	Security of supply	Transformation to a sustainable energy system
Infrastructure planning	Governing competing DH infrastructures	Developing and expanding DH is suitable for the cost-efficient use of CHP	Identifying and implementing suitable DH infrastructures in fossil-based energy systems	Identifying and implementing suitable DH infrastructures in fossil-free energy systems
Cost principles	Minimizing per unit supply costs; few concerns about savings because space is more important	Minimizing per unit supply costs; few concerns about savings because CHP is inexpensive and plentiful	Dilemma between short- and long-term marginal costs, with short-term marginal costs, winning based on existing investments (sunk costs)	The dilemma between short- and long-term marginal costs, with a need to integrate better long-term marginal costs (future investments)

Source: <https://www.sciencedirect.com/science/article/pii/S0360544214002369>

Integrating biomass, geothermal, hydroelectric, wind farms, and solar panels into existing energy grids comes with its pros and cons. Shifts in the long-term concerns regarding resource sustainability, global warming, and energy independence have contributed to making renewable energy a priority worldwide. The recent innovations in energy storage systems, smart grid technologies and energy conversion efficiency have made the supply from renewables more reliable, thus making integration simpler and more feasible.

Table 2.2: Cleaner Fuels for District Heating

Fuel	Description	Status	Examples
Waste Heat	Industrial waste heat in nearby communities can be captured and fed into DH systems to offset fossil fuels. Can also include water treatment plants, power plants, supermarkets, data centers, etc.	Common in northern and western Europe	Szlachecin (Poland) installed CHP based on waste heat from a sewage treatment plan for DH; China has several projects using industrial waste heat (e.g., Chifeng in Inner Mongolia, Qianxi City in Hebei)
Biomass/Biogas	Biomass can be collected from agriculture (straw, manure) and forests (wood chips) for use in CHP and heat plants. Biogas, from landfill gas and wastewater treatment plants, can also be used to support heat generation.	Common	Austria, Belarus, Croatia, Estonia, Finland, France, and Sweden all have CHPs that use agricultural waste, wood, and pellets to provide heat
Hydrogen	Most hydrogen is produced through steam reacting with a hydrocarbon fuel (usually natural gas). However, green hydrogen may also be produced through RE-powered electrolytic and biological processes. While not economic today, it could replace natural gas for CHPs	Emerging	As of yet, no commercial applications

Note: The data in the table was collected by the author.

Table 2.3: Decarbonization Options for District Heating Systems

Option	Description	Status	Examples
Heat Storage	Heat storage (e.g., a hot water tank) can reduce the need for fossil-fuel boiler use by shaving peak loads and operating when clean heat options are not available. It also smooths the daily heat load variation caused by the domestic hot water and air conditioning systems and can be replenished at night when loads are low. It can also act as a water emergency source in case of a network burst to maintain the static pressure. Storage can also allow coupling with electricity systems, so excess RE electricity supply can be converted to stored heat.	In use	Several of Austria's DH companies use heat storage in the form of thermal energy storage towers. Hamburg is using excess wind energy to run electric boilers for DH. They are also piloting an aquifer thermal storage system which will pump hot water 1.3 km underground to deploy as needed for DH heat supply.
Building-level substations	Moving centralized substations and heat exchangers to the building (BLS) can convert DH to a more modern demand-driven mode. The demand-driven mode, combined with consumption-based billing, provides tools and incentives to customers to save heat energy.	In use	In Finland, each building has its own substation separating the responsibility of the DH company and the building owner. The BLS is owned by the customer and provides both space heating and DHW.
District cooling	District cooling can offer a more economical and environmentally sound option than individual cooling. The advantages include lower operating costs and competitive capital investments; environmental sustainability (because of the ability to use existing lowtemperature sources); and high operational safety, flexibility, and availability.	Emerging	More than a dozen DH companies in Finland and Sweden were providing district cooling in 2021.

Source: <https://docs.nrel.gov/docs/fy25osti/89809.pdf>

Table 2.4: Cleaner Technologies and Practices for District

Technology	Description	Status	Examples
Heat Pumps	Heat pumps have been deployed in DH for more than 15 years. The most developed systems utilize various heat sources for heat pumps (ambient air; ground soil; sewage; sea, river, and lake water; and various types of industrial, commercial, and residential waste heat).	In use	In use across Europe. Examples include a 105 MW heat pump to support DH and cooling in Helsinki, Finland; a 500 MW heat pump plant in Stockholm using wastewater treatment with water temperatures of 7-22°C; and an 8 MW heat pump installed in Berlin's DH system.
High-Tech Solar Collectors	Allows customers to benefit from solar heat from early morning until late evening, even during early spring and late autumn days due to their enhanced off-center incident radiation performance.	Emerging	In 2019 in Jelling Grønnegade, Denmark, the solar heating system produced ~10,000 MWh, which led to the wood boilers being shut down from April to September when solar production was highest. Solar collector projects are also being considered for several countries in the Western Balkans, with one in Kosovo recently approved ¹ .
Waste Incineration Based Cogeneration	Waste incineration can produce heat and power in a CHP. Thus, unrecyclable waste can be incinerated for energy production, replacing fossil fuels and reducing carbon emissions.	In use	In Vantaa, Finland, a €300 million waste incineration CHP plant was built in 2014 that now generates 920 GWh of heat and 600 GWh of electricity annually. The plant incinerates 340,000 tons/year of mixed waste in an under-pressure bunker at 1,000°C. ²
Waste Gasification-Base Cogeneration	Gasification technologies involve a circulating fluidized bed gasification process to partially burn biomass or waste at high temperatures using a controlled amount of air.	Emerging	The CHP plant Kymijärvi II, launched in 2012 in Lahti, Finland, gasifies recycled household and industrial waste with advanced gas-purifying technology. The Kymijärvi II plant produces 90 MW _{th} and 50 MW _e for Lahti and surrounding cities ³ .

Source: <https://www.worldbank.org/en/region/eca/publication/toward-a-framework-for-the-sustainable-heating-transition#:~:text=This%20report%20presents%20a%20comprehensive%20analysis%20of%20the,while%20helping%20countries%20decarbonize%20their%20economies%20by%20mid-ce>

2.1. Economic and Market Considerations

The implementation of renewable energy is economically feasible only when effective market structures are established, coupled with strong policies that invite investment and guarantee reliability within the power grid. Financial instruments, such as feed-in tariffs (FiTs), carbon pricing, capacity markets, and power purchase agreements (PPAs), are widely used to accelerate the transition to renewable energy sources. As the International Renewable Energy Agency [1] indicates, feed-in tariffs, in which renewable energy producers are paid a set price for their electricity, provide reliable revenues and reduce the risks associated with investments. Furthermore, instruments of carbon pricing, such as carbon taxes and emissions trading systems (ETS), seek to internalize the pollution cost of electricity generated from fossil fuel sources, thereby making renewable options more attractive in the energy market [1]. However, capacity markets maintain sufficient electricity generation capacity to meet demand on the mercenary principle by paying electricity suppliers for the availability of a portion of their power. This undermines the unpredictability that comes with renewable energy sources.

Novel approaches to ensure the sustainable profitability of renewable energy go beyond conventional financial motivators. Adopt a flexible pricing model that permits renewable resources to act as reserve suppliers so that they can participate in ancillary service markets. This strategy not only increases the economic and operational efficiency of the grid, but also makes renewable energy projects more appealing financially due to other sources of income. In addition, decentralized energy markets and peer-to-peer trading systems that enable surplus selling by prosumers are increasingly becoming mainstream, thus supporting local energy self-sufficiency and lowering dependency on central systems.

Industry integration of renewable energies into wholesale electricity markets is also governed by regulatory elements which stipulate the conditions for granting priority access to dispatch, grid access, and long-term commitments on investments. Policy coherence and clear market signals as a prerequisite for investment in renewables infrastructure are also underscored in a report by the International Energy Agency.[3] Private investment in renewable energy markets is possible in countries that have a well-defined primary energy policy, for example, Germany's Energiewende and Denmark's quasi-permanent policies on renewables. These countries are able to attract private funds by introducing a market friendly atmosphere and diminishing uncertainty.

In addition, new financial products such as CFDs are helping investors in renewable energy to mitigate electricity market volatility by providing a stable price. Hirth & Steckel (2016) [4] have shown that CfDs contracts enable highly expensive renewable energy projects because they provide clear income security – a feature most needed during periods of energy market turmoil.

2.2. Renewable Energy Investments with Policy Co-Design

Policies that enable investment and those that restrict it have a significant influence on choices around investment in the energy gap. This is because investment decisions are complex and involve significant sums of money over long periods of time [5][6]. Investors measure the possible investment returns and their profitability against other investments by evaluating

market opportunities and risks including their investment, market conditions, technology, and policies [6]. The factors such as energy price fluctuations, technology enhancement, regulatory changes, and political risks may contribute to the uncertainties [5]. Barriers can be contemplated as high capital expenditures, limited access to capital, infrastructure shortcomings, and policy compliance [5][7]. Firms face obstacles of two types of barriers, that is, deterring and revealed barriers is where the difference occurs based on whether an adopting firm possesses advanced technological capabilities (D’Este et al. 2012) [8]. According to [8], these barriers are categorized as either revealed barriers, which are those which restrict efforts to innovate, while deterring barriers are problems that stem from meeting various activities. The impacts of these barriers are mainly evident in market related issues including the presence of established businesses shredding competition forming an effective new entry market.

Policymakers and investors can enhance the investment environment by resolving issues and removing barriers through enabling policies that provide economic incentives, reinforce steady regulations, support infrastructure spending, finance new developments, and have well defined vision of the energy sector within the economy [6]. Policies are important for nurturing the reasons for shaping the processes of the emergence and diffusion of low-carbon economic changes [9][6]. This literature underlines that the most effective approaches to facilitating transitions tend to include some mixture of incentive policies and regulatory frameworks that encourage low-carbon solutions and constrain high-emission alternatives. Regime incumbents can either slow down or complicate the shift to low-carbon activities, or they can do so by changing their existing orientations and resource allocation toward investing in new technologies (Geels 2014, 2018). As path dependence shows, socio-technical systems and institutions get locked into developmental pathways, and the policies that seek to achieve these patterns are called pro-active policies. To overcome more stubbornly resistant stakeholders, it becomes essential for well-established players to employ more modern techniques in the post-competitiveness era. The co-design and co-creation frameworks aim to enable the attempt towards the achievement of sustainability transitions by engaging the relevant actors in the pertinent problems.

The concept of co-creation in the context of a sustainable heat transition seeks to facilitate the challenge of decarbonization through stakeholder active engagement and collaboration in a circular and iterative manner. However, the introduction of a co-design approach alone is not sufficient to ensure adoption in prevailing policies or planning frameworks. This suggests that participation is necessary from the “owners of the system” across various levels of spatial domains to implement a multi-level governance system that can effectively manage the diverse actions of various decision-makers. The engagement of key stakeholders in structured co-design processes has the capacity to lead to result-oriented concrete solutions in the context of competing interests, which is in sharp contrast with consulting processes where participants merely express their views without any focus on producing a decision.

2.3. Policy and Regulatory Frameworks (EU)

The European Union (EU) has created an extensive policy and regulatory framework to strengthen the renewable district heating (RDH) systems for achieving energy efficiency, reduction in greenhouse gas emissions, and attaining neutrality in climate by 2050.

2.3.1 Renewable Energy Directive (RED) and Its Revisions

The Renewable Energy Directive (RED) came into existence in 2009 with subsequent amendments made later on. It establishes concrete targets for incorporating renewable sources of energy in the EU mix. The most significant one is Directive (EU) 2023/2413 which recently came into force and it places greater focus on the heating and cooling sectors. Article 23 specifies an obligation for an annual growth rate of 1.1 percentage points for the renewable share in heating and cooling while Article 24 relates to district heating and cooling and prompts the using renewable and waste heat resources. The directive puts additional emphasis on energy communities together with the need to train and certify installers for quality and effectiveness of system implementation

2.3.2. Energy Efficiency Directive (EED)

The RED is complemented with the Energy Efficiency Directive (EED) which aims on improving internal energy efficiency on different levels like the heating and cooling. It calls upon the member states to design and implement strategic papers for building renovations and modernization of existing infrastructure to allow effective RDH systems. Furthermore, the directive supports the use of high efficiency cogeneration and advanced district heating and cooling systems..

2.3.3. Energy Performance of Buildings Directive (EPBD)

The Energy Performance of Buildings Directive (EPBD) aims to improve the energy efficiency of buildings throughout the Europe Union. It obliges each member state to establish a minimum energy performance standard for new and existing buildings, promote the use of renewable energy within these buildings, and devise renovation policies. This directive also defines the concept of nearly zero-energy buildings (NZEB) which are intended to achieve optimal energy performance but have the greatest portion of their energy needs provided through renewable energy sources.

2.3.4. Governance Regulation

Regulation (EU) 2018/1999 sets the base for the member states to complete the national integrated energy and climate plans (NECPs) in order to achieve the EU energy and climate objectives. Member states are supposed to explain their pledges to the EU renewable energy expansion campaign by presenting actions to improve RDH system. The regulation also emphasizes the need for regional planning as well as active citizen participation in the development and implementation of these plans.

2.3.5. Support Mechanisms and Financial Incentives

In an effort to transition into RDH, financial support mechanisms and other fiscal incentives are provided by the EU. These encompass the funding programs for research and innovation including the European Horizon 2020 and Horizon Europe, the Cohesion Fund, and the European Regional Development Fund (ERDF), which support the development and deployment of the advanced RDH enabling technologies and infrastructures. Furthermore, the EU Emissions Trading System (ETS) gives a financial incentive to invest in renewable energy or energy efficient technologies via the cost that is imposed on carbon emitted, thereby incentivizing famines in greenhouse gases emissions.

2.3.6. National Implementation and Regulatory Frameworks

Notwithstanding the establishment of general directives by the EU, the adoption and governance of RDH systems is still largely the prerogative of member states. This has resulted in continuous variation of approaches in different countries' levels of market sophistication, government control, and subsidization. In particular, the findings of the models of district heating and cooling markets in the context of the new Renewable Energy Directive focus on the best and worst practices among member states, allowing them to learn from each other.

2.3.7. Challenges and Future Directions

While the deployment of RDH systems is underway, there are issues such as the lack of sufficient stakeholder investment, technological investment requirements, regulation challenges, and the need for proper stakeholder engagement on each level. In addressing them, the European Union modifies its policies and directives, funds research and innovation, and promotes collaboration among member countries and other stakeholders. The Heating and Cooling Sector Strategy of the European Union is being built and refined, so that more steps and measures will enable the so-called decarbonization – the reduction of carbon emissions in the heating and cooling sector – by increasing the parts of renewables as well as the energy efficiency.

Undoubtedly, the policy and regulatory framework set by the Union for Renewable District Heating Systems has its strength and undergoes continuous change. This is because the EU has a deep commitment to mitigating climate change as well as energy initiatives. The framework is multi-faceted as it sets objectives and policies targeting the use of renewable energy sources like biomass, geothermal, and solar energy in district heating systems. To achieve the desired results, these regulations must be assessed and modified consistently. This evaluation owes to a more detailed analysis of existing district heating networks, their performance, innovation bottlenecks, and plans to improve effective heating network performance. In overcoming problems related to capital expenditure on infrastructure, the use of new technologies, and the mobilization of the public, the EU seeks to enable the use of renewable energy in district heating systems.

3. METHODOLOGY

The study will try to map out the core strategic decisions and key factors that can lead to the successful decarbonization and sustainability outcomes in advanced European district heating and cooling systems. Under a case study approach anchored by the thesis methodology and cross-checked with multiple secondary sources, the present work analyses the integration of renewables and waste energy into these systems. These findings are further corroborated by employing H2RES energy optimization modelling and LCOH assessments for both technical feasibility and economic performance. This multi-dimensional framework allows for a proper evaluation of various technical, financial and policy innovations, thereby illuminating the main drivers of increasing renewable integration and sectoral decarbonization.

3.0. Data Collection Methods

To scrutinize renewable district heating systems, specialists gather data from a wide range of sources which include government documents and reports, academic books and articles, and conducted interviews. This is done using both primary methods, such as interviews and site visits, and secondary methods, such as literature review and statistical evaluation. The thoroughness of these academic approaches enables higher accuracy and dependability of the gathered information, which helps to get a broad understanding of key performance metrics covering economic feasibility studies aided with comprehensive cost breakdowns and environmental measures perceiving greenhouse gas emissions and local air quality improvement levels.

3.0.1. Conducting a Background Study

The primary data for analysis of renewable district heating systems is collected through direct field observations, measurements, and interviews with relevant stakeholders that focus on system operation and user experience. Thermal field measurements are indispensable for capturing certain key defining features of systems such as thermal energy flow, heating, cooling, energy consumption patterns, and productivity of the system. This data gathered exceed captures relevant information such as means of heat production, effectiveness of energy distribution, and energy loss sources in the system.

In order to understand these dynamics better, carefully designed surveys and questionnaires are administered not only to households with residential heating, but also to industry professionals, energy systems specialists, and operators who work the daily shift in charge of district heating. The purpose is to assess the level of consumer satisfaction, perceptions regarding the costs of energy, and operational issues, so that the responses received represent a reasonable coverage of the users' experiences and concerns.

In addition, structured interviews and focus groups are gathered from policymakers who formulate energy legislation, energy service providers, and local governments responsible for city development. These discussions aim at more sensitive issues such as the legal barriers to utilizing renewable energy, the subsidization of eco-friendly technologies, and urban development issues pertaining to the growth of district heating systems in the urban centers.

Pilot schemes and demonstration projects are important within this framework as they implement the renewable district heating systems in practice. These systems are put in place and studied in different climates and urban centers. This allows researchers to examine real performances against theoretical estimations and identify both the benefits and weaknesses of the systems. With these insights, strong and weak socio-economic influences that guide consumer choices around technology, as well as energy policies, can be framed. These systems are analyzed from multiple angles: technical and socio-political which guide most consumer behavior. This blend leads to a more profound understanding of renewable district heating systems. This compounds all the socio-technical systems insights within which consumers and stakeholders operate. [\[35\]](#)

3.0.2. Secondary Data Collection

Other secondary sources of data include government reports and academic papers as well as industry journals, and statistical records. There are gaps that need to be filled, especially in relation to government policies, which need to be facilitated by reports, and regulatory

documents issued at either national or regional levels. Renewable energy sources such as district heating systems have specific criteria that need to be fulfilled in order to gain maximum benefits, which in turn help in achieving environmental and economic incentives set at different levels. [35]

The Journal of International Energy Agency and other peer-reviewed journals explore system performance, efficiency improvements, and economic feasibility studies in both IEA and Euro heat and Power industry reports, as well as case studies from Euro heat and Power. Their reports reveal important market trends, technological breakthroughs, and best practices which are of value to new projects. Further, Oberstar and other national energy agencies supply vital quantitative data as well as open data on energy production, heat demand, and other developing market trends vital for planning and decision making.

GIS data is used to strategically visualize and estimate the heat demand for urban areas while working on future district heating network expansions. This helps in understanding the relevant spatial dynamics. Such multi-faceted and rich sources of information assure a complete analysis of renewable district heating systems and enhance primary data with real-world contextual applicability. This multi-faceted approach to research increases its relevancy and robustness with respect to the fast-evolving nature of energy production and consumption sector.

3.1. Cost calculation method

Accounting for initial investment, operational and fuel expenditures, and the expected life span of the heating units is crucial when making comparisons between different heating solutions. In this case, the expenses relevant to the purchase of the equipment, installation fees, and upgrading of the existing systems must be considered as initial investment costs. These costs are spread out over the expected life span of the unit using annualized calculations in order to depict a more accurate image of the financial obligations.

Operational expenses can come from the routine maintenance, repairs, and additional services needed for efficient operation. These expenses can vary widely depending on the type and efficiency of the heating system. Fuel expenditure represents the ongoing costs associated with the energy needed to operate the heating system. These can vary based on market rates and the fuel type used, be it natural gas, electricity, oil, or renewables.

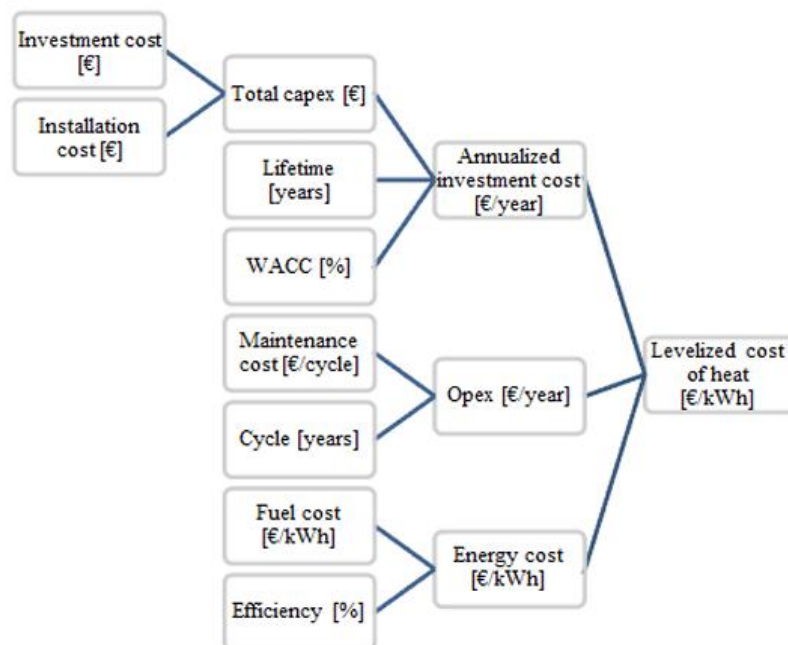
Finally, heating units expected lifespan is one of the most important parameters determining cost effectiveness. Systems with longer operational lives tend to have much higher upfront costs, while those with shorter life cycles typically experience frequent replacement costs which over time increases total cost. Cost analysis of this nature help organizations efficiently determine which option, in this case a heating system, is the most appropriate economically aimed at meeting set requirements.[10] Eq (1)

$$\text{Annulized cost} = \frac{WACC}{1-(1-WACC)^{lifetime}} * \text{Total Capex} \quad (1)$$

Source: <https://www.witpress.com/Secure/elibrary/papers/ESUS13/ESUS13009FU1.pdf>

where the WACC stands for Weighted Average Cost of Capital, or the interest rate that satisfies the owner, and Total Capex stands for the total investment costs, cost of the unit + installation costs.

Additionally, the maintenance cost is considered for each unit, fuel cost, and unit efficiency. The calculation flow chart is shown in Figure.



Calculation flow chart for calculating the levelized cost of heat.

Source: <https://www.witpress.com/Secure/elibrary/papers/ESUS13/ESUS13009FU1.pdf>

Decentralized heating technologies

The overall ownership expenses associated with different decentralized heating technologies are being examined. Since there is a lack of data from other countries, all the cost information and assumptions regarding these heating solutions come from a report by the Danish Energy Agency [10]. The heating systems are designed to handle peak demand efficiently. The prices for gas and electricity are sourced from the European Commission [12], not including VAT. Because there's no information on gas prices in Finland in the European Commission statistics, the gas boiler option has been left out for that country. It's essential to understand that while solar heating is considered to have full direct coverage in a theoretical scenario, this isn't practical, and it should be complemented with other heating solutions. Additionally, solar radiation levels differ across various locations; for this analysis, the Danish context is used as the reference point for solar thermal. The efficiency of heat pumps, represented by the coefficient of performance (COP), varies with the source temperature, resulting in a lower COP for air-source heat pumps during colder weather.

Table 3.1: Cost of decentralized heating solutions in €/kWh

Country	Gas Boiler	Air Source Heat Pump	Ground Source Heat Pump	Solar Thermal*	Electrical Boiler
Bulgaria	0.116	0.161	0.199	0.121	0.118
Denmark	0.173	0.216	0.249	0.129	0.284
Finland	N/A	0.173	0.210	0.122	0.156
Ireland	0.129	0.193	0.228	0.125	0.216
Italy	0.156	0.194	0.229	0.126	0.218
Latvia	0.115	0.174	0.210	0.122	0.156
Lithuania	0.123	0.170	0.207	0.122	0.147
Portugal	0.141	0.188	0.223	0.125	0.199
Slovakia	0.120	0.184	0.220	0.124	0.188
Slovenia	0.148	0.178	0.214	0.123	0.170
Sweden	0.180	0.191	0.226	0.125	0.209
United Kingdom	0.128	0.187	0.222	0.124	0.196

*Solar thermal needs to be coupled with other heating solutions as well to get full coverage.

Source: <https://www.witpress.com/Secure/elibrary/papers/ESUS13/ESUS13009FU1.pdf> (Table 3.1 & 3.2)

Table 3.2: Cost of heat from different DH schemes for low-energy buildings in €/kWh.

Country	Inner City				Outer City			
	Gas Boiler	Biomass Boiler	Geothermal Plant	CHP Surplus/Waste	Gas Boiler	Biomass Boiler	Geothermal Plant	CHP Surplus/Waste
Bulgaria	0.091	0.109	0.142	0.066	0.097	0.117	0.155	0.069
Denmark	0.126	0.109	0.144	0.066	0.137	0.117	0.157	0.069
Finland	0.106	0.106	0.143	0.066	0.114	0.114	0.156	0.069
Ireland	0.099	0.108	0.146	0.066	0.106	0.116	0.160	0.069
Italy	0.094	0.097	0.149	0.066	0.100	0.104	0.163	0.069
Latvia	0.092	0.104	0.145	0.066	0.098	0.112	0.158	0.069
Lithuania	0.103	0.102	0.145	0.066	0.110	0.110	0.158	0.069
Portugal	0.097	0.095	0.145	0.066	0.104	0.101	0.158	0.069
Slovakia	0.100	0.107	0.146	0.066	0.108	0.115	0.160	0.069
Slovenia	0.112	0.106	0.144	0.066	0.121	0.114	0.157	0.069
Sweden	0.117	0.110	0.143	0.066	0.126	0.118	0.156	0.069
United Kingdom	0.086	0.106	0.145	0.066	0.092	0.114	0.158	0.069

4. CASE STUDIES AND ANALYSIS

4.0. Methodology for Case Study Selection

The first stage of the analysis aimed at finding appropriate case studies that would give an understanding of how different technologies, models and practices of district heating and cooling (DHC) systems in Europe are structured and how these systems incorporate renewable energy sources and use waste heat and cold. This selection process unfolded in distinct three phases. [12]

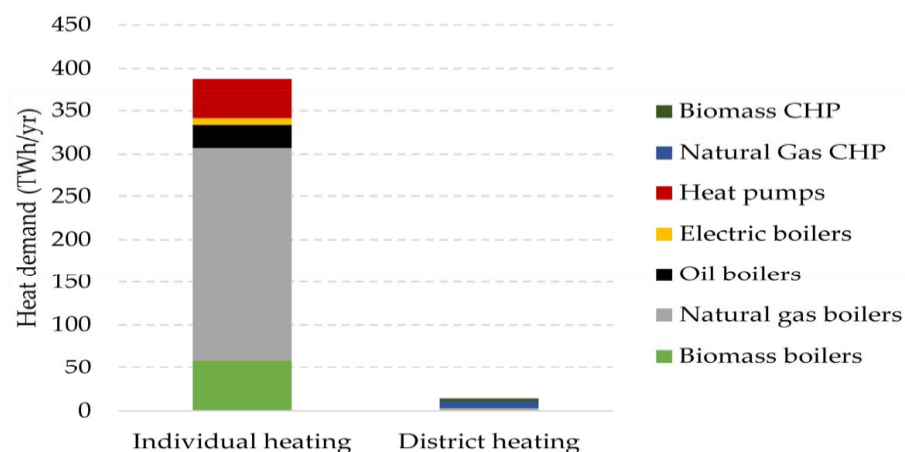
Identifying and reaching out to potential case studies.

Conducted extensive literature review to liaise with international and national DHC associations, engage DHC companies, reach out to professionals in the field, and issue a public request for case study submissions.

- Appraised network performance based on economic feasibility, pricing for consumers, innovation, competition, market share of the heating industry, internal and external competitive factors, energy mix, environmental sustainability, and replicability. And
- Evaluated complementary case studies and their geographical dispersion, types and ownership structures and business models of the networks instead of regulatory framework, energy technologies and sources, customer structures, and other socio-economic advantages which the DHC system can provide to the region, in addition to multi criteria fuel switching strategies, energy economy buildings, and cooperation with electricity;
- Finally analyzed data and stakeholder participation willingness for the selected study area. We reviewed the initial questionnaire responses and integrated the most relevant ones into a worksheet with salient features and indicators of the targeted DHC networks.

4.1. Heating Sector in Italy

In Italy, natural gas boilers serve as the main source of heating. These gas boilers are heavily depended on to generate electricity and thermal energy.[31] In addition, the expansion of district heating systems remains insufficient due to the extensive coverage of the gas grid, making it so that only approximately 3.5% of total heating in Italy is provided by district heating.[21]



Current individual and district heating demand in Italy by fuel

4.1.1. District Heating Deployment and Energy-Saving Scenarios

The implementation of district heating (DH) systems is important in lowering carbon emissions from building infrastructure within urban locations. The Heat Roadmap Project findings suggest that Italy can reach a 60% maximum for district heating. The project also aided in establishing a cost framework for extending the DH network based on population density stratification. Two scenarios for the extension of district heating were identified.[31]

In the first scenario, labeled as Low DH, there is an approach which is slower and assumes that by 2050, district heating will only be able to satisfy 20% of heating demand from Italian buildings. In contrast, the High DH scenario assumes an overly aggressive stance toward the decarbonization of building stocks, assuming that centralized production will cater to 50% of the heating demand by the year 2050. The reference scenario is a compromise that looks at the middle ground of the two Low DH and High DH scenarios. [12]

In addition, two scenarios were developed to assess the possibilities of saving energy in the buildings sector. Based on available information, the ideal objective in Italy is to reduce demand for energy, particularly in heating, by around 30%. A cost curve has also been developed which addresses exclusively passive measures, such as insulation and window replacement, for the Low ES scenario which attempts to achieve a 20% reduction in energy demand by 2050 and a 40% reduction under the High ES scenario. The reference scenario assumes a middle ground of 30% for that same year. A table summarizes the targets set for 2050 across these different scenarios. In each case, it has been assumed that achieving these objectives will follow a linear progression within each scenario.[21]

Table 4.1: District heating deployment and implementation of energy-saving measures in the proposed decarbonization scenarios of the heating sector.

Scenario	Share of Heat Demand Supplied by District Heating by 2050	Heat Demand Reduction by Means of Energy-Saving Measures by 2050
Reference	35%	30%
Low ES/Low DH	20%	20%
Low ES/High DH	50%	20%
High ES/Low DH	20%	40%
High ES/High DH	50%	40%

Source: <https://www.mdpi.com/2075-5309/14/8/2267>

4.1.2. Technical and Economic Assumptions

The development of district heating (DH) starts with the deployment of the fourth generation DH network and occurs simultaneously with the setup of substations that cater to heating demand. Active measures, such as the energy efficiency of a building, are restricted to passive measures that entail adding insulation or placing new windows to replace old ones. A cost curve for the DH grid encompassing limits of urban planning and built structures, population density, climatic region and other urban features such as the built environment has been devised. The main technical–economic assumptions are displayed in a table here.

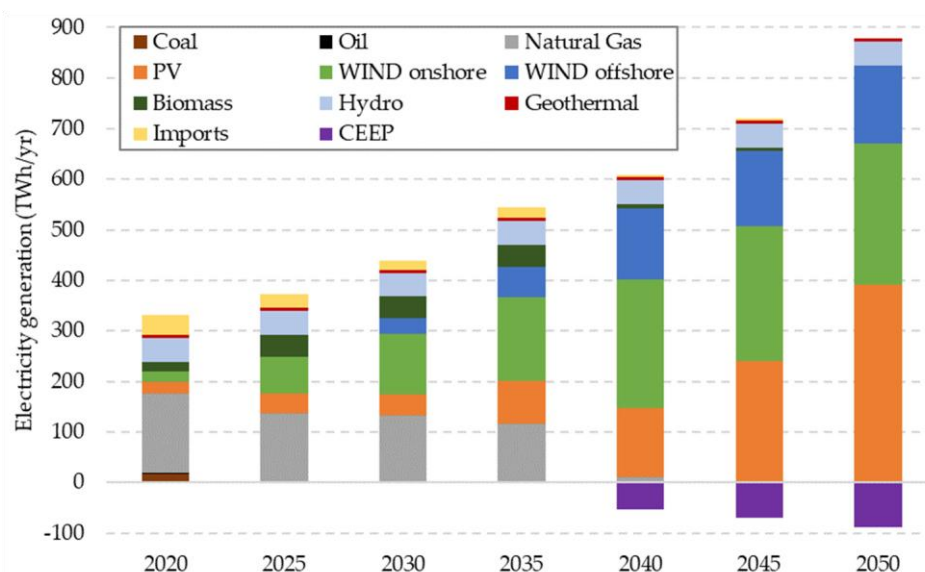
Table 4.2: Main input data for the H2RES model of the Italian energy system

Technology	Units	INV 2020 (M€/Unit)	INV 2030 (M€/Unit)	INV 2040 (M€/Unit)	INV 2050 (M€/Unit)	Efficiency/Full Load Hours	Refs.
PV	MW	0.92	0.58	0.42	0.33	1517	[18,19]
On-shore Wind	MW	1.79	1.07	0.92	0.86	2418	[18]
Off-shore Wind	MW	3.22	1.93	1.66	1.59	2759	[18]
PEMFC CHP	MW	1.3	1.1	0.9	0.8	50%	[20]
SOFC CHP	MW	3.3	2	1.3	0.8	60%	[20]
Alkaline Electrolyser	MW	0.65	0.45	0.3	0.25	66.5–78	[20]
SOEC Electrolyser	MW	4.5	1.9	1.3	0.78	77–83.5%	[20]
PEM Electrolyser	MW	0.92	0.65	0.45	0.4	58–70.5%	[20]
H2 Storage (tanks)	MWh	0.057	0.045	0.027	0.021	-	[20]
Biomass Boiler	MWth	0.47	0.447	0.425	0.404	79–85%	[20]
Gas Boiler	MWth	0.278	0.265	0.252	0.24	90%	[20]
Centralized HPs	MWth	1.2	1.07	1.02	0.96	3.3 (SCOP evaluated)	[20]
Individual HPs	MWth	1.56	1.32	1.22	1.13	3.1 (SCOP evaluated)	[20]
Geothermal HP	MWth	1.932	1.836	1.74	1.566	4.6 (SCOP evaluated)	[20]
Electric Boilers	MWth	0.89	0.85	0.81	0.77	100%	[20]

Source: <https://www.mdpi.com/2075-5309/14/8/2267>

**** H2RES**** The objective of H2RES is to minimize the (discounted) yearly operation and system costs. Since the model is intended for the development of future energy systems, all the future costs are brought to a net present value. H2RES takes into account the costs of operation, investment, fuel, generator ramping, energy import, and CO₂ emissions. [35]

Results: Under the baseline scenario, it is assumed that additional measures to improve energy efficiency will achieve a 30% reduction in building heating needs by 2050. In addition, it is estimated that district heating (DH) will provide approximately 35% of the total heat demand by the same year. Under this reference scenario, a related simulation has been done to analyze complete decarbonization possibilities of the Italian energy system. The above depicts the expected change of electricity generation composition by fuel in the reference scenario from now 2050. [22]



Source: <https://www.mdpi.com/2075-5309/14/8/2267>

In the previously stated case, it is predicted that all individual heating systems will be electrified by 2035, while the electricity and heating sectors will be nearly completely decarbonized by 2040.

- We expect considerable adoption of heat pumps early in the simulation as they are already commercially viable and perform effectively. Heat pumps will most likely become the dominant technology for supplying heat at both the decentralized and centralized levels of renewable energy systems.
- Biomass use in the electricity sector will be negligible and completely absent in the heating sector by 2050.
- Even in places such as Italy that receive many fewer heating hours than much of northern Europe, expanding district heating remains essential for reducing carbon emissions in buildings. Optimistically, up to 40% of Italy's heating requirements could be met with fourth-generation district heating.
- The potential of fourth-generation district heating can be fully realized to reduce thermal sector costs, improve thermal storage utilization, and increase the degree of freedom with which renewable energy sources, that cannot be dispatched, are integrated into the power system.
- Improving energy efficiency clearly has benefits in heat demand reduction and energy production; however, this comes at the expense of higher annual costs and an increase in initial expenditure. Indeed, conservation steps often constitute one of the biggest cost categories, accounting for from 34% to 64% of total spending.

In terms of assessing the effects of different approaches to decarbonizing our buildings, we must analyze how these systems interact with each other. We need to consider the impact of the entire energy system.[\[22\]](#)

4.2. Case study Odense (DK): integrating waste heat from a large data center. [\[12\]](#)

In Denmark, district heating is the prevalent form of heating in the country, where most DH systems are community owned and use clean energy sources (See table below). The intention behind decarbonizing heating and cooling is one of the key drivers towards Denmark's efforts of lowering the emissions of CO₂ by 70% by 2030, aiming at total discontinuation of fossil fuel dependency for both heating and electricity. Currently, the focus area of the work is largely on planning the shift away from natural gas heating towards either district heating or individual heat pumps, as well as making the existing district heating and cooling systems more sustainable. [\[12\]](#)

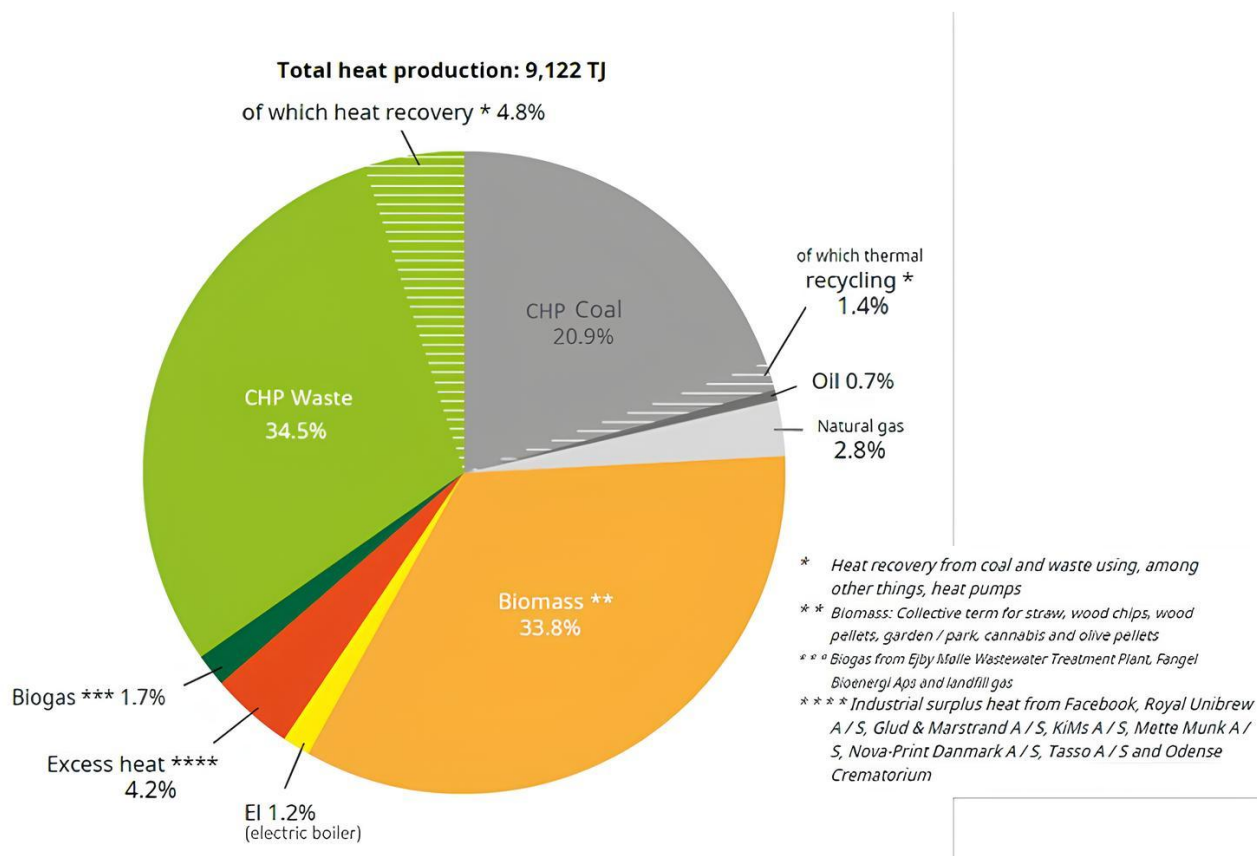
Fjernvarme Fyn, the municipal utility provider, serves as the primary source of heating for district heating (DH) and Faaborg-Midtfyn, Nordfyn, and Assens, where the population figures are 51,700, 29,700, and 1,070 respectively. The major competitor for DH is heat pumps since they offer comparable pricing. However, their life span only lasts between 15 to 18 years, whilst the DH system has been in use for over 90 years. The chart below shows the costs of individual natural gas (yellow) and oil heating (red) solutions, which are marked as more expensive than DH (green). This is mainly due to taxes that Denmark imposes for the environment. [\[12\]](#)

DHC in Denmark - Key facts	
Regulation	- Regulator / Supervision authority - Danish Utility Regulator (Forsyningstilsynet) - Other authorities: Energy Supplies Complaint Board (Ankenævnet på Energiområdet): issues complaints not regulated by the heat supply act - Role of municipalities - Most municipalities own their public utilities - Develop and review the local heat plans, approve new projects when they have the highest socioeconomic benefits - Ownership (in terms of capacity, 2019) - Municipality owned companies (60%) - Consumer-owned cooperatives (35%) - Private companies (5%)
Incentives	- DHC support schemes - Environmental taxes - Heat Supply Act (1979) - Local heat planning as part of urban planning - Energy Savings Obligation Scheme (2006) - Electricity production subsidy for CHP using RES - Direct premium tariff for use of biogas - RES exempted from fossil energy taxes
Market	- Total DHC sales to customers (2017) - DH: 30 391 GWh - DC: 4 147 GWh - Main clients (in terms of sales, 2017) 65% residential, 30% tertiary, 5% industrial - Main operators (in terms of turnover, 2017) - Municipality owned companies: HOFOR, AffaldVarme Aarhus, VEKS, Fjernvarme fyn, Aalborg, TVIS, Vestforbrænding

Odense City – Fyn island	
Population (2020)	204 895
Demographic trend (2016-2020)	+ 0.74 %/year
Density (2020)	673.2 inhab./km ²
Housing (number of dwellings, 2020)	99 529
Housing in multi-flats buildings (2020)	41 922
Heating degree days (T _{ref} = 15°C)	3 720
Building regulation (national)	- Danish Building Regulations 2018 (BR18) - The municipalities could until 2018 choose to oblige or not the connection to DH through the local heat planning (zoning)

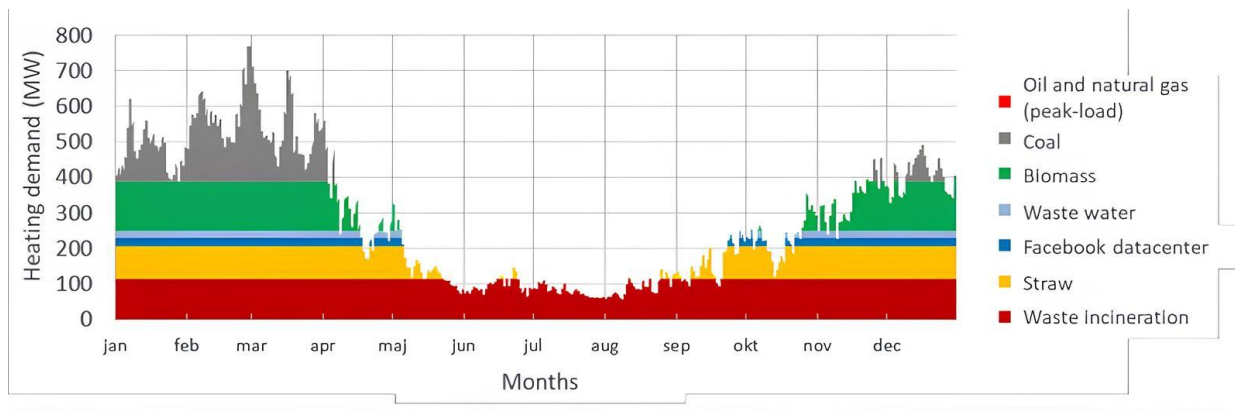
Source: <https://www.odense.dk/byens-udvikling/byens-vision>

Every heat emitter is linked straight to the DH grid eliminating the need for any heat exchangers. All consumers utilize the same type of low temperature emitters so the mixing loop is not a requirement, allowing for substantial cost savings. Each building substation now only has to supply hot tap water through the heat exchanger or hot water tank ensuring high quality water for the consumers.



DH energy production mix in 2020 (source: Fjernvarme Fyn)[13]

Source: https://www.ca-eed.eu/wp-content/uploads/2021/10/2_IS6.6_Facebook_DK_Chan-Nguyen.pdf



Heat production and priority order of the DH[13]

Source: https://www.ca-eed.eu/wp-content/uploads/2021/10/2_IS6.6_Facebook_DK_Chan-Nguyen.pdf

DH Prices and Tariffs

Heating an average Danish household warmed will cost approximately 1,750 EUR (13,000 DKK) which includes the annual rate of 1,750 EUR along with the consumption of 18.1 MWh each year. This rate is one of the lowest in Denmark for homes that are roughly 130 square meters. Further, the district economically range tariff has five important components that pertain to the expenses which the operator has to bear. [12]

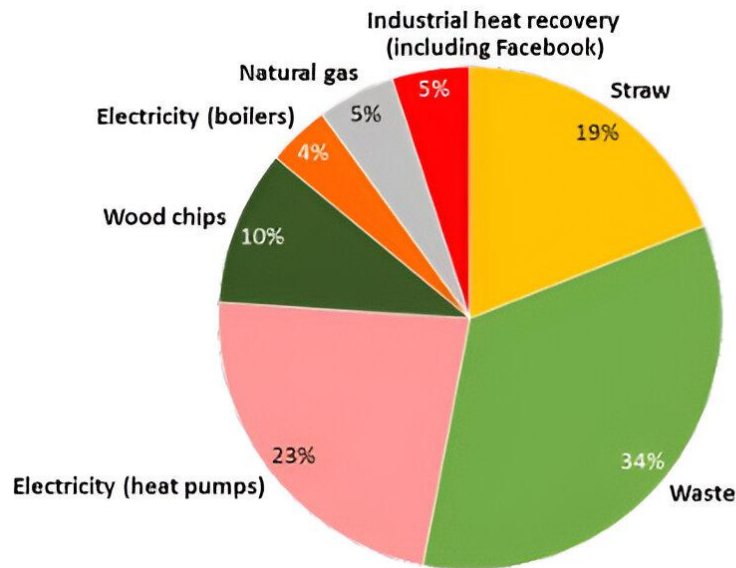
1. A connection fee, which is approximately 3,360 EUR for single family houses (25,000 DKK).
2. Two fixed charges that make about 20% of the total annual bill: one is a fixed yearly meter fee (DKK/y), and the other is an annual energy contribution based from the heated area (DKK/m²/y).
3. Over two variable charges, two fixed services account for roughly 80% of the annual expense. A charge for energy consumed (DKK/kWh) which is adjustable according to the actual consumption; A water flow or “transport fee” (DKK/m³) relative to the maximum volume of district heating water flowing into the client’s secondary system, including a limit for large clients. This specific charge aims at promoting better management of the system by reducing the return temperature and flow of water.

The above illustration illustrates those systems with insufficient cooling (left side with a temperature difference of 14 degrees) have their tariffs set at 32 percent higher than systems that are optimally cooled (right side with 30 permitting cooling). [12]

Prospects

Fjernvarme Fyn, looking forward, intends to utilize the waste heat available in the local industries and in its own production facilities. The company is also intent on enhancing its sale of district cooling, which combines the use of large heat pumps for both heating and cooling. It is expected that by 2030, electric heat pumps will be a significant part of the district heating, as shown in the pie chart bigger below.[13]

Expected energy sources for heat production in 2030 (source: Fjernvarme Fyn)



Source: https://www.ca-eed.eu/wp-content/uploads/2021/10/2_IS6.6_Facebook_DK_Chan-Nguyen.pdf

4.3. Case study of Helsingborg (Sweden)

This study describes how the three municipal energy companies involved in district heating and located in different cities formed the connection networks through the EVITA interconnector. This involves supporting districts from different towns where each of the companies owning the district heating system has a monopoly on other required forms of energy such as electric power and energy management: [12]

- Öresundskraft serves Helsingborg which had approximately 140,500 people as of 2016.
- Landskrona Energi serves Landskrona and its population in 2016 was about 32,500.
- Kraftringen serves Lund, Eslöv, Lomma. The last town had in 2016 around 121,000 people.

Helsingborg City		
Statistics (2019)	Population	147 734
	Demographic trend (2015-2019)	+1.74 %/yr.
	Density	423.8 inhab./km ²
	Housing (number of dwellings)	70 808*
	Housing in multi-flats buildings	45 218 (64%)*
	Heating degree days	3,034
Regulation	Building regulation (national)	• National energy performance standard (2017) • New building standard favouring DH over electricity is planned for 2020

Key facts and figures	
DHC market share	DH: 80 % of the area covered
RES and waste heat share	100 %
CO ₂ emissions (heating)	48 kg/MWh
Installed capacity	DH: 320 MW EVITA pipe: 60 MW
Energy production	DH: 1.04 TWh/y
Km network (double-pipe)	DH: 570 km EVITA pipe: 30 km

Source: <https://www.statistikdatabasen.scb.se/pxweb/en/ssd/>

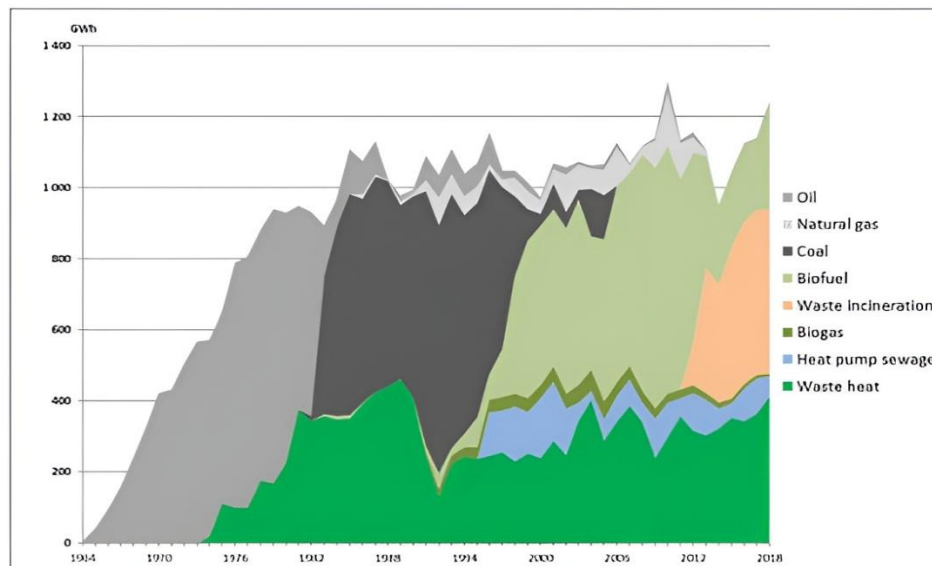
In Sweden, Öresundskraft is based as of 1964, and while the last 30 years have been rather stable for them, for the last decade it has also dominated 80% of the heating market. The newer connections do tend to improve efficiency in the older buildings, which is what drives the ever-increasing demand for heating. The primary rest of the income comes from the construction and servicing of energy-efficient buildings. The variable cost for district heating and for heat pumps as an alternative to district heating is almost identical.

District heating boasts significantly lower connection fees which improves cost predictability and stability as compared to heat pumps which are typically 2 to 3 times more expensive than district heating. [12][14]

Use of RES and waste heat

The energy transition in Helsingborg's DH network has received assistance from national policies and regulations. In 2019 the distribution of the types of energy used for producing heat in Helsingborg's DH grid was as follows:

- 42% Waste-to-energy CHP (73 MW heat)
- 32% Waste heat mainly from the chemistry industry (45 MW)
- 18% Biofuel CHP (130 MW)
- 8% Heat pumps valuing waste heat from sewage, using green electricity (30 MW)



Source: <https://c2e2.unepccc.org/collection/c2e2-publications/>

Helsingborg's Prices and Tariffs

As with any other district heating system, there are price differences. For example, the 2018 average cost of district heating for multi-family residential buildings in Helsingborg was 81.5 EUR / MWh VAT inclusive (833 SEK/MWh) which would mean that with the VAT facilitation, the price becomes 65.2 EUR/MWh (666 SEK)[14]. To make costs more sustainable, the utility owned by the city of Helsingborg has placed a cap on the district heating price by Swedish average district heating prices. The offer from Ostrobothnia Power Company is also special in that they have implemented the “DH Gold” feature which allows the user to offset the negative impacts of consumption of 48 g/kWh. However, this comes at a price premium of 0.02 SEK/kWh. More generally, these types of features are aimed at large institutional investors and other owners of real estate who are willing to reduce their carbon footprint. Although, indeed, the Evita interconnector has not actively contributed to changing the prices of district heating, it does support long-term price stability.[14]

Prospects

DH used to burn coal, but has since made significant progress, first by switching to heating oil and later moving onto coal, waste heat, wood pellets, and waste-to-energy. Currently, they do not utilize fossil fuels at all. Further reducing carbon footprints in relevant facilities is considered essential by Öresundskraft in the quest to increase sustainability. In particular, incineration waste to energy plants can do better by improving their operational efficiencies through less plastic waste being put into the furnace. The city plans to implement a carbon capture and storage (CCS) system to be operational by the end of 2025, and hopes to turn waste into energy with negative emissions.

4.4. Case study Bordeaux (FR): Energie des Bassin's

The primary goal of Bordeaux Metropolis' strategy for improving the "high quality of life" is the acceleration in the energy transition. The Metropolis further aims to achieve 100% renewable energy use in the city by 2050, with a 32% target to be met by 2030, and locally sourced energy to meet 30% of this target. Bordeaux Metropolis has implemented five major District Heating and Cooling (DHC) networks, including the "Energie des Bassin's" networks, which is the focus of this case study and currently contributes 250 GWh per year. There are plans to identify additional urban areas that can contribute towards the target of 700 GWh, with 300 GWh already planned.

Bordeaux Metropolis		
Statistics (2017)	Population	791 958
	Demographic trend (2012-2017)	+1.4 %/yr.
	Density	1 370 inhab./m ²
	Housing (number of dwellings)	420 238
	Housing in multi-flats buildings	143 230 (34%)
	Heating degree days (with a reference temperature of 15°C)	2 034
Regulation	Urban regulation	Zoning: new and renovated buildings in areas supplied by a "classified" DH network are obliged to connect
	Building regulation (national)	Thermal regulation for buildings (RT2012): provides a construction bonus for virtuous DH networks (according to their CO ₂ content)

Key facts and figures	
DHC market share	DH: ca. 100 % of the covered area DC: ca. 50 %
RES share	70 %
CO ₂ emissions	DH: 62 kg/MWh DC: 11 kg/MWh
Installed capacity	DH: 41 MW DC: 9,4 MW
Energy production	DH: 40 GWh/y DC: 8 GWh/y
Km network (double-pipe)	DHC: 18 km

Source: <https://www.bordeaux-metropole.fr/publications?thematique=haute+qualit%C3%A9+de+vie>

Governance and ownership/Financial model

The operating company "Energie des Bassins" possesses and manages the network, which is structured as follows: - A 60 % share rests with Mixéner, which is a fusion of Bordeaux Metropolitan Energies (a public private partnership where Bordeaux Metropolis owns 68%) and the private managing company Idex; - Dalkia, who is wholly owned by the EDF group ("Electricite de France"), holds 40% ownership. While EDB operates as a private network (allowing the operator to apply different negotiated tariffs to various clients), it has implemented a standard tariff which is charged indiscriminately to all customers whether residential or business in the Chartrons and Bacalan districts, which has been set for 30 years. Also in the appendices is set forth the pricing structure for heating and cooling delivered at the substations. As is the case

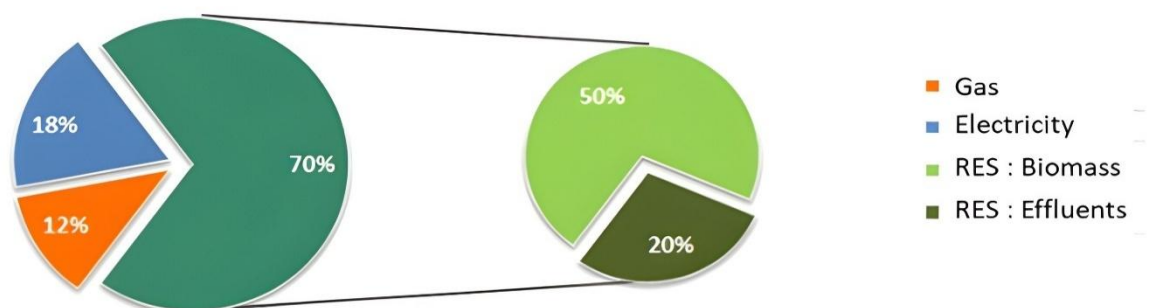
with many district heating and cooling networks that focus on renewable and waste energy, EDB's configuration has a relatively high basic charge (which is an indicator of the operational, maintenance, and other investment activities expenses) coupled with low variable charge (also an indicator of cheap renewable resources like geothermal energy or waste energies of heating recovered from the effluent treatment works). This configuration means that clients are especially crucial within this type of DHC network.[15][12]

Prices observed in 2020		
	Incl. VAT	Excl. VAT
Heating		
Connection fees	27,2 €/m ²	32,7 €/m ²
Variable component	29,1 €/MWh	30,7 €/MWh
Fixed component	92,5 €/kW	97,6 €/kW
Cooling		
Connection fees	20,7 €/m ²	24,8 €/m ²
Variable component	51,9 €/MWh	62,2 €/MWh
Fixed component	82,9 €/kW	99,5 €/kW

Use of RES and/or waste heat

With considerable governmental support to create a model DHC system that integrates appropriate renewable energy resources, the DHC project sited in the “Bassins à flot” district was based on three fundamental sources of energy:

- Biomass from woodchips from a 150 km radius forest around Nouvelle Aquitaine region. Covering 2.8 million hectares of French territory, Nouvelle Aquitaine is the most forested region of France. Hence, it was obvious that this area was best suited to establish a biomass platform to help the DHC network.
- Heat recovery from the newly modernized urban Waste Water Treatment Plant (WWTP) Louis Fargue:
- This urban WWTP, which was enlarged in 2012 to receive 276,000 m³ of effluent per day, is very conveniently situated as one of the major encircled facilities for the DHC grid.
- Geothermal energy existing at a depth of 30 m in the Garonne River alluvium sandstone (with the returned spent water at 32 degrees Celsius):
- Geothermal energy along the Garonne River was considered as an option from the outset. It was eventually used for providing cooling for the “Cité du Vin” museum located in the Bacalan district.[16]

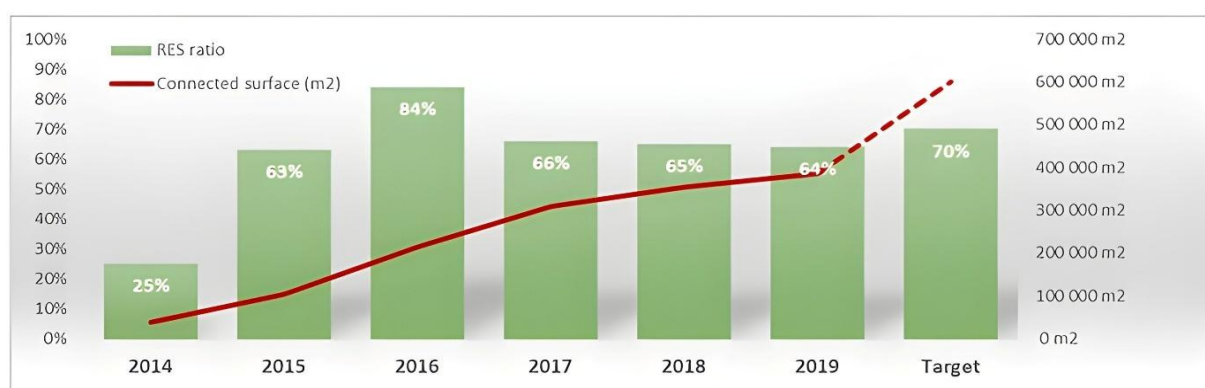


Source: [https://www.academia.edu/11055354/From the smallest cell to the metropolis Bordeaux 50 000 Homes Along Public Transport Routes](https://www.academia.edu/11055354/From_the_smallest_cell_to_the_metropolis_Bordeaux_50_000_Homes_Alone_Public_Transport_Routes)

As the “Bassins à Flot” area progresses, the DHC network has achieved over 60% share of renewable and waste energy supplies. This success can be attributed to:

- A stepwise implementation of a biomass plant that has two 2.5 MW boilers coming on line in different years.
- Installation of thermal storage comprising two 60 m³ tanks which can deliver 3.5 MW for one hour.
- Decentralized configuration of substations in the Chartrons district, which enables each substation to independently control its heat pump and gas boiler, making it possible to increase production capacity with the development of the district.

This will rise to 70% with the completion of the urban district expected by the end of 2023.[16]



Renewable ratio and connected surface evolution

Source: [https://www.academia.edu/11055354/From the smallest cell to the metropolis Bordeaux 50 000 Homes Along Public Transport Routes](https://www.academia.edu/11055354/From_the_smallest_cell_to_the_metropolis_Bordeaux_50_000_Homes_Alone_Public_Transport_Routes)

4.5. Case study Querfurt (DE): modernizing and decarbonizing a DH system through local Biogas production

Germany aims to achieve climate neutrality by 2050 at the latest, having commenced a “Climate Protection Program” at the end of 2019 with particularly aggressive goals for **2030**. A central element is the introduction of a new national CO₂ pricing scheme for the transport and heating sectors, which is set to commence in 2021. Prices will increase gradually from **25 €/tCO₂ to 60 €/tCO₂ by 2026**. In addition, there are many other activities being undertaken to enhance the efficiency of district heating and cooling networks and transition them to renewable energy sources and the use of waste heat. Querfurt, like many rural towns in Eastern Germany, experienced population loss to Western Germany after the country was reunified. To counteract this population decline, the town attempted to improve quality of life through an urban renewal effort that began in the early 1990s focused on the energy efficiency of the town’s apartment buildings. Some of these renovations included those serviced by district heating. However, the urban renewal program did not address the district heating network, which was plagued by low sales, excessive competition from gas suppliers, and inefficient infrastructure.[12]

DHC in Germany - Key facts		
Regulation	Regulator / Supervision authority	- DHC is not a regulated activity in Germany - Other authorities: Federal Cartel Office (<i>Bundeskartellamt</i>), national competition authority
	Role of municipal owned companies	- Main owners of CHP facilities and operators of DH systems - Can offer their utility services to other regions of Germany - Can propose incentives through their local strategy
	Ownership (main schemes)	- Public-Private Partnership (PPP) - Municipality owned (<i>stadtwerke</i>) - Private
Incentives	DHC support schemes	- Heating Network Systems 4.0 Programme for DH covering 50% of the annual consumption with RES with low temperature - Grants from the Federal Office for Economic Affairs and Export Control (BAFA), through the Market Incentive Programme (MAP) - Feed-in premiums and tenders for renewable electricity, including CHP - Low interest rate loans and grants by the public bank KfW, through the MAP - Energy tax on fossil fuels - Environmental tax (increasing CO2 tax applying since 2021)
Market	DHC Final Energy Consumption	- DH : 111 154 GWh (2020 without industrial heat) - DC : 291 111 MWh (total sales in 2017 – Euro Heat and Power)
	Main clients (in terms of sales, 2020)	41% residential, 38% industrial, 21% tertiary
	Main operators (in terms of turnover, 2017)	Vattenfall, Stadtwerke München, Wärme Hamburg, MVV, EnBW, enercity AG, Dalkia, Engie, Getec

Source: <https://tilia.info/>

Business model

In order to achieve the set goals, the national aid programs that support biogas combined heat and power systems were used. Investment subsidies were financed by the Market Incentive Program (MAP) and a feed-in tariff was available under the Renewable Energy Act (EEG) as well as the CHP Act (KWKG). Consequently, the district heating (DH) network was able to create an additional revenue stream from electricity sales which, together with the DH system's heating by-product, was sufficient to cover the initial capex. The total investment cost was **€3.5 million**, of which **€2.45 million** was financed by debt, representing 70% of the total investment. The business model was set to provide the DH operator with a profit margin of **3-5% over the costs**, and if higher margins were achieved, the tariffs would be lowered to pass the benefits to the consumers and maintain low prices. Therefore, the advantages of the DH grid are enjoyed by residents in the city. Clients are usually contracted for 10 years, with an additional 5 years extension option.

Disconnections may be scheduled for at the end of the contract period, or may be executed mid-term, provided that the fixed tariff portion is tendered for the remaining duration of the contract. After modernization, the price level for DH services was greatly reduced and has since become stable, which renews the attractiveness of the service and increases the number of connections. The DH business is currently profitable and, also, stable. Pricing includes:

- A connection charge for new clients to take care of the connection costs.
- A basic fee of 20 EUR/MW/y.
- A small average charge of 65 EUR/MWh.

Use of RES

The starting situation

As discussed previously, the district heating (DH) operator took control of an old, relatively inefficient gas-powered network known for its steep operational costs. By the early 2000s, social and economic factors resulting from this inefficient energy supply-initiated conversations of

whether to eliminate the DH service altogether, which was overly expensive (130 EUR/MWh) and burdened by significant fixed costs due to the exodus of numerous large customers. During that period, Querfurt was looking for an integrated energy policy that would support the development objectives of the city. The district heating system could serve as a cornerstone of the city's development strategy. [17]

To maintain the district heating supply, however, these and other major issues needed to be resolved:

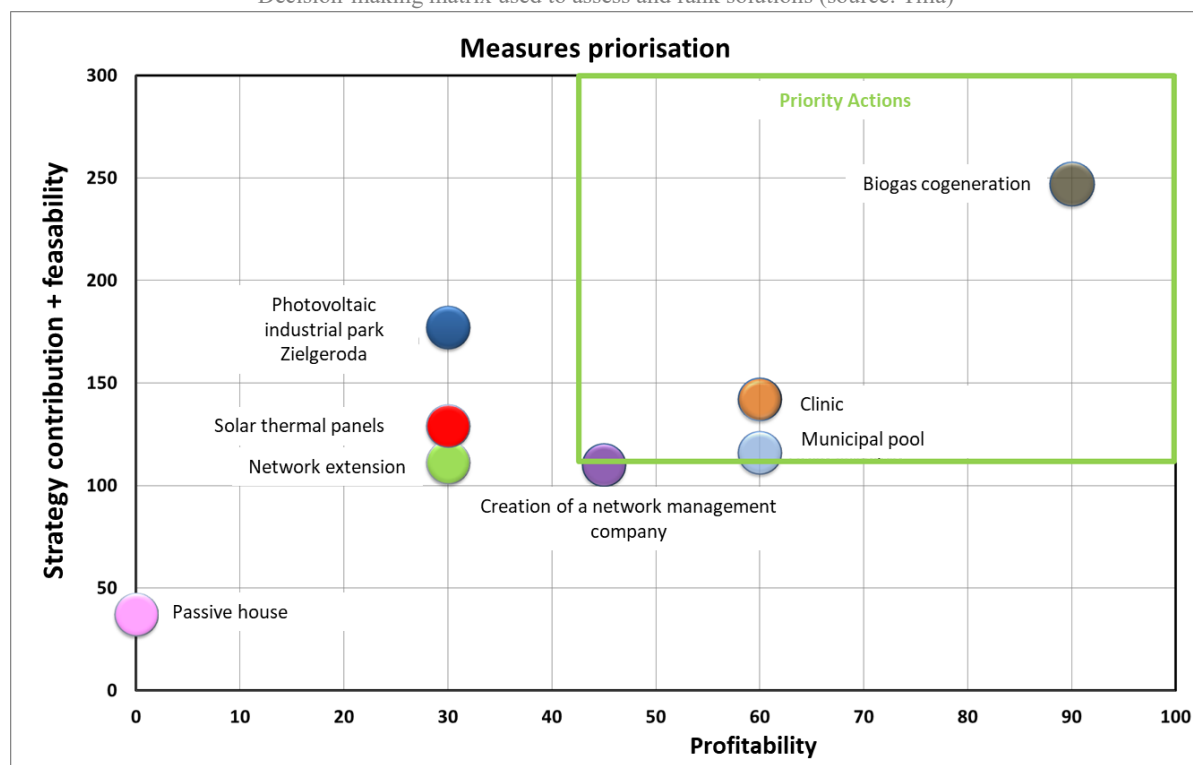
- reduction of prices
- switched to a decarbonized DH system in accordance with the country's laws.
- feed new structures into the existing system.

Modernization project methodology and development

In this case, the solution opted for originated from a study carried out between 2009 and 2013. This study included an assessment and ranking of energy scenarios and projects to be executed while integrating demographic factors, urbanization, and economic development of the city. The best end result was the integration of the existing power generation plants with a new biogas baseload generation facility stratum produced locally. [12]

Prepared this project in consultation with the local community as stakeholders. The selection of a better option which resulted in a reduction of dependency on the volatile market prices of natural gas, as well as an increase in the economic gains to the region, was made after assessing all the options against the jointly defined social, economic, and environmental impacts criteria set by the municipality. This created new opportunities for local agricultural producers, public institutions (for example, hospitals), and energy efficiency services providers.

Decision-making matrix used to assess and rank solutions (source: Tilia)



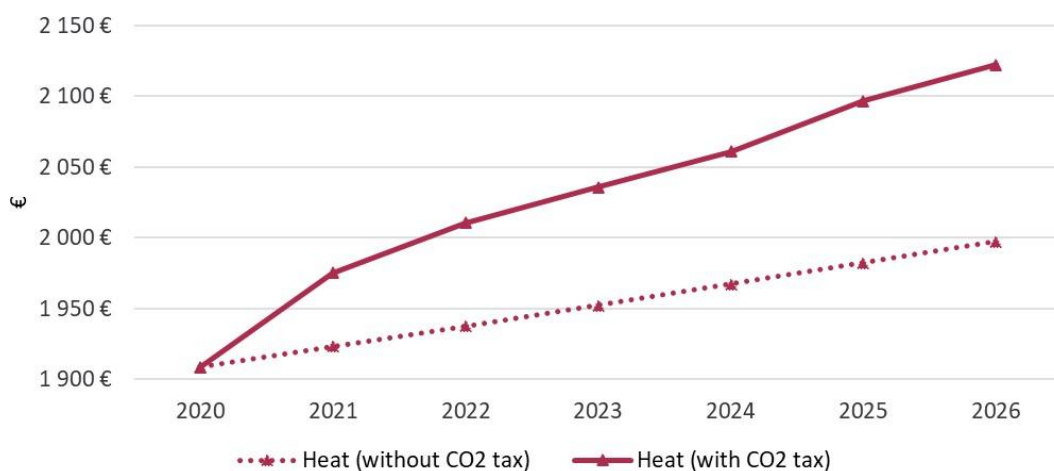
<https://tilia.info/>

The project met its high expectations and showed outstanding results:

- Carbon emissions reduction: 40%
- Average reduction of the heat bill: 30%
- City return on equity: 25%
- Sales increase: 17%

Prospects

Adopting colder systems is not realistic at the moment due to the current heat emitters accessible in buildings. For now, the district heating provider appears to be optimistic in the near term because the current combined heat and power (CHP) feed-in tariff will expire shortly, and they expect to gain new business due to rising natural gas prices. As a result, they may decide it is time to invest in new facilities and remove the existing CHP as the first step in that process.



Expected impact of CO2 taxes on a full annual cost of individual gas heat supply for a typical household in Querfurt

Source: <https://tilia.info/>

Distant CO2 taxes are likely to affect the supply cost of gas heating, which would make the supply of biogas district heating more favorable. The estimated annual cost of district heating is expected to range between 1900 and 1950 EUR/y in this timeframe and the use of renewable energy sources (RES) contributes to price stabilization. Based on these taxes, one of the future strategies for district heating could be the addition of biomass energy, i.e. wood, as options like geothermal or solar thermal energy require low temperature operating systems or high temperature heat pumps which are capable of around 85°C. Unfortunately, those heat pumps are too expensive at the moment and do not receive funding in Germany. The district heating company is also considering the possibility to use heat pumps in combination with solar photovoltaic systems to upgrade the supply of the district heating grid. In the vicinity, there are no available sources of waste heat.[17]

Summary of Case Studies

Case Study	Policy Drivers & Regulations	Technical Solutions & Innovations	Financial Model & Incentives	Stakeholder Engagement & Ownership	Key Differentiators / Challenges
Odense, Denmark	National 70% CO ₂ reduction target by 2030; Carbon taxation.	Integration of waste heat from a Facebook data center; Large-scale heat pumps; Low-temperature emitters connected directly to the grid.	Municipal utility ownership; High environmental taxes on competing fossil fuels make DH cost-competitive; One of the lowest household heating costs in Denmark.	Municipally owned utility (Fjernvarme Fyn); Collaboration with large industrial data center.	Strength: Highly efficient use of diverse waste heat sources. Challenge: Competition from individual heat pumps.
Italy's heat sector	Lack of a strong, specific national mandate for DH expansion. Limited DH market share (~3.5%).	Deep renovation of building stock to reduce heat demand by 20-40%. Deployment of 4th Generation DH (4GDH) networks operating at lower temperatures	High capital expenditure (CAPEX) for both building renovation and new DH network infrastructure is a significant barrier.	Successful implementation would require collaboration between national government, municipalities, private DH operators, and building owners.	It highlights the immense challenge of decarbonizing a heating sector dominated by individual gas boilers. Primary Challenges: High Capital Costs.

Case Study	Policy Drivers & Regulations	Technical Solutions & Innovations	Financial Model & Incentives	Stakeholder Engagement & Ownership	Key Differentiators / Challenges
Helsingborg, Sweden	National policies supporting waste-to-energy; Carbon pricing.	EVITA interconnector linking three city networks; 100% RES & waste heat mix (WtE, industrial waste heat, biofuel CHP, sewage-sourced heat pumps).	Price cap set at Swedish average; "DH Gold" premium option for zero-carbon heat.	Collaboration between three municipal energy companies (Öresundskraft, Landskrona Energi, Krafrtingen).	Strength: High reliability and inter-city resilience. Challenge: High upfront cost for consumers switching from individual systems.
Bordeaux, France	Metropolis target of 100% RE by 2050; Obligatory connection in "classified" DH zones.	Tri-generation: Geothermal (river alluvium), biomass (local woodchips), waste heat from sewage treatment (WWTP). Thermal storage.	Public-Private Partnership (PPP: 60% Mixéner [public], 40% Dalkia/EDF); 30-year fixed-price tariff.	PPP structure balances public oversight with private operational expertise.	Strength: Innovative multi-source renewable mix. Challenge: High fixed connection costs for customers.
Querfurt, Germany	National Climate Protection Program; CO ₂ price on heating; Feed-in Tariffs (EEG, KWK-G).	Modernization of an inefficient gas network; Baseload shift to locally produced biogas CHP.	70% debt financing; Business model capped at 3-5% profit, with savings passed to consumers; Significant consumer price reduction (30%).	Strong community and agricultural stakeholder involvement; New opportunities for local farmers.	Strength: Successful revitalization of a failing system; strong local economic benefits. Challenge: Future need to adapt to lower temperatures and integrate new technologies.

5. Challenges and Opportunities

5.1 Incentives and strategies to encourage RE investment

Custom incentives and strategies have worked to encourage the implementation of renewable energy (RE) projects so far. The existing literature suggests that there are different types of incentives that can facilitate the deployment of renewable energy. As a rule of thumb, such types of incentives can be divided into four groups:

- research and development (R&D)
- fiscal and tax incentives
- initiatives for market development
- incentives related to grid connection and tariffs.

Research and Development (R&D)

Countries are able to boost research and development with the objective of improving existing renewable energy (RE) technologies by establishing a new research center or by creating more novel approaches. Because R&D efforts usually involve high risks and uncertainties, support from the government is crucial. Trying to achieve technological self-sufficiency like what Chinese wind turbine manufacturers do with their governments R&D programs, is one way for countries to become self-sufficient in the production of solar panels and wind turbines. Moreover, nations that do not possess the requisite skills to produce the components will only see their expenditure increase with the importation of RE infrastructure. For these reasons, focusing on investment in R&D should be the key for all countries willing to embrace renewable energy.

Fiscal and tax incentives

Fiscal policies include tax exemptions and the non-levying of duties on the import of RE equipment, which assists in its gradual assimilation into the energy system. The absence of such taxes makes the cost of electricity more competitive than gas and oil. These measures can further be complemented through taxation of fossil fuel based electricity generation which makes it costlier and alters the inter-source competition. Also granting low interest loans to construct household renewable energy plants is tax effective.

Market development incentives

Renewable Energy (RE) can be greatly hampered by bureaucratic hurdles, which can present significant challenges. These hurdles could hamper efforts to seek government sponsorship for initiatives, especially when the approved initiatives are constrained in their potential appeal. Such a scenario ends up eroding the appeal of those prospective investors. Adapting a policy that features fixed tariffs over investment to capture the renewable energy investors and allowing them to freely engage in clean energy initiatives can counteract this problem. The installation of new rules for the testing and certification of small power producers, as well as the standardization of these measures, will greatly increase the activity of RE market players.

Grid connection and tariff incentives

Due to problems related to grid capacity, most investors are reluctant to invest in renewable energy projects. The implication of this is that electricity production occurs, but the existing grid infrastructure is unable to accommodate it fully. Consequently, a portion of the electricity generated remains unused or is sold in restricted volumes. Such a situation stifles investment in renewable energy systems.

A common route to facilitate grid connections is to use Feed-in Tariffs (FiTs). In this approach, the government establishes a target price for the produced electricity that is significantly higher than the market price, thereby increasing the profit margin and potential investment into the market. Though necessary is a law mandating power grid companies to offtake electricity from these renewable energy producers.

5.2. Economic Challenges and Opportunities

5.2.1. Challenges

High Initial Capital Expenditure: The introduction of Renewable District Heating (RDH) systems entails a rather substantial capital investment when it comes to infrastructure. Not only does this consist of constructing the necessary pipes and establishing a network for distribution, but also integrating energy sources like solar thermal, biomass, and geothermal energy into the system. Those costs at the outset can be easily discouraging for prospective investors, especially in regions with limited financial supporting mechanisms. Without grants, subsidies, or, even, financing that is relatively simple to access, many will remain skeptical toward investing in RDH projects, thereby preventing a wider spread of sustainable heating alternatives in those regions.^[1]

Market Competition and Energy Pricing:

Renewable District Heating (RDH) systems often struggle to compete with fossil fuel-based heating systems, as these systems tend to have lower operational costs due to subsidies and existing market frameworks.

In order to be successful, RDH providers need to ensure that their pricing is competitive, all the while ensuring that their business is financially viable. Achieving this is no simple feat. Their work includes regulation, estimating renewable system construction and maintenance costs, and shifting to a more renewable friendly consumer market that currently uses conventional heating systems.

The need for more sustainable energy solutions in conjunction with attractive prices for customers is what creates the challenge of ensuring the longevity of RDH systems.

Financial Risk and Uncertainty:

Investors might have a hard time looking for Renewable Decentralized Hybrid (RDH) projects, and that is largely attributed to some risk factors. One of the primary worries is the changeability of the policy environment relating to renewable energy; these policies seem to shift with the political environment and the governing party, which makes investors cautious.

Alongside policy risks, the shift in energy prices can pose their own set of economic risks. Pro and contra volatile energy prices make any attempt at predicting ROI a guessing game, so, again, these energies look primarily unstable.

Another concern is the emergence of new renewable technologies. It is not hard to conceive that a new emerging technology could offer much better solutions to the problems, but it is certain it will also create many problems when it comes to testing the new technology's long-term efficiency and stability.[\[23\]](#)

This is why funding is quite elusive in RDH projects and getting it can be quite the task due to the effects mentioned previously. For investors to protect themselves, they will most likely want higher returns, which, in turn, increases the cost of capital needed for these initiatives. It's easy to see how this collection of difficulties inhibits capitalism from shining on extremely promising renewable energy projects.

5.2.2. Opportunities

Long-Term Cost Savings:

Investing in Renewable Distributed Heating (RDH) systems may be costly at the beginning, but the economic benefits in the later years can be very pleasing. The operational costs often fall on these systems as they are powered by renewable energy obtained from the local area instead of purchased imported fuel. Such an alteration increases energy self-sufficiency and shields the economy from the violent oscillation of fossil fuel prices that negatively impact the budget. Such stabilization in energy spending enables RDH systems users to have a more secure and sustainable financial appreciation in the future, safeguarding them in regards to the variability of the energy sources. [\[1\]](#)

Integration of Waste Heat Sources:

The economic feasibility of novel sources of district heating (NSDHC) systems can be tremendously enhanced through the capture and use of waste energy from industrial and data center operations, and various other establishments. Instead of letting this energy escape our systems, it can be harnessed to improve the efficiency of our heating solutions. This simultaneously reduces the consumption of primary energy and serves as an inexpensive and dependable source of energy. Ultimately, we achieve a reduction in operational costs, and environmental benefits by mitigating greenhouse gas emissions. Ideally, this innovative approach to rethinking energy consumption can promote more sustainable activities across many industries. In the final analysis, employing waste heat is a win-win scenario for everybody: we spend less, and our society and planet gain more.

Technological Advancements

Developments in the last few years in renewable energy sources and energy storage, such as batteries, are improving responses to the Renewable District Heating (RDH) systems challenges. For instance, modern solar thermal panels, better designed wind energy technologies, and new biomass approaches are increasing the efficiency of energy resource capture and conversion to heat.

Advanced energy storage systems, like novel batteries, and thermal storage are critical to match energy supply to demand. These systems provide continuous and reliable heat supply even when renewable sources are not producing power.

Further, development and research in this area is critical for lowering the installation and operational costs for RDH systems. Let's discuss why focusing more on these technologies has significant societal impact, such as improved energy productivity, reduction of heat waste, and making these clean energy systems acceptable to the public. There is no doubt that these new developments are changing the face of RDH systems for the positive which will surely lead to cheaper and greener systems in the years to come.

5.3. Technical Challenges and Opportunities

5.3.1. Challenges

Integration of Renewable Energy Sources:

Understanding the challenges posed by heating systems is essential, especially with the increasing energy demand. One persistent issue faced by diverse international economies is the use of district heating systems that rely on district energy systems fueled by renewable sources like wind and solar. Changes in weather, time of the day, and even seasonal shifts have the potential to affect the availability of heat. Meeting the demanded supply during peak seasons is exceptionally difficult to achieve as an imbalance between energy production and consumption may arise.

In such cases, boilers after a backup heating plant become critical to maintain a balance. Such boiler plants functioning on natural gas or biomass energy can fill the gaps during sizeable droughts in wind or solar energy as they aid in generating the needed heat, at the barrel of oil while the offer is at the bottom. Biomass has an added edge in such situations as it tends to produce heat and is a carbon-neutral fuel, making it safer for the environment. Blending these technologies allows for a shift on dependent systems into sustainable ones while increasing the elasticity and resilience of district heating infrastructure to better cater to its users.[\[24\]](#)

Infrastructure Adaptation:

Numerous district heating systems have already been established operating at high temperatures, which are inefficient and increase environmental pollution. In order to accomplish low-temperature renewable district heating (RDH) systems, major adaptations need to be made to the current structure. This would mean increasing the insulation of the pipes to decrease heat loss and improve system efficiency. [\[25\]](#)

Additionally, the application of heat pumps is another very critical component in this change. These pumps are used to capture and raise heat from lower-temperature energy sources like geothermal energy or waste heat from industrial facilities. The retrofit cannot be limited to replacing components alone; existing plumbing and interconnections may have to be changed as well. Ultimately, the aim is to achieve a more cost-effective, sustainable method of heating that serves the community while protecting the ecosystem.

System Complexity:

Managing the interactions of diverse renewable resources components such as solar panels, wind turbines, hydro stations together with storage units and shifting preferences of consumers is a multi-dimensional problem. To solve this problem, there is a need for intelligent control systems that can manage the real-time energy supply and demand balancing on the grids.[\[24\]](#) Additionally,

these systems also have to rely on Predictive analytics, which is a form of data mining whereby past data is used to forecast consumption and production of energy. Knowing in advance how demand will change and when renewable resources will be available, seven operators can control the system in a way to provide dependable residual supply resources. This not only increases the efficiency in energy usage, but also enhances the reliability and sustainability of energy resource systems to a level where the community's needs can be fulfilled in an efficient manner.

5.3.2. Opportunities

Advancements in Heat Pump Technology:

Things such as modern heat pumps have it so that large installations take in renewable energy and turn it into heat. Heaters that rely on heat from the environment are some of the most eco friendly systems available. They draw heat from the air, water, or even the ground and so consume significantly lower levels of energy than traditional systems. By converting heat energy from the environment into usable energy it is easy to see how these heaters assist in lowering a household fossil fuel dependency and directly support the march towards a more sustainable future.

Hence, the most notable outcome is that it can reduce their energy expenditures and at the same time reduce harmful greenhouse emissions. Adopting heat pumps is a tremendous step towards achieving energy self-sufficiency which helps in combating climate and at the same time provides a conducive environment.

Integration of Waste Heat:

The Strategies on Maximizing the Value of Industrial Byproducts: Waste liquid and air can be utilized to enhance the performance of the Recovered District Heating (RDH) systems. Every industry and even data centers and similar structures create a certain amount of waste heat. They are bundled up in the uncontrolled industrial processes. It has been established that, in fact, during the majority of manufacturing steps, large amounts of energy in the form of heat is created and gotten rid off for free. Recovering this heat will certainly reduce resource consumption and do the opposite for energy that is essential for providing warmth.

This approach has some particular advantages. It cuts down on the deleterious effects of the environment with regards to emitted heat and assists in curtailing the generation of greenhouse byproducts. Furthermore, utilizing waste heat can assist in higher productivity and lower operational cost, thus increase the overall efficiency of the economy. Essentially, it implies that employing left over energy from industry for heating purposes is one of the ways to improve the energy economy balance of the country which is desirable both from an economic and ecological point of view. [\[26\]](#)

Thermal Energy Storage:

Effective Management of Supply and Demand: The adoption of thermal energy storage systems enables more efficacious energy management. During the periods when energy consumption is low, excess heat can be captured and stored within thermal reservoirs. This thermal energy, when preserved, can then be utilized during peak energy consumption conditions. This enables the stored heat to be utilized whenever the general population utilizes the heaters or other energy-intensive devices.

This methodology improves not only the flexibility of the energy system but also its dependability. The stored thermal energy can be tapped into during peak periods, alleviating the burden on the grid. In turn, this helps to avert outages and facilitates an uninterrupted energy supply. Additionally, tapping into thermal energy storage may result in lower expenses and higher efficiency while furthering our ambition to lower greenhouse gas emissions. In summary, there is no doubt that with any sensible energy policy, thermal energy storage will be a most fundamental element in achieving a sustainable and robust energy system.

6. Policy and Strategic Recommendations

The creation and implementation of policies and strategic frameworks aimed at improving the feasibility, efficiency, and sustainability of Renewable District Heating (RDH) systems are essential contributions of the government and regulatory bodies. Policies are relevant to favor RDH growth and allow it to compete with conventional heating options. This section will discuss government strategies. One method is to offer financial incentives in the form of grants, subsidy arrangements, or tax concessions to encourage investment in renewable energy technologies. Another financial mechanism is to adopt carbon pricing, such that companies are financially encouraged to minimize greenhouse gas emissions, thereby rendering RDH relatively more attractive than fossil fuel options.

Furthermore, promoting stakeholder collaboration among local authorities, energy companies, and community groups will also foster new ideas and more effective implementation of RDH projects. Having input from a range of stakeholders will help the governments formulate a comprehensive policy atmosphere that not only caters to each stakeholder's specific needs but also acknowledges the peculiarities of their respective challenges in transitioning to sustainable heating solutions.

6.1. Government and Regulatory Strategies

6.1.1. Carbon Taxation and Emission Regulations for Renewable District Heating (RDH)

In an effective transition from fossil fuel-based district heating systems to renewable alternatives, enforceable carbon pricing strategies and enforceable emission regulations at the government level are imperative. These measures are capable of reflecting the environmental costs arising due to carbon emissions and thus channelizing the economic choices made by businesses and consumers. It creates incentives in favor of low-carbon heat-producing technologies while simultaneously raising the RDH systems' competitiveness.

This section will provide an in-depth analysis of all these instruments, including carbon taxes, emission trading systems (ETS), and performance-based regulatory measures. A carbon tax places a direct cost on carbon emissions, thereby creating incentives for entities to reduce carbon output, usually through investment in cleaner technology in the process. At the same time, emissions trading functions within a market-oriented framework allowing the trading of emissions allowances among companies, thus bringing about a reduction in emissions comprehensively.

On the other hand, performance-based regulation sets tangible targets to reduce emissions or enhance energy efficiency to spur innovation and hold the responsible agent accountable. Each of these options will be analyzed in detail, combined with a rigorous array of real-life case studies and examples from policy contexts illustrating their successful use and pointing toward valuable lessons on best practices for environmentally sustainable and economically sensible transformation to renewable district heating solutions.

Carbon Taxation: Penalizing Fossil Fuels to Promote RDH

Carbon taxes impose a cost directly linked to CO₂ emissions from heat generation. Such a system not only raises the operating costs associated with fossil-fueled systems but also enhances the economic attractiveness of renewable alternatives. A good carbon tax should, therefore, be sufficiently high to change behavior but not so high as to create an unmanageable inflation level in energy prices. For example, Switzerland has implemented a CO₂ tax on heating fuels of CHF 120 (roughly €123) per ton of CO₂. Revenue generated from that tax is redistributed to residents and businesses to ease energy costs (Swiss Federal Office for the Environment, 2021). Likewise, the carbon tax instituted in Sweden in 1991 has been an important factor in decreasing emissions from district heating by 75% by discouraging coal or oil system use; [28].

The effectiveness of carbon taxes will depend mostly on the way in which revenues are recycled. When revenues are reinvested in renewable heating projects, they tend to be more effective. For instance, 90% of revenues generated through carbon pricing in Canada are returned to households as rebates, and the remaining 10% will go towards financing clean energy initiatives (Department of Finance Canada, 2023). This policy generates public support while at the same time funding infrastructures for renewable heating. Nevertheless, it is important for policymakers to be aware of a phenomenon called carbon leakage, whereby firms may move to locations where climate regulation is less stringent. Border carbon adjustments (BCAs), such as the EU's Carbon Border Adjustment Mechanism (CBAM)[27], can be used to provide a level playing field for domestic renewable heating suppliers [32].

Emissions Trading Systems (ETS): Cap-and-Trade for District Heating

Defined to control total emissions with a price mechanism by allowing district heating companies to sell and buy emission allowances based on their needs, such a system allows most cost-effective emission reductions, compared to carbon taxes. The EU ETS-regarded as the largest carbon market in the world-includes major installations for district heating, from which it evidently requires these operations to purchase allowances for every ton of emitted CO₂ (European Environment Agency, 2023)[32]. The EU ETS has been effective in reducing emissions from district heating by 43% since it was created in 2005, encouraging biomass and waste heat replacement (Euroheat & Power, 2022).

The mechanism of an ETS can be influenced by how allowances are allocated. For example, free allowances to safeguard competitiveness in the heating sector of Poland, which relies on coal, could hamper a clean energy transition. Auctioning allowances, as seen in Germany, generates revenues to be spent on renewable energy projects (Pahle et al., 2021). Meanwhile, China's national ETS launched in 2021 is beginning to incorporate district heating sector, with pilot projects in cities such as Beijing using ETS revenue to support the installation of heat pumps [29].

Emission Performance Standards (EPS) and Fossil Fuel Bans

Emission Performance Standards (EPS) are, among other measures, the cleanest measure by which carbon dioxide emissions per unit of heat produced from various fuels could be controlled. Norway's ban on oil boilers in buildings in 2020 effectively forced a rapid switch to electric heat pumps and district heating solutions, leading to a dramatic 60% drop in heating emissions after five years (Norwegian Ministry of Climate and Environment, 2021).

Likewise, the municipality of Copenhagen has laid down specific municipal provisions that will disallow the use of coal in district heating systems by 2025 but will offer other alternatives such as biomass, geothermal energy, and waste heat (Copenhagen Municipality, 2022).

With the introduction of the Clean Heat Market Mechanism (CHMM), expected to take place in the United Kingdom in the year 2024, the heating suppliers would be charged to raise a percentage of low-carbon heating systems installed per year; otherwise, it will cause financial penalties (UK Department for Energy Security and Net Zero, 2023). Such actions give more assurance to investors in renewable district heating and ensure compliance through financial penalties.

6.2. Stakeholder Collaboration Frameworks

The successful implementation of Renewable District Heating (RDH) systems will involve cooperation between different groups, which are government agencies, utilities, private investors, and end-users. With these well-planned collaborative frameworks, they can align economic incentives, regulatory support, and technological advances, streamlining the changes toward sustainable heating solutions. This section discusses the important methods of stakeholder engagement, including Public-Private Partnerships (PPPs) as well as collaborations between municipal governments and utilities, complemented by community-based initiatives, all cited by empirical data and policy references.

6.2.1. Public-Private Partnerships (PPPs): Bridging Investment Gaps

The financing and management of renewable district heating (RDH) systems are possible through public-private partnerships (PPPs), which bridge the gap between governmental control and utilization of the private sector's drive. Governments offer finances, land-rights, or regulatory assistance; private companies contribute their investment and expertise.

A strong example is Helen Oy, an energy company in Helsinki, Finland. The Helsinki municipality holds a 58 percent stake in the company to ensure its stewardship towards climate goals, while private investors fund geothermal and waste heat recovery projects (Helen, 2023). According to a 2022 report by the International Renewable Energy Agency (IRENA), PPPs can reduce the cost of RDH projects by 15-20% compared to fully publicly funded projects, primarily through competitive bidding and mechanisms for sharing risks (IRENA, 2022).[\[33\]](#)

Nevertheless, lucrative transacting of PPPs must be underpinned by transparent contract agreements to avert contention over profit-sharing issues or service quality. In the UK, the PFI for district heating has actually been charged with placing local authorities into long-term

contracts with inflexible pricing mechanisms (National Audit Office, 2020). To mitigate such risks, Denmark has put in place that all PPP agreements under the "Greening the Grid" program shall be renegotiated periodically to adjust the tariffs according to the movement in renewable energy prices[30].

6.2.2. Municipal-Utility Collaborations: Localized Governance for RDH Expansion

In many cities, municipalities are the main customers and regulatory backers of RDH systems. By making heating options part of an urban development framework, municipalities will be able to enjoin connections to renewable energy networks and to smooth the permitting process. For instance, Vienna's regulation on Solar District Heating states that newly constructed residential buildings must either connect to RDH systems or use solar thermal installations, leading to a 34% decrease in fossil fuel use since 2010 (City of Vienna, 2023). In a similar arrangement, Göteborg Energi, Gothenburg's municipal energy company, is actively collaborating with local industries to harness waste heat from refineries, accounting for 30% of the city's heating requirement (Göteborg Energi, 2022).

One dilemma is to balance economic feasibility with environmental sustainability. In Poland, coal is still the main heating fuel, putting the municipal utilities unwilling to go ahead with renewable energy initiatives for fear of rising consumer costs (Forum Energii, 2021). To resolve this, the EU's Heat Planning Directive (2023) shall require municipalities to undertake cost-benefit analyses on RDH alternatives, to enable fairer transitions (European Commission, 2023).

6.2.3. Community Engagement and Prosumer Models

The participation of the end-user is essential for the successful implementation and acceptance of renewable district heating (RDH) systems. Germany serves as a useful model with its "Bürgerwerke" of consumer cooperatives where households pool their resources and jointly invest in RDH infrastructure. This cooperative style allows members to share the financial advantages of the system by receiving returns from the heat generated and sold to the network. In a way, this model fosters community engagement and generates solid public support for renewable energy projects.

Pricing schemes in Sweden are also an innovative technique to engage consumers with RDH systems. RDH as Dynamic pricing models create incentives for households to carry out heating during off-peak hours. This counteracted consumption behavior, helping to effectively discount energy consumption through an overall 12% increase in efficiency of the system. This reinforces the idea that well-designed pricing schemes can promote sustainability and trigger effective energy management. Several policy measures are underway to stimulate consumer-engagement in district heating projects. For example, in Norway, the Government gives extensive subsidies covering 50% of the connection fee for households opting to join RDH networks, consequently reducing the costs that may deter households from renewable heating options.

Awareness of the benefits of RDH has also been advanced by the implementation of educational campaigns. An example of such efforts is the Heat Heroes program in Denmark, which informs consumers of the advantages of RDH systems and thereby assists in garnering acceptance in the wider community. By providing clear information and support, these initiatives empower individuals to make decisions that contribute to achieving sustainable energy goals.

6.3. Long-Term Strategic Planning

The Imperative of Phased Transition Roadmaps

Renewable District Heating (RDH) systems need to be developed into well-structured long-term planning that considers phased approaches involving strategies at both short-term technical feasibility and long-term decarbonization ambitions. The International Energy Agency (IEA) cites a three-stage transition framework of short-term, medium-term, and long-term phases that facilitate the gradual adaptation of infrastructure while ensuring energy security (IEA, 2023). Thus, in the initial phase (0-5 years), hybrid systems in integrating leftover fossil fuel capacity with renewable energy are essential to preserving reliability during the early implementation stage. "Renewable Heating Act," for example, allows the temporary use of gas-biomass co-firing in district heating within Germany but obligates an increase in renewable contributions at an annual pace (BMWK, 2022).

The medium-term phase (5-15 years) should dedicate investments to setting up large heat pumps and gathering waste heat; examples can be seen in Stockholm's Exergi system, currently sourcing 80% of its renewable heat from industrial waste heat recovery. The last phase (15-30 years) should use its resources to fully decarbonize the system, integrating seasonal thermal storage and hydrogen-compatible infrastructure, with Denmark's "Energy Island" project serving as a pioneering model by connecting offshore wind energy to district heating systems using hydrogen.

Technological Pathways and Innovation Priorities

Strategic planning should mainly focus on identifying and nurturing essential technological support through specific R&D investments and demonstration initiatives. A new generation of district heating (4GDH) systems in the range of 50-70°C allows for a higher share of renewable energy, with researchers estimating that such systems can increase efficiency by 40% compared to conventional ones (Lund et al., 2022). The EU has invested €2.1 billion in the "Thermal Energy Storage Innovation Fund" to enhance pit thermal storage technologies that can retain summer solar energy for winter utilization (EU Commission, 2023). Meanwhile, the digital transformation is making great progress—the AI-assisted heat demand forecasting system in Helsinki is reducing inaccuracies in peak load by 22% for better production planning (VTT Technical Research Centre, 2023). In contrast, technology roadmaps need to reflect regional differences; the Nordic countries are focusing on heat pumps and storage solutions, while systems in Eastern Europe will need customized biomass solutions during the transition phase.

Policy and Market Architecture for Sustainable Implementation

The sustainability of such systems in the long term lies primarily in developing flexible policy frameworks and market systems. As part of its initiative on "Heat Network Zoning," the UK intends to connect to district heating in certain zones for 20% of buildings by 2035. The carbon

contract-for-difference (CCfD) system, which has been piloted in the Netherlands, provides stability of investment through guaranteed carbon price floors for renewable heating projects (PBL, 2023). Integrated planning that incorporates just transition principles is very important; for instance, the Scottish Government's "Heat in buildings strategy" allocates 30% of its funding for support to low-income communities in order to avoid energy poverty (Scottish Government, 2022). One such is regular five-year assessments on policy, as entrenched in Austria's "Renewable Heating Law," so that it remains relevant with regard to technological advancements and market changes (Austrian Climate Ministry, 2023).

Integrated Urban Planning and Sector Coupling

For the strategic deployment of RDH, strong integration between urban planning and energy system planning must be established. Through this "Energy Mapping" initiative, the City of Copenhagen identifies heat source sites with the use of 3D city models, thus providing a reduction of 15% in network costs. The "Smart Energy Cities" concept is about the joint planning of heating, electricity, and transport systems; for example, Gothenburg's energy utility uses surplus wind energy to feed district heating, achieving 90% renewable energy use. Planning for the future must also consider demographic changes; Japan's "Heat Network 2050" aims to expand district heating in line with projected decreases in the urban population.

7. Conclusion and Future Work

This thesis conducts a very extensive examination of the various economic, technological and policy barriers that relate to the transition towards Renewable District Heating (RDH) systems. It analyses financial challenges that inhibit investment, identifies technological issues to be resolved for effective implementation and examines necessary policy frameworks to support this shift. The research further provides strategies which can be easily recommended to boost the feasibility, efficiency, and sustainability of RDH systems. Such strategies range from innovative financing approaches through improvements in technology integration all the way to providing supportive regulatory guidelines to promote a smoother transition to environmentally sustainable heating solutions. Key findings include:

7.1. Key Findings

7.1.1. Economic Viability

Renewable District Heating (RDH) systems' economic feasibility construes a complex interaction of relatively high initial investments against much lower operational savings in the long-term that, in turn, are influenced by policies, technologies, and availability of local resources. The capital costs of RDH infrastructure, including distribution networks (ranging from €1500 to €3000 per meter for fourth-generation systems), heat generation facilities (biomass CHP costing €500-€800/kW), and thermal storage (pit storage costing €20-€50/kWh), are usually around 2-3 times those of standard fossil-fuel systems (for instance, IRENA, 2022). However, with sheer determination in specific cases, such strategies can drastically increase financial feasibility. The capital cost of hybrid systems that combine different renewable sources with waste heat recovery, such as the Stockholm installation (53 MW from waste-to-energy combined heat and power and 45 MW from industrial waste heat), achieve capital costs slightly 15% to 20% lower than those

alone. Hence, the installer's return will be improved by better asset use while sustaining a supply reliability of 98% (Stockholm Exergi, 2023 Annual Report).

Policy instruments acts are vital in closing the existing cost differentials. Through carbon pricing instruments, Sweden's CO₂ tax (now €120/ton) has made biomass competitive by 40% against natural gas since 2015 (Swedish Energy Agency, 2023). Feed-in tariffs for renewable heat like that of a fixed €0.085/kWh for solar thermal contributions in Germany (BMWK Renewable Heating Act, 2022 amendment) guarantee cash flows and improve bankability. Updated Renewable Energy Directive (RED III) by the EU requires a minimum annual increase of 2.1% in renewable heating share, which will lead to an expected investment of €12.8 billion into RDH by the year 2030 (European Commission Impact Assessment, 2023).

Technological advancement creates an environment for prices to fall anywhere along the value chain. Fourth-generation district heating (4GDH) systems working at 50-70°C have reduced heating piping losses to 5-10% as compared to 15-25% in traditional systems, while AI-powered demand forecasting in Helsinki has delivered reductions in peak capacity needs by 22% (VTT Technical Research Centre, 2023). Exploiting the benefits of waste heat offers particularly interesting economic conditions. For instance, Odense's recovery of waste heat from a data center reached production costs of €0.032/kWh, which is 45% less than gas-fired alternatives (Fjernvarme Fyn Case Study, 2022).

Financial innovations are equally important. For instance, green municipal bonds for Copenhagen fund 60% of RDH expansion at 1.8% interest rate (Copenhagen Climate Budget, 2023), and the KfW development bank of Germany grants 70% of project expenses to renewable heating initiatives at 0.5% interest rates for 20 years. Energy-as-service models-their 30-forces price stability for consumers and assigns technology risks to operators in Bordeaux's contracts for 30 years at a fixed price of €65/MWh, including VAT (Energie des Bassins Financial Statements, 2022).

Regional factors greatly influence the economics. Northern European systems benefit from rich waste heat resources (meeting 30% to 50% of the demand) and high fossil fuel taxes, while Mediterranean regions capitalize on solar thermal potential (€0.04-€0.06/kWh LCOH). IEA predicts that with appropriate policy backing, RDH could supply 50% of global urban heating demand by 2050 at costs that would stand in competition against electrification alternatives (IEA Net Zero Scenario, 2022). But challenges still prevail in coal-dependent regions such as Poland, where coal subsidies undermine RDH economics, although the EU Just Transition Fund has infused with €3.5 billion to upgrade heating systems (Forum Energii Analysis, 2023).

Future sustainability enhancement will need, among other things: 1) Definition of standard LCOH methodologies taking into account externalities (as proposed in the EU's Heating and Cooling Costing Guidelines, 2024), 2) Risk-sharing tools' setup, such as Denmark's district heating guarantee fund (which covers 30% of lender losses), 3) Digital marketplaces for the trading of waste heat under testing in Rotterdam's industrial cluster. A strengthened economic argument for RDH will arise through these system wide interlinkages of grid flexibility (evaluated at €15-25/MWh in EU markets) and health costs (evaluated at €20-50/MWh for less particulate emissiveness), as displayed by Querfurt's biogas-fed network (40% GHG reduction,

25% ROI) and Helsinki's hot water system exploiting waste heat (with a renewable share of 90% at €0.07/kWh). With synchronized policy apparatuses, technological breakthroughs, and fiscally innovative solutions, RDH systems are progressively establishing their capacity for farm implementation of climate goals and pecuniary remuneration in various markets.

7.1.2. Technological Integration

Innovative system design and improved operations have accomplished multifaceted renewable technologies integrated into district heating systems' operations, becoming key in their role in carbon emission reduction. Modern renewable district heating (RDH) systems utilize advanced technical configurations to enable the co-utilization of multiple renewable energy sources, which maximizes efficiency while ensuring reliability. Fourth-generation district heating systems operate at lower temperature levels of 50-70°C, thereby reducing heat losses considerably to only 5-10% as opposed to the 15-25% losses characteristic of high-temperature systems. Innovations such as pre-insulated flexible piping and low-temperature emitter designs, according to Lund et al. (2022), underpin these development advantages. These systems also leverage a range of renewable resources, such as extremely efficient large heat pumps with coefficients of performance (COP) from 3.5 to 4.5, which utilize ambient heat from seawater and wastewater, as demonstrated in projects involving Stockholm and Berlin (Euroheat & Power, 2023).

Adequate advanced thermal storage solutions are needed to accommodate fluctuating renewable sources. Examples of this pit thermal storage is the very large 70,000m³ facility in Vojens, Denmark, which promises great inter-seasonal storage and over 85% round-trip efficiencies. Phase-change materials are very good for daily energy cycling (Dalenbäck, 2021). The role of digital technology for optimization of these systems is very important, as AI-based demand forecasting methods provide less than 5% prediction error (VTT Technical Research Centre, 2023). Furthermore, blockchain-based peer-to-peer heat trading models are experimented with in Rotterdam's M4H district. The prospect of increasingly coupling RDH with power-to-heat technologies is exemplified by the 50-MW electric boilers of Copenhagen that produce heat from surplus wind energy with a record efficiency of almost 98%. In addition, prototypes of hydrogen-ready boilers are now going through assessment stages under the H21 project in Leeds as future decarbonization efforts (Northern Gas Networks, 2022).

Newer developments in waste heat recovery technologies capture low-grade capture from different applications such as a supermarket refrigeration in Oslo with a 1.2MW system and cryptocurrency mining (Boden, Sweden) (IEA DHC Annex XII, 2023). Some benefits of integrating these technologies nevertheless yield challenges such as the need for standardized interfaces and dynamic hydraulic balancing within more complex networks. Strategies addressing these challenges include real-time monitoring based on pressure and temperature sensors combined with automated valve controls. In the look ahead, the anticipated integration of CO capture technologies from biomass combined heat and power facilities planned under the Bio-CCS initiative of Stockholm and subsequently development of high-temperature heat pumps for the industrial heat recovery phase will contribute toward the next stages in technological integration. This will enhance RDH's role in achieving net-zero emissions goals (ETIP-DHC, 2023 Roadmap).

7.1.3. Policy and Stakeholder Collaboration

Effective policy frameworks and stakeholders' collaboration are needed for the successful implementation of Renewable District Heating (RDH) systems. The most recent effort is on the part of the European Union, updating the Renewable Energy Directive (RED III, 2023) with a mandate for an annual share in renewable heating increment of 2.1%. This complements the Energy Efficiency Directive, emphasizing the need for detailed municipal heat planning (European Commission, 2023). All these regulations create the necessary market incentives, whereas carbon pricing strategies such as Sweden's CO₂ tax (€120/ton) and Germany's emissions trading system (€35/ton in 2023) provide the required economic signals to heighten RDH compared with fossil fuels (IEA, 2023). However, this is differently executed in different countries. Denmark, for example, requires every municipality to prepare plans for decarbonization where district heating plays a significant role, whereas the upcoming Municipal Heat Planning Act (2024) in Germany requires cities with a population of over 20,000 to identify sources of waste heat for possible integration into a RDH system.

To address the diverse value chains within RDH systems, stakeholder collaboration models have emerged. Public-private partnerships (PPPs) have demonstrated some success in providing public services, such as the case of the energy firm Helen Oy in Helsinki. This is a municipal enterprise (58%) funded with private investments for geothermal expansion while upholding public climate goals (Helen Annual Report, 2023). Collaborative frameworks in the UK, like the Heat Network Zoning Alliance, integrate local governments, utilities, and consumer organizations to scale up infrastructure development (UK Department for Energy Security, 2023). At the grassroots level, energy cooperatives like Germany's Bürgerwerke promote local involvement in RDH projects via share ownership, which is important for acceptance as it discerns that 70% of decisions around heating occur at the building level.

Indeed, the interaction of policy with stakeholder engagement is well exhibited in funding strategies. The EU Innovation Fund will grant €3.6 billion for transnational RDH projects (2021-2027), obliging project teams to incorporate at least three involved countries and different stakeholders (European Commission, 2023). In the same way, the Fonds Chaleur in France relies on regional committees of local authorities with industry stakeholders to assess project proposals. Such multistakeholder funding arrangements have resulted in promising projects like Bordeaux's integrated geothermal-biomass network, which combines the expertise of municipal planning with private operator Dalkia and contributions from agriculture for the biomass supply (Energie des Bassins, 2022).[\[38\]](#)

Emerging best practices underline the need for adaptive governance frameworks. For instance, Austria's Renewable Heating Law calls for reassessment every five years to adjust support mechanisms to emerging technological advancements (Austrian Climate Ministry, 2023). In the meantime, real-world assessment of stakeholder engagement strategies in the Smart Energy City initiative of Finland employs living lab approaches. This initiative can be seen in the establishment of the District Heating and Cooling Stakeholder Platform of the EU in 2022, demonstrating how organized knowledge-sharing would enhance its learning across different market environments. The RDH systems are becoming more complex, which hydrogen-ready infrastructure and recovery of heat from industrial waste add to their challenge; therefore, it is necessary to develop collaborative policy platforms that would be used to harmonize the

technical, economic, and social elements of the energy transition (ETIP DHC, 2023 Strategic Research Agenda).

7.2. Future Research Priorities

7.2.1. Hydrogen Integration Pathways

Incorporating hydrogen into district heating systems offers ample opportunities for decarbonization, especially in regions suffering from challenges in electrification or high accessibility problems for biomass. The current piloting initiatives rely on three major approaches for hydrogen incorporation: direct burning in modified boilers to allow for 20-30% mixture of hydrogen with natural gas, hydrogen-powered combined heat and power (CHP) plants, power-to-hydrogen-to-heat systems, including high-temperature fuel cells, or hydrogen boilers. The UK's H21 project in Leeds has conducted successful tests involving pure 100% hydrogen burning in retrofitted district heating boilers with thermal efficiencies of 92-95%; an approach comparable to natural gas, while emitting zero CO₂. Meanwhile, "Energy Island," a project of Denmark, is leading efforts in the transformation of offshore wind energy into hydrogen on a much larger scale through pipeline networks that could reach both industrial consumers and hybrid hydrogen-district heating systems.

However, the technical barriers are enormous, especially with regards to material compatibility: existing steel pipelines risk hydrogen embrittlement, which would probably require their replacement with polyethylene or composite alternatives, whilst retrofitting costs have been estimated at €1.2-2.0 million per kilometer.

The largely economic potential for hydrogen-renewable-based district heating (RDH) depends primarily on specific system design as well as the cost of renewable hydrogen incurred through production processes. Currently, it takes between €4-6/kg-levelized cost to produce green hydrogen by electrolysis (equivalent to €120-180/MWh thermal), but analysts predict it may go down to €2-3/kg by 2030 owing to scales of economy and reduction in costs of electrolyzers. A hybrid system using hydrogen with heat pumps and thermal storage holds much promise; research at Aalborg University, for instance, shows that linking a 20% hydrogenated seasonal storage can achieve about 15-20% reductions in integrated systems-built costs when used in a high renewable penetration scenario.

The plans of the Hydrogen Backbone Initiative of the EU include the tie-in of district heating with 23 transmission system operators proposing dedicated networks for hydrogen supply to the major heat source area by 2030. Further steps in policy development to promote hydrogen integration include the allotment of €900 million in subsidies for hydrogen-ready heating solutions under Germany's H2-Direkt program and the Netherlands' "HyHeat" initiative, which mandates a blending of hydrogen on a 5% scale by district heating systems by the end of 2027.

Establishment of the technical standards remains a serious challenge since ongoing initiatives of ISO/TC 197 have begun to develop safety protocols aimed at the management of hydrogen in urban heating environments. Looking forward, finding innovative methods of thermal storage in hydrogen technologies-metal hydrides or liquid organic hydrogen carriers with integration into hydrogen production and industrial waste heat recovery (see Sweden's HYBRIT project)-seems to be promising routes for making more efficient and cost-effective systems such as these. Though

developing, hydrogen tomorrow would still be an important feature in the decarbonization of district heating today, mostly in processing areas and regions not readily sourcing renewable electricity.

7.2.2. AI and Digital Twin Applications

The integration of artificial intelligence (AI) and digital twins is currently responsible for huge transformations in the planning, operation, and optimization strategies and technologies deployed in renewable district heating (RDH) systems, in effect substantially improving the efficiency and reliability in comparison to obsolete systems. AI applications for the RDH cover the entire value chain-from demand forecasting to predictive maintenance for the futuristic era. Machine learning advancements now predict heat loads with 92-95% accuracy using real historic operational data for the next 24 hours (VTT Technical Research Centre, 2023). Virtually, power company Helen in Helsinki, which uses artificial intelligence (AI)-based neural networks, has decreased the peak load prediction errors by 22%, saving €2.1 million annually simply by minimizing overcapacity causes (Helen Annual Report, 2022). Moreover, digital twins-real virtual copies of the real heating system-enable real-time behavior simulations based on varying conditions, such as that manually done in Copenhagen's district heating system with 45,000 IoT sensors across 1,500 km of pipeline. This has led to using 18% less electricity, hence maintaining a supply reliability of 99.98% (Hofor Energy, 2023).

Digital twin technology is an instance of planning and expansion of the RDH network. THERMOS, backed by the European Union (EU), has developed an open-source suite of digital twin tools, aimed at potentially reducing by up to 30-40% the cost of designing heat networks by initiating automatic terrain evaluation, and hydraulic modeling. (Another marked example is a specific digital twin for Glasgow, which integrates 3D models of buildings and future climate forecasts to identify optimized infrastructure planning solutions for network expansion with the vision to increase renewable heat utilization from 35% to 65% by 2030 (University of Strathclyde, 2023). These models consider socioeconomic factors, such as how consumer behavior can impact demand response potential, as has been modeled by the Digital Twin Platform at Aalborg University.

AI and digital twins have ushered the development of more advanced intelligent district heating systems. For example, blockchain-based peer-to-peer heat trading initiatives, such as the pilot project by the Energy Web Foundation in Berlin, are utilizing AI to bring a dynamic price setting capacity for heating based on ongoing renewable energy availability and network constraints-aka, real-time dynamic heat rate adaptation (Energy Web, 2023). Additionally, digital twins are now to couple weather forecasting models with a 500m resolution to anticipate variations in renewable energy production, with the Odense waste-heat-based network which can ensure a steady supply. Even in the face of varying industrial output, this network problem failed to deter its 99% supply reliability record. It is poised to improve with revolutionary AI applications like applying quantum computing to the optimization of specific challenges-although it has encouraged the deployment of additional generative AI technology for scenario development. The EU's Quantum Flagship program, for instance, delivered remarkable acceleration of the mathematical computation times for sophisticatedly linked heat networks.

Additional challenges lie in the way that these technologies will be implemented with respect to data standardization and cybersecurity. The Open District Heating Initiative (2023) has put forward common data protocols in order to enhance interoperability among different AI systems, with the IEC standard also being aligned for addressing specific cybersecurity requirements within RDH (IEC, 2023). According to expectations, the integration of these technologies should help in redirecting a significant proportion of the system costs-along toward, at minimum, 15-25% as a safe bet-toward greater incorporation of renewable energy. And this is all geared toward attaining the EU ambition to have as high a proportion as 50% of renewable district heating by 2030 (ETIP DHC, 2023 Roadmap)[37]. All these changing paradigms underline that there is the need to think beyond operational efficiency and to fundamentally rethink how thermal energy system design should be in a renewable energy world.

7.2.3. Equity and Just Transition in RDH

The move from fossil-fuel district-heating systems to renewable district heating systems has its advantages and disadvantages in energy equity. There is some thought that policy will need to be developed to guarantee that benefits accrue appropriately across different socioeconomic groups while addressing barriers to benefiting the disadvantaged. The most recent study found that unless deliberate interventions are undertaken, the multiplication of renewable district heating (RDH) could worsen energy poverty; to wit, in Eastern Europe, where connection costs averaging €3500-€5000 can eat away some 15-20% of annual incomes for low-income households (Energy Poverty Advisory Hub, 2023). The just-transition approach for RDH must focus on three important themes: affordability, accessibility, and inclusive governance, which all demand unique policy and stakeholder engagement strategies.

Affordability Mechanisms and Social Tariffs

Progressive tariff structures provide an essential mechanism for keeping heat affordable during energy transition. Scottish Fuel Poverty Strategy introduces income-based sliding scale tariffs for renewable district heating, restricting energy costs to 6% of household income for vulnerable groups (Scottish Government, 2022). In parallel, Denmark's "Heat for All" initiative combines subsidy schemes for connection fees covering 50-70% of the costs with social tariffs for consumption, which are 30-40% lower than standard market rates (Danish Energy Agency, 2023). Likewise, Article 22 of the EU Energy Efficiency Directive now obliges member states to set in action measures aimed at alleviating energy poverty as they plan or develop district heating; models such as Vienna's "Wärmebonus" program offer €200 annual rebates for low-income households connected to renewable heating networks (City of Vienna, 2023).

Spatial Equity and Network Expansion

Geographical inequalities in access to renewable district heating pose an additional equity issue because rural areas typically incur connection costs approximately 3-4 times higher than those in urban localities, owing to low-heat densities (Euroheat & Power, 2022). [36] An innovative solution, such as Finland's "hybrid micro-district" model that combines small-scale biomass boiler systems with solar thermal collectors for rural communities, realizes 60%-70% renewable energy contributions at about the same costs as in urban settings (VTT Technical Research Centre, 2023). Zoning for heat networks in the UK explicitly considers equity concerns in their expansion

planning, with priority given to those neighborhoods reporting high fuel poverty (UK Department for Energy Security, 2023). [37]

Workforce Transition and Community Ownership

It is necessary to consider the impacts of RDH transitions on the labor market, particularly in areas dependent on fossil fuel heating industries. Sweden's Fossil-Free Heating Transition

Program includes retraining measures financed by €25 million for the period 2021-2025, also laying down requirements for RDH operators to source 30% of their workforce from affected communities (Swedish Energy Agency, 2023). Community ownership schemes are important for fairness, public acceptance, and, for example, 12% of renewable heating networks in Germany are administered by energy cooperatives whereby 3-4% returns go to local investors as opposed to prices that are 15-20% lower than those of utilities run by investors [36].

Participatory Planning and Energy Democracy

An effective just transition would have real community involvement in the decision-making process related to heating systems. France's Climate and Resilience Law (2021) mandates that, through citizen assemblies that are randomly selected, "energy citizens' assemblies" participate in municipal heating planning to contentious the proposals and establish projects' priorities. The EU Energy Communities Initiative provides technical and financial support for community-led RDH efforts, with 127 initiatives started since 2020, generally achieving 10-15% greater energy savings than top-down techniques.

Monitoring and Accountability Frameworks

New standards for assessing and measuring the just transition metrics are enhancing the assessment of equity ramifications emanating from RDH. For instance, for the Global District Energy Climate Awards, social impact assessments are required covering 15 indicators, among which are disconnection rates, employment impacts, and health outcomes. Also from 2026 to 2032, the EU's Social Climate Fund will expropriate €65 billion for the express purpose of alleviating energy poverty through the transition of heating, with disbursement of the money dependent on successful equity performance goals (European Commission, 2023). [32]

Concluding that, shifting to Renewable District Heating (RDH) systems is both a technical necessity and a complex socio-economic task. Its success depends on strong policy support, smart financial tools, and collaboration across stakeholders. Major challenges include high upfront costs, competition from fossil fuels, and locked-in infrastructure. However, case studies show these challenges can be addressed. Solutions such as waste heat integration, fourth-generation low-temperature networks, and public-private partnerships help overcome barriers. These innovations improve energy security, cut carbon emissions, and save money in the long run. Decarbonizing the heating sector requires a holistic and coordinated effort. This means using advanced technology, enacting supportive policies like carbon pricing and mandates, and ensuring fairness throughout the transition. Only with this approach can RDH realize its potential as a key part of sustainable urban energy systems.

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