

Article

Environmental Impact of District Heating System Retrofitting

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Abstract: Retrofitting of district heating systems is a comprehensive process which covers all stages of district heating (DH) systems: production, distribution and consumption. This study quantitatively shows the effect of retrofitting measures and represents strengths and weaknesses of different development scenarios. Improvements in production units show improvements in fuel use efficiency and thus indirectly reduce CO₂ emissions due to unburned fuel. For this purpose, validated district planning tools have been used. Tool uses mathematical model for calculation and evaluation of all three main components of the DH system. For the quantitative evaluation, nine efficiency and balance indicators were used. For each indicator, recommended boundary values were proposed. In total, six simulation scenarios were simulated, and the last scenario have shown significant reduction in CO₂ emissions by 40% (from 3376 to 2000 t CO₂ compared to the actual state), while share of biomass has reached 47%.

Keywords: environmental impact; district heating; retrofitting



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1. Introduction

The world is experiencing a surge in the use of renewable energy for generating electricity, and for heating and cooling. This can be explained by the fact that many respected information sources declare that fossil fuel resources are diminishing, especially in the last decade, and clear evidence of a climate change, which stems in large part from the use of fossil oil and gas [1,2].

The Paris Protocol set new ambitious goals regarding climate change, and since December 2015 the EU is committed to greenhouse gas reduction targets; a 40% cut compared to 1990 levels by 2030, and 60% cut below 2010 levels by 2050. The overarching goal of this agreement is to limit the global average temperature rise by 2030 to below 2 °C compared with pre-industrial levels. Additionally, more ambitious goals are set within EU Green Deal, where a central objective is to set out the trajectory for the EU to be climate neutral by 2050 [3]. While renewable energy is critical for achievement of these set goals, the shift to renewables is also driving a surge in demand for metals and minerals used in renewable energy sources and new infrastructure [4]. Most of the economic, social and environmental risks were addressed in [5], in which the authors concluded that international efforts to promote renewable energy appear to be reinforcing patterns of displacement that exacerbate vulnerability and inequality among and within states. The evaluation of the transition towards renewable energy by [6] led to the conclusion that it effectively creates a “decarbonization divide” between those who benefit from RE and those who are harmed.

Energy demand in the European Union building sector is responsible for about 40% of energy consumption. The reduction in the energy use for heating and cooling in buildings and the introduction of renewables in district heating and cooling sectors are top priorities to achieve reduction in fossil fuel consumption and CO₂ emissions [7]. Significant energy

savings are only possible if the energy sectors are prioritized and capital investments are mobilized and available for modernization and refurbishment in those sectors. It has been found that in the North European climate, human behavior can lead to 50% higher heating demand and 60% higher heating power than the standard reference values for energy-efficient buildings [8].

The development of (4th generation district heating) 4GDH involves meeting the challenge of constructing more energy-efficient buildings, as well as the integration of district heating into a future smart energy system based on renewable energy sources [9]. To respond adequately and meet challenges of developing the district heating sector, it is necessary to have a district heating (DH) system planning tool to evaluate different development pathways.

Energy balances performed annually by EUROSTAT show that the amount of energy wasted in conventional thermal power plants located in the European Union (EU), when they are working in condensing mode, is greater than the amount of energy that residential and commercial buildings use for heating. If this waste heat could be used in district heating networks, it would be possible to significantly decrease the amount of imported fossil fuels and CO₂ emissions into the atmosphere, and as result increase the security of economic energy supply, whilst being more environmental friendly [10]. The economic and environmental benefits from district heating are obvious in places where infrastructure has historically been developed and waste heat from combined heat and power (CHP) and industry is available for further utilization for heating needs. However, the volatility of prices for imported fuels, as well as global economic instability, can be a reason for volatility in thermal energy prices in DH networks. As a response to what is happening in the global market, heating operators are forced to adjust tariffs for their services. For example, the planned very sharp tariff increase of 27% in Riga city [11]. Cogeneration and district heating networks should experience significant growth in coming years. The study [12] indicates that the market shares for district heating for buildings may increase to 30% in 2030 and 50% in 2050. However, the penetration of larger scale district heating networks to 80% and higher may take decades; for example, in Copenhagen it took more than 40 years [13]. Study [14] provide some estimations of possible district heating sector development scenarios leading up to 2050 (an overview of scenarios is provided in Energy Roadmap 2050 by the European Commission, 2011). An energy-efficiency scenario indicates a strong reduction in thermal energy demand by about 30% as compared with the reference scenario. The widespread use of energy in the European construction sector creates opportunities for the implementation of energy conservation measures (ECM) in residential buildings. If ECM is implemented in buildings connected to a DH system, it can affect the operation of DH stations, which in turn can change both revenue and electricity production in CHP plants [15]. Taking this into account, before the decision-making step, it is vital to make a careful assessment of development scenarios/projects in terms of environmental impact as well. In order to investigate in detail the feasibility of the selected energy system development option, it is important to make a detailed assessment of it.

During the production of heat or electricity at industrial process plants, combustion of fuel is one of the main origins of greenhouse gas emissions. Some economically reasonable actions that would reduce the emissions include changing fuels and retrofitting the plant's energy system in order to increase fuel use efficiency and lower CO₂ and NO_x emissions [16,17]. It would be advantageous to plan for power production plants located in the vicinity where there are significant heat demands, in order to facilitate the development of district heating networks [18,19]. Among the solutions for the achievement of environmental sustainability in the energy sector, DH with CHP systems is increasingly being used. Study [20] on the development of the DH network addressed the issue of reducing the presence of pollutants in a city (especially in terms of nitrogen oxides (NO_x) and particulate matter (PM) emissions), showing that it is possible to achieve a reduction in ground level average NO_x concentration ranging between 0.2 and 4 µg/m³.

The configuration and operational features of a DH system significantly affect its environmental performance. Relevant environmental performance indicators, such as total emissions, pollutant concentration (NO_x , CO, PM), and health damage external costs, were defined within study [21]. Results show that lower pollutant emissions are associated with the installation of a DH system compared to autonomous residential boilers. While NO_x emissions are mostly related to natural gas-fired boilers, emissions of $\text{PM}_{2.5}$ are mostly produced by coal/biomass burning, according to the study [22].

2. Materials and Methods

Energy-efficiency evaluation of district heating systems is comprehensive and extended process, which can be performed in very different ways. The evaluation and assessment of district heating systems always consider different assumptions and simplifications. If these assumptions are not accurate, this will lead to uncertainties and probable errors in the expected results, and this cannot be avoided since any theoretical-mathematical model can simulate different scenarios only for correctly predetermined processes. In the case of district heating system, there are plenty of socio-economic factors, governmental limitations and geopolitical interests, which may be accepted provisionally with some degree of probability. Mathematical description of certain physical processes such as heat exchange in pipelines, heat losses in buildings, combustion of fuel, etc., can be described quite accurately and then validated by real data from physical experiments, while multi-elemental district heating systems require another approach to solve and predict the expected result [23]. Precise and accurate prediction of heat demand is vital for DH operators. While short term heat load numerical prediction can be carried out using available statistic data [24], the current study is focused on long-term planning, where goals of national and EU energy policy and different socio-economic factors are taken into account. Planning of DH systems can be performed with different techniques, which are broadly presented in scientific literature [25–27].

For the detailed assessment of a district heating system, a validated district planning tool has been used. Validation of the tool was performed by comparing calculated values with the actual state of the system with real data provided from the district heating operator's data storage and management system [28]. The tool uses a mathematical model for calculation and evaluation of the three main components of the DH system:

- Heat production;
- Heat distribution;
- Heat consumption.

There are some uncertainties which can impact the accuracy of the presented results or parameters, which cannot be defined at the time of planning:

- Compatibility of technology (low temperature district heating vs. high energy demand of non-renovated buildings);
- Rates of the city growth (new customers);
- Changes in the demand profiles, etc.

This planning tool is based on the mathematically described heat energy production, distribution and consumption processes within one district heating system. All the relationships consider changing heat energy consumption, which was carefully studied and validated within previous studies [28].

The district heating planning tool includes nine separate blocks. Each block has input and output parameters and they are interconnected to tie up all processes in a common calculation algorithm. The scheme of the planning tool with all nine blocks (Introduction, Production, Production Several Heat Sources, Distribution, Consumption, Living Stock, Emissions, Economics, Visualization-Criteria) including the main parameters is presented in Figure 1. Any spreadsheet software is considered an appropriate software for the planning tool.

Production	Distribution	Consumption	Building stock	Emissions	Economics	Visualisation - Criteria
Load, MW		Hours for heating, h		Electricity specific factors,		
Working hours, h		Hours for DHW, h		kgCO ₂ /kWh		
Produced energy, MWh		Heat load for heating, MW		Heat specific factors,		Electricity to Heat ratio
Fuel consumption, m ³		Heat load for DHW, MW		kgCO ₂ /kWh		Overcapacity - installed/load
Efficiency, %		Heat energy demand, MWh		Emission factors for dif. fuels,		Fuel balance fossil vs. renewable
Self-consumption, MWh		Temperatures, °C		kgCO ₂ /kWh		Operational efficiency
Electricity/heat ratio		Heated area, m ²				Load factor
	Diameter, m		Area, m ²		NPV	Efficiency of fuel use
	Length, m		Volume, m ³		IRR	Emission factor for electricity
	Supply/return temp., °C		Dimensions, m		Investment, mil.EUR	Emission factor for heat energy
	Outside temp., °C		Area of the district, m ²		Payback time, years	Total emissions, tCO ₂
	Soil temp., °C		Max. load, MW		Fuel price, EUR/MWh	Energy-efficiency of the system
	Normative heat losses, W/m		Standard HW cons., l/day		CO ₂ price, EUR/tCO ₂	Heat density annual, MWh/m ²
	Heat losses, MWh		Ventilation load, MW		Electricity price, EUR/MWh	Distribution efficiency, MWh _{loss} /MWh _{pr}
	Thermal conductivity, W/(mK)				Discount rates, %	
	Surface heat transfer, W/(m ² K)					

Figure 1. Smart District Heating Planning Tool overview.

For the simulations of development scenarios a real district heating system was considered, which is located in Riga. There are the following main characteristics of the existing DH system:

Multiapartment buildings—51,000 m² of heated area;

Distribution pipeline network—2 km (buried in the ground 1.1 m, overground transit through the building basement—0.9 km);

Heat capacity installed—3 MW natural gas water heating boilers 2 pc (total 6 MW).

Six different development scenarios for this particular district heating system were proposed and simulated, which are presented in Table 1. Additionally, the sixth scenario is assumed to be a combination of the most efficient and perspective development solutions.

Table 1. Description of simulation scenarios.

Changing Parameters	Scenario	Reference Scenario (Actual State)	Low Refurbishment Rate	Moderate Refurbishment Rate	High Refurbishment Rate and Low Temperature Supply	Low Refurbishment Rate and Low Temperature Supply
Distribution network		Not refurbished	100% refurbished	100% refurbished	100% Refurbished Temperatures in distribution network 60/35 °C	100% Refurbished Temperatures in distribution network 60/35 °C
Production units and fuel		2 natural gas boilers (2 × 3 MW)	2 natural gas boilers (2 × 3 MW), natural gas CHP unit (600 kW)	2 natural gas boilers (2 × 3 MW), natural gas CHP unit (600 kW), wooden biomass water boiler 2 MW	2 natural gas boilers (2 × 3 MW), natural gas CHP unit (600 kW), local solar collectors	1 natural gas boiler (3 MW), natural gas CHP unit (600 kW), wooden biomass water boiler 3 MW
Building stock refurbishment rate		Not refurbished	3% per year	5% per year	7% per year	3% per year

Thermal energy production units were prioritized by their efficiency and sustainability. Base load is covered by co-generation units and biomass fired boilers and solar collectors if they are available, and fossil energy units are used to cover peak demand.

Trends in national and European energy policy were used to justify the chosen values for different scenarios. Directive 2012/27/EU of the EU on energy efficiency defines that from the year 2014, 3% of the public buildings owned and occupied by its central government should be renovated each year to meet at least the minimum energy performance requirements. A refurbishment rate of 3% per year is considered low, since it corresponds to the minimum required rate applicable only for buildings owned by government, while the private sector could also attract European co-funding programs to speed up the renovation process [29].

Regulation No. 222 of the Cabinet of Ministers of Latvia states that: “Methods for calculating the energy performance of buildings and rules for energy certification of buildings” [30], which determines the minimum levels of energy performance and efficiency for heating in new buildings. Starting from 1 January 2021, the minimal requirement for new single-family houses is less than 50 kWh/m²/year, and for multiapartment residential buildings, less than 40 kWh/m²/year. A renovation rate of 7% is considered very ambitious but possible, if renovation measures are prioritized by national and EU co-financing programs. Higher values are unlikely to be possible, and are actually limited by the availability qualified workforce and citizen activity. While 5% per year is chosen as a moderate value for the evaluation of intermediate values, more results will be observed in order to estimate possible trends and for extrapolation purposes. Based on previous studies on average energy efficiency improvements among refurbished buildings, it was possible to predict at least a 30% reduction in heat energy consumption after the building undergoes the refurbishment process [28]. Evaluation and simulations were made for a 15-year period. Reduced temperature regimes of 60/35 °C were proposed as the minimum possible supply temperatures that can be used for preparation of domestic hot water. Reducing supply temperatures below 60 °C can jeopardize hygienic requirements and cause additional electricity consumption for domestic hot water preparation [31,32]. It is important to highlight that reducing the supply temperatures in the district heating network is not possible without additional renovation measures in the multiapartment buildings; otherwise, the existing building heat supply system will be undersized and will not provide the required comfort level during peak cold periods during the seasons where heating is required.

3. Results

For each scenario production program or each production unit, demand profiles on a monthly basis were developed. In Table 2, the example for a “Low refurbishment rate” scenario is presented:

For each scenario, results were presented in a form of a table with 12 efficiency criteria, where all values are marked in a color from green to red to indicate whether the parameter meets certain requirements. An example of the output from the planning tool in Figure 2 is given as a reference for the “Low refurbishment rate and low temperature supply” scenario.

When the distribution network is 100% renovated, a co-generation unit is installed, wooden biomass fired water boiler 3MW is installed, and flow /return temperature in the distribution network is 60/35 °C, residential sector energy efficiency increases by 30% in 3% of the buildings every year (15-year perspective).

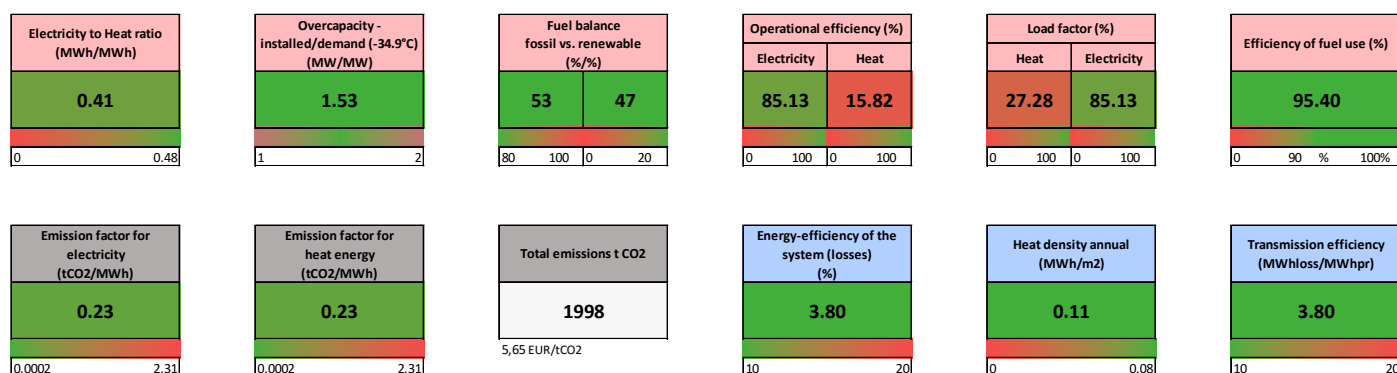


Figure 2. “Low refurbishment rate and low temperature supply” scenario criteria evaluation results.

Additionally, all results for all scenarios are presented in Table 3.

Table 2. Production program for “Low refurbishment rate” scenario.

Installed Heat Capacity	6.97	MW	Total Emissions		2990.447	tCO2	Production programs							
Capacity of installed cogeneration unit	0.50	MW el	Emissions for heat		2112.16	tCO2								
	0.64	MW th	Emissions for electr		878.29	tCO2								
Peak load for heating period (heat)	3.85	MW												
Peak load for heating period (electr)	0.50	MW												
Cogeneration heating plants														
	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Hours year		744	672	744	720	744	720	744	744	720	744	720	744	
Working hours of cogeneration unit	h	744	672	744	720	744	720	744	744	720	744	720	744	8760
Working hours of natural gas boilers	h	744	672	744	720	0	0	0	0	0	744	720	744	5088
Heat energy to the network	MWh	1443	1284	1237	874	339	307	311	313	307	623	1017	1335	9392
Average heating load	MW	1.94	1.91	1.66	1.21	0.46	0.43	0.42	0.42	0.43	0.84	1.41	1.79	
Cogeneration unit el.load	MW	0.50	0.50	0.50	0.50	0.36	0.33	0.33	0.33	0.33	0.50	0.50	0.50	
alfa (electr/heat)		0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785	
Cogeneration unit produced electr.	MWh	372	336	372	360	266	241	245	246	241	372	360	372	3783
El. self-consumption of cog.unit	MWh	46	46	50	27	15	14	15	13	14	17	47	39	343
Electricity to the grid	MWh	326	290	322	333	251	227	230	233	227	355	313	333	3440
Heat load of cogeneration unit	MW	0.64	0.64	0.64	0.64	0.46	0.43	0.42	0.42	0.43	0.64	0.64	0.64	
Heat energy produced by cogeneration unit	MWh	474	428	474	459	339	307	311	313	307	474	459	474	4819
Heat energy poduced by heating boiler (ng)	MWh	969	856	764	416	0	0	0	0	0	149	558	861	4573
Natural gas consumption	1000 m³	219	196	195	151	76	69	70	70	69	123	168	207	1611
Efficiency water boiler		0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	
Efficiency cogeneration unit		0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	
Total efficiency		0.90	0.90	0.90	0.89	0.87	0.87	0.87	0.87	0.87	0.88	0.89	0.90	0.89
Heat energy produced with renewables	MWh													0

Table 3. Summary of results for simulation of all scenarios.

	Reference Scenario (Actual State)	Low Refurbishment Rate	Moderate Refurbishment Rate	High Refurbishment Rate and Low Temperature Supply	Low Refurbishment Rate and Low Temperature Supply
Emissions, tCO ₂	2372	2990	2102	1737	1998
Loss in the network (% from consumed energy)	10.61	5.77	6.40	2.71	4.15
Consumption, MWh	10,230.79	8849.63	7928.86	7161.55	8849.63
Produced from renewable sources, MWh	0.00	0.00	3036.79	2078.62	3701.51
Electricity to Heat ratio (MWh/MWh)	0.00	0.40	0.43	0.45	0.43
Overcapacity - installed/demand	1.39	1.61	2.31	1.99	1.53
Fuel balance fossil vs. renewable (%/%)	100/0	100/0	64/36	72/28	56/44
Operational efficiency (%)					
Electricity	0.00	86.36	83.78	53.65	82.55
Heat	17.89	15.38	10.78	8.64	14.49
Load factor (%)					
Heat	28.02	27.85	28.04	19.34	24.98
Electricity	0.00	86.36	83.78	53.65	82.55
Efficiency of fuel use (%)	93.00	89.00	93.61	88.71	95.40
Emission factor for electricity (tCO ₂ /MWh)	N/A	0.23	0.23	0.23	0.23
Emission factor for heat energy (tCO ₂ /MWh)	0.22	0.22	0.23	0.23	0.23
Total emissions tCO ₂	2372	2990	2102	1737	1934
Energy-efficiency of the system (losses) (%)	10.61	5.77	6.40	2.71	4.15
Heat density annual (MWh/m ²)	0.13	0.11	0.10	0.06	0.10
Transmission efficiency (MWhloss/MWhpr)	10.61	5.77	6.40	3.82	4.15

4. Discussion

Various renovation rates of 3%, 5%, and 7% in the residential sector have shown a reduction in energy consumption in a 15-year perspective by 14%, 23% and 30%, respectively. The estimated reduction shows the overall trend in the energy sector, especially energy for domestic needs, and shows that existing DH network operators will face a situation when the capacity of the existing infrastructure will not be used at full potential. This situation may lead to a reduction in DH company revenues, which, in turn, will raise the question of tariff increase. However, there is always a possibility that growing cities and towns will attract new customers to increase the amount of heat energy sold. The attraction of new customers and decommissioning of decentralized fossil fuel heating plants will provide great benefits for future development perspectives, from both an economic and an environmental perspective.

The last three scenarios include renewable energy sources, a wooden biomass fired water boiler equipped with a flue gas condensing unit with total efficiency 112% (by lower heating value—LHV efficiency) and solar collectors. In these scenarios, overall efficiency has increased and fossil vs. renewable fuel balance has noticeably shifted towards renewable energy, reaching a maximum of 44% in the last “Low refurbishment rate and low temperature supply” scenario. Additionally, CO₂ emissions were reduced in the last three scenarios, even compared with the “Reference scenario” (Actual state), where a CHP unit is not installed. Compared with the “Low refurbishment rate” scenario, where CO₂ emissions are the highest, the last three scenarios show a reduction from 30% to 42%. Within this study, wooden biomass was considered as a CO₂-neutral fuel, with an emission factor equal to “0”, according to the Republic of Latvia Cabinet Regulation No. 42 (23.01.2018) “Method-

ology for Calculating Greenhouse Gas Emissions” [33] and EU DIRECTIVE 2003/87/EC 13.10.2003 [34]. However, the U.S. Environmental Protection Agency [35] and other scientific literature sources report CO₂ factors that are different from “0”. It is useful to note, even if wooden biomass is considered to be a CO₂-neutral fuel, without a properly planned reforestation policy, standard CO₂ emissions from burning wooden biomass (0.403 tCO₂/MWh) are twice as high than those from natural gas (0.202 tCO₂/MWh), according to the Joint Research Centre of the European Commission [36]. In combination with increased load on traffic and use of heavy traffic, the environmental impact of biomass fuels needs to be reassessed, taking into account all the embedded energy input before the biomass goes into the furnace of heating plant. Nevertheless, it is important to understand that biomass gives an opportunity for countries, which are highly dependent on energy imports to develop local economy and produce energy from local sources.

Comprehensive assessment of the simulation results shows that the “Low refurbishment rate and low temperature supply” scenario is the most technologically and environmentally acceptable, and meets the targets of national and EU energy policies. For this particular DH system, the payback period of such a development scenario would be 5.78 years (without EU funding). Estimations are made using average equipment and construction costs during the period 2016–2019. Taking into account the extremely high price volatility on steel, wood and services during the last 6 months, there is very high risk that the obtained results are overestimated and the payback period may be considerably increased. However, for equipment in DH systems, payback periods are slightly higher than average, and could be predicted to be up to 10 years, considering an equipment service life up to 35 years.

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