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

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 CO$_2$ 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 CO$_2$ emissions into the atmosphere, and as result increase the security of economic energy supply, whilst being more environmentally 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 CO$_2$ 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/m$^3$. 
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\textsubscript{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\textsubscript{x} emissions are mostly related to natural gas-fired boilers, emissions of PM\textsubscript{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.
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.

| Scenario Changing Parameters | 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) | 2 natural gas boilers (2 × 3 boiler (3 MW), MW), natural gas CHP unit CHP unit (600 kW), local solar collectors | 2 natural gas boilers (2 × 3 boiler (3 MW), MW), natural gas CHP unit CHP unit (600 kW), wooden biomass water boiler 3MW |
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 [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:
Table 2. Production program for “Low refurbishment rate” scenario.

| Installed Heat capacity | 6.97 | Total Emissions | 2990.447 tCO2 |
|-------------------------|------|-----------------|----------------|
| Capacity of installed cogeneration unit | 0.50 | Emissions for heat | 2112.16 tCO2 |
| MW el                   | 0.64 | Emissions for electr | 878.29 tCO2 |
| Peak load for heating period (heat) | 3.85 | | |
| Peak load for heating period (electr) | 0.50 | | |

**Production programs**

**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 | 720 | 744 | 720 | 744 | 720 | 744 |
| Working hours of cogeneration unit | h | 744 | 672 | 744 | 720 | 744 | 720 | 744 | 720 | 744 | 720 | 744 | 8760 |
| Working hours of natural gas boilers | h | 744 | 672 | 744 | 720 | 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 | 0.50 | 0.50 | 0.50 | 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 | 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 | 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 | 0.64 |
| Heat energy produced by cogeneration unit | MWh | 474 | 428 | 474 | 459 | 339 | 307 | 311 | 313 | 307 | 474 | 459 | 474 | 4819 |
| Heat energy produced by heating boiler (ng) | MWh | 969 | 856 | 764 | 416 | 0 | 0 | 0 | 0 | 0 | 149 | 558 | 861 | 4573 |
| Natural gas consumption | th.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 | 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 | 0.87 |
| Total efficiency | | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 |
| Heat energy produced with renewables | MWh | | | | | | | | | | | | | 0.89 |

**Heat energy produced with renewables**
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).

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

| Emissions, tCO2 | Reference scenario (actual state) | Low refurbishment rate | Moderate refurbishment rate | High refurbishment rate and low temperature supply | Low refurbishment rate and low temperature supply |
|-----------------|-----------------------------------|------------------------|-----------------------------|--------------------------------------------------|--------------------------------------------------|
| Emission factor for electricity (tCO2/MWh) | 0.23 | 0.23 | 1998 | 3.80 | 0.11 |
| Emission factor for heat energy (tCO2/MWh) | 0.23 | 0.23 | 0.00 | 10 | 0.00 |
| Total emissions tCO2 | 2,372 | 2,990 | 2,102 | 1,737 | 1,998 |
| Energy-efficiency of the system (losses) (%) | 2022 | 2022 | 2022 | 2022 | 2022 |
| Heat density annual (MWh/m²) | 0.13 | 0.13 | 0.11 | 0.11 | 0.11 |
| Transmission efficiency (MWh/loss/MWhpr) | 0.13 | 0.13 | 0.11 | 0.11 | 0.11 |
| 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 |
| Electricity to Heat ratio (MWh/MWh) | 0.41 | 1.53 | 53 | 47 | 85.13 | 15.82 |
| Operational efficiency (%) | 17.89 | 15.38 | 10.78 | 8.64 | 6.40 |
| Load factor (%) | 28.02 | 27.85 | 28.04 | 19.34 | 24.98 |
| Efficiency of fuel use (%) | 93.00 | 89.00 | 93.61 | 88.71 | 95.40 |
| Emission factor for electricity tCO2/MWh | N/A | 0.23 | 0.23 | 0.23 | 0.23 |
| Emission factor for heat energy tCO2/MWh | 0.22 | 0.22 | 0.23 | 0.23 | 0.23 |
| Total emissions tCO2 | 2,372 | 2,990 | 2,102 | 1,737 | 1,998 |
| Energy-efficiency of the system (losses) (%) | 10.61 | 5.77 | 6.40 | 2.71 | 4.15 |
| Heat density annual (MWh/m²) | 0.13 | 0.11 | 0.10 | 0.06 | 0.10 |
| Transmission efficiency (MWh/loss/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) "Methodology 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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References

1. Shafiee, S.; Topal, E. When will fossil fuel reserves be diminished? Energy Policy 2009, 37, 181–189, doi:10.1016/j.enpol.2008.08.016.
2. Luo, M.; Ji, Y.; Ren, Y.; Gao, F.; Zhang, H.; Zhang, L.; Li, H. Characteristics and health risk assessment of PM2.5-bound pahs during heavy air pollution episodes in winter in urban area of Beijing, China. Atmosphere 2021, 12, 323, doi:10.3390/atmos12030323.
3. BP Annual Review 2020, British Petroleum 2020. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed on 15 August 2021).
4. European Commission. EU Climate Action and the European Green Deal, 14 July 2021. Available online: https://ec.europa.eu/clima/policies/eu-climate-action_en (accessed on 15 August 2021).
5. The World Bank. The Growing Role of Minerals and Metals for a Low Carbon Future. 2018. Available online: https://www.worldbank.org/en/topic/energy/publication/minerals-and-metals-to-play-significant-role-in-a-low-carbon-future#:~:text=The%20rise%20of%20green%20energy,new%20World%20Bank%20report%2C%20%E2%80%9CThe (accessed on 15 August 2021).
6. Kramarz, T.; Park, S.; Johnson, C. Governing the dark side of renewable energy: A typology of global displacements. Energy Res. Soc. Sci. 2021, 74, 101902, doi:10.1016/j.erss.2020.101902.
7. Sovacool, B.K.; Hook, A.; Martiskainen, M.; Brock, A.; Turnheim, B. The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa Global Environ. Change 2020, 60, 102028, doi:10.1016/j.gloenvcha.2019.102028.
8. Remeikienė, R.; Gasparėnienė, L.; Fedajev, A.; Szarucki, M.; Dekić, M.; Razumienė, J. Evaluation of sustainable energy development progress in EU member states in the context of building renovation. Energies 2021, 14, 4209, doi:10.3390/en14144209.
9. Dalla Rosa, A.; Christensen, J.E. Low-energy district heating in energy-efficient building areas. Energy 2011, 36, 6890–6899.
10. Lund, H.; Östergaard, P.A.; Chang, M.; Werner, S.; Svendsen, S.; Sorknæs, P.; Thorsen, J.E.; Hvelplund, F.; Mortensen, B.O.G.; Mathiesen, B.V.; et al. The status of 4th generation district heating: Research and results. Energy 2018, 164, 147–159, doi:10.1016/j.energy.2018.08.206.
11. Jouhara, H.; Olabi, A.G. Industrial waste heat recovery. Energy 2018, 160, 1–2., https://doi.org/10.1016/j.energy.2018.07.013.
12. Submission of Heat Tariffs Set (Offered) by JSC “RĪGAS SILTUMS” to the Public Utilities Commission. Available online: https://www.rs.lv/lv/saturs/rigas-siltums-tarifs (accessed on 15 August 2021).
13. David, A.; Mathiesen, B.V.; Averfalk, H.; Werner, S.; Lund, H. Heat roadmap europe: Large-scale electric heat pumps in district heating systems. Energies 2017, 10, 576, doi:10.3390/en10040576.
14. Thornton, R. Copenhagen’s District Heating System: Recycling Waste Heat Reduces Carbon Emissions and Delivers Energy Security; International District Energy Association: Westminster, MA, USA, 2009; 9p. Available online: http://www.districtenergy.org/assets/pdfs/White-Papers/Copenhagen-Clean-District-Heating-final-Web4.pdf (accessed on 15 August 2021).
15. Colmenar-Santos, A.; Rosales-Asensio, E.; Borge-Diez, D.; Blanes-Peiró, J.J. District heating and cogeneration in the EU-28: Current situation, potential and proposed energy strategy for its generalization. Renew. Sustain. Energy Rev. 2016, 62, 621–639.
16. Dils, K.; Bennstam, M.; Trygg, L.; Nordenstam, L. Energy conservation measures in buildings heated by district heating—A local energy system perspective. Energy 2010, 35, 3194–3203.
17. Kosorovsk, D.; Aksenov, A. Use of condensing economizers with developed surfaces to improve the energy efficiency of conventional gas-fired heat generators in boilers. E3S Web Conf. 2021, 263, 04024, doi:10.1051/e3sconf/202126304024.
18. Daglis, V.; Vaitkus, L.; Balčius, A.; Gudzinskas, J.; Lukoševičius, V. Low grade heat recovery system for woodfuel cogeneration plant using water vapour regeneration. Therm. Sci. 2018, 22, 2667–2677, doi:10.2298/TSCI171020081D.
19. Chen, J.; Huang, S.; Shahabi, L. Economic and environmental operation of power systems including combined cooling, heating, power and energy storage resources using developed multi-objective grey wolf algorithm. Appl. Energy 2021, 298, 117257, doi:10.1016/j.apenergy.2021.117257.
20. Li, X.; Wu, X.; Gui, D.; Hua, Y.; Guo, P. Power system planning based on CSP-CHP system to integrate variable renewable energy. Energy 2021, 232, 121064, doi:10.1016/j.energy.2021.121064.
21. Ravina, M.; Panepinto, D.; Zanetti, M.C.; Genon, G. Environmental analysis of a potential district heating network powered by a large-scale cogeneration plant. Environ.Sci. Pollut. Res. 2017, 24, 13424–13436, doi:10.1007/s11356-017-8863-2.
22. Ravina, M.; Panepinto, D.; Zanetti, M. District heating networks: An inter-comparison of environmental indicators. Environ. Sci. Pollut. Res. 2021, 28, 33809–33827, doi:10.1007/s11356-020-08734-z.
23. Le Truong, N.; Gustavsson, L. Cost and primary energy efficiency of small-scale district heating systems. Appl. Energy 2014, 130, 419–427.
24. Rusovs, D.; Jakovleva, L.; Zentins, V.; Baltputnis, K. Heat load numerical prediction for district heating system operational control. Latv. J. Phys. Tech. Sci. 2021, 58, 121–136, doi:10.2478/lpts-2021-0021.
25. Kudela, L.; Špiláček, M.; Pospíšil, J. Influence of control strategy on seasonal coefficient of performance for a heat pump with low-temperature heat storage in the geographical conditions of central europe. *Energy* 2021, 234, 121276, doi:10.1016/j.energy.2021.121276.

26. Siksnelyte-Butkiene, I.; Streimikiene, D.; Balezentis, T. Multi-criteria analysis of heating sector sustainability in selected north european countries. *Sustain. Cities Soc.* 2021, 69, 102826, doi:10.1016/j.scs.2021.102826.

27. Lebedeva, K.; Borodinecs, A.; Krumins, A.; Tamane, A.; Dzelzitis, E. Potential of end-user electricity peak load shift in latvia. *Latv. J. Phys. Tech. Sci.* 2021, 58, 32–44, doi:10.2478/lpts-2021-0010.

28. Zajacs, A.; Borodinecs, A. Assessment of development scenarios of district heating systems. *Sustain. Cities Soc.* 2019, 48, 101540, doi:10.1016/j.scs.2019.101540.

29. Latvian Public Broadcasting, State to Grant Public Loans for Apartment Building Renovation, 2021. Available online: https://eng.lsm.lv/article/economy/economy/state-to-grant-public-loans-for-apartment-building-renovation.a411764/ (accessed on 15 August 2021).

30. Regulations No. 222 of Cabinet of Ministers of Latvia “Methods for Calculating the Energy Performance of Buildings and Rules for Energy Certification of Buildings”, Available online: https://likumi.lv/tas/id/322436-eku-energoefektivitates-aprekina-metodes-un-eku-energosertifikacijas-noteikumi (accessed on 15 August 2021).

31. Toffanin, R.; Curti, V.; Barbato, M.C. Impact of legionella regulation on a 4th generation district heating substation energy use and cost: The case of a swiss single-family household. *Energy* 2021, 228, 120473, doi:10.1016/j.energy.2021.120473.

32. Hajian, H.; Ahmed, K.; Kurniatski, J. Estimation of energy-saving potential and indoor thermal comfort by the central control of the heating curve in old apartment buildings. E3S Web Conf. 2021, 246, 09002, doi:10.1051/e3sconf/202124609002. (accessed on 15 August 2021).

33. Republic of Latvia Cabinet Regulation No. 42 (23 January 2018). “Methodology for Calculating Greenhouse Gas Emissions”. Available online: https://likumi.lv/ta/en/en/id/296651 (accessed on 15 August 2021).

34. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0087&from=LV (accessed on 15 August 2021).

35. U.S. Environmental Protection Agency, Emission Factors for Greenhouse Gas Inventories, 2014. Available online: https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf (accessed on 15 August 2021).

36. Koffi, B.; Cerutti, A.; Duerr, M.; Iancu, A.; Kona, A.; Janssens-Maenhout, G. CoM Default Emission Factors for the Member States of the European Union—Version 2017, European Commission, Joint Research Centre (JRC) [Dataset] PID. Available online: http://data.europa.eu/89h/jrc-com-emf-comw-ef-2017 (accessed on 15 August 2021).