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Dynamic Modelling of Data Center Waste Heat Potential Integration in District Heating in Latvia

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Abstract: As demand for data centers (DC) has increased rapidly, so has their electricity consumption. Cooling DCs is essential to maintain optimal temperatures for the operation of servers and equipment. The consequence of the cooling process is that most of the electricity consumed in DCs, including cooling, is eventually dissipated as heat that is released into the atmosphere without any useful application. Recovering and reusing waste heat offers a sustainable solution to reduce primary energy consumption and minimize the environmental impact. Using waste heat from DCs to heat buildings can significantly improve the energy efficiency and environmental sustainability of DCs. Therefore, this research analyzes the existing potential of waste heat recovery from data centers in Latvia and proposes a system dynamic modelling approach for evaluation of the future impact of waste heat on the national heat supply. The overall waste heat generated by DCs in 2022 was 51.37 GWh at a temperature of 65 °C. By 2050, the total heat energy production potential from DCs will increase to 257 GWh, with 201 GWh being utilized.

Keywords: data center; waste heat; district heating; renewable energy; heat pumps; system dynamic modelling; stella modelling

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1. Introduction

Sustainable digital infrastructure is a critical policy area in the European Union (EU). As stated in the decision to establish the Digital Decade Policy Program 2030, digital transformation is key for reaching the European Green Deal objectives and such technologies must maximize the impact of policies dealing with climate change and environmental protection [1]. The overall industrialization strategy is directed towards simultaneous environmental improvement and digital transition development [2]. Data centers (DCs) are a crucial digital infrastructure that processes and stores data using electricity [3].

The energy efficiency of DCs is an emerging concern, as more and more data are saved, processed, and transferred to offer a multitude of digital services. It has been suggested that centralized DCs are more energy efficient than individual and distributed information technology. Moreover, to direct electricity consumed by the information and communication technology hardware and basic infrastructure, DCs require vast amounts of cooling energy, traditionally produced with air conditioning units, however, the electricity consumed in a DC almost completely converts to heat. The heat from data centers is mostly not utilized, even though various solutions already exist. As the capacity and size of data centers increase, their energy consumption and associated CO_2 emissions increase [4]. Recovering and reusing waste heat offers a sustainable solution to reduce energy waste and minimize the environmental impact. Using waste heat from DCs to heat buildings can significantly improve the energy efficiency and environmental sustainability of DCs, as buildings are responsible for around 40% of the total energy consumption and 36% of GHG emissions worldwide. In the EU, more than 75% of the energy used to heat a building comes from fossil fuels, so district heating (DH) operators have focused on recovering and using this waste heat in DH, limiting energy consumption, and reducing CO_2 emissions [5].

Globally, DCs consume 3% of the energy available, creating 4% of greenhouse gas emissions [6]. During use of the equipment in the DC, waste heat is created. The impact of waste heat on technical equipment is alleviated using cooling technological solutions, which increases energy use by 40% [7]. Waste heat recovery and reuse within DCs provides a possibility to both reduce the electricity consumption of DCs and increase the use of renewable energy in heating. The reuse of waste heat within DCs was identified as one of the cheapest heat energy production solutions compared to the use of natural gas and other electricity solutions [8].

The use of waste heat as an energy source in Latvia has been studied in several areas. One study investigated the total national waste heat potential of industrial plants and the distribution of its sources. The total waste heat potential was 272 GWh per year and 14% of the total supply was in rural areas [9]. In another study, a total of the industrial waste heat potential was evaluated for a part of the capital city of Riga [10]. However, the use of low-temperature waste heat from other sources, including DCs, is understudied in Latvia.

2. Literature Review

2.1. Data Centers as Heat Energy Producers

The use of DC's waste heat for district heating (DH) has been evaluated in different global regions and climates. A heat pump is the main technology to increase the outlet temperature to be aligned with the heating network temperature. In the following section, the results of several case studies [11–16] will be described to evaluate the potential results of waste heat recovery system design in DCs.

Jang et al. have evaluated the performance characteristics of a water-source heat pump system to use as a heat energy producer in the residential area of Incheon City in South Korea. The proposed system decreased the overall energy use in the DC by 12.3% and 21.2% in residential housing. The most significant use of the recovered waste heat was observed in January with 65% of the energy from the DC used in residential housing [11].

Güğül et al. assessed the feasibility of the creation of a zero-energy consumption DC with a waste heat recovering system in Kocaeli, Turkey. As a result, the proposed system design decreased electricity consumption by 40% and saved 30,793 m^3 of natural gas with a payback time of six years in combination with a photovoltaic panel instalment [16].

He et al. proposed a DH system design for DC waste heat recovery in Hohhot, China. With a supply heating water temperature of 54 °C, the heat pump produced 73.92 MW of heat load, which alleviated the use of coal by 18 thousand tons per year and decreased the power usage effectiveness (PUE) by 0.13 to 1.17 [12].

Oró et al. evaluated the use of waste heat recovery systems from air-cooled DCs focusing on a DC with 1 MW power in Barcelona, Spain. The overall heat reuse reached 55%, but economically the solution was unfeasible for most of the cases due to the low demand for heat energy in the region [14].

The case studies show significant potential for using the waste heat from DCs as an energy source in domestic heating. Especially, use in colder climates has a high potential to increase the energy efficiency of DCs as well as supply energy to close-by communities.

2.2. Evaluation of Heat Production

Several methods are used for the evaluation of waste heat potential in DCs as energy sources. Primarily, the use of an empirical model or TRNSYS are two main techniques for evaluation [11,14,17–19].

The waste heat potential in TRNSYS is evaluated by recreating a possible system design for a case study [11,14,17]. To perform the evaluation, information on the building, the temperature variations, heat demand, and technical information on each of the elements is required to assess the waste heat potential. The empirical models require fewer data points to evaluate the waste heat potential compared with TRNSYS models [18,19]. This enables evaluation of the potential on a national level with multiple DCs involved.

In addition, empirical models could be used to create SD models for evaluation of the waste heat over time. Pakere et al. evaluated the national potential of industrial waste heat use and proposed further development scenarios based on the possible policy scenarios created [9]. The same framework has been used in the evaluation of waste heat potential on the district level in Riga, Latvia [10].

2.3. Aim and Scope of the Article

Previous studies on waste heat potential from DCs have mainly assessed the overall potential for utilization locally or in district heating systems. However, the technical feasibility and economic benefits of waste heat integration are dynamic depending on several aspects of the overall energy system, e.g., availability of RES electricity for heat pumps, and the development of investments. Therefore, this article proposes a novel methodology by using an SD approach for the in-depth forecasting of waste heat potential from DCs. This paper aims to evaluate the waste heat potential from DCs and the possible development scenarios for waste heat implementation as an energy source on the national level.

3. Methodology

The methodological framework (Figure 1) in the study is divided into three main sections. The first section includes a waste heat potential assessment through a stakeholder survey to identify the waste heat sources and energy consumption, an empirical waste heat assessment, and the mapping of the quantitative results to evaluate the technical potential and conduct spatial analyses. In the second section, an SDs submodel is developed to evaluate possible adoption scenarios of the technological solutions. In the third step, the developed submodel is integrated within the national energy sector model to evaluate the future role of low-temperature waste heat sources in DH systems.

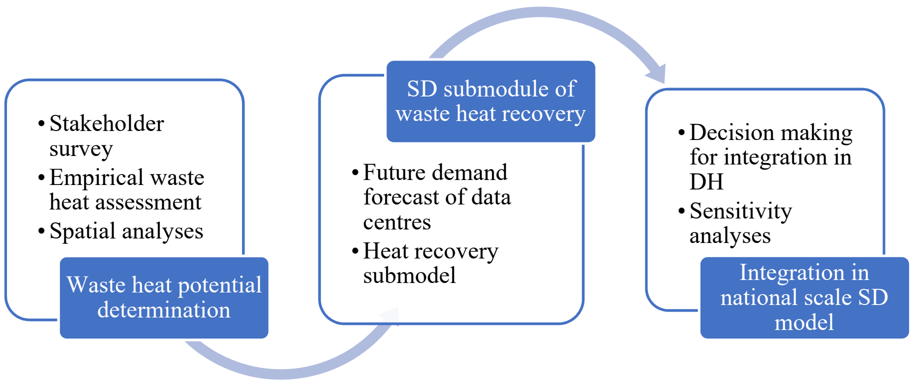

Figure 1. Methodology framework of the current research.

3.1. Waste Heat Potential Determination

The power of information technology (IT) equipment is required to evaluate the waste heat potential of a DC. Several methods for the evaluation of IT equipment power exist. The methodological framework, which uses the nominal power and number of different pieces of equipment, has been developed by Cheung et al. [19].

To reduce the number of data points required, an alternative framework is proposed with the use of the power usage effectiveness (PUE) coefficient used by Oró et al. [14]. The PUE coefficient describes the proportion of the total energy consumed with the energy consumption of IT equipment [20]. Alternatively, if no information on the DC's PUE coefficient was available, the estimation from Cho et al. of a typical DC's energy consumption with a PUE coefficient of 2.27 was used. To evaluate the waste heat potential of a DC, the assumption from Cho et al. that 80% of the electricity power used by the IT equipment creates waste heat as a side product to perform computational operations was used [21]. The information was gathered via a stakeholder survey with three data submission options: the first option contained only the information on annual electricity consumption, the second option contained both electricity consumption and the DC's PUE coefficient and the third option contained the nominal power and a number of different technical components of the DCs to perform the calculation by the methodology developed by Cheun et al. [18]. As the survey was distributed among the operators of data centers containing technical parameters available for the target audience, the reliability of data is considered high by the authors of the publication. A total of 40 possible DCs were identified, which were operated by 29 different organizations. The survey was disseminated to the operators of the data centers from October 2022 to January 2023.

For the evaluation of the coefficient of performance (COP) for heat pumps, assumptions on the heat source and heat sink temperatures are used. The outlet temperature from the DC is assumed to be around 18.7 °C, but the necessary inlet temperature for the DH is 65 °C [22]. The calculation was performed based on the Lorenz efficiency method [23]. The COP was used to determine the total heat energy produced by the heat pump and electricity consumption. Heat energy production was evaluated annually without the differentiation of the seasons.

To evaluate the technical feasibility of heat pump use in DCs, an energy reuse factor (ERF) was calculated for every DC based on the relation of the waste heat recovered compared to the total electricity consumption [14]. Additionally, the distances between the DC and the domestic heating network were evaluated by the proximity analysis via the ArcGIS Online software. The payback time (PBP) and the levelized cost of energy (LCOE) were calculated for the economic feasibility evaluation. The payback time was used as a metric based on Jovet et al. assessment of the decision-making in industrial waste heat recovery long-term project planning and the same calculation method was used in this study [24]. The calculation of LCOE was based on the method described in Lotfi et al. on the evaluation of LCOE for microgrids [25].

After the evaluation was completed for every DC, the waste heat potential on the national level was summarized, and the average values of the ERF, PBP, and LCOE were calculated to evaluate the effectiveness of the intervention. The calculated values were used as a base scenario for the SD model.

3.2. SD Submodule of Waste Heat Recovery and Integration in the National Scale SD Model

The SD model evaluates the DC's potential waste heat production with heat pumps on the national level. The comparison of the energy solutions is based on the average heat production cost of different solutions. The heat energy costs for waste heat from DCs are evaluated based on the investment cost for heat pumps, connection costs for DCs to DH networks based on the results of the proximity analysis, electricity prices, and heat supply shortages. The overall system model loop diagram is summarized in Figure 2. Three basic loops are observed: a balancing loop between potential and utilized energy, a balancing loop in the form of investment decisions, and a reinforcing loop in the form of a lack of thermal energy.

The balancing loop between potential and used energy describes a diffusion system with a process of decision-making. The potential of energy generated from waste heat passes to the energy used and returns to the thermal energy potential at the end of the technical life of heat pumps. The second balancing loop describes the creation of investment decisions. Capital investment is one of the main aspects of the investment decision, which is calculated using (1) [26].

$$KI = \frac{II * (1 - AESF) * CS}{\left(1 - \frac{1}{(1+AESF)^{TDC}}\right) * OHDC} \tag{1}$$

where:

KI—capital investment in data centers, EUR/MWh,
II—data center investments, EUR/MW,
AESF—a fraction of available EU funding,
CS—price change fraction,
TDC—technical life cycle of heat pumps, years,
OHDC—DC heat pump working hours, hours/year.

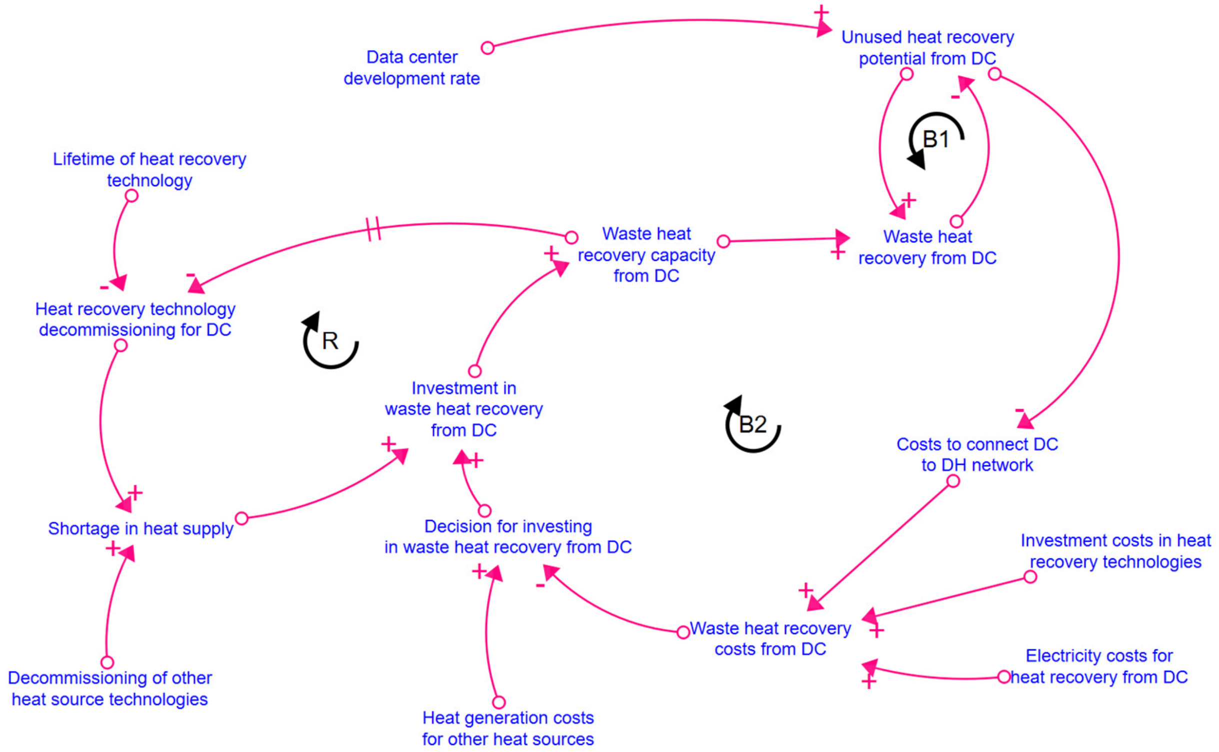

Figure 2. System model loop diagram for waste heat integration.

Reduction in the heat energy tariff is also facilitated by a decrease in the total investment and electricity costs. As the tariff for the generated heat decreases or other energy sources of heat generation increase, the investment decision is reinforced using (2) [26]. After increasing the total investment, the installation capacity of waste heat recovery systems and the amount of energy generated from waste heat used in the future also increases.

$$ILDC = IF * \frac{(KII + ST)}{\frac{PL}{OHDC}} * 1000 \quad (2)$$

where:

ILDC—investment decision for the installation of a data center waste heat recovery system, MW/year,
IF—investment fraction for data center waste heat recovery systems,
KII—total annual investment, GWh/year,
ST—lack of heat energy, GWh/year,
PL—order time, years.

The initial waste heat recovery system potential was estimated from the results of the static evaluation described in Section 2.1. Furthermore, the increase of the waste heat potential in DCs is impacted by the macroeconomic performance prediction for the IT industry. The assumption of Liao et al. on the role of the investment-GDP ratio was used to evaluate the increase in energy consumption overall [27]. Based on historical data, a fraction of the IT industry's turnover from the total national turnover was used to determine the fraction of energy consumption increase within the IT industry [28]. The GDP and investment ratio was calculated dynamically based on the average rates of change in the 2012–2021 period [29,30]. Based on it, the total electricity consumption was calculated.

The difference between the values in the previous and current year are used to calculate the available power capacity for building DCs. In it, the power is distributed from larger to smaller DCs. The available capacity is divided among a priority order from largest to smallest DC, which uses average electricity capacity for three categories: with electricity capacity above 0.9 MW, from 0.4 to 0.9 MW, and below 0.4 MW. The electricity capacity of the planned newly built data centers is subtracted from the total available capacity, reducing the value of the stock.

The heat energy production potential created by existing and new DCs is dispersed to the waste heat utilization after the implementation of the solution. Based on the 25-year technical life cycle of the heat pumps, the waste heat utilization decreases over time [23]. The decision for the DC's waste heat utilization is based on the energy tariff of the solution compared to other heat energy production technologies. For the evaluation of the energy tariff, four criteria are used: investment cost for the heat pump, new pipeline building cost, operation and maintenance costs for the heat pumps, and electricity price [9,23,31].

The overall tariff evaluation framework is summarized in Figure 3. After evaluation of the cost of heat energy produced with heat pumps, it is compared with other heat energy sources' costs and possible production rates to evaluate the most cost-effective method to meet the heat energy demand. The heat energy demand is estimated on an annual basis without seasonal variation.

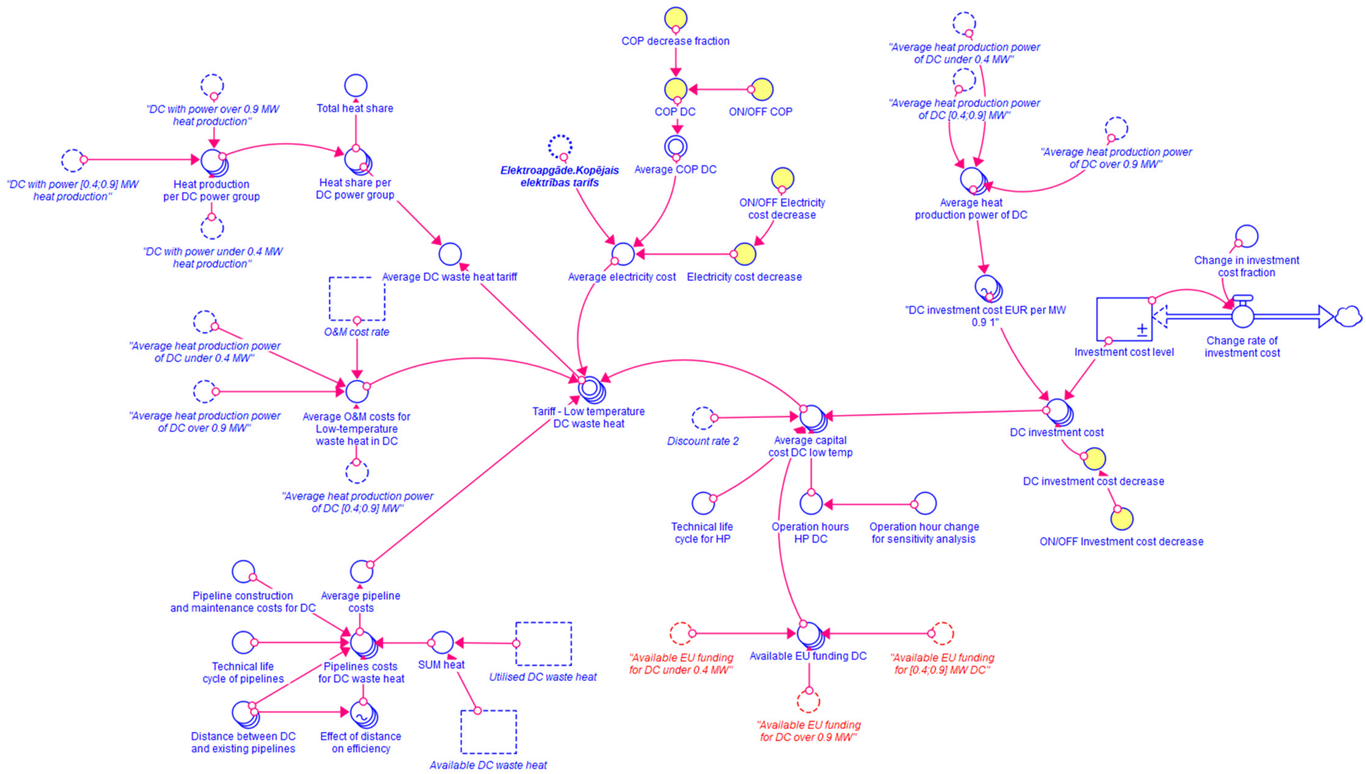

Figure 3. Heat energy tariff evaluation.

The developed waste recovery submodel is integrated within the national SD model developed and described by Pakere et al. [9]. The national scale SD model developed in previous studies encompasses both energy production and consumption, resulting in a more precise description of the entire energy supply system [26]. The optimal resource for heat or power production is selected based on a comprehensive cost analysis that compares different technologies. The model also includes power generation by using both fossil and renewable energy sources and sectoral linkage of the heating and power sector through cogeneration plants and heat pumps.

4. Results

40 possible DCs were identified from the initially created dataset. 26 out of 40 were confirmed DCs, whereas the operators denied the remaining 14 possible DC locations or did not have additional public information. Based on the results of the survey, a map of DCs was created, see Figure 4. Of 26 DCs, 11 submitted information on energy consumption and the data for the remaining 15 was filled out using the publicly available data. Most of the DCs (24) were in Riga and one was in the city of Ogre and Valmiera. The distribution of DCs is shown in Figure 4.

(**a**) (**b**)

Figure 4. Distribution of DCs (marked with orange dots) in (**a**) Latvia, (**b**) Riga based on survey results.

The electricity consumption of identified DCs and server rooms ranges from 0.02 to 20.15 GWh/year, with an average value of 3.83 GWh/year. The PUE coefficient value ranges from 1.24 to 2.27 with an average of 1.9. The national waste heat potential of DCs is 51.37 GWh/year, which can be utilized to create 63.12 GWh of heat energy with air-to-water heat pumps with COP 4.37. The values of the ERF coefficient are between 0.40 and 0.69 with the highest ERF value being in the DC with the lowest PUE coefficient. The distances between the DCs and DH networks are in the range of 3 to 2265 m, with an average of 371.7 m. The summary of distances between DCs and DH networks is shown in Figure 5. The payback time for the introduction of heat pumps in DCs is from 6.44 years for the biggest DC to 14.98 years for the smallest.

The results of the static assessment of waste heat utilization in DCs were used in the SD model to evaluate the further development of the industry. The energy tariff was evaluated for the three different sizes of DC identified and is summarized in Figure 6. The national value for the heat energy tariff is higher by 59.08 EUR/MWh compared with the average of the three DC types. Furthermore, the use of waste heat in small DCs is economically feasible only up to the year 2034, by which the modelled national heat energy tariff becomes lower. The energy tariff evaluation shows the economic feasibility of heat pump use for waste heat utilization in DCs over 0.4 MW.

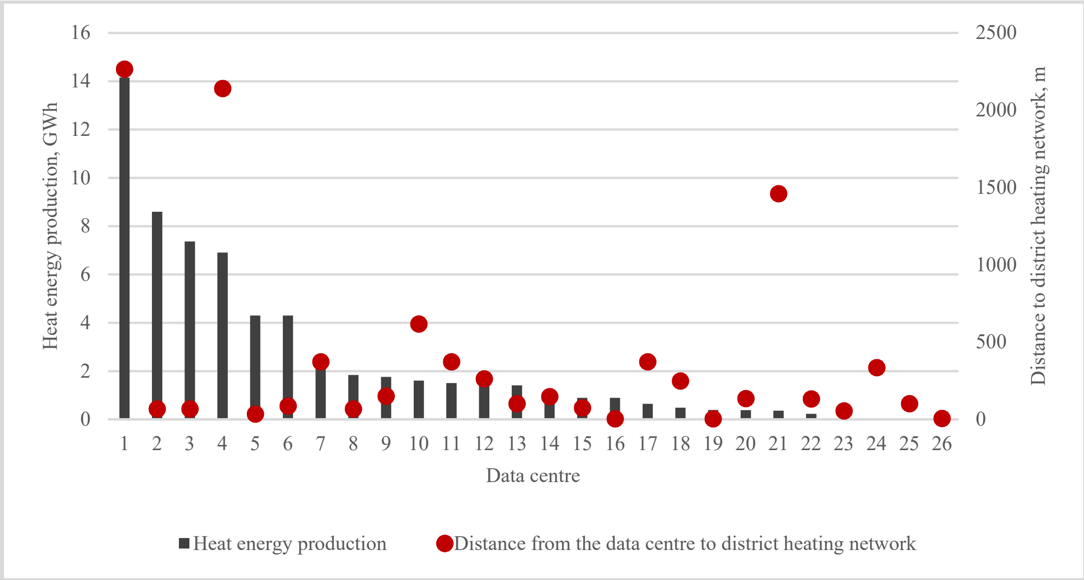

Figure 5. Waste heat production of DCs compared to the distance to the DH network based on survey results.

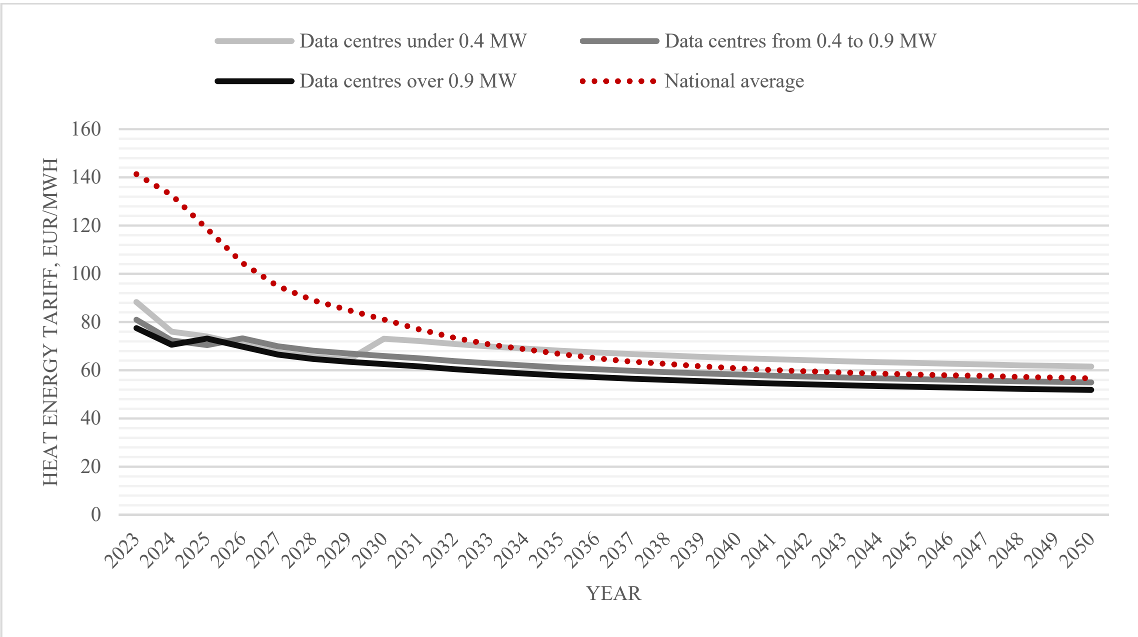

Figure 6. System dynamics results on heat energy tariff calculation for the different sizes of DC.

The overall trend shows the lower application of heat pump technologies in small DCs due to the lack of economic feasibility. After the year 2035, all the DCs with power over 0.9 MW should utilize the waste heat due to the lower price of heat energy which is estimated within the larger SD model, which takes into account the overall development trends in the energy sector and has shown high accuracy in predicting the energy prices.

The overall trend of waste heat utilization on the national level can be seen in Figure 7. With the increase in the number of DCs due to macroeconomic indicators, the overall heat energy generation potential from DCs increases. The lower economic cost of heat energy produced by DCs compared to other heat energy production technologies increases the overall utilization value. By the year 2050, out of 256.69 GWh of total waste heat, 200.62 GWh will be utilized.

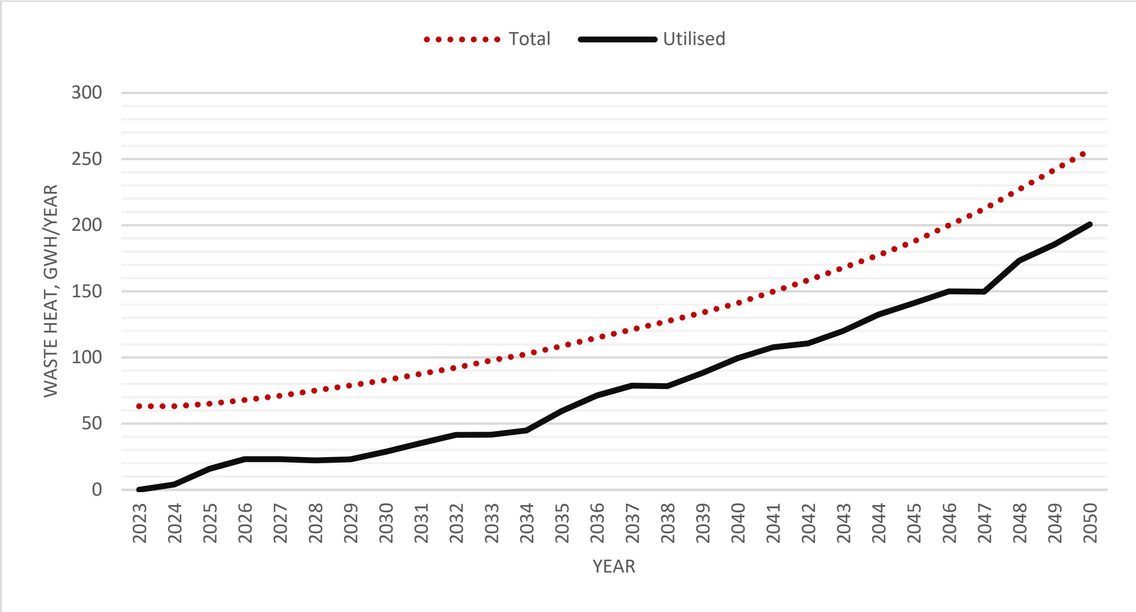

Figure 7. DC waste heat utilization rate on the national level based on system dynamics results.

The modelled national energy portfolio for DH is summarized in Figure 8. A total of 2.6% of the national heat supply is DC's waste heat regeneration systems in 2050. An overall relative increase in the national energy portfolio is observed between 2023 and 2050, which is created by the utilization rate described in Figure 7.

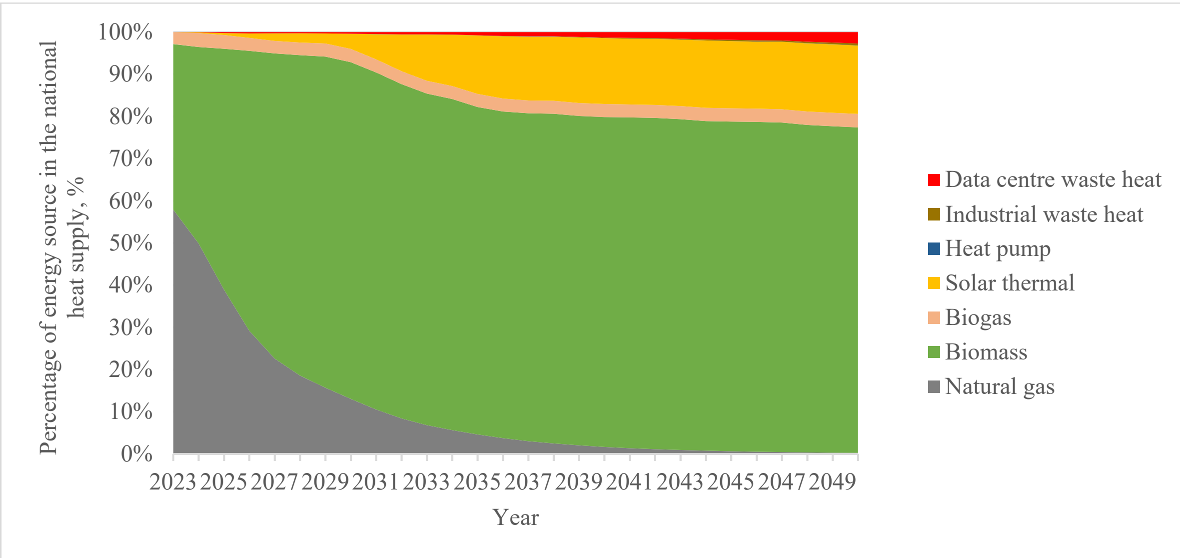

Figure 8. National relative energy portfolio for Latvia in the 2023–2050 period based on system dynamics results.

Furthermore, a sensitivity analysis of the model on the price of electricity and operational hours was performed. The results of the sensitivity analysis are summarized in Figure 9. The model showed high sensitivity to electricity prices over 260 EUR/MWh with a decrease in the total amount of utilized heat. The model showed high sensitivity to the operational time of heat pumps below 6570 h/year and a COP coefficient below 4.75.

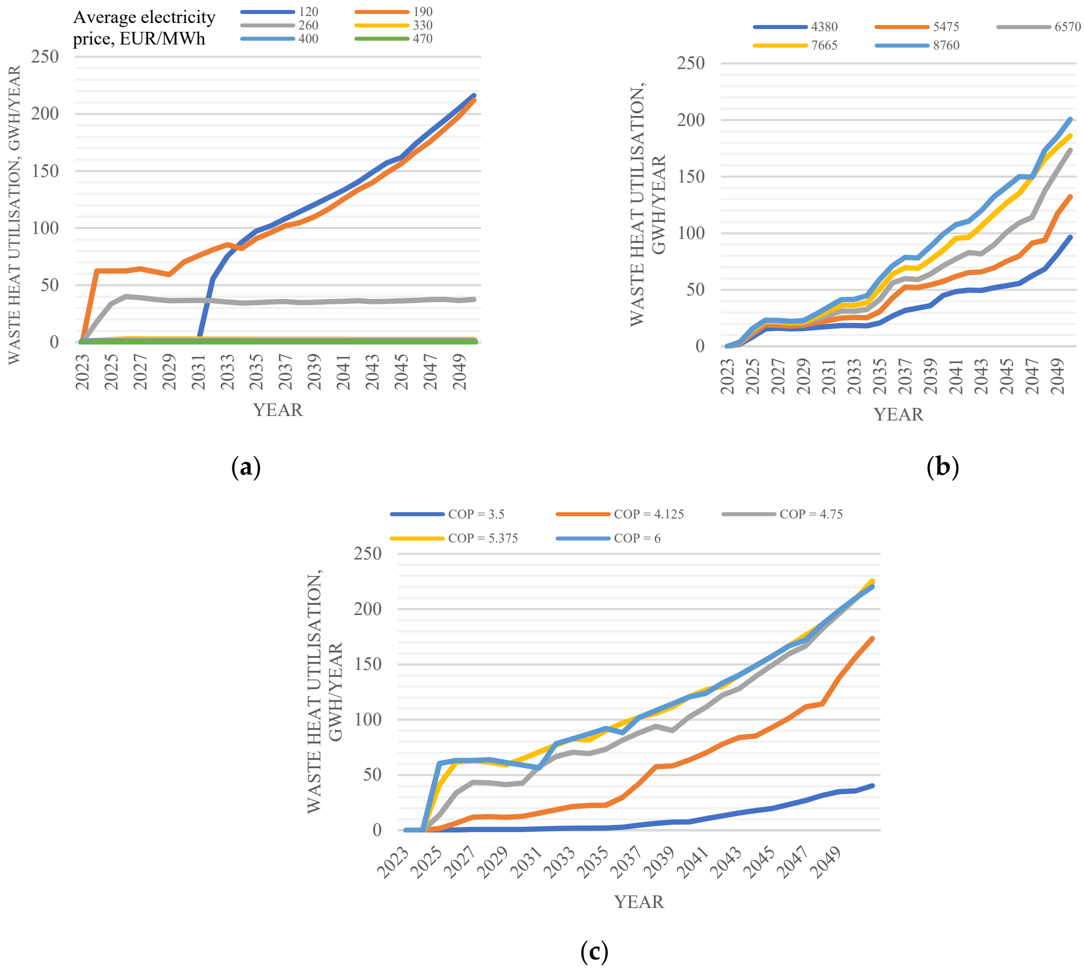

Figure 9. The sensitivity analysis (**a**) on the average prices of electricity, (**b**) operational hours of heat pumps, and (**c**) COP coefficient of heat pumps.

5. Discussion and Conclusions

This paper evaluated the use of waste heat generated by DCs as a heat energy resource in Latvia. A methodological framework consisting of empirical calculation of the existing waste heat and SD model was proposed. The results described both the static and dynamic evaluations of waste heat potential and its implementation in Latvia. The results reveal the pathways to facilitate technology adoption on a national level.

The evaluation of the preliminary assessment of DCs revealed the heterogenic distribution pattern concentrated in the capital city of Latvia, which limits the use of DC's waste heat as an energy source on the national level. The development of a decentralized network of DCs regionally is required for more equal use of its waste heat, which would increase the use of renewable energy in the DH networks as the current distribution of data centers is concentrated in the capital city. On the one hand, the distributional pattern allows for the centralization of the production of renewable heat energy due to the geographical proximity, but at the same time, it significantly increases the peak demand for electricity, especially during the winter months. In this regard, decentralization of the DC network would increase the use of waste heat in DH, evenly distributing the increases in peak electricity demand.

The overall waste heat generated by DCs is 51.37 GWh, which could be used to create 63.12 GWh of heat energy at the temperature of 65 °C. The assessment of individual DCs revealed the correlation between the payback time and waste heat production: the DCs with a higher waste heat potential have a shorter payback period for the heat pumps. The implications of that require an additional incentive for smaller DCs to participate in the waste heat regeneration system installation. This notion furthermore is confirmed by the evaluation of the heat energy tariffs between different DCs and utilization rates within different DC types in the modelled scenario.

The SD model evaluated the changes in waste heat utilization potential. By 2050, the total heat energy production potential increased to 257 GWh, with 201 GWh being utilized. The overall waste heat utilization rate is highly sensitive to electricity prices and the COP coefficient, which posits a higher feasibility with the decrease of national electricity prices and temperatures of DH as the overall performance of heat pumps and operational costs generating heat energy would improve. This furthermore amplifies the notion of greening the electricity grid to support the transition to renewable heat energy generation.

The findings revealed the necessity for stakeholder engagement to support the use of heat energy created by DC's waste heat. This is particularly important for the DCs with the highest energy consumption and waste heat production due to the decreased payback time and lower price for the implementation of such solutions. Furthermore, the biggest DC analyzed is operated by the same market operators. The overall incentive framework and cooperation between DC operators and DH companies are necessary for the utilization of waste heat.

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