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Integration of WtE and district cooling in existing Gas-CHP based district heating system – Central European city perspective

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ABSTRACT

District heating and cooling systems represent a valuable infrastructure that can facilitate the integration of various energy sources into urban energy systems. One of those sources is municipal waste. By applying the waste-to-energy concept, landfilled waste amounts can be significantly reduced, and heat, cold and electricity can be produced via combined heat and power plants. This research investigates the possibility of integration of combined heat and power waste incineration plant into the existing gas-based district heating system in the central European city. To secure 365 days of heat demand, the influence of the introduction of a warm district cooling system is simulated, where heat is distributed via the existing heat distribution network to distributed chillers, building sites locations. The results show 33% higher energy-from-waste potential in summer compared to winter, which is an opposite trend to heating demand and compatible with yearly distribution of energy needs for covering cooling demand. Despite the identified compatibility on a seasonal scale, to cover up to 100% of district cooling energy consumption with energy-from-waste, heat storage is needed, due to differences in short-term heat production and demand. This synergy has positive effects on the energy production efficiency and operation of the waste to energy plant and district heating system which results in the highest reduction in fuel consumption as well as in decrease in greenhouse gas emissions. Results of this research can be used for a better understanding of interactions between analysed technologies/systems in the wide range of cities with a continental climate.

1. Introduction

The European Commission has set an ambitious goal with the newly issued European Green Deal where the main goals are zero net greenhouse gas (GHG) emissions by 2050 and the decoupling of the economic growth from the use of resources [1]. To reach these goals, the actions need to focus on boosting the efficient use of resources by moving to a clean, circular economy. To reach climate neutrality by 2050, the actions contributing to investing in environmentally-friendly technologies and decarbonising the energy sector will be needed [2]. This is further emphasised by the new, more ambitious European Union (EU) goal, which targets at least 55% of GHG reduction by 2030 compared to 1990 levels [3]. While the Circular economy, as well as European waste-related legislation, emphasize material recovery of waste to "close the loop", energy recovery also has a role in it [4]. There are many recyclable materials in waste streams that could be materially recovered, but also there are significant shares of mixed and residual wastes whose material recovery is too complex. Here energy recovery finds its role in returning part of resources, in a form of energy, back to the economy, which at the same time leads to a decrease in import, increase in energy security and decrease in overall environmental impact.

The intersection of the circular economy and decarbonisation of the energy sector can be achieved through Waste-to-Energy (WtE) process. By applying the WtE concept, the amount of waste disposed on landfills can be reduced, and electricity and heat can be produced in a combined heat and power (CHP) plant. The distribution of the produced energy to the buildings in densely populated areas is most efficiently done with district heating and cooling (DHC) systems [2]. This could be especially important in the service buildings sector since it is expected that the energy demand for electricity, heating and cooling will increase in the following period [5].

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Despite the predicted increase in demand, the utilisation of the DHC on the global level remains low as well as the awareness of the DHC benefits, especially district cooling (DC) whose utilisation is much lower [6]. To increase efficiency and reduce future emissions, a focus on further development should be put on the integrated system which can provide required energy, either as electricity, heating or cooling, by utilising available local energy/waste resources [7]. This especially could be beneficial for the urban areas where limited space and resources are available thus requiring smart planning and sustainable development of the urban infrastructure with a focus on integration and multifunctionality of different urban infrastructure systems (electricity, district heating and cooling and natural gas, solid waste, and buildings) [8].

Integration of these systems is also essential since it provides needed flexibility for the penetration of higher shares of the renewables in the production of electricity, heating and cooling [9] thus providing a pathway to the smart energy systems [10] and decarbonisation [11]. One of the energy sources which are partially renewable but need to be modelled similarly as renewable energy sources, due to fluctuating quantity and quality, and whose integration is considered favourable in these types of systems is waste, especially if the energy production from it replaces landfilling [12]. The production of energy from municipal waste needs to be connected with the constant demand for heat, cold and electricity to ensure higher efficiencies of the transformation system [13]. In previous publications, the waste quantities are generally considered constant during the year, and because summer periods could result in energy throwaways; thus, the alternative application like DC needs to be considered to improve energy efficiency [14].

Previous research, related to energy recovery of waste, considered available waste quantity for its recovery constant or its linear increase is assumed. The linear increase is a result of linear extrapolation from historical data which do not take into account social, economic and legislative influences [15]. The trends in European countries are different and cannot be prognosed with linear extrapolation and without taking into account all of these parameters [4]. This is mainly due to relative decoupling of waste generation and economic growth, i.e. income of the citizens [16], which can be explained through the waste Kuznets curve hypothesis and reaching its inflexion point [17], but it also can be boosted through waste prevention instruments [19] and legislation driven changes [4].

These long term changes of waste amounts have been taken into account in previous research [19] and the importance of taking into account expected changes has been emphasised [20]. For a more precise prognosis of middle and long term trends, a prognostic model which takes into account a wide spectre of socio-economic and legislative factors is used [21]. At the same time, in the literature review publications that take into account and model the influence of short term changes in quantity and quality of waste, in smaller time steps which could influence the results of the DHC system analysis where loads are highly influenced by seasonality, i.e. temperature distribution during heating and cooling periods were not found.

The importance of local energy sources including waste as an energy source in local, especially urban, energy systems was identified [22], while waste is classified in the category of primary energy sources in district heating (DH) [23]. Thus, unexploited potentials of waste and renewable heat were previously mapped [24] and evaluated [25]. The importance of exploiting local energy sources for covering local energy needs is particularly emphasised in cities which account for between 60 and 80% of global energy consumption [26], due to high population density and GDP generating activities [27,28]. Because of this, they are also generating huge quantities of waste where significant amounts cannot be recycled and materially recovered. In this context, WtE technologies can play a significant role in satisfying local energy demand using unrecyclable, mixed and residual, municipal solid waste as a local energy source [4].

The use of waste in DH systems was also previously analysed, and its importance in reaching a climate-neutral heat supply is emphasised in Ref. [29]. In this path, WtE plants are also included, but to reach final climate neutrality, incineration of non-biologic municipal waste needs to be reduced by 85%–2050. In these considerations, possible benefits from DC are not considered. In Ref. [30] operation of cogeneration plant is analysed where waste is used for covering baseload and biomass for peak demands, and in Ref. [31] it was found that the use of WtE technologies in combination with energy storage can justify higher establishment costs of energy recovery of waste. While these papers looked upon the financial side of the specific plants [13], also looked upon fuel efficiency impact of a reduction of cooling, heating and electricity loads in the overall polygeneration district system and in Ref. [32] overall energy sustainability and greenhouse gas emissions of the entire system is analysed. In reviewed literature, papers look upon the economic sustainability of waste fuelled DH plants and DH systems, as well as efficiency and emissions under the influence of demand-side changes. However, they did not analyse the possible impacts of the introduction of DC as well as waste recovery on the current DH system, especially not under the influence of expected fluctuations in quantity and quality of available burnable municipal waste fraction. The results of this paper also shed a light on the sustainability benefits of the integration of WtE and DC in the DH system from an energy, environmental and system integration point of view.

Except for the better utilisation of renewables, DH systems provide several other advantages compared to on-site electricity-driven devices such as lower energy requirements, peak period saving potentials, the lower unit cost of cooling, reduced environmental impact, more reliable service, space savings at the end-user site [33]. On the other hand, the investment cost of such systems is much higher due to the large distribution system network and large energy production capacities [33]. To reduce the cost of large distribution networks, the innovative concept needs to be further developed [34]. The usage of DC in hot climates has proven to significantly contribute to fuel savings and reduction of carbon dioxide (CO_2) emissions [35]. The influence of the warm DC in combination with waste-to-energy plant in the moderate continental climate will be presented in this study, taking into account time distribution in quantity and quality of generated waste fractions that are suitable for energy recovery, which was identified as a research gap by the literature review. Thus, this research will, on the case study of the middle-sized central European city with existing gas-CHP based DH system, analyse the integration and interactions between warm DC system, waste-to-energy technologies and exiting energy system. As a case study city, the City of Zagreb, represents a city that does not meet EU targets in the field of waste separation, this analysis encompasses a period of the next 20 years in the waste management developments, thus covers the influence of expected changes on the analysed systems. Smart energy system approach shows integration of multiple sectors (power, heating and cooling, transport, waste, and wastewater management etc.) where higher saving of CO_2 could be achieved, but the focus of this research is on improving waste management and expansion of DH/DC systems. By meeting EU waste management goals, it can be expected that, due to an increase in waste separation, a quantity of mixed waste suitable for incineration decreases over the years [36], which can lead to a two-phase decrease in production and use of energy from waste (EfW) incineration when compared to previously laid out transformation path for the decarbonisation of Hamburg's DHS, where a significant decrease in only expected as a part of the waste phase-out step [29]. This is because the first decrease is induced mainly by changes in waste management and the second one by changes in the energy sector/legislation. Also, it is important to emphasize that a major role in how this shift will be played out, once again, depends on the maturity of the existing waste management system in a particular country/city.

The City of Zagreb was previously also used as a case study city for analyses of integration of WtE technologies. Thus, in Ref. [37] comparison of influences of different configurations of municipal waste management systems on the overall sustainability of waste management and recovery system is analysed and presented through Primary Energy Return Index (PERI). In this holistic analysis, DH played important role in integrating energy recovery technologies. This approach was extended in Ref. [4], where the role of WtE technologies in “closing the loop” of overall material and energy cycles is elaborated. In this research, the positive influence of energy recovery on the sustainability of material recovery is monitored by tracking coverage of energy needs of the entire waste management and recovery system and the influence it has on the sustainability of produced (recycled) materials. In these LCA-based researches, it is also found that interaction of waste management and DH systems lead to significant benefits, but they considered analysed city only as a source of waste, while the entire waste management and recovery system is considered as a user of produced energy vectors. On the other hand, as it can also be seen, DC was not considered as an option at all, and, all analyses are done for specific years only.

Thus, here presented analysis covers a research gap that was not sufficiently addressed in previous publications and its results, for years, can be used for a better understanding of interactions between analysed technologies and systems in the wide range of central European cities, with a continental climate, regardless of the level of waste management system development. Through presented results and discussion, this research will answer the following research question: can the integration of waste to an energy-based cogeneration plant in combination with a warm DC system increase the overall sustainability of the existing gas-CHP based DH system of the city with continental climate?

The study is organised into six main sections. After the Introduction, in which the literature review shows previous studies related to the DC and utilisation of WtE production, the Methods section presents the modelling of the system. The third section presents a case study while the scenario development is explained in the fourth chapter. The Results and discussion section show the main results focusing on the effects of the DC and WtE plant on fuel consumption and CO_2 emissions. The paper ends with a Conclusion section where also future work recommendations are given.

2. Methods

For the simulation of the energy system in the case study city, two energy planning tools were used and soft linked. The Low Emissions Analysis Platform (LEAP) was used for the modelling of the demand and the Advanced energy system analysis computer model (EnergyPLAN) was used for the simulation of the yearly system's operation on an hourly basis. Since the data for the modelling of the demand were to some extent available to the authors, only minor modifications were done to allow modelling of the DC system operation. Detail explanation of the modelling of the demand and data needed for simulation will be provided in the following subsections.

2.1. Energy demand modelling

As explained before the energy demand of the city was done in the LEAP software which is an energy planning software based on the accounting framework, which is a user-friendly, scenario-based and integrated energy-environment model-building tool [38]. The energy demand by 2030 was modelled based on the business as usual scenario shown in Ref. [39] and energy demand was further modelled until 2040 by extrapolating data from 2015 to 2030 until 2040. Since the focus of this paper is on the investigation of the possible influences of the DC on the cities energy system, cooling demand was additionally modelled. In the used energy demand data [39], cooling demand is included as a part of electricity consumption. Currently, cooling is mostly used in the service (commercial) sector, so the cooling demand was modelled only for that sector.

Potential yearly cooling demand was calculated using the LEAP modelling software. The total floor surface area in the service sector, the potential of cooling demand and cooling floor area are used as inputs in the model. The potential of cooling demand and cooling floor area is calculated and given as per country data in Ref. [5]. To simulate the hourly operation of the energy system, the cooling demand needs to be distributed on an hourly basis. The cooling load model was developed by using the HOTMAPS data [40], where cooling load data for the service sector are available according to the type of day, time and outside temperature for the NUTS 2 in EU28. Cooling load data are given in hourly resolution. A year-long profile was generated from the generic profiles for service cooling provided in this HOTMAPS repository. Firstly, the structure of the one year, composed of working days, Saturdays, and Sundays, was developed. The average hourly temperature for the analysed city was adapted from PVGIS using a typical meteorological year [41] and assigned to every hour of the previously composed year. Using the established type of day data, distinguishing each hour of the day and corresponding temperature, the cooling load was assigned to every hour of the composed year. The cooling demand in every hour was scaled according to the annual total cooling demand.

The electricity load distribution curve was adopted from ENTSO-e [42], and scaled for the case study city demand, while distribution curves for DH and individual heating demand were created using Heating Degree Day (HDD) method [43] and data on the heat demand from DH supplier.

2.2. Waste distribution modelling

The second part of the modelling to which was given particular attention was modelling of the hourly waste distribution curve, which was used for the estimation of the energy production from waste CHP. The hourly distributions were modelled based on detailed data obtained from the waste management company and the city government. As a majority of datasets that can be obtained in this way are aggregated monthly data or data from waste characterisation which are done only in few times during the year, obtained data were interpolated to construct a dataset that covers an entire year.

By combining waste composition data and the average chemical composition of each waste fraction [44], mixed waste heating values were calculated by the means of the Mendeliev equation. Interpolated data for the quantity of collected waste and heating value are then multiplied to get the energy value for each hour. Through this, seasonal changes in energy-from-waste potential are modelled, but long-term changes are also influenced by socio-economic changes as well as legislation influenced changes [45].

EnergyPLAN model analyses one year of energy system operation and the time component is analysed through sequential analysis for each corresponding year [46]. Energy potential from WtE technologies in EnergyPLAN is modelled through yearly energy potential and yearly distribution curve. While the yearly distribution curve is modelled using the previously mentioned methodology for modelling seasonal changes, yearly energy potential is modelled based on actual waste generation and composition data and waste quantity and quality prognosis generated data. Waste generation till 2040 is predicted using the LCA-IWM prognostic model [47,48] which by taking into account a wide range of socio-economic parameters that influence waste production [49], as well as waste management legislation defined goals, reduces prediction errors. Using this prognostic model quantity and composition of waste fractions in a targeted year is calculated. From forecasted data, using the Mendeliev equation and methodology presented in Ref. [50], yearly energy potential from municipal solid waste in the analysed city is calculated. Using these two datasets, the long-term energy-from-waste potential outlook can be given by scaling hourly values according to the total WtE potential obtained in the corresponding year from Ref. [36].

3. Characteristics of the case study city

The proposed method can be used in multiple contexts beyond the case study shown in this manuscript whose characteristics are further explained. The energy system of the City of Zagreb is well integrated with the national and European energy systems concerning electricity generation and supply. Two cogeneration plants are located inside of the city administrative boundaries and they supply electricity, heat, and steam. Other fuels are supplied by well-developed supply and distribution channels.

Regarding final energy consumption analysed in the City of Zagreb SECAP [39] the total consumption, is around 43 PJ. The final energy consumption is 25% supplied by natural gas, 35% by oil derivates, 18% by electricity, 13.5% by heat, and rest by other fuels, of which 6% from biomass. Almost 64% of the total consumption is related to the buildings of which 7% is related to City-owned buildings, 29% on commercial and service buildings and 64% on households. The total surface of the buildings corresponds to energy consumption and 67% of the floor area is used as residential.

Regarding the municipal solid waste management system in the City of Zagreb, 99% of its just under 800 thousand inhabitants (around 1250 people per km^2) are participating in the organised municipal solid waste collection [51,52]. Even though a great majority of inhabitants are covered by the general waste collection system, awareness of the importance of primary waste separation is not sufficiently developed and only 14% of municipal solid waste is separately collected. This has a big influence on conducted analysis as it is expected that this percentage increased with time if European waste management goals are to be met, which have a direct influence on the quantity and quality of mixed waste available for energy recovery [36]. As primary waste separation is newly implemented, it is expected that the biggest changes are to be expected in the following years as the efficiency of primary separation increases.

Based on data from the Municipal solid waste report [53], 252,219 tonnes of municipal waste are collected in the City of Zagreb, from which 216,631 tonnes is mixed municipal waste that is landfilled. In all separately collected waste, Bio-waste makes 22%, i.e. 7,847 tonnes. These numbers are for a period before integration of primary waste separation system via four bins and green islands and describe the unsustainable situation.

The hourly distributions were modelled from detailed data obtained from the waste management company in the city, a report on the composition and morphological characteristics of collected waste [54], and the waste management plan of the case study city [55]. Data on the waste composition are modelled on the quantity and composition of municipal solid waste for each city district. This analysis is conducted four times for twelve months which resulted in data that represents changes in the average composition of waste during four seasons. Obtained data were interpolated to construct a dataset that covers an entire year (Fig. 1). In contrast to waste composition data, waste quantities were obtained on the monthly basis (Fig. 2).

4. Simulation and scenario development

As previously mentioned, demand was modelled in LEAP and simulation of the different scenarios was done in EnergyPLAN software. The EnergyPLAN is an energy system analysis model with the focus on comparing different regulation systems' ability to integrate variable renewable energy sources. It is based on the simplified modelling of the energy system in which inputs for demand (hourly electricity, heat, cooling demands) are aggregated yearly, and demands in various sectors and supply side are installed capacities of production units and hourly distributions for renewable energy sources and WtE potential. The software outputs are yearly, monthly and hourly values of electricity production, import/export, balances, critical excess production, the share of renewables and CO_2 emissions [56].

The four basic scenarios were developed, respectively Business as usual (BAU), Waste to Energy (WtE), District cooling (DC) and a combination of the last two (WtE DC). BAU scenario is considering the influence of cooling demand on the city energy system if the cooling demand in the service sector is covered by electric heat pumps, thus increasing the electricity load. The WtE scenario is investigating the influence of the WtE combined heat and power plant on the cities energy system and operation of the DH system. The DC scenario is introducing a warm DC system where it is presumed that the 25% in 2025, 50% in 2030 and 90% in 2040 of cooling demand in the service sector are shifted from electric heat pumps to the DC system. The needed heat supply is calculated by using the COP value of 0.7 for single-phase LiBr water absorption chillers [35]. The last scenario is combining the production of heat and electricity in the waste CHP plant, gas CHP plant and DC system.

Additionally, two scenarios were added where BAU and WtE DC scenarios were simulated in a closed system to see if there is any critical excess electricity production (CEEP) or critical import needed. Lastly, the WtE DC scenario was simulated with electricity market conditions to see how the CO_2 emissions, fuel consumption, electricity production and heat production will change in these conditions thus providing a total of seven simulated scenarios. The historical hourly electricity price distribution was obtained from the local power exchange CROPEX [57].

The analysis takes into consideration the time needed for the construction of an incineration based WtE plant and the transformation of the waste management system. Thus, the integration of WtE in the energy system is modelled from 2025. During the period from 2020 to 2025, a transformation of the waste management system in the City of Zagreb is expected – an increase in primary separation of waste, rerouting residual mixed waste from landfills to incineration and anaerobic digestion of bio-waste. From 2020 to 2040, changes in mixed residual waste collection, its composition, as well as quantities of separately collected waste fractions are prognosed and WtE potential is calculated, and changes are tracked. Changes are tracked/prognosed both in short- and long-term scales, by which both seasonal and long-term changes are modelled.

Incineration-based WtE CHP plant was used for energy recovery of a residual mixed waste fraction. It is modelled based on data

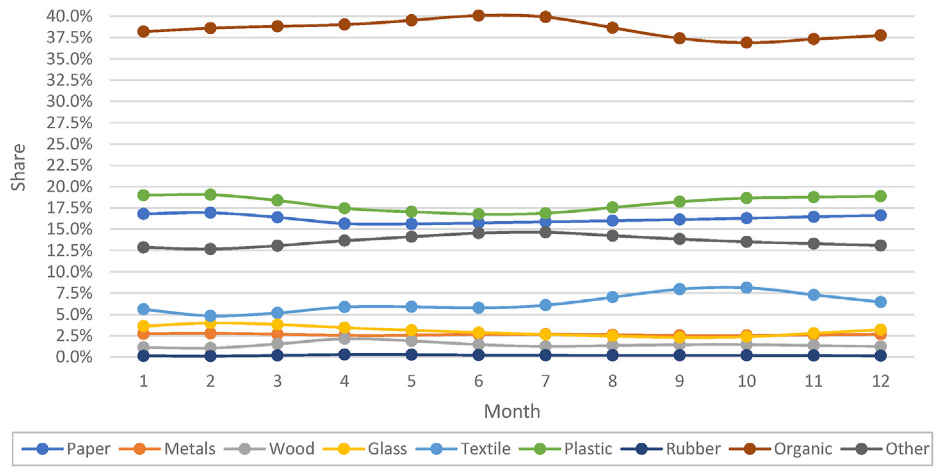

Fig. 1. Changes in the composition of collected waste throughout the year.

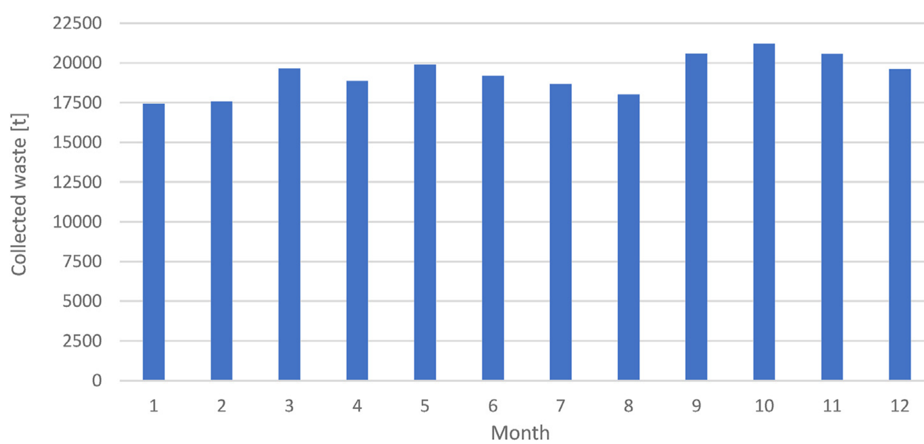

Fig. 2. Changes in the quantity of collected waste throughout the year.

from Ref. [36] and represents a modern WtE plant with an efficiency of 90.5% and a cogeneration ratio of production of electricity and heat of 0.22. Collected bio-waste is processed in an anaerobic digestion plant in which production is modelled in the dependence of the substrate characteristics [58], while produced biogas is subsequently used in the CHP plant.

5. Results and discussion

The results section is organised into several subsections. Firstly, EfW potential is calculated which is then combined with other energy production capacities available in the city, future capacities, and demand from 2020 to 2040 are described. Secondly, the hourly operation of the DH system in summer days with and without DC demand is presented. After that, the production of both heat and electricity in different scenarios and different years is shown. Finally, total fuel consumption and CO_2 emissions for different scenarios are compared.

5.1. Energy-from-waste potential

Contrary to gas CHP and boilers, energy generation of WtE plant is restricted by the energy content of collected waste, thus it is important to model the hourly energy production curve, similarly as it is done when modelling renewable energy sources. In EnergyPLAN this is done through modelling an hourly parametric distribution curve that shows the distribution of energy generation through the year and yearly energy input from waste. The parametric distribution curve is modelled by multiplying interpolated data for the quantity of collected residual (mixed) waste and its heating value and dividing obtained hourly data by maximum hourly value (Fig. 3).

While Fig. 1 had shown the maximum yearly change in the composition of 3% per fraction, Fig. 2 had shown that in October there is 22% more collected municipal solid waste than in January. As can be seen, when combined, this can lead to up to a 33% difference in the available energy potential of mixed municipal solid waste during the year (Fig. 3). Also, the parametric distribution curve shows the biggest EfW potential in summer months which decreases as average temperature drops, leading to the smallest EfW potential in the winter months – 67% of maximum available energy potential which is calculated in summer months. This is opposite to energy needed for covering heating demands and in line with yearly trends in energy needs for covering cooling demand. The only exception from this rule can be seen during August when summer tourist-related migrations decrease the number of citizens in continental European cities, but in this period energy demand is also lower.

Overall yearly energy inputs from waste for analysed years are calculated based on prognosed waste quantity data and its characteristics. From the prognosed future quantities of the separately collected fractions of municipal solid waste, data for residual

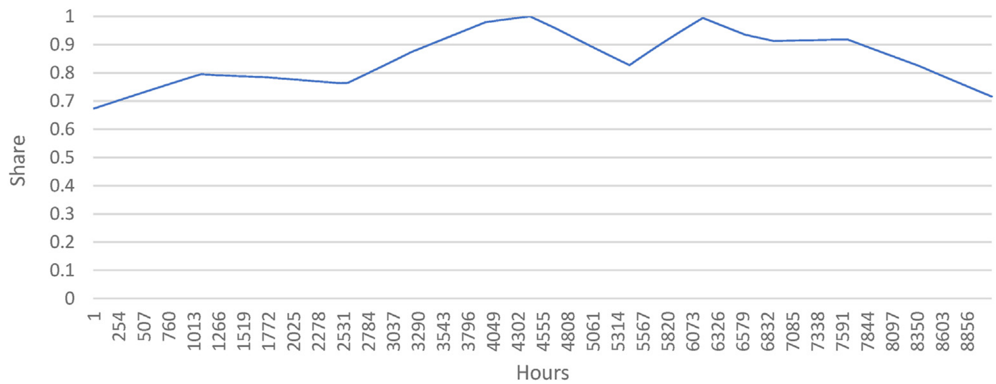

Fig. 3. Parametric distribution of energy-from-waste potential through the year.

(mixed) waste and bio-waste fractions used for energy generation are separated and shown in Fig. 4.

As can be seen, a significant decrease in the quantity of collected residual waste, as well as a significant increase in bio-waste quantity, are expected in the first five-year period. This is due to the influence in newly introduced primary waste separation for which is expected to result in the satisfaction of EU waste management goals for 2020 (50% of different waste materials should be prepared for recovery and recycling as well as reduction of landfilling by 65% compared to 1995 levels). In the next period, this trending is continued but at a much slower pace, especially in the scope of decrease of residual waste generation. Even though stricter EU waste management goals for 2030 and 2035 are expected to be met, especially regarding increased targets regarding waste separation and its preparation for recycling (60% till 2030 and 65% till 2035 for municipal waste and 70% till 2030 for packaging waste) and decrease in waste landfilling (maximum of 10% of municipal waste till 2035), needed changes to meet them are smaller and expected at the same time, socio-economic developments lead to an increase in overall waste generation. This connection between an increase in waste generation and socio-economic development is well observed in the past and is used in the planning of “business as usual” scenarios. This coupling of socio-economic developments with greater waste generation is described by the Waste Kuznets Curve hypothesis [59], which shows this connection until a certain threshold in socio-economic development is reached, after which waste generation decreases. As reaching this threshold is observed only in some households, i.e. in some provinces in Italy [60] and Japan [59], this type of system modelling can be appropriate in some cases. On the other hand, even though absolute decoupling trend is not present in the EU, the link between socio-economic indicators and waste generation is weaker as time passes, which indicates a relative decoupling trend [17], which is also assisted with the introduction of Circular Economy influenced legislation changes that could also lead to absolute decoupling with time. Because of this, “business as usual” modelling using long-range extrapolations based on historical data is not an appropriate approach for analyses that consider legislation influenced changes in waste management systems.

LCA-IWM prognostic model, based on actual waste quantities and composition data, takes into account all identified these trends and changes and gives an outlook about, not only the quantities but also the composition of mixed waste in a future period, as well as the composition of bio-waste fraction by separately tracking quantities of garden waste and kitchen waste. Using biogas potential data for those waste fractions [58], biogas production is calculated. The energy potential of produced energy vectors from waste is calculated also based on its composition; through the use of residual waste composition, lower heating value is calculated [50], and using the composition of bio-waste fraction, and methodology presented in Ref. [37], methane content of biogas is calculated and thus its heating value. These values for characteristic years are shown in Fig. 5.

The heating value of residual waste in the first period increases significantly. This, for the most part, can be connected to a decrease in bio-waste share due to the introduction of a separate collection system. A slight increase in biogas heating value occurs due to the larger methane content because the share of green garden waste in a separately collected bio-waste fraction is increased.

By combining prognosed quantities of produced residual waste, as well as produced biogas, and calculated heating values of these two energy vectors overall potential for WtE can be calculated. Results of this calculation per analysed municipal solid waste-derived energy vector, as well as overall available energy potential, is shown in Fig. 6.

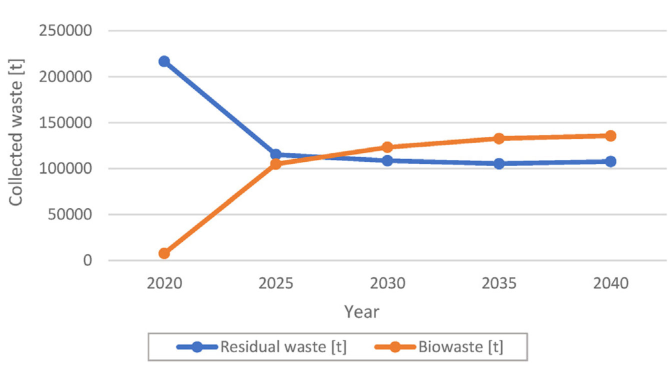

Fig. 4. Collected waste quantities of energy recovery suitable fractions.

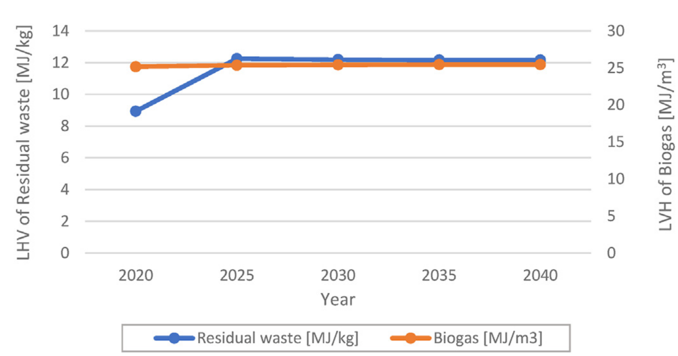

Fig. 5. Heating values of energy vectors derived from waste.

By redirecting the majority of generated residual (mixed) waste from landfills to WtE technologies, landfilling of municipal waste can be drastically reduced and, at the same time, significant amounts of energy can be obtained for covering local energy (heating and cooling) needs. Also, for covering local energy needs, the energy potential of biowaste can be utilised through biogas production and use. As it can be seen from Fig. 6, overall available energy from waste potential shows a slight decrease in the period from 2020 to 2030 after which it slowly increases to 2040. Even though the overall change is small, a significant shift from around 2%–33% biogas share in overall energy potential can be observed.

5.2. Energy production and demand

The DH system of the city is based on the gas CHP plants and auxiliary gas boilers for covering peak demand. There is also installed thermal storage which has around 750 MWh of capacity in the regular operating conditions. As shown in Table 1, in 2020, the total electricity generation capacity is 482 MW, and gas CHP heat generation capacity is 380.5 MW. Auxiliary boilers' capacity is 527.5 MW and remains the same through all scenarios and years. In 2023 new capacities are added to the gas CHP plant respectively, 150 MW_e and 114 MW_t. The new plant is currently under construction by the national electricity company and it is expected to be in operation from 2023 to 2050 [61]. This investment may pose the risk of being a stranded asset or even result in the missing of the CO_2 reduction targets in the city of Zagreb if more stringent climate policies are implemented [29]. In all scenarios which are considering the utilisation of municipal waste, the WtE plant is added in 2025 with capacities of 20 MW_e and 60 MW_t. The size of the WtE plant was determined based on the waste quantities predicted for the period from 2025 to 2040. Since the available quantities of waste are reduced over time, unused capacities could be utilised by importing the waste from neighbouring municipalities of Velika Gorica, Zapresic and others or by shifting supply to waste biomass [36]. With the expansion of the waste collection area, the expansion of the supply of DH and DC for Zagreb and nearby cities could be possible as is shown in Ref. [62].

The energy demand for the city is modelled in LEAP software, and the total demand of the cities sectors which were modelled in SECAP for 2020 is around 12.5 TWh, and for 2040 around 12 TWh, respectively. The overall demand is slightly decreasing due to the increase in energy efficiency in the BAU scenario, but since the current renovation rate is only 0.7% this reduction is small [65]. Demand in the buildings sector, since service sector buildings are the focus of the research, is shown by different energy carriers in Fig. 7. There can be seen that the demand is also slightly decreasing

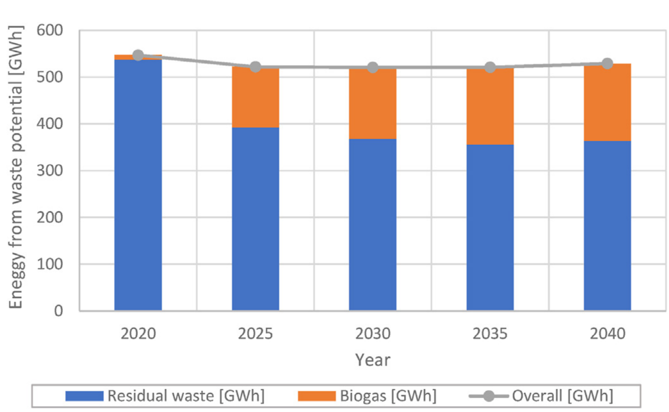

Fig. 6. Energy-from-waste potential for analysed years.

from 2020 to 2040, from 8 TWh to slightly below 7.7 TWh.

In Fig. 8, which is showing demand in the DC scenario it is noticeable that the share of natural gas and electricity is slightly reduced while the DH is increased. This has happened because modelled cooling demand is a part of the electricity and heat demand, which increased from 2020 to 2040, from 278 GWh to 611 GWh, and shifted from 0% DC share to up to 90% of DC share.

Furthermore, Fig. 9 is showing the total heat production in the district heating for the BAU scenario and the DC scenario. The total heat production is subdivided into the heat demand for heating, heat demand used for the cooling and the heating network losses. The heat losses are modelled as a fixed percentage of the heat production starting from the current 2020 when the losses are 12% and are further reduced to 10% in 2025 and 8% in 2040, respectively [66]. More detailed heat losses in Zagreb DH have been explained in Ref. [67], moreover, in the same publication Zagreb DH system has been compared to Aalborg DH which used 20% heat from WtE plants in 2012. In 2040, when 90% of the cooling demand in the service buildings sector is switched to district heating, heat demand for cooling has a significant share of 22% in total heat production.

5.3. Heat and electricity production in different scenarios

To compare the influence of the DC demand on the summer operation of the DH system, two slices of systems operation are shown in Fig. 10 and Fig. 11.

Fig. 10 shows DH demand, production of heat in WtE plant, gas CHP operation and heat balance for those hours. As it can be seen, the resolution of changes in heating and cooling is hourly as it is dependent on daily movements and habits of citizens, while WtE changes are under the influence of seasonal changes and yearly movements, thus its modelling resolution is much more coarse. This can be seen on a detailed hourly comparison diagram (Fig. 10) where only slight oscillations for 100 h can be seen.

Due to the supply of domestic hot water (DHW) through the DH system, heat demand exists during the whole year. In the typical summer, the demand is increased in the morning and evening hours and reduced almost to zero during the night. Since the WtE plant has relatively constant heat and electricity production when short periods are looked upon, the surplus heat in the times without demand needs to be thrown into the environment, which is shown with negative values of the balance. This results in the surplus heat production of up to 45 GWh during the one year of the system operation.

When the DC system is introduced (Fig. 11), the surplus heat production is used for the DC supply and the operation hours of gas CHP are increased as well. This results in better efficiency of the gas CHP and more effective production of both heat and electricity. Surplus of the heat production is balanced with the increased demand by using heat storage, which in the previous case was always full, due to the small heat demand during summer months.

The overall yearly production of electricity for three different scenarios (Fig. 12) shows that in the scenarios with DC the operation of gas CHP is better utilised. Although the electricity demand is reduced in those scenarios due to the increase in heat demand, gas CHP is more used in backpressure mode to produce electricity than in condensing mode as gas power plant (PP). Since the electricity demand is reduced compared to BAU scenarios, the excess electricity is exported, which has a beneficial influence on the systems fuel consumption and emissions (Fig. 14 and Fig. 15). In the scenarios which are simulating the exchange of electricity, the gas CHP is more utilised in covering heat demand, thus increasing the electricity export, and the electricity balance is secured with small electricity imports.

Table 1
Heat and electricity production capacities [61,63,64].

	CHP		Boilers	WtE (in scenarios with WtE)	
Year	Electricity production capacity [MWe]	Heat production Capacity [MWt]	Heat production capacity [MWt]	Electricity production capacity [MWe]	Heat production Capacity [MWt]
2020	482	380.5	527.5	–	–
2023	632	494.5	527.5	–	–
2025 to 2040	632	494.5	527.5	20	60

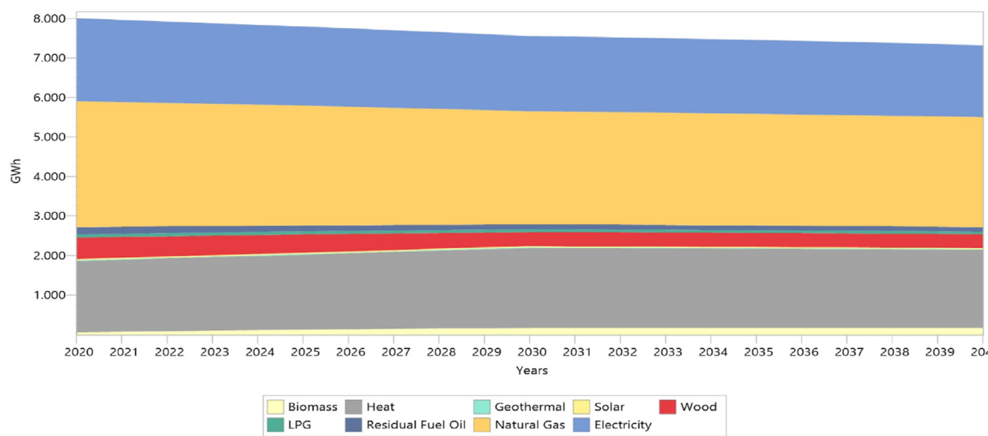

Fig. 7. Energy demand in buildings from 2020 to 2040 in the BAU scenario.

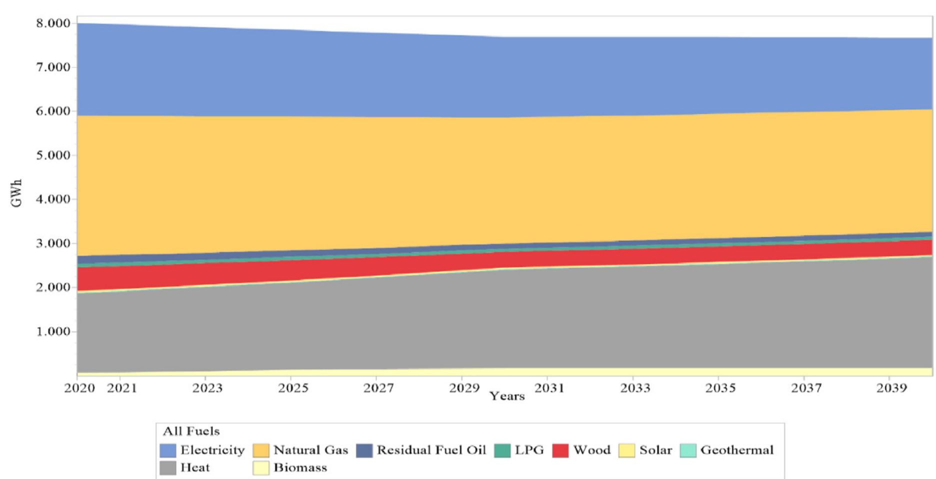

Fig. 8. Energy demand in buildings from 2020 to 2040 in the DC scenario.

On the other hand, the heat demand is significantly increased in the scenarios with DC since it is presumed that the building which is using DC for covering cooling demand will also use DH for covering heating demand thus increasing the heat production through the whole year. Fig. 13 shows the comparison of three different scenarios from 2020 to 2040 in which the heat production is increased by 67%, from 2150 GWh to 3584 GWh.

Heat productions from both gas CHPs and boilers are increased when DC is introduced but, when electricity balance is done through the market, the share of gas CHP in heat supply is increased from 65% to 72% thus achieving more fuel savings compared to scenarios without electricity market simulation. Electricity market simulation is considering the exchange of electricity within the country based on the historical day-ahead market electricity prices in Croatia. This is different from the previous situation where the system was simulated as a closed one, without electricity trading on the market and electricity exchange.

5.4. Fuel consumption and CO_2 emissions

The influence of the DC system and the WtE plant on the overall fuel consumption and CO_2 emissions is shown in Figs. 14 and 15. The results of the BAU scenario, the DC scenario and the WtE DC scenario are shown in these figures. BAU is a scenario without DC and WtE plant. DC is a scenario with DC and without WtE plant while the WtE DC is a scenario where both options are included. These scenarios were simulated with a priority put on covering heat demand. BAU and WtE DC scenarios were simulated without

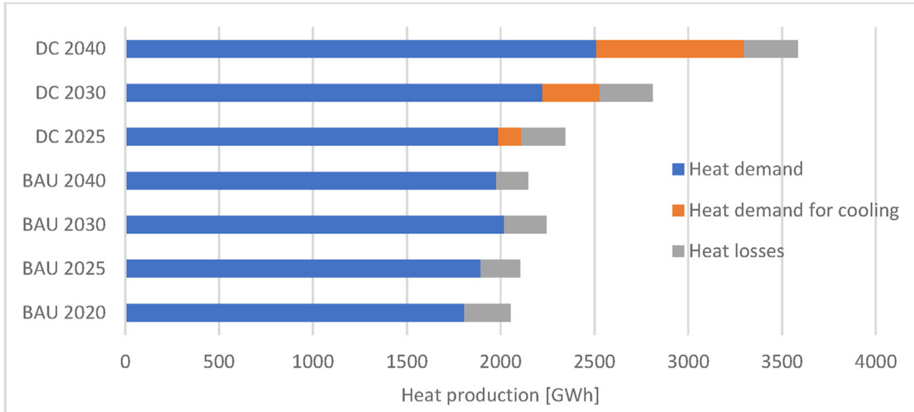

Fig. 9. Total heat production in district heating is divided into heat demand, cooling heat demand and heat losses.

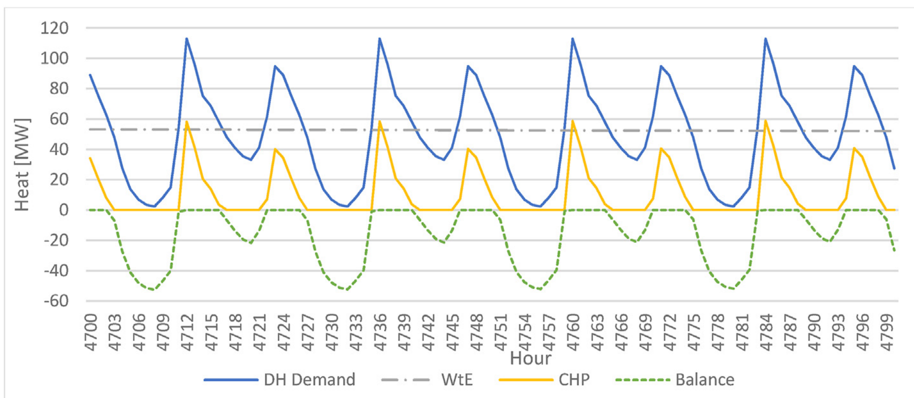

Fig. 10. Operation of DH system for 100 h in July 2040 in WtE scenario.

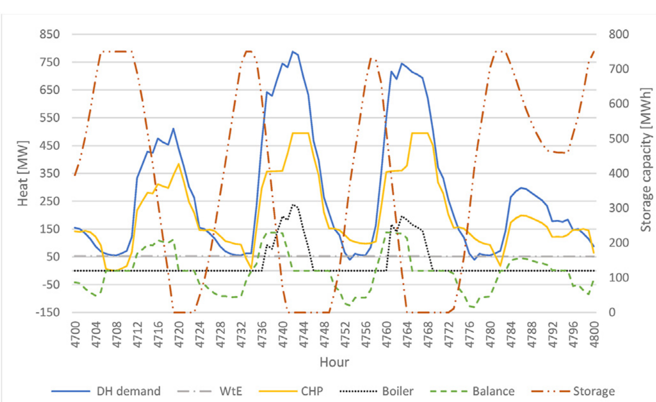

Fig. 11. Operation of DH system for 100 h in July 2040 in WtE DC scenario.

electricity exchange possibility in scenarios named CEEP, and the WtE DC scenario was simulated with electricity market conditions.

The simulation results in all scenarios show a reduction of both fuel and CO_2 emissions over time. This is a result of the increased energy efficiency in buildings in the BAU scenario. All scenarios have the same starting point in 2020 and 2023, and the most significant differences can be seen in 2040 since in scenarios with DC it is simulated that 90% of cooling demand in the service buildings sector is supplied by DC instead of electricity as in BAU. When the WtE plant is introduced it slightly increases the fuel consumption because waste is included in the total fuel balance and the plant operation is inflexible, i.e. depends only on waste availability and its characteristics, as the possibility of waste storage/accumulation is not taken into account. On the other hand, the introduction of the DC system significantly reduces fuel consumption since the increase in heat demand allows more operating hours for gas CHP and WtE plants, thus resulting in more efficient fuel use. The share of DC which can be covered by the WtE plant ranges from 65% or almost 100%, if heat storage is used, in 2025, to 34% or 62%, if heat storage is used in 2030. The lowest share of covering DC demand is in 2040, around 24% regardless of heat storage since the DC demand is much higher than the heat produced in the WtE plant. Since the WtE plant is limited by the capacity and waste input, with increasing DC demand, after 2025, the DC optimises the production in gas CHP but does not have additional influence on the utilisation of energy from the WtE plant.

The simulation of the closed system, without electricity exchange, shows higher fuel consumption, but DC slightly reduced overall fuel consumption as well. Simulation with electricity market conditions shows the best result considering fuel consumption since electricity is imported instead of production in gas CHP in condensing mode as PP unit when it is needed, which results in more than 2.5 TWh fuel savings compared to BAU 2020 scenario.

The results of the CO_2 emissions in different scenarios are following the same pattern as the fuel consumption results since the introduction of DC also reduces emissions. The difference can be seen in the WtE scenario where emissions are lower than BAU, although fuel consumption is slightly higher. Since the WtE plant

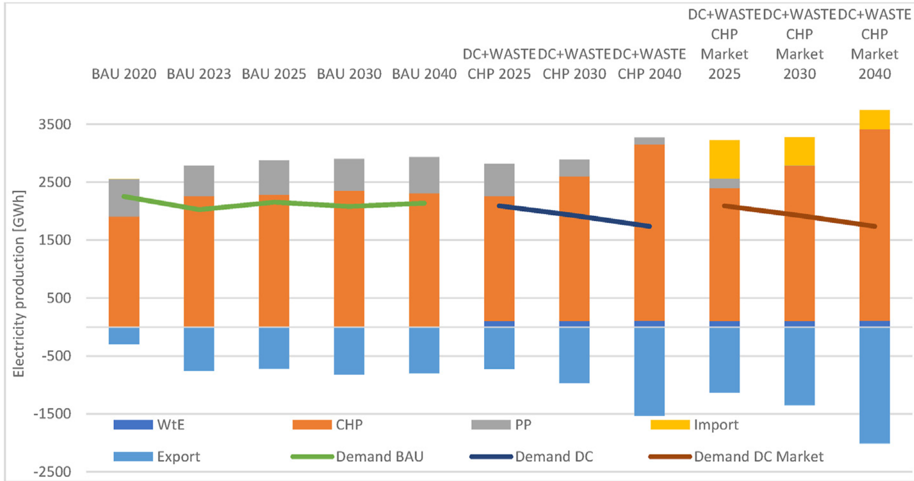

Fig. 12. Yearly electricity production and demand in three different scenarios.

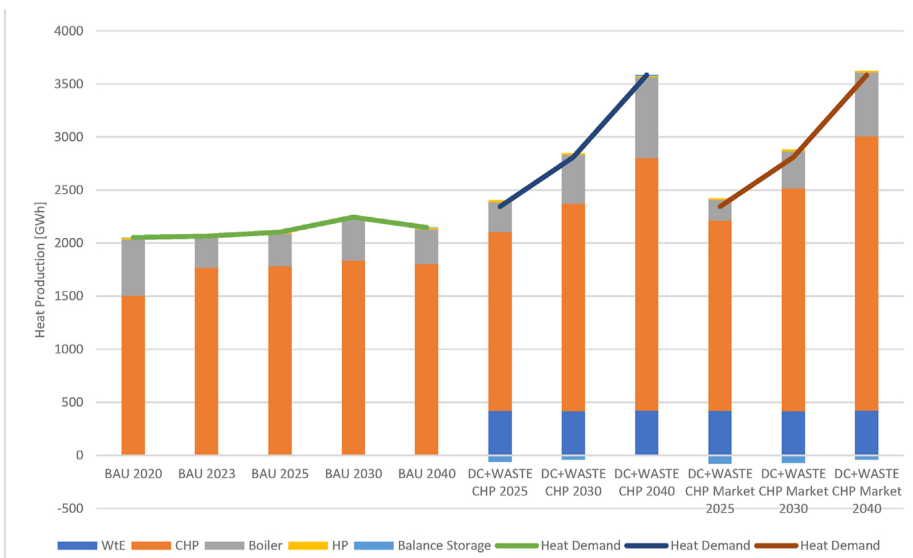

Fig. 13. Yearly heat production and demand in three different scenarios.

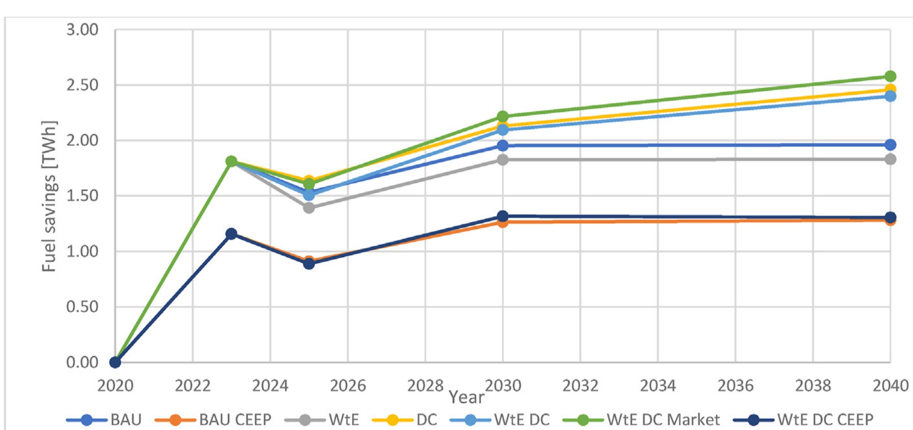

Fig. 14. Yearly fuel savings in seven different scenarios compared to BAU in 2020.

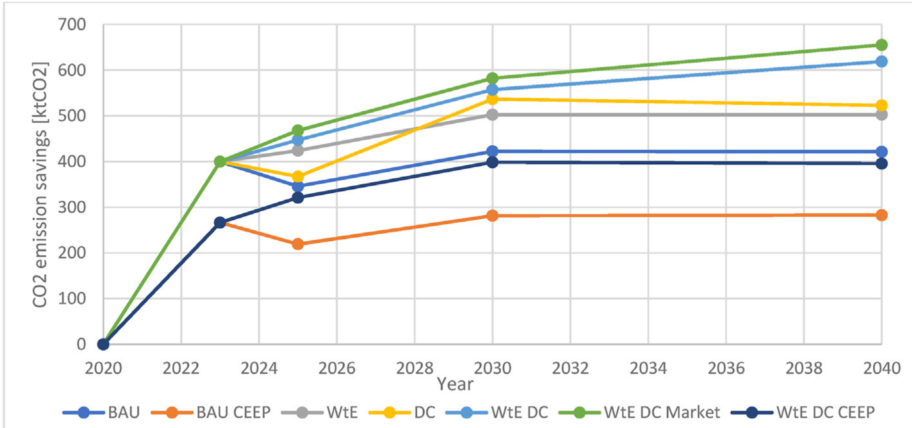

Fig. 15. Yearly CO_2 emissions savings in seven different scenarios compared to BAU 2020.

has a lower efficiency than gas CHP, overall, more fuel is used, but the biodegradable part of the waste is considered carbon neutral so in the end, CO_2 emissions results are lower. The scenario with the lowest emissions is the WtE DC market where emissions are 2806 $ktCO_2$. The emissions reduction, which can be contributed to the DC and WtE plant in 2040, when compared to the BAU scenario, is 227 $ktCO_2$/year, or a reduction of 7.4% of the overall emissions. When compared to BAU in 2020 emission savings are more than 655 $ktCO_2$/year or 19%. Additional savings in the scenarios could be achieved by the integration of different measures in the system, firstly by increasing energy renovation of buildings rate and on introducing cleaner ways of heat production using geothermal, solar or biomass [68] which were not considered in this study although there is a significant potential for mentioned resources. Also, gas CHP is part of the ETS system and has a better opportunity for a fuel switch towards synthetic gas or biogas with a possibility to use carbon capture and storage after 2030 depending on the CO_2 emission prices [69]. Furthermore, the fuel switch from the individual natural gas boilers to the district heating system should be supported in the urban areas to better utilise the district heating system and to reduce individual gas boilers emissions.

6. Conclusion

The results of the simulation of the introduction of the DC system and WtE plant in the central European city have been shown in this analysis. Due to analysing DC integration on the existing DH network, it is important to take into account changes not only in heating and cooling demand but also changes in supply, especially on basis of seasonal changes. Because of this, in the analysis of the energy from the waste introduction in the DHC network, particular care was given to modelling the changes in the available quantity of waste and its characteristics during the year. This made it possible to construct a yearly energy distribution curve that shows up to 33% lower energy from waste potential during the cold part of the year in comparison to warmer months, which can have a significant influence on energy analysis results. This could be addressed in short term, few days period, by introduction of waste pit [70] but that would not solve seasonal differences, while additional flexibility could be added by balancing heat and power production through different operational modes [71].

The overall energy demand is declining from 2020 to 2040 due to the increase in energy efficiency. Due to the introduction of the DC system, the overall electricity demand is significantly reduced while the heat production is increased by more than 60% in 2040, thus securing the more efficient utilisation of the gas CHP plant. The overall fuel consumption is therefore reduced up to 16% compared to 2020 BAU consumption, and CO_2 emissions have been reduced by 19%. This is due to the better utilisation of gas CHP plants and the replacement of natural gas with municipal waste for part of the electricity and heat production. Although these reductions are not negligible, they are far from the EU climate-neutral targets by 2050 as well as 2030, 55% CO_2 reduction target [1]. To reach the EU climate targets further energy efficiency measures, as well as renewables production capacities, needs to be implemented. The buildings renovation rate needs to be increased from 0.7% to at least 2% [65], while the renewables need to be included in the heat production. During the building's renovation, a faster switch from individual gas heating to DHC or heat pumps need to be secured to utilise the decarbonisation of DHC and electricity systems. Also, climate neutrality will be impossible to meet without further decarbonisation of the transport sector and therefore the optimal transition strategy and possibility for energy system integration need to be investigated to secure the lowest transition cost. Thus, the presented findings are in line with previously published research [29] and represent a good transition model which can paw the path to a climate-neutral economy. Although the current scenarios are not considering a ban on natural gas CHP plants this could be investigated in further research to reach a carbon-neutral city by 2050.

Additionally, the introduction of the DC system has been shown to have benefits both on the operation of the WtE plant and gas-fired CHP plants in the city. Since it provides additional heat demand during the summer months, it eliminates excess heat production from the WtE plant, whose production is increased during the warmer period of the year, and provides more operation hours for the gas CHP plant, thus providing better fuel to energy conversion economy. The increased demand during summer could also contribute to the feasibility of the introduction of renewables like solar thermal, which could be used to gradually replace natural gas CHP and contribute to further reduction of CO_2 emissions. Integration of energy from waste CHP plant and warm DC system can increase the overall sustainability of the DH system in the city with a continental climate. Integration also reduced overall fuel consumption, decreased CO_2 emissions, and eliminated excess heat production during the summer months. At the same time operating hours of existing gas CHP plants were increased. Taking all of this into account, this research gives a positive answer to the research question by identifying that integration of energy from waste CHP plant and warm DC system can increase the overall sustainability of the DH system in the city with continental climate by reducing overall fuel consumption, decreasing CO_2 emissions and eliminating excess heat production while at the same time increasing operating hours of existing gas CHP plants.

Since the economics of the system are not yet investigated, future work will be focused on comparing the overall system's cost with and without DC and WtE plant, considering seasonal changes in energy from waste potential. Furthermore, the analysis will also need to consider carbon tax and evaluate the investment in gas CHP. Also, during the simulation, it was noticed that the introduction of buffer heat storage provides the possibility to align surplus heat production from the WtE plant with heat demand. The optimal sizing of such storage needs to be further investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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