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ORIGINAL PAPER

Influence of waste-to-energy plant integration on local immission load

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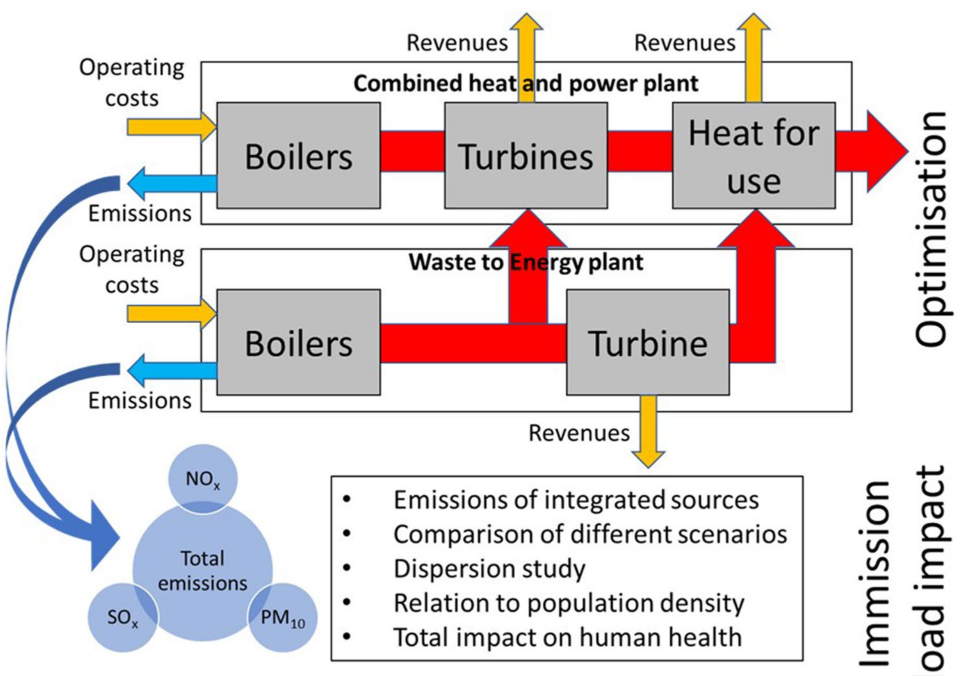
Abstract
Landfilling is still the most common way of municipal waste treatment in around half of the EU countries. It has been shown that diverting some of the waste-to-energy recovery makes it possible to reduce emissions of various pollutants, especially when the waste replaces lower-quality fossil fuels in heating plants. A methodology is presented to determine the influence of a waste-to-energy plant with a processing capacity in the range of 10 to 150 kt/y integrated into an existing district heating system on the air pollution load in the surrounding area. The change in emission production is determined using an optimisation tool previously developed in the GAMS environment. The parameters of the existing heating plant, such as the fuels used, the boiler output range, etc., are considered. A Gaussian scatter model is then used to determine the immission loads of individual pollutants in the surrounding area. Using the methodology, it is possible to directly quantify the impact of waste-to-energy plant integration on the health burden of the surrounding population in comparison with the reference state. This strategy is presented via a case study involving real-world data, in which it turned out that the immission load can be significantly reduced (up to 83%) compared to the original state in the calculation scenario.

Graphical abstract



Keywords Waste-to-energy · Optimisation · Immission load · Integration of heat sources · Dispersion model

Extended author information available on the last page of the article

Abbreviations

CAQI	Common air quality index (−)
CHPP	Combined heat-and-power plant
CU	Cogeneration unit
DALY	Disability-adjusted life years (y)
DHS	District heating system
EIFs	Environmental impact factors
HTP	Human toxicity potential (1,4-dichlorobenzene equivalents/kg emission)
i	Number of considered substances
IL index	Index of immission load (−)
LCA	Life cycle assessment
LHV	Lower heating value (MJ/kg)
l_i	Immission load index value of the i-th substance ($\mu g/m^{-3}$)
MSW	Municipal solid waste
n_i	Immission concentration of the i-th pollutant ($\mu g/m^{-3}$)
PM_{10}	Particulate matter of size less than 10 µm diameter
WtE	Waste-to-energy
WtEP	Waste-to-energy plant

Introduction

Energy recovery from municipal solid waste (MSW) can be seen as an effective way of waste treatment and reducing landfilling, which has many negative consequences, such as land grabbing, the risk of a fire hazard or groundwater contamination. In the event of a landfill leachate leak, the groundwater in the vicinity of the landfill may become non-potable for a long time (Panagopoulos 2022). An often-discussed factor is the effect of global warming due to the formation of landfill gas. For example, Sauve and Van Acker (2020) report that under European conditions, a ton of landfilled waste generates 124–841 kg CO_2eq depending on the composition of the waste, the rate of capture and recovery of landfill gas, and the management of leachate. Despite the fact that waste-to-energy technologies stand at a lower level than material recycling according to the European waste hierarchy, they have an irreplaceable place in the circular economy and, thanks to the diversion of waste from landfills, they can significantly contribute to reducing air emissions (Van Caneghem et al. 2019).

An optimisation model for refining the estimate of the waste-to-energy (WtE) project economics was introduced in the authors' previous work (Putna et al. 2018a). The integration of a WtE plant (WtEP) with the existing combined heat-and-power plant (CHPP), which delivered heat to the district heating system (DHS), was considered. This model, which worked for one-day intervals, dealt with the optimal operation of all integrated heat sources and took into account their technical parameters. The model considered, for example, the output range of the boilers used, the parameters of the steam produced, the variable efficiency of the steam turbine, and the available capacities. The purpose of the first version of the model was to minimise the variable operating costs of heat production. The calculation was performed in two steps—for CHPP only and CHPP with an integrated WtEP. By comparing the operating costs for these two systems, an acceptable price of heat was calculated, which was further used to estimate the economic return of the WtEP project (Putna et al. 2018b). Later, an environmental criterion was added to the model, and according to set weights, the optimal operation of all integrated heat sources was sought in terms of economy and greenhouse gas emissions. The respective case study found that by selecting the appropriate capacity, savings of nearly 1000 kg CO_2eq/t MSW were possible (Putna et al. 2020). In general, this credit is significantly influenced by the waste composition, absorption capacity of the DHS compared to WtEP capacity and energy production fuel mix (emissions of current CHPP). In the studied case, lignite as a primary fuel for CHPP was substituted and a large amount of heat (6.44 GJ/t of waste) was delivered from 40 kt/y WtEP capacity. Both aspects caused credits to be high compared to the study presented by Reimann (2012). However, Astrup et al. (2009) confirm possible downstream savings of up to 1373 kg CO_2eq/t of waste for incineration assuming that greenhouse gas-inefficient energy sources are replaced and the reference waste treatment scenario also entails high greenhouse gas emissions. The detailed use of the LCA methodology in the assessment of different methods of municipal waste treatment in a case study in Hong Kong was introduced by Woon and Lo (2013). The paper shows the importance of diverting waste from landfills in this regard.

The CO_2eq savings are also dependent on the capacity of WtEP and, therefore, the relation between WtEP capacity and CO_2eq represents an input for complex multi-objective reverse models, as described by Nevrlý et al. (2019). Reverse models in waste management typically allocate intermediate and final processing capacities.

Studies have been found in the literature that has addressed the integration of WtEP into DHS and analysed the impact of this integration on reducing emissions. Specifically, Matak et al. (2021) describe a specific example of the reduction of CO_2eq emissions due to the savings of primary fuels in the partial replacement of heat from natural gas with energy from waste incineration. Santin et al. (2020) address the environmentally optimal way of producing energy from waste depending on the distance from DHS, considering the mutual cooperation with other heat sources. However, the approach presented in this paper is unique in the way that an optimisation model that considers the interaction of the original and new elements of the technology is used for emission quantification. Subsequently, these data are used in the dispersion model to calculate the air pollution load and in combination with settlement data, it is possible to analyse and quantify the direct impact of WtEP integration on the air inhaled by the population in the vicinity of the source.

Abdallah et al. (2021) present a multi-objective model for optimising the management of various waste streams from the economic point of view, energy recovery and carbon footprint at the country level. He and Lin (2019) explain how substituting fossil fuels with energy recovery from waste can reduce air pollution at the national level. The authors also compare similar studies from different countries. In this case, of course, it cannot be determined precisely how energy is replaced in individual cases. A review made by Istrate et al. (2020) compares life cycle assessment studies of MSW management systems. These studies assess the environmental impact of different waste management methods, including WtE. However, these studies assess waste management either globally or considerably simplify the factor of heat substitution from primary energy sources. Such a global view neglects the coordinates of a WtEP. Only heat delivery to common DHS is essential. In the extreme case, the same results are obtained for various positions and connection points of WtEP considering the same amount of heat dispatched.

Besides CO_2eq rates, other emissions such as NO_x, SO_x, PM or O_3 are monitored and assessed by life cycle assessment (LCA) studies. As presented by Saharidis and Konstantzos (2018), the impact of air pollution has an immediate effect on public health. The effect of replacing fossil fuels in refuse-derived fuel cement plants on human health has been addressed by Mari et al. (2018). In this way, it is possible to significantly reduce emissions around the source. The reason is significantly stricter emission limits than for conventional heating plants burning solid fuels. In addition, real emission values in installations operating in the EU are normally 10–100 times lower than the limit values (Van Caneghem et al. 2019). The authors discussed in detail the exposure of metals and dioxins at various levels. However, maintaining the existing combustion source was assumed and the integration of multiple plants had not been addressed. Fan et al. (2018) summarise relevant recent works made in the area of process integration paradigms, including WtE.

Therefore, the concept of new technologies and their siting should address local air pollution at an early stage of process development. The idea of such a model has been proposed by Nevrlý et al. (2018).

It can be assumed that the emissions at stack from the WtEP correspond to the capacity of the plant, the used flue-gas cleaning system and the composition of the waste. However, contribution to local pollution and public health is subject to both population density and dispersion conditions nearby the intended plant. Whereas a WtEP operated in remote areas has a nearly negligible direct overall impact on human health through air emissions, the impact of a plant operated in a city centre is much higher. On the other hand, emissions from other sources should be considered in the integrated system. To the best authors' knowledge, such a complex approach has not been presented so far.

The paper contributes to developing advanced optimisation tools for siting of WtEPs as examples of processing facilities. It highlights the need for locality-dependent inputs in terms of emissions balance and emissions dispersion into the ambient for candidate locations to construct a new WtEP.

The so-called human toxicity potential (HTP), which normalises pollutants in terms of harmfulness, serves for the general assessment of the impact of air emissions on human health. However, this is mainly a parameter valid for the global level, as it takes demographic data in a limited way (McKone and Hertwich 2001). A more detailed assessment of the impact of air pollutant concentrations on human health is a complex issue. Manisalidis et al. (2020) evaluated this effect in three selected pollutants from different points of view. The authors searched for mechanisms of damage to human health through the effects of, among others, PM, CO, NO_x and SO_x. To quantify the effect of air pollutants on human health, a characterisation factor at the endpoint level DALY (disability-adjusted life years) was defined. It expresses the years that are lost or that a person is disabled due to a disease or accident. The methodology and calculation description are explained by Huijbregts et al. (2016). Al-Hemoud et al. (2018) presented a practical application of this methodology in a case study of the impact of PM on the state level. For a correct assessment, a large amount of demographic data, information on the occurrence of various diseases in the population or background concentrations of the relevant pollutants must be available. Owusu and Sarkodie (2020) assessed the effects of ambient air pollution on human health at the global level. In some cases, however, it is important to analyse the impact of a particular source of pollution or a planned project.

This paper extends the contribution of the methodology for determining the impact of a WtEP integrated with the existing heating plant on the ambient air pollution in the locality. Unlike the approaches found in the literature, it compares a potential future source of air pollution with the current source and can thus clearly identify the potential benefits in terms of pollution. The output data are further combined with demographic data of the surrounding population and thus provide a basis for quantifying the resulting benefits or risks in terms of impact on human health. The result is a comparison of the concentrations of selected pollutants in the place of residence of the population, which can further serve as an input for the calculation of the endpoint indicator of the overall impact on human health. The methodology partly uses the original optimisation models mentioned above, extended by calculating the emissions of selected pollutants using the Gaussian dispersion model SYMOS´97 (see section Methods). The immission concentrations are then determined for different considered WtEP capacities in the surroundings of the integrated heat sources. The entire procedure is presented via a case where the impacts of integration of WtEPs featuring various processing capacities are assessed. The main benefit compared to the approaches found in the literature is considering the parameters of the technology of the replaced source and any other requirements for its operation.

Methods

The following terms are used later on:

Emissions—Emissions, in this case, mean the amount of pollutants discharged from the stack per time period. Emissions from WtEP and CHPP are distinguished. Emissions are evaluated on an annual basis as a sum of emissions generated during CHPP and WtEP operation in several modes during the year.

Immissions—Immissions are generally subject to coordinates *x, y* and time. In our case, a continuous steady-state source of pollution (CHPP and WtEP) and average weather conditions are considered. Therefore, immissions are only subject to *x* and *y*. Only immissions from the investigated system of WtE and CHPP are included. Other sources are excluded. No background pollution is considered. If reduced immissions are mentioned in the paper, it is meant comparison of isolated immission resulting from WtE and CHPP only.

Integrated WtEP—The cooperation of WtEP with another (top and back-up) source is assumed. All of these sources supply heat to a single DHS.

Population density—subject to coordinates *x, y* and daytime. The change in population density over time is neglected in our case. It is expressed as permanent residents registered by the authorities.

Immission load (IL)—An indicator of the immission load in a location, taking into account the different impacts of monitored pollutants on the population's health in an aggregated form (year). Subject to coordinates *x, y*. A minimum threshold is set to limit the affected area.

In the first phase of the calculation, the total air emissions of the considered pollutants are calculated based on the WtEP capacity (see section Calculation scenario). Discharged emissions are dispersed over the location, and the immissions field is evaluated with the help of software for modelling air pollution originating in stationary sources. In order to evaluate the immission load, an index of immission load (IL index) was defined (see section Immission load index (IL index)).

Calculation of emissions

The calculation of annual emissions related to WtEP operation is based on reported data from the existing WtEPs in the Czech Republic (see section Pollutants emissions). The constant quality of processed waste and the constant efficiency of a flue-gas cleaning system is assumed. Emissions are considered constant through the operation period, and they are proportional to the capacity of the WtEP. However, WtEP supplies heat and power, and therefore it cuts down emissions from a heating plant (CHP) to which it is integrated. The emissions balance from WtEP and CHPP is crucial for the overall assessment of the integrated system and changes after integrating the WtEP.

The optimum cooperation between CHPP and WtEP is strongly dependent on heat demand, electricity prices, etc., and is mostly driven to minimise costs/maximise profit. As the consumption of fossil fuels varies at the CHPP, so does the production of CO_2. In addition to carbon taxes for fossil fuels, CO_2 emissions are subject to trading. Whereas produced CO_2 can influence the operation depending on the price of CO_2 allowances, other emissions are only subject to the given emission limits. As mentioned in introduction, the optimisation model described in detail by Janošťák et al. (2019) is used to calculate the optimum operation mode of the integrated system WtEP + CHPP for specific WtEP capacity. Emissions related to the operation of WtEP and CHPP are evaluated individually. The model works with the optimisation of energy flows in the technology, as shown in Fig. 1.

The evaluated technology is split into three basic blocks—boilers, turbines and heat output to the end-users. The blocks are interconnected by possible energy flows in the form of steam. This considers different steam parameters and thus the possibilities of its utilisation. The output range, energy efficiency and variable operating costs are specified for individual boilers. Depending on the application, the steam from the boilers is used to generate electricity in the turbine or it goes directly to the end-user. Turbine generators are given a range of absorption and energy efficiency in the form of linear dependence of net electric power on the input heat energy. The steam flows from each turbine to another turbine, to the final heat recovery, or is dissipated in the case of a condensing turbine.

The objective function, which is minimised, is the cost of heat generation minus the revenues from the electricity

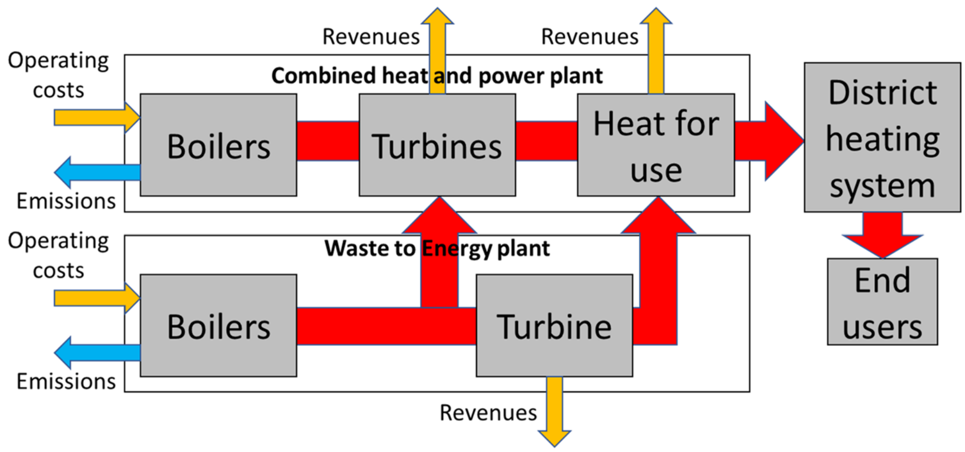


Fig. 1 Schematic of the optimisation model

sales. The primary boundary condition governs the required heat demand over a calculated time period. If it is not possible to cover the heat demand completely by the WtEP, the minimum boiler output in CHPP and other boundary conditions of the optimisation calculation are respected. This sequence operation makes the expected mode of CHPP operation much more accurate. Total emissions of air pollutants are obtained for a given capacity of WtEP and other boundary conditions.

Air pollutants considered

There are many processes, such as dispersion, chemical reactions and various transformations, between the release of pollutants into the atmosphere at the point of origin and their transition to the place of settling. This cycle is completed by the deposition of the pollutants on the ground. In this paper, the pollutants' harmfulness is considered in terms of their impacts on human health. However, the methodology can also be used to assess the impact of WtEP integration on the environment. In that case, other pollutants would be considered, which would be standardised using environmental impact factors (EIFs) (Guo et al. 2022).

Three pollutants were selected for the case study. Countries' government agencies use the air quality index for air quality evaluation. Its calculation varies depending on the country. European Environment Agency's Common Air Quality Index (CAQI) has been used in the EU since 2006 (Air Quality Now 2007). CAQI includes NO_2, PM_{10} and O_3 as mandatory components. Optional pollutants also include SO_2. Based on that, three pollutants were selected for the case study.

- *Sulphur dioxide*, which is one of the primary pollutants, is formed directly in the source and is not subject to further changes. SO_2 irritates the eyes and respiratory system, while in high concentrations, it can cause respiratory problems.
- *Nitrogen dioxide* is a secondary pollutant, which means it is partially formed by conversion from primary pollutants. Usually, it comprises about 5% of the nitrogen oxides discharged from the combustion source (The European IPPC Bureau 2019). However, NO_2 is also produced subsequently in the atmosphere by the reaction of NO and O_3. In terms of its impact on human health, NO_2 affects the respiratory system (Colls 2002). Moreover, it is associated with increased cardiovascular and respiratory mortality. The dispersion model used has a particular module for this pollutant, simulating the subsequent atmospheric formation.
- *Particulate matter* collectively denotes fine solid and liquid particles dispersed in the atmosphere. The PM_{10} fraction, which includes all particles whose aerodynamic diameter is less than or equal to 10 µm, was considered. PM causes severe cardiovascular and respiratory diseases. The problem is not only the tiny particle size, which makes it possible to penetrate the circulatory system but also the fact that other highly toxic substances are relatively quickly linked to these particles.

Calculation of air pollution concentrations

The standard tools for pollutants immissions assessment at certain coordinates distant from emissions source are dispersion models. There are plenty of available models with various complexity and preciseness, and demand on input data. For the case study, the Gaussian plume approach based on the analytical solution of the diffusion equation was chosen, the most used and most straightforward type of the model (Braniš 2009). On the other hand, its use is subject to some simplifications (Turner 1994). Gaussian models have proven to be well suited for similar applications despite their limitations (Schauberger et al. 2011). Some of these models are reference models accepted by authorities in particular countries.

The calculation of immission concentrations in our contribution follows the commonly used methods for creating dispersion studies. The SYMOS'97 dispersion model, one of two reference models for the Czech Republic, is used. This model was chosen for its suitability for modelling pollution dispersion in urban areas above the roof level of buildings and rural areas. This model was introduced in 1998, and its last update was released in 2013. It is available as a commercial software package (IDEA-ENVI 2019). The possibilities of using the Gaussian dispersion models and their principles are described in detail by De Visscher (2014). However, there are a large number of dispersion models capable of solving this issue; only in the database of dispersion models of the European Topic Center on Air and Climate Change (EIONET) there are 142 registered models now. These models are usually developed by universities or national institutions such as hydrometeorological institutes. The model demands the following input data:

1. Location of the pollution sources—contains the locations of the pollution sources in the selected coordinate system and the description of the area's relief. S-JTSK coordinate system commonly used in the Czech Republic was chosen for the case study.
2. Pollution sources data—emission values for individual sources and all pollutants evaluated are described here. Besides, information on flue-gas stacks and operating hours is specified.
3. Meteorological data—it is necessary to specify the wind rose that corresponds to the locality, including the frequency of the individual stability classes and wind speed classes to the dispersion conditions in the atmosphere.
4. Reference points—define the grid in which the air pollution concentrations will be calculated.

The main output of the model for the case study is the average immission concentration in the points x, y of the defined grid and for selected pollutants.

The immission load index (IL index)

In 2018, the World Health Organization (WHO) released the ambient air pollution factsheet (World Health Organization 2018). It lists the maximum recommended SO_2, NO_2, PM and O_3 immission values, which were determined based on a series of epidemiological studies. To be able to correlate the influence of all the pollutants, an IL index based on the recommended annual average values was established. For SO_2, the value had to be standardised to the annual average, compatible with the unit of the other pollutants. Guideline values and values for IL index calculation purposes are listed in Table 1.

The IL index calculation formula is in the form:

$$index = \frac{\Sigma^i \frac{n_i}{l_i}}{i} \tag{1}$$

where n_i denotes the immission concentration of the i-th pollutant, l_i the IL index value of the i-th substance and i the number of substances considered. If the value of the IL index is higher than one, it means that the recommended immission concentrations are exceeded on average at the reference point.

Case study

A case study was performed for the presentation, which shows the use of the described methodology at a specific locality in which a partial replacement of the energy mix based on lignite with MSW is considered. In the first phase, the emissions of pollutants before and after the integration of the WtEP are determined by the optimisation part of the tool, and subsequently the impact of the integration on the ambient air pollution is assessed.

The operation of integrated sources is optimised on the basis of economic indicators, i.e. to achieve minimum operating costs for heat production, including revenues from the sale of cogeneration electricity. The key input parameters thus particularly include the price of the fuels and the price

Table 1 Recommended immission limits for selected pollutants according to WHO and the respective index values

Air pollutant	Averaging period	Guideline value according to World Health Organization (2018) (μg/m^{-3})	IL index value (μg/m^{-3})
SO_2	10 min	500	8
	24 h	20	
NO_2	1-h	200	40
	annual	40	
PM_{10}	24-h	50	20
	annual	20	

of produced electricity. These parameters to some extent affect the mode of operation of individual units. In this case, the price of electricity was considered to be 86 EUR/MWh, the operating costs of lignite boilers 31 EUR/MWh of fuel and the operating costs of gas boilers 36 EUR/MWh, including emission allowances. WtEP's operating costs are not relevant in this case as it is a negative fuel source. Heat delivery from the WtEP is always preferred.

Description of the technology and location

An analysis of the WtEP integration into the existing CHPP was performed. The surveyed locality is in the region of South Bohemia in the Czech Republic. The CHPP technology follows the schematic in Fig. 2. The CHPP uses two main lignite boilers, a backup and a peak natural gas-fired boiler, and four natural gas-fired cogeneration units (CUs). In addition to the CUs, a 20-MWe steam-condensing turbine with two controlled extractions is used to generate electricity. Heat is supplied to the end-users at three levels—high-pressure steam, low-pressure steam and hot water. The lignite boilers generate high-pressure steam. Low-pressure steam is extracted from the first bleed, produced by reducing the high-pressure steam, or, to a certain extent, from the CUs. Hot water is produced in the hot water heaters using the second extraction from the turbine, the CUs or the low-pressure steam. The heating plant supplies heat at the rate of 692 TJ/y. Of that, 33% by medium-pressure steam, 50% low-pressure steam and 17% by hot water. The figure shows the essence of optimisation calculation. In the first step, the operation of the original CHPP is modelled; in the second step, the integrated WtEP with potentially lower specific emissions is considered. In both variants, the boundary conditions are met and the same amount of heat is exported at all levels. Due to lower variable operating costs, heat from lignite boilers is replaced by heat from the WtEP and the total emissions of a specific pollutant are lower.

It is expected that the prospective WtEP will supply heat to the DHS at all three levels. The conventional WtEP concept with grate combustion of MSW was chosen. WtEP capacity is subject to investigation. WtEPs with an annual processing capacity of up to 50 kt MSW tend to use a back-pressure steam turbine in terms of energy production. For higher capacities, a condensing extraction turbine would be used. Based on the analyses carried out previously, the calorific value of MSW at 9.3 GJ/t is considered. A WtEP with a back-pressure turbine can produce about 7.2 GJ of thermal energy per tonne of incinerated waste. A WtEP with a condensing extraction turbine then, due to the higher efficiency

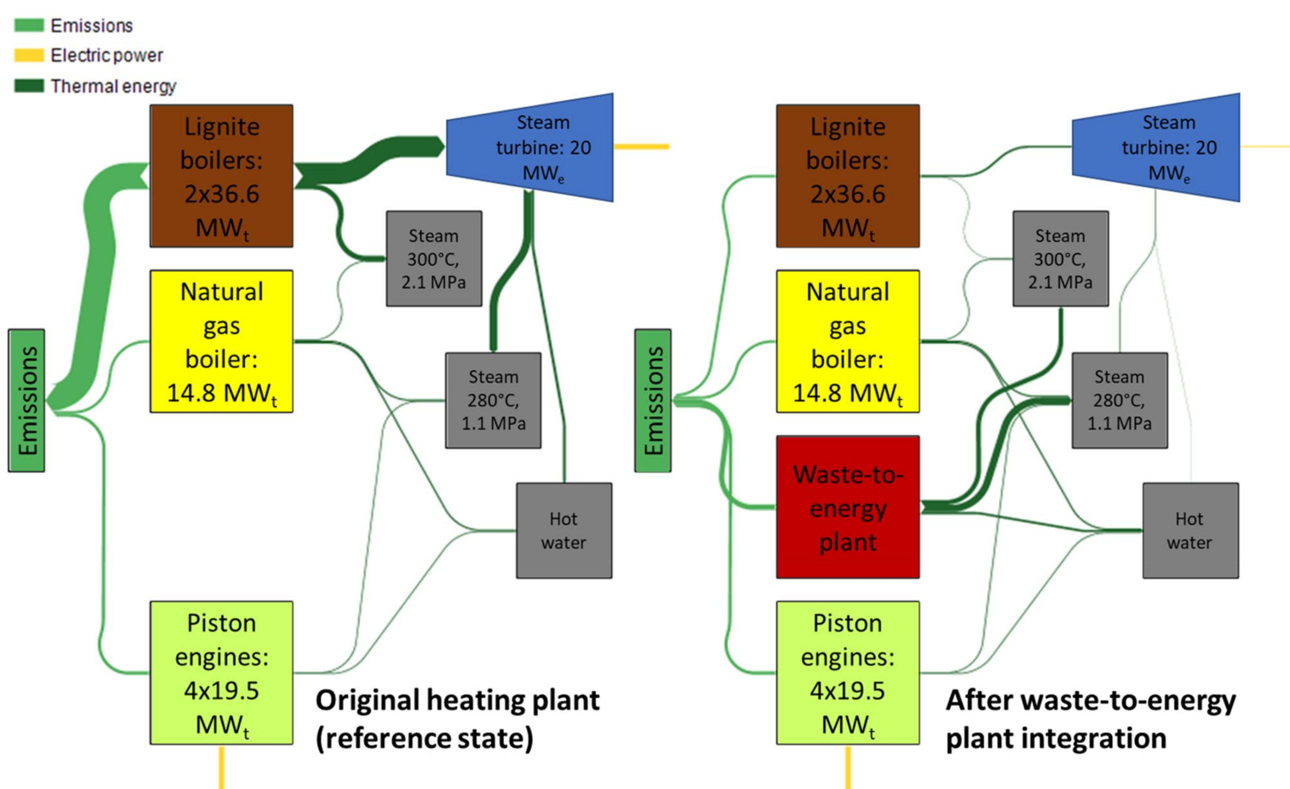


Fig. 2 The energy flow diagram in the analysed CHPP technology

of electricity production and maintaining a minimum flow through the condensation section of the turbine at a maximum steam extraction, produces a maximum of 6.2 GJ/t MSW. Several WtEP technological shutdowns are considered per year, during which the heat is supplied to the DHS only from the heating plant.

Parameters of flue-gas outlets (stacks) are also crucial for the analysis of immission load. For the discussed WtEP, the stack height is 80 m, the flue-gas temperature is 130 °C, and the inner diameter of the stack is 3.3 m. Lignite boilers and the gas boiler share a typical stack with a height of 85 m and a diameter of 2 m. The third stack is used for CUs, is 32 m tall, features an inner diameter of 1.3 m, while the corresponding flue gas leaves at the temperature of 108 °C.

Calculation scenario

In addition to the sale of the generated electricity and heat, the revenues of the assessed heating plant also come from the provision of ancillary services as defined in the Directive 20,019/72/EC, namely the positive spinning reserve. The optimisation of ancillary services and the description of the market were discussed by Zhou et al. (2018).

Ancillary services are provided by CUs. To respond quickly enough to a demand for power change, they must be operated in a rotating mode at least at their minimum power output regardless of the current heat demand.

Pollutant emissions

The WtEP emissions were determined as the average of the four WtEPs operated in the Czech Republic. Determination of the emissions from the heating plant was based on the data from the Register of Emissions and Air Pollution Sources published annually by the Czech Hydrometeorological Institute (2019)—the authority responsible for emission inventories. These emissions must be split among the individual boilers in the assessed heating plant, as summarised in Table 2. It has been verified that the data for lignite boilers approximately correspond to the emission factors for lignite combustion on a fluidised bed with limestone desulphurisation in a wet scrubber and PM control by an electrostatic precipitator according to the United States Environmental Protection Agency (2016). The highest specific emissions of SO_2 are reported for lignite boilers, and natural gas is considered to be sulphur-free. Emissions of the gas boiler and the CUs are, therefore, negligible. For NO_2, on the other hand, slightly higher emissions are considered for the WtEP. With PM_{10}, the WtEP emissions are roughly half of those generated by the lignite boilers. Particulate matter emissions from natural gas boilers are neglected.

Table 2 Specific emissions of the assessed pollutants (Czech Hydrometeorological Institute 2019)

Pollutant	Pollution source	Specific emissions (g/MWh power input in fuel)
SO_2	WtEP	8.37
	Lignite boiler	51.83
	Natural gas boiler	0.20
	Cogeneration unit	0.20
NO_2	WtEP	18.55
	Lignite boiler	14.79
	Natural gas boiler	10.82
	Cogeneration unit	10.82
PM_{10}	WtEP	0.63
	Lignite boiler	1.25
	Natural gas boiler	0
	Cogeneration unit	0

Results and discussion

Using the model SYMOS´97, the average immission concentrations of the three pollutants were calculated for the considered area (see section Calculation of air pollution concentrations). Figure 3 shows the average contribution to the immission load in the 20×20 km square area (400 km^2) depending on the WtEP capacity.

It is essential to choose the appropriate size and density of the grid. In the model case, the concentration of air pollutants increases sharply with increasing distance from the source of pollution; for SO_2 and $PM_{10,}$ it reaches a maximum of approximately 0.5 km from the source and then asymptotically decreases to zero. For NO_2, the maximum concentration due to secondary conversion from the primary pollutants is observed at distance 1.1 km. For the case study, the area was chosen in the form of a square with an edge length of 20 km, in the centre of which the site was located. This grid size was chosen to present the methodology, but the analysis showed that a significantly larger grid would have to be used for the relevant results, even though it is a relatively small source of pollution. The grid density was set to 0.1 km due to computational solvability. Therefore, the number of reference points was 40,401. It should be noted that for more accurate results—for example, in the areas with the highest population concentration or at the point of contact of the smoke plume with the terrain—it would be necessary to use a denser grid. In the first phase, an analysis of the relationship between the size of the grid and the included immission load was performed by calculation on a less detailed network of 200×200 km. At a distance of 20 km from the source, the average concentration of SO_2 and PM_{10} is at the level of approximately 19% of the maximum concentration and then 56% for NO_2.

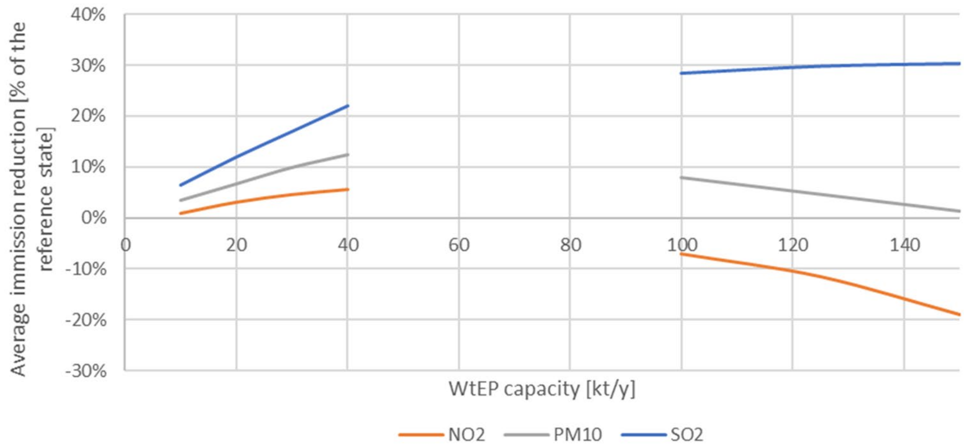


Fig. 3 Average annual immission load reduction in the considered area depending on the WtEP capacity

The total amount of selected pollutants contained in the ground layer at a distance of up to 15 km from the source corresponds to 24% of pollutants contained in the ground layer at a distance of 100 km from the source for SO_2 and PM_{10} and only 9% for NO_2. An important factor in assessing the impact on human health is the determination of the cut-off or counterfactual concentration below which this effect cannot be observed or is negligible. The 24-h average interim target levels issued by the WHO are 40 µg/m^3, 45 µg/m^3 and 25 µg/m^3 for SO_2, PM_{10} and NO_2, respectively (World Health Organization 2021).

A certain limitation of the methodology is the assessment of the immission load in the immediate vicinity of the source, which cannot be accurately estimated by the dispersion model used. Pollutant concentrations in this area depend on the height of the stack. Fachinger et al. (2018) found an increase in air pollution concentrations from a small biomass heating plant for some pollutants (NO_x and PM_{10}, poly-aromatic hydrocarbons and sulphate) by up to 130% against background concentrations at a distance of 50 m from the facility. The reduction of the evaluated pollutants is illustrated in Fig. 3. It is necessary to mention that the immission loads from both WtEP and the heating plant are very low in comparison with the allowed immission concentrations according to WHO. This is partial since these are average values from the whole area of 400 km^2. At the points with the maximum immission concentrations, i.e. the points of contact of the smoke plume with the terrain, the calculated concentrations were about 7 times higher for NO_2 and 25 times higher for SO_2 and PM_{10} than the average. When implementing WtEP with a capacity of 40 kt/y, the monitored pollutants would be reduced by 6–22%. Only emissions from the assessed sources are considered, the background pollution is neglected. The reason is that the background concentrations are significantly higher than the contribution from the assessed source in this case, while the aim was to show only the effect of the integrated WtEP. It would make sense to include background concentrations if, for example, the contribution from the source would cause the immission limits to be exceeded in some places. For comparison, the graph also shows the technological concept of WtEP with a higher processing capacity (above 100 kt/y).

The trend of reducing the air pollution load defined by the IL index would continue up to a capacity of approximately 150 kt/y, mainly thanks to the reduction of total SO_2 emissions. However, the immission load resulting from PM_{10} is already comparable to the reference state without WtEP at this capacity and the immission load resulting from NO_2 is about 19% higher. This is due to relatively higher NO_x emissions from municipal waste incineration compared to negligible SO_x and PM emissions. It should be noted that these results cannot be fully generalised for any WtEP. NO_x production is largely dependent on the combustion process, and there is a wide range of options for reducing these pollutants, with different measures appropriate for different technological concepts. Liu et al. (2020) assessed the effect of flue-gas recirculation on NO_x reduction in a WtEP with a capacity of 500 t/d, which is not considered for lower capacity model technology due to investment costs.

Without the WtEP, the IL index value is only around 0.012. This means that on average, only 1.2% of the reference values according to Table 1 are reached in the discussed area. At a capacity of 40 kt/y, the immission load is reduced by 22% compared to the reference state, at a capacity of 150 kt/y by 29%.

Unlike conventional dispersion studies, the purpose of which is to determine the values of air pollution and compare them with the current values of (background) air pollution concentrations, the presented methodology evaluates the direct impact of the population on the operation of the considered source. In the second step, the immission load data were therefore paired with the population density data in the area. The inverse distance weighting method was used (Lu and Wong 2008), using which the four nearest reference points were found in the grid of reference points for the individual coordinates of the dwelling, and the average air pollution concentration at the location of the dwelling was determined on the basis of the values of air pollution concentrations in these reference points. This was done for a total of 58,700 inhabitants living in 14,400 dwellings in the area. The results also showed significant differences in individual areas, where pollution decreased significantly with increasing distance and also depended on the direction. The results show that the pollution from the source is negligible in all calculation variants in comparison with the valid air pollution limits or guideline values according to the WHO (see Table 1). This offers a comparison with background concentrations, which are published annually by the Czech Ministry of the Environment (Czech Hydrometeorological Institute 2021). For the given area, this background concentration is 2.8 μg/m^3 for SO_2, 17.0 μg/m^3 for PM_{10} and 7.7 μg/m^3 for NO_2. Even in this current pollution, the assessed source contributes only slightly (up to 1%) for PM_{10} and NO_2. However, it is significant in the order of 0.1% in terms of SO_2 emissions. Figure 4 compares the areas in which the IL index value was more significant than 0.01. The red area (162 km^2) applies to the CHPP before the integration of the WtEP. The yellow area (100 km^2, or 62% of the red area), on the other hand, applies for the CHPP after the integration of a 40 kt/y WtEP.

Based on the assigned average concentration, it was also possible to determine the absolute amount of the population exposed to pollution by multiplying the concentration at the place of residence, the number of inhabitants and the average concentration at the place of residence. The population that is significantly affected by emissions may be limited by the air pollution concentration threshold, which in this case was considered to be zero. Table 3 shows the summarised data showing the total amount of selected pollutants to which the population in the area in question is exposed, comparing the values for WtEP with a capacity of 40 kt/y and a separate heating plant. These values can be further used to evaluate the endpoint indicator DALY.

It is obvious that the potential integration of this WtEP project would bring a reduction in the average air pollution concentration in the evaluated area for NO_2, SO_2 and PM_{10} by 6.4, 22.1 and 13.8%, respectively.

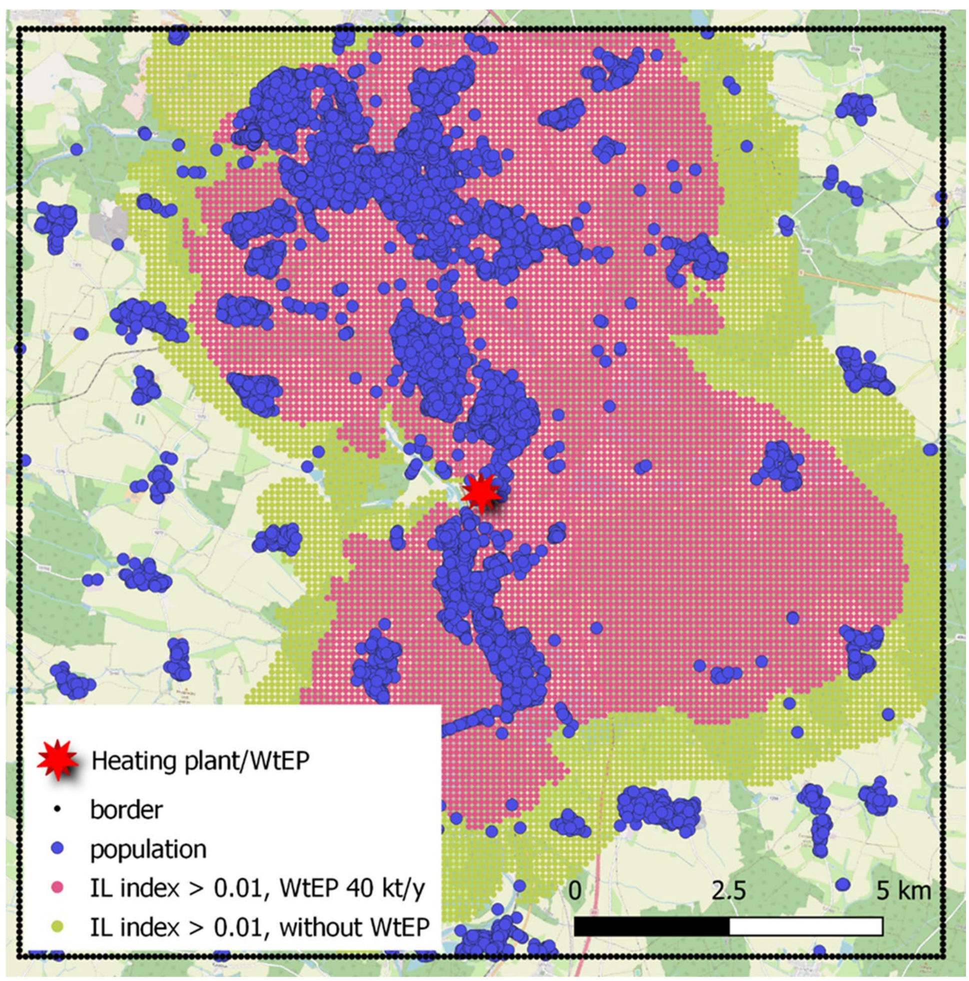


Fig. 4 Area with the IL index value greater than 0.0001 for the CHPP without the WtEP and with the WtEP with the capacity of 50 kt/y, CHPP and WtEP location is indicated by the star

Table 3 Specific emissions of the assessed pollutants

		Original heating plant	WtEP 40 kt/y
	Population with IL index > 0.01	47 302	38 536
Explosion amount (μg/m^3.person)	NO_2	1,530.2	1,431.6
	SO_2	15,714.0	12,239.0
	PM_{10}	354.1	305.3

Conclusion

The paper offers a methodology for assessing the impact of WtEP integration into existing DHS on immission load in the surrounding area. Commonly presented dispersion studies analyse the impact of the WtEP project itself or eventually compare it with the original heat source. The described approach, however, comprehensively deals with the change in the mode of operation of all integrated sources and thus allows a more accurate estimation of ambient air pollution. It is also possible to simulate the effect of different boundary conditions. However, it can be, for example, the supply of technological steam with higher parameters than can be provided by WtEP, keeping the backup boiler in hot reserve, etc.

The case study analysed the integration of the WtEP with the existing CHPP. The WtEP capacity was considered in the range of 10–40 kt/y. Technological variants with a capacity of over 100 kt/y have been added for comparison. It was found that the integration of WtEP in all variants caused a significant reduction in emissions of the considered pollutants. The optimal WtEP capacity in terms of the impact of emissions on human health was found. Specifically, the optimum capacity ranged from 120 kt/y to 180 kt/y, depending on the pollutant. For the possibility of overall comparison, the so-called IL index has been established, which evaluates all the pollutants in summary.

At the optimal WtEP capacity, the immission load was reduced up to 83% compared to the original state. In the end, the affected area was evaluated where the immissions were higher than the stated threshold. This, in combination with population distribution data, can serve, for example, to estimate the number of people affected and its change after WtEP integration.

The presented methodology addresses only direct emissions in the vicinity of the facility. The inclusion of secondary emissions, such as landfill emissions including in particular CH_4, H_2S or odour gas emissions (Huang et al. 2022), which are also reduced by WtEP integration, would also provide more accurate results. Only NO_2, SO_2 and PM_{10} were selected for the presentation of the methodology. The reason was that World Health Organization (2018) provides their index values and it is possible to mutually standardise their concentrations, and, at the same time, it is possible to estimate their production from all considered sources with relative accuracy given that the production of these substances is subject to mandatory reporting. A potential improvement in the methodology could be the inclusion of other pollutants, such as CO, HCl or further division of PM_{10} into a more dangerous $PM_{2.5}$ subgroup.

In general, in the case of the integration of WtEP into DHS in the conditions of Central Europe, the use of waste heat in the summer, when heat demand is not high enough, is a great challenge. If this energy would be further utilised, for example, for district cooling purposes or stored in some way, this would lead to a further reduction in total emissions. In a case study, Nami et al. (2019) determined sustainability index of 1.4 in the implementation of third-generation DHS with absorption chilling using heat from a WtEP, thus achieving a significant reduction in the carbon footprint. This study has shown that this approach makes sense even in countries with colder climates. Social LCA could potentially be another suitable tool for a comprehensive impact assessment of WtEP integration into DHS (Popovic and Kraslawski 2015).

The proposed approach can be integrated into complex location problems, where processing capacities are sited with the help of network flow models. State-of-the-art multi-objective models extend economic aspects with environmental issues only partially.

The developed methodology considers pollutants dispersion in the surrounding area around the source of pollution. Immission fields can further interfere with the field of inhabitants (density) for quantification of health impact. As a result, the WtEP capacity-dependent impact curve is obtained, which is the desired input to the network flow model.

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Data availability The datasets generated during the current study are not publicly available due to the large amount of data and their interpretation but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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