WASTE-TO-ENERGY STRATEGY CONCEPT FOR A COAL-FIRING POWER PLANT IN THE CZECH REPUBLIC: PART B – WASTE GASIFICATION/PYROLYSIS APPROACH

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ABSTRACT
The scope of this work follows up on the previous part A, which focuses on the energy use of waste through combustion for the benefit of the proposed Opatovice waste-to-energy (WtE) power plant concept. Part B discusses the application of gasification technology to the WtE concept. Different technologies, including plasma gasification and pyrolysis, and their potential for converting mixed municipal waste into energy are explored. This work also highlights the challenges and considerations in implementing these technologies, such as the need for the producer gases to be cleaned towards the quality level of natural gas combustion and the importance of waste homogeneity. The environmental impact of these technologies is also discussed, with a focus on emissions and waste management. This study also evaluates the potential consequences of not implementing any advanced technologies, such as continued reliance on fossil fuels and increased landfilling rate, along with other environmental and energy supply considerations. Gasification technologies offer opportunities to reduce landfilling and achieve partial energy independence. However, the implementation of such a technology is dependent on various factors, including the availability of alternative fuels and the capacity of natural gas supplies. This study emphasises the need for further research and development in this area.
Keywords: municipal waste, coal decline, gasification, waste-to-energy, energy concept, regional strategy.

1 INTRODUCTION

According to Statista data vault, the global waste production will most likely attack the rate of 2.6 billion metric tonnes in 2030, with the USA, China and the EU being dominant players [1], while open dumping remains a serious environmental threat in many regions [2].

In certain scenarios, the conventional combustion as we know it [3]–[6] even though enriched by modern flue gas aftertreatment technologies [6]–[9], may be replaced by more advanced technological approaches on thermochemical waste-feedstock conversion, such as pyrolysis [10], [11], hydrothermal carbonisation [12] and gasification [13]. The later one represents a beneficial approach to generate energy-rich producer gas [14]. The facility self-sufficiency may be supported by waste gasification implementation; the local environmental footprint may also be reduced. Moreover, the gasification process is a source of solid residue, a carbonaceous market article with specific physical and chemical properties, utilisable in numerous industries. In dry form, its lower heating value may reach 30 $MJ \cdot kg^{-1}$ with bulk density of 250 $kg \cdot m^{-3}$, which are considerably good parameters for subsequent burnout [13]. Such material can also be applied to the sorption processes in gaseous [15] or liquid [16] environments with positive environmental impact [17], due to the nature of their production and origin.

On the other hand, the process of waste gasification bears several drawbacks which need to be addressed prior to the approach becoming wide-spread and challenging to the conventional pathways. Among the drawbacks, production of harmful impurities, especially

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tars, are the crucial ones [18]–[20]. Moreover, legislation does not cover the waste gasification process properly in many European countries. It can be stated, that having granted the operation allowances is very difficult with the lack of decisive environmental footprint evaluation on the policy level, despite the effort of the European Commission to regulate and integrate such approach through imposing strict technical requirements and operating conditions on waste incineration plants, including gasification [21].

2 WASTE-TO-ENERGY (WTE) GASIFICATION APPROACH

In the context of the plan for the Opatovice WtE, gasification technologies are only feasible if the entire gasification process is carried out until the final phase of the energy use of the output products. Combustion of the generated gases is ideal for cleaning them to the quality of natural gas. The reason for this is compliance with emission limits and compliance with the parameters of the combustion equipment. If the gas was not cleaned enough, it would have to be burned in a separate unit with stricter flue gas cleaning, similar to the WtE requirements.

Gasification technologies are currently promoted as an alternative to WtE and are often presented as a beneficial option for cities and municipalities [22]. A variant of the technological concept of alternative energy systems can provide new possibilities in the field of WtE processing and eliminate the disadvantages of standard units for the direct energy use of municipal waste. The technology of mixed municipal waste (MMW) gasification is scarcely used in the world [2], and there is not much experience for this technology available. In terms of efficiency, a classic oxidation process is advantageous, however, local heat utilisation is required. The problem of heterogeneity of MMW could be solved by mechanical biological treatment (MBT) before the gasification unit. Coal regions in the EU are seen in Fig. 1.

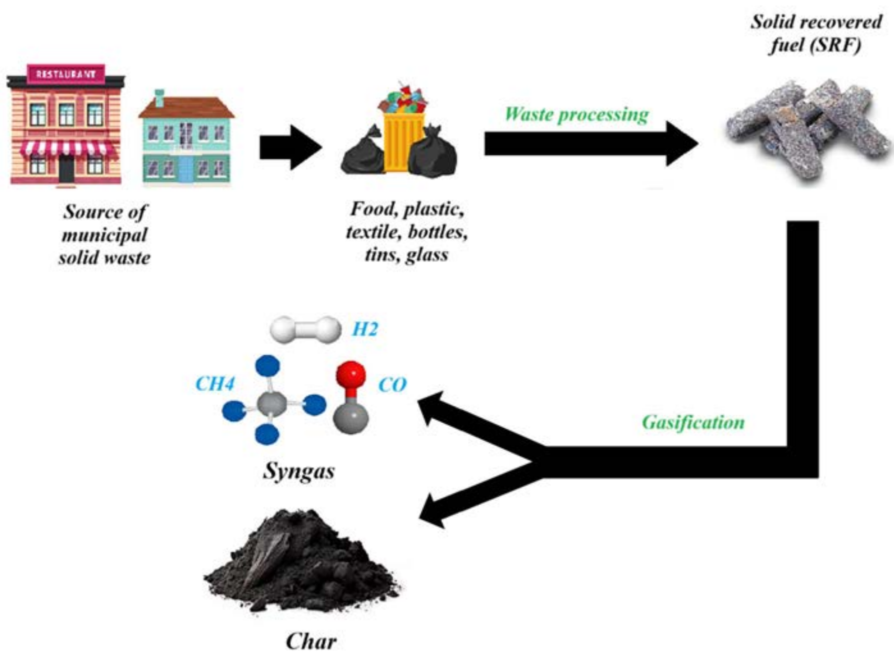

Figure 1: Solid recovered fuel gasification process.

2.1 Fixed bed gasification

Fixed bed gasification can provide a satisfying thermochemical reaction process for different types of feedstocks. The process temperatures usually range between 700 and 1200°C and the operation is relatively easy in small to medium scale applications [14]. Oxidising media, allowing the thermal decomposition of the feedstock in sub-stoichiometric conditions (equivalence ratio of 0.05–0.5), can be atmospheric air, or steam/oxygen in the case of more advanced technologies with higher syngas yield. Products of fixed bed waste gasification are synthetic gas, solid residue (gasification char) with high C content, and, usually, condensate, containing tar compounds [18]. The feedstock should be adjusted accordingly, with respect to the reactor design and operation conditions. The feedstock parameters should include decent particle size, moisture content <60%wt. (usually <30%wt.), and ash content <20%wt. (usually <10%wt.) [14]. Good homogenisation of the multi-component feedstock should be sufficed as well as proper form should be applied (fluff, pellets, briquettes) [13]. Similarly to the combustion approach, applying fixed bed gasification in Opatovice WtE requires advanced MSW adjustment line to produce reliable waste-based feedstock and avoid technical obstructions, such as clogging of the feeding system, or unstable decomposition in the grate area. Moreover, it is important to maintain the formed tars and select proper means of their capture and separation from the producer gas. In fixed bed gasification application, tars usually occur in the range of 0.1 to 150 $g \cdot m^{-3}$ for biomass [19]. In the case of MSW based feedstock gasification, very low tar concentrations can be reached in special applications [13].

2.2 Plasma gasification

In plasma gasification, the necessary heat for the gasification reactions is supplied in the electric arc created in the plasma torch.

The method of processing waste and converting it into energy via plasma gasification, during which solid material vitrification also occurs, includes energy recovery from waste in the form of high-quality synthesis gas. Vitrification creates an inert slag in which the metals are bound in an amorphous silicate matrix, from which they do not leach out under atmospheric influences [23].

The technology of plasma gasification is commonly used in the world, but the application of waste feedstock is relatively novel. The whole process begins with the preparation of input materials. A reactor is typically equipped with three plasma burners with support systems. They are followed by a synthesis gas processing (cleaning) system. The produced gas may be used in gas turbine or engine or be burned directly. The gas production and processing systems are completely closed, so they do not produce any toxic components.

The homogeneity of the waste is essential for this technology, just like for conventional gasification, so it is advisable that the processed MMW first passes through the MBT [24].

During combustion in common industrial systems, the maximum continuous temperature of up to 2000°C is usually reached. The zone of molecular fission begins when a temperature of 2700°C is reached. The plasma at the outlet of the burners reaches a temperature of 3000 to 4000°C. The gasification itself takes place above the coke bed, which serves as a catalyst and heat distributor. The maximum temperature of the synthesis gas at the outlet is 1700°C. These temperatures ensured a sufficient reaction rate for the reactor to operate at atmospheric pressure, the size of the gasifier was kept to a minimum, and it was possible to use much cheaper materials instead of high-temperature resistance materials.

At the indicated temperatures, molecules of organic substances are split in the reactor, preferably into H_2 and CO components. The heating value of synthesis gas depends on the type of processed waste, but its lower limit ranges from 15 to 22 MJ·kg^{-1} [25].

Disadvantage of plasma gasification is high electrical input of plasma torches. Plasma torches typically operate in the range of 50–500 kilowatts (kW). Some industrial-scale gasifiers may use even higher power levels [24]. However, plasma burners can be fully connected to the renewable energy sources (PV farms) and utilise intermittent, pollution-free energy.

2.3 Pyrolysis

Pyrolysis is a process of thermal treatment of organic substances with the exclusion of access to oxygen, air, or other gasifying substances. In this chemical process, dry distillation, thermal cracking, low-temperature carbonisation, or coking occur. The use of pyrolysis on inhomogeneous mixtures such as MMW is very difficult. The reaction products are gases, pyrolysis char with residues from inorganic phases, and pyrolysis oil. Pyrolysis takes place in three stages – drying, carbonisation, gasification [10], [11] (Fig. 2). The stages of pyrolysis are shown in Table 1.

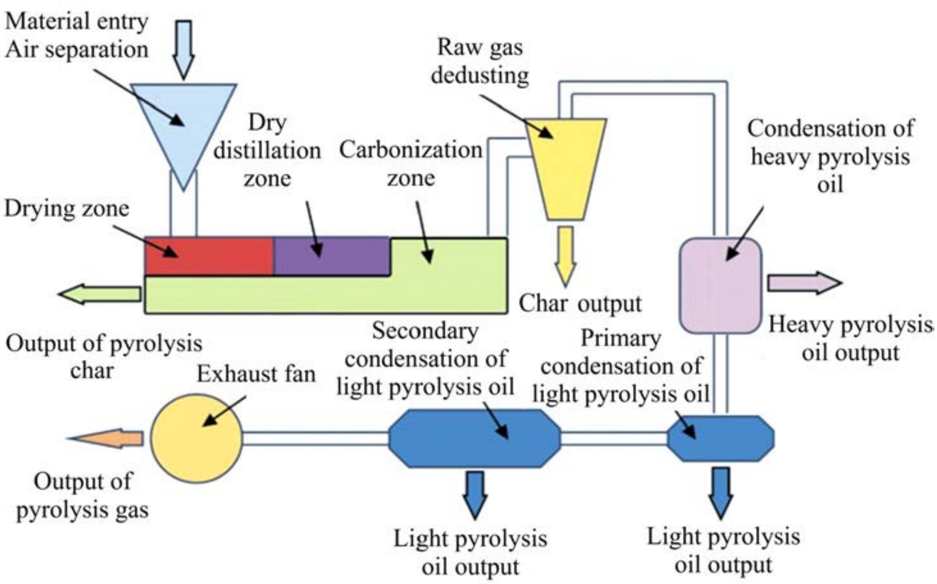

Figure 2: Scheme of the pyrolysis unit.

In the temperature range up to 150°C, physically bound water will vaporise. This process consumes approximately 2,250 kJ of energy per 1 kg of water, therefore it is favourable to place a press or a drying unit in front of the reactor, in case the input material has a high moisture content (e.g. sewage sludge, MSW).

Carbonisation occurs at temperatures from 300 to 500°C. The molecular organic substances such as cellulose, proteins, fats, and plastics are split off, producing gas, liquid hydrocarbons, and a residual solid part – pyrolysis char.

Table 1: Stages of pyrolysis depending on the temperature of the process.

Gas formation/ Temperature	Chemical reaction
100–200°C	Thermal drying, physical separation of water
250°C	Deoxidation, desulphurisation, splitting of bound water and CO_2, depolymerisation, beginning of H_2S splitting
340°C	Fission of aliphatic hydrocarbons, formation of methane and other aliphatic hydrocarbons
380°C	Carbonation phase
400°C	Cleavage of carbon-oxygen, carbon-nitrogen bonds
400–600°C	Conversion of bitumen components into pyrolysis oil and tar
600°C	Cracking to produce gaseous hydrocarbons with a short carbon chain, formation of aromatics according to the following
Above 600°C	Dimerisation of ethylene to butene, dehydrogenation to butadiene, diene reaction with ethylene to cyclohexane, thermal aromatisation to benzene, and higher volatile aromatics

In the gas phase above the temperature of 500°C, the products formed during carbonisation are further split. In the process, stable gases are formed from solid carbon and liquid organic substances: H_2, CO, CO_2, and CH_4.

The quantitative distribution and qualitative composition of products are determined by the following factors.

- Chemical composition, water content, and particle size of the input material.
- Operating conditions such as degassing temperature, heating time, residence time, pressure, gaseous atmosphere, and catalytic effects of substances present.
- The type of reactor in which the reaction takes place (fluidised bed, rotary kiln, shaft, etc.).

2.4 Gas cleaning of syngas made by fixed bed gasification, plasma gasification and pyrolysis

All harmful pollutants that could possibly damage the gas combustion equipment must be removed from the produced synthesis gas. SO_x and NO_x emissions are orders of magnitude lower than with traditional combustion.

Sulphur and solid particles are removed from the gas using high-temperature filtration. To reduce NO_x emissions, steam, water, CO_2, or N_2 are injected into the combustion chambers of turbines that use synthesis gas as the main fuel. NO_x emissions from the thermochemical conversion plant are generally lower than in the case of conventional combustion. In the case of plasma gasification, it is even below 10 ppm.

In the other hand, gasification and pyrolysis faces tremendous obstruction in the formation of tars. The tars condensate below around 450°C and tend to foul pipeline and downstream segment. Their separation is an economical burden, and the feasibility of the whole process is lowered, especially in the case when the gas is being cooled down to ambient temperature, for instance, for pipeline transportation purpose [26]–[29].

2.5 Energy production

Synthesis gas produced in a plasma gasifier is used by a combined cycle generator to produce electricity and heat. Fig. 3 shows a specific case of gasification; the figure also shows individual outputs from the gasifier.

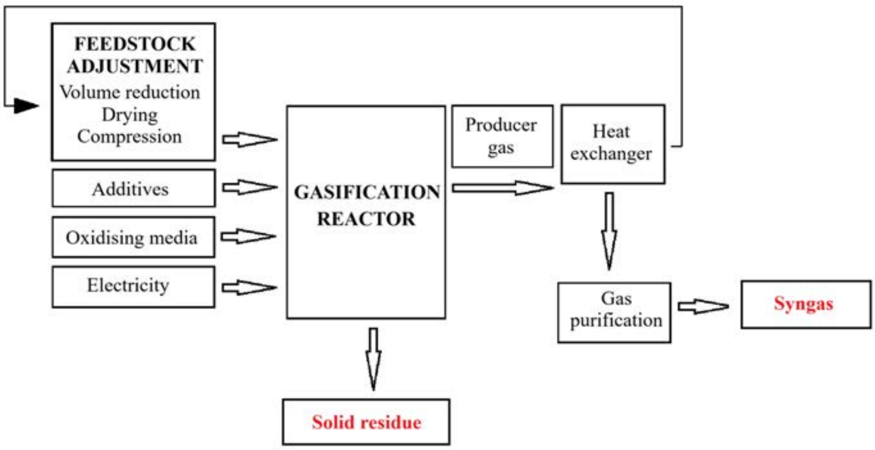

Figure 3: General scheme of gasification technology and a specific project example.

Determining the gasification price calculation is very problematic due to the lack of a reference for relevant waste in Europe and only a rough professional estimate can be established.

The individual stages of the process and the need to prioritise the technological concept of the MBT lead to a higher price for the equipment than for the MBT itself [30]. Abroad, this concept is mainly used for hazardous waste, medical waste, and biomass. The reference in Japan admits partial use of municipal waste without more precise specifications. MBT is an established waste treatment technology in many European countries, such as Germany and Austria [31]. On average, about 25 new MBT plants are constructed annually in Europe [32]. There are a few plasma gasification projects in Europe (e.g. Tee Valley located in Great Britain) which use RDF fuel as input material [33]. The start of the UK project implementation was made possible only on the assumption of guaranteed prices from the UK government. The economic terms of the guarantees have not been disclosed.

3 ENVIRONMENTAL EVALUATION OF THE GIVEN ENVIRONMENTAL INVESTMENT

3.1 Waste management

From the waste management point of view, the WtE application through either of the selected thermochemical conversion (including combustion with MBT, described in Part A of this study) offers opportunities to reduce landfilling in the region with a positive impact on the environment. The capacity of the planned WtE cannot accommodate all the waste produced in Pardubice and Hradec Králové regions, therefore it cannot ensure the full end of landfilling, however, it will significantly limit landfilling in these regions, at the rate of approximately 150 kt of MMW per year.

It is also essential to deal with conversion residues. The amount that is produced is influenced by the type of fuel, more precisely, by the ash content in the given fuel and conversion rate. The amount of ash in waste is approximately 20–25%wt., which should be further used in the industry, or landfilled. Landfilling is the predominant form of slag/ash/char disposal in the Czech Republic.

3.2 Air

According to decree on the permissible level of pollution, the WtE has set some of the strictest emission limits for combustion equipment. In addition, some of these devices have even stricter limits with the Integrated Permit issued by the relevant regional authorities.

Further tightening comes from the so-called best available techniques (BAT) limits for new devices. Emission limits are shown in Table 2.

Table 2: Emission limits for new equipment.

Pollutant emissions	**Decree set limits of (24-hour average) ($mg \cdot m^{-3}$)**	**New BAT (24-hour averages) ($mg \cdot m^{-3}$)**
SO_2	50	5–40
HCl	10	2–8
HF	1	1
NO_x	200	50–150
TZL	10	2–5
Cd, TI	0.05	0.005–0.02
Hg	0.05	1–10
CO	50	10–50
Total organic matter	10	3–10
Heavy metals	0.5	0.01–0.3
PCDD/PCDF[1]	0.1	0.01–0.08
NH_3	10	2–10

[1]In ($ng \cdot m^{-3}$)

An important topic in the context of WtE construction is the emission of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs). Their limits are set by law. The total number of PCDDs according to the number and position of bound chlorine is 75 and the number of furans (PCDFs) is up to 135. Out of the total number of these 210 cogeners, only 17 are monitored as potential carcinogens and only one has been shown to have a carcinogenic effect [34]. These substances are a common part of the environment, including food, and thus also part of MMW.

From real WtE operations, for example, SAKO Brno WtE power plant with 230 kt of MMW fuel input, and of 22.7 GW of installed electric power and 2 million GJ of annual heat energy output, it is possible to find out that due to combustion conditions, incoming dioxins are decomposed rather than threatening. Subsequently, although approximately one third is synthesised again, the majority of those newly created dioxins are attached to flue gas cleaning products. From the point of view of a comprehensive WtE assessment, this is not a source of dioxins, but on the contrary, it removes these dioxins from the environment, and

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thus, significantly fewer dioxins end up in landfills than would have been in the case if the original waste is not energetically utilised.

4 OPTION OF NOT REALISING THE GIVEN INVESTMENT AND ITS POTENTIAL EFFECT ON THE ENVIRONMENT

It may also happen that the WtE construction process will be stopped or cancelled altogether. The potential consequences in the event of the process cancellation variant were analysed thoroughly and its potential impact on the environment was evaluated.

4.1 Energy and supply options for central heat supply

The key motivation for the construction of WtE is in increased energy independence in the form of heat supply for the central heat supply system in the affected regions. Therefore, if the construction of WtE does not take place, it will be necessary to replace it with another source, or at least partially keep the original coal source in operation, along with the environmental impact and abandoning the ideas if Green Deal, set by the European Commission [35].

4.2 Biomass

The possibilities of alternative replacement of WtE capacity with biomass are very limited, due to the large number of the already existing and planned projects for this type of fuel in the Czech Republic. The heating value of wood chips is 8.5–12.5 $MJ \cdot kg^{-1}$ depending on the quality. The total consumption of mainly forest biomass as a substitute for Opatovice WtE is theoretically calculated at approximately 120,000–170,000 metric tonnes per year, depending on the quality of the wood chips.

4.2.1 Coal

Based on the Czech government's updated statement from 2023, the use of coal will be phased out by 2033 if there is a substitute for it [36]. Therefore, the option of preserving the coal source is rather theoretical and quite unreasonable, but not impossible. In the case of cancellation of the WtE implementation and the lack or unaffordability of natural gas, it will be possible to at least temporarily maintain an economic source of heat until a meaningful and long-term alternative is found. The variant assumes the preservation of at least one existing coal source and the burning of the equivalent of lignite with a WtE capacity. Compared to the existing source, the consumption of primary energy in fuel will thus be reduced, and it is possible to consider that up to 200,000 metric tonnes of coal will be avoided through the WtE operation.

4.2.2 Natural gas

Natural gas as a primary energy source is the most likely option since the construction of gas sources is the easiest option for rebuilding the current Opatovice power plant facility, however, this option is currently capacity-limited on the side of natural gas supplies at the connection point. Natural gas supplies are dependent on imports from abroad, which are not always stable and safe that they can be completely relied on [37]. In 2023 and 2024 Europe faced critical natural gas import shortages which the International Energy Agency (IEA) estimated as a 30 billion m^3 gap [38].

4.3 Waste management

Waste management is a fundamental sector that would suffer if the Opatovice WtE power plant is not implemented. It will be necessary to find an alternative outlet for MMW, which has been almost exclusively landfilled so far, and other landfilled and energy-usable components of municipal waste. According to the forecast of the Ministry of the Environment, in 2030 it is necessary to use 284 kt of MMW in both regions in different manner than landfilling. Several different WTEs are proposed in the Czech Republic. These include WtE Mělník with a capacity of 320 kt or WtE Spolana Neratovice with a capacity of 160 kt, both in Central Bohemian region. If the construction of these facilities were successful, their capacity in the Central Bohemia region would be 480 kt. However, after comparison with the planned production of MMW in the Central Bohemia region, the capacity of the planned incinerators for other regions is only 50 kt. Moreover, this reserve can also be used for other types of municipal waste produced in the Central Bohemian region, which are still landfilled, such as bulky waste. It clearly follows that the currently planned WtE capacities in the Central Bohemian region will be usable for other regions to a very limited extent or not at all. Thus, avoiding landfilling in Pardubice and Hradec Králove regions will be difficult without a WtE plan.

4.4 Impact on the environment

The impact of cancelling the planned Opatovice WtE power plant will also have an impact on the environment, both in terms of air quality and the climate in general. Both the air and the climate would be affected for two reasons: Firstly, the persistence of fossil fuel burning facilities with higher emission limits than waste, where emission limits are set very low, will remain in operation. The second reason is the disposal of unused waste in landfills, with a consequent production of landfill gas, which mainly contains CH_4, an undesirable greenhouse gas in the atmosphere.

Legislatively, according to the hierarchy of waste management, energy use is superior to landfilling. Emissions from landfills after 2030 will have to be eliminated due to the end of landfilling according to the Waste Act [39].

The negative impact on climate policy and the real impact on the climate is mainly due to higher greenhouse gas emissions, with main representation of CH_4. Quantifying this impact is difficult because it is not clear to which landfills the waste will be taken and whether these landfills are degassed the resulting CH_4 is used for energy production and in what percentage. Fig. 4 shows the predicted emissions from landfills in the event of non-application of MMW Opatovice WtE.

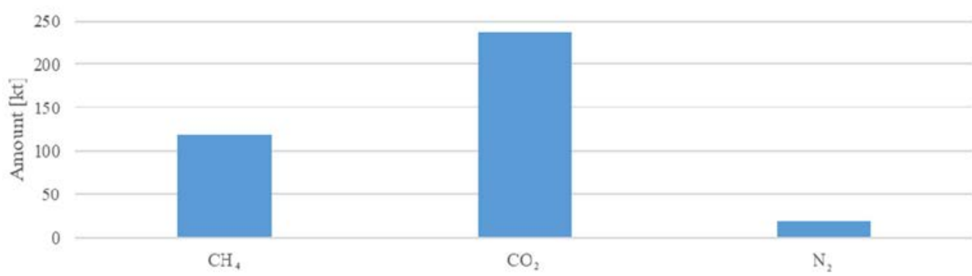

Figure 4: Expected emissions from the body of the landfill throughout its lifetime.

The legislation does not establish emission factors for municipal and hazardous waste landfills. Therefore, US EPA emission factors were used to calculate emission production – document by United States Environmental Protection Agency [40], stating the concentrations of compounds that landfill gas contains and which were determined based on measurements at MMW landfills after throughout the USA (these sources quantify the basic components of landfill gas as follows: CH_4 = 50%–70%, CO_2 = 27%–47% and N_2 up to 5%, traces of other gaseous components). Depending on their composition and technical parameters, the production of landfill gas at municipal waste landfills ranges from 100 to 250 m^3 of landfill gas per 1 t of deposited waste.

From the above, it is possible to derive the total expected average production of landfill gas at the level of approximately 281 million m^3 during the lifetime of the landfill of 15 years, which represents the total average production of pollutants during the lifetime of this stage of the landfill at the level shown in the graph in Fig. 4.

Free ventilation of landfill gas into the air, in the values shown in Fig. 4, does not occur if the landfill is degassed.

However, from the point of view of the effect on the population, other substances that can be the cause of odours are important (CH_4, CO_2, and N_2 are odourless). The expected production of odorous substances during the operation of the landfill was calculated based on modelling. Due to the high number of compounds, the substances with the highest concentration ratio in landfill gas and which have an adverse effect on human olfactory cells were selected. The emission of these substances is shown in the graph in Fig. 5.

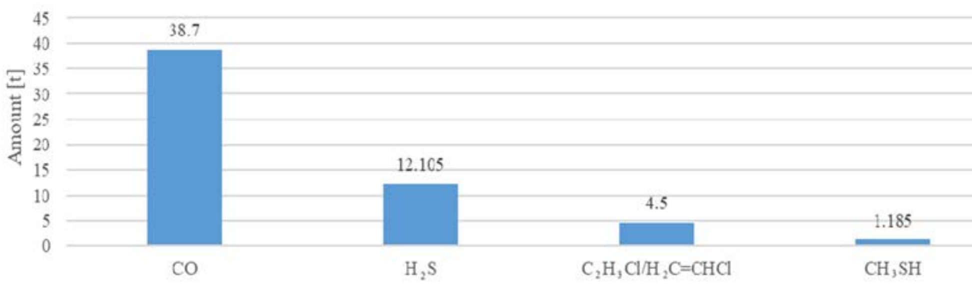

Figure 5: Emissions from the body of the landfill during its active operation (2022–2037).

5 CONCLUSION

In this extensive study, the concept of newly built WtE in currently operating Opatovice power plant, Czech Republic, is being discussed from the technical and environmental points of view. The current, fossil-based strategy in the regions of Pardubice and Hradec Králové appears to be beyond sustainability in the context of European climate goals. The strategy of new WtE for this selected region is based on conceptual study of incineration plant (Part A), as well as plant equipped with other thermochemical conversion processes, namely gasification and pyrolysis (Part B). It was found, that either of the selected scenarios would lead to the melioration of current state when fossil resources are utilised, both in the conversion process and landfill emissions. Surroundings landfills would be receiving around 150 kt of waste material less, annually, contributing to 281 million m^3 of pollutant production during the 15 years lifetime of the landfill. Moreover, the energy stability of the region would be increased, and all national and European legislation liabilities fulfilled. The concept of new WtE plant must be evaluated from the economic feasibility point of view as well as all legislation requirements must be met, prior the construction. Such processes are, however, often hindered when political and social aspects meddle into technically and environmentally sound affairs.

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