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Modelling of Existing Heating Plant Replacement with a Waste to Energy Plant and a Peak-Load Natural Gas Boiler

Ondřej Putna*, František Janošťák, Martin Pavlas

Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
Ondrej.Putna@vutbr.cz

The paper assesses the possibility of replacement of a heating plant with a waste-to-energy (WtE) plant as base heat source, together with a natural gas boiler for covering power peaks and as thermal backup. The decision of the Commission of the EU Member States of July 2017 shows a tightening of the emission limits for NO_x, SO_2 and other substances for thermal sources with a power over 50 MW_t to enter into force in 2021. In the Czech Republic, this restriction may affect a number of heating plants, which are currently in operation and they can become economically unsustainable. In addition to the requirements for greening of obsolete coal-fired heat sources, decreasing cost of electricity or the inappropriate dimensioning of due to current or future heat demand in the district heating system (DHS) can be other factors that affect the economy of these sources negatively. This fact, together with the planned ban on landfilling of untreated municipal waste from 2024 in the Czech Republic, represents the potential for the implementation of WtE projects in localities with DHS. Using the techno and economic mathematical models, the methodology of designing the proper processing capacity of a WtE plant and the gas boiler heat output is discussed. Achieving the best economy is prerequisite of the calculations. Additional boundary conditions are considered, such as the coverage of heat demand or the operating parameters of both heat sources. Furthermore, the economically optimal mode of operation of the two sources is presented on the basis of the operational data from real heating plants. The typical profile of demand for heat during the year and fluctuations at different time levels are taken into account. The paper also summarizes the relationship between key parameters such as the heat price and the available waste treatment cost.

1. Introduction

Waste to energy plants (WtEP) are, in addition to their main purpose which is waste treatment, sources of electrical and thermal energy. Efficiency of power production in these plants is rather low due to their technological design and risk of high-temperature corrosion of heat-exchanging surfaces (Villani and De Greef, 2010). Withdrawal of electricity is therefore no problem. It is the heat production and its subsequent withdrawal which becomes crucial for the whole economy of the project. Sufficient heat utilization increases energy efficiency R1, and thus helps attain values of 0.65, as required by the legislation (Grosso et al., 2010).

WtEP with waste processing capacity exceeding 100 kt/y are the most common types of WtEP in Europe but even plants with significantly lower capacities (10-50 kt/y) are not rare (Reimann, 2013). Stehlík (2016) describes potentials of small WtEPs. Compared to high capacity WtEPs, economy of low capacity WtEPs is even more coupled with heat sale. Due to economic reasons, higher steam conditions and subsequently also higher efficiency of electricity production are not preferred in this type of plants (ISWA, 2012). These economic reasons pertain to high investment costs related to purchase and running steam boiler at higher pressures levels. Further, the market availability of small condensing turbines is rather limited. Specific investment costs of reaching high efficiency of power production in small WTE capacities are not sufficiently compensated by high profits from sale of the electricity. Owners of WtE plants may then prefer technological solutions where steam of low parameters is produced, and electricity is cogenerated using simple and robust steam expansion module. This is also the technological concept considered in mathematical models in section 2. Electricity produced this way preferably covers the technology's own demand; profit from sale of excess electricity is negligible. One of the

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benefits of low capacity WtE is that they may be established even in locations with low heat demands. WtE are further important as facilities processing regional waste.

Looking at a typical annual heat demand profile in the Czech Republic, we may conclude that WtE technology with annual processing capacity of 10 kt (considered in the models) requires district heating system network (DHS) with heat demand of approximately 100 TJ/y. DHS are relatively common in the Czech Republic. According to the Czech Statistical Office, DHS is currently used by ca. 38 % of all Czech inhabitants. And according to the Czech Energy Regulatory Office, there are ca. 80 DHS's with heat demand exceeding 100 TJ/y. At present, the vast majority of heat for central heating is produced from fossil fuels, particularly from coal (Euroheat & Power, 2017).

First, coal is the worst fuel in terms of CO_2 emissions (Eggleston et al., 2006) and second, some of the coal-fired heat sources may become economically unsustainable for the following reasons. One of the reasons is that emission limits for heat sources over 50 MW_t is to be restricted since 2021 (Institute for Energy Economics and Financial Analysis, 2017). Compliance with the new limits will most likely be extremely difficult for combustion plants fired by Czech lignite, or the new restrictions will probably yield significant investments into greening of the technology. Other reasons for the economic unsustainability of the heat sources may include approaching end of their life-time or gradual decrease in heat demand and improper dimensioning of output of the existing heat plant boilers that is associated with it. This new situation will call for changes to the concept of heat demand in several locations operating DHS. It is the establishment of WtE that may be the answer to these problems. Ferdan et al. (2017) presents the potential savings of greenhouse gas emissions when replacing fossil fuel energy sources with WtE plants.

Due to the above discussed requirements on R1 efficiency, irregular annual profile of heat demand and relatively high specific investment costs, it is inappropriate to dimension WtEP to cover maximum heat demand anticipated in DHS. Optimum solution is to design small WtEP with low waste processing capacity and low thermal output, and cover heat demand peaks with gas-fired heat-only boiler station (GFBS) which functions as a thermal backup at the same time. This paper uses mathematical models to evaluate economy of WtEP in combination with GFBS. Prerequisite of the evaluation is a common owner of both units which may thus be operated in mutually optimal mode.

Most papers discussing WtEP establishments presume connection of WtEP to a sufficiently large DHS network so that the plant may constantly supply maximum thermal output to the network. Rest of the heat demand is supplied from other heat plants. Example of this approach is given in paper by Panepinto and Zanetti (2018) which analyses WtEP in terms of economic and environmental aspects. The acceptable heat price from the WtEP in this case mostly corresponds to the variable cost of its production at the secondary heat source. The novelty of this article is a comprehensive assessment of the economy of a WtEP with GFBS, while full coverage of the heat demand in the DHS and construction on the greenfield land is considered.

2. Mathematical model

First, a techno-economic model of hot-water GFBS was developed. Basic heat demand in DHS is covered by WtEP. GFBS covers peaks and provides backup during the heating season. Size of the DHS and capacity (thermal output) of WtEP are the variables in the model. Storage tank of relevant size to compensate fluctuations in the heat demand during a day is also assumed in the model. Thanks to this assumption, short-term fluctuations may be neglected, and the model is calculated on a daily basis, which means 356 times intervals.

The model used real operational data from DHS with annual heat demand of 600 TJ (daily averages). Changes to the heat demand was attained by multiplying with the coefficient <=1, so that the final demand lies within the 100-600 TJ/y interval. In terms of output, GFBS is dimensioned to provide 150 percent maximum average daily heat demand a year, regardless of the WtEP's capacity. Depending on the size of DHS, this means a range of 10-60 MW_t. GFBS in the model consists of three modules, depending on rated output. The smallest module always has output of 10 MW_t. GFBS with output of 10 MW_t corresponds to one 10 MW_t module; GFBS with output of 30 MW_t corresponds to one 10 MW_t module and one 20 MW_t module, and so on. This arrangement ensures wide control scope ranging from 10 percent of the smallest module (which is 1 MW_t for all GFBS outputs) to full output of all modules.

When the heat demand exceeds output of the WtEP, the remaining heat is supplied from the GFBS (minimum output must be respected). If the heat demand is fully satisfied from WtEP, GFBS may be shutdown. Shutdown is considered when the GFBS is not necessary for a period of time of min. one week. GFBS functions as a backup source, which means it's on stand-by during the heating season. The stand-by mode means that a boiler is filled with water (the so called wet lay-up) and operators are on call so that the boiler may be operating at full capacity within few hours on short notice. The heating season lasts normally from 1 September till 31 May in the Czech Republic, and if the GFBS isn't needed, the boiler may be cleaned and dried (the so dry lay-up). During this season, WtEP supplies only heat to produce hot potable water. A potential, ca. 2-day drop-out of

heat supply is not a big problem (until GFBS resumes operations or until the heat is supplied from WtEP again). Benefits of dry lay-up include partial decrease in operating costs, especially regarding service personnel.
Figure 1 displays an example of coverage of heat demand in DHS which requires 100 TJ/y of heat, GFBS with one module of 10 $\mathrm{MW_t}$ output, and WtEP with output of 5 $\mathrm{MW_t}$ (ca. 20 kt/y). In this example, WtEP fully covers heat demand for 263 days a year. During winter season, peaks must be covered from GFBS. In January or March, the drop in heat supplied from WtEP is obvious and is caused by operations of GFBS at minimum output. It is important to note that simultaneous running of WtEP and GFBS requires that the excess heat is wasted; if both units are owned by the same entity, source of wasted heat is irrelevant. Since the GFBS functions as a thermal backup, it is in dry lay-up conditions only during summer months even though there is no need for extra heat during May and September.

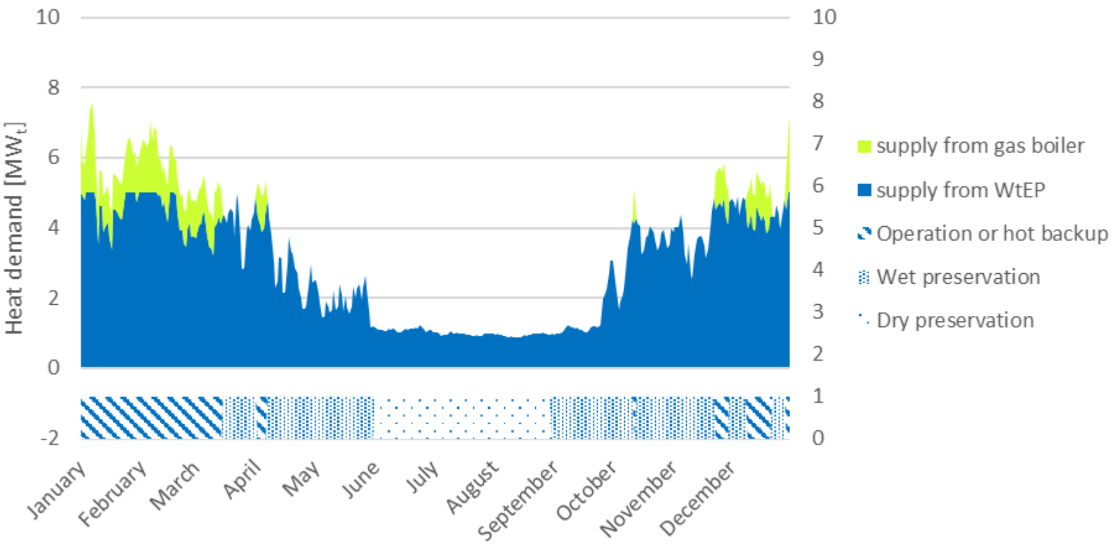

Figure 1: Example of heat demand covered from WtEP and GFBS

Daily costs of running GFBS were calculated for the model and the costs were later summed up for the whole year. Table 1 illustrates major costs items divided into three groups. Personnel costs may fall into fixed as well as variable costs since they don't depend on real output but they are expected to go down during a long-term shutdown in summer months. This also concerns maintenance costs.

Table 1: Costs of the gas-fired boiler station

Investment costs	Fixed operating costs	Variable operating costs
Depreciation	Personnel	Personnel
	Maintenance	Natural gas
	Inspection, adjustment and testing	Water
		Electricity

As discussed above, main output from this sub-model is annual costs of running GFBS depending on size of DHS and thermal output (capacity) of WtEP. Calculation of these costs was performed for 100 different DHS size options and 100 different WtEP size options, which amounts to the total of 10,000 calculations. The costs were later calculated for a unit of GJ of heat supplied into DHS, and they represent decrease in heat prices at the entrance to the DHS network. Figure 2 illustrates relevant dependence. Increase in capacity and thermal output of WtEP results in decrease in costs of running a GFBS, all the way to the level of fixed costs which tend to be relatively low regarding this type of units (compared to variable costs). White area (see Figure 2) concerning small DHS and large capacity WtEP illustrates situations when efficiency R1 is likely to be insufficient due to low heat demand; that’s why they weren’t included in the calculations.

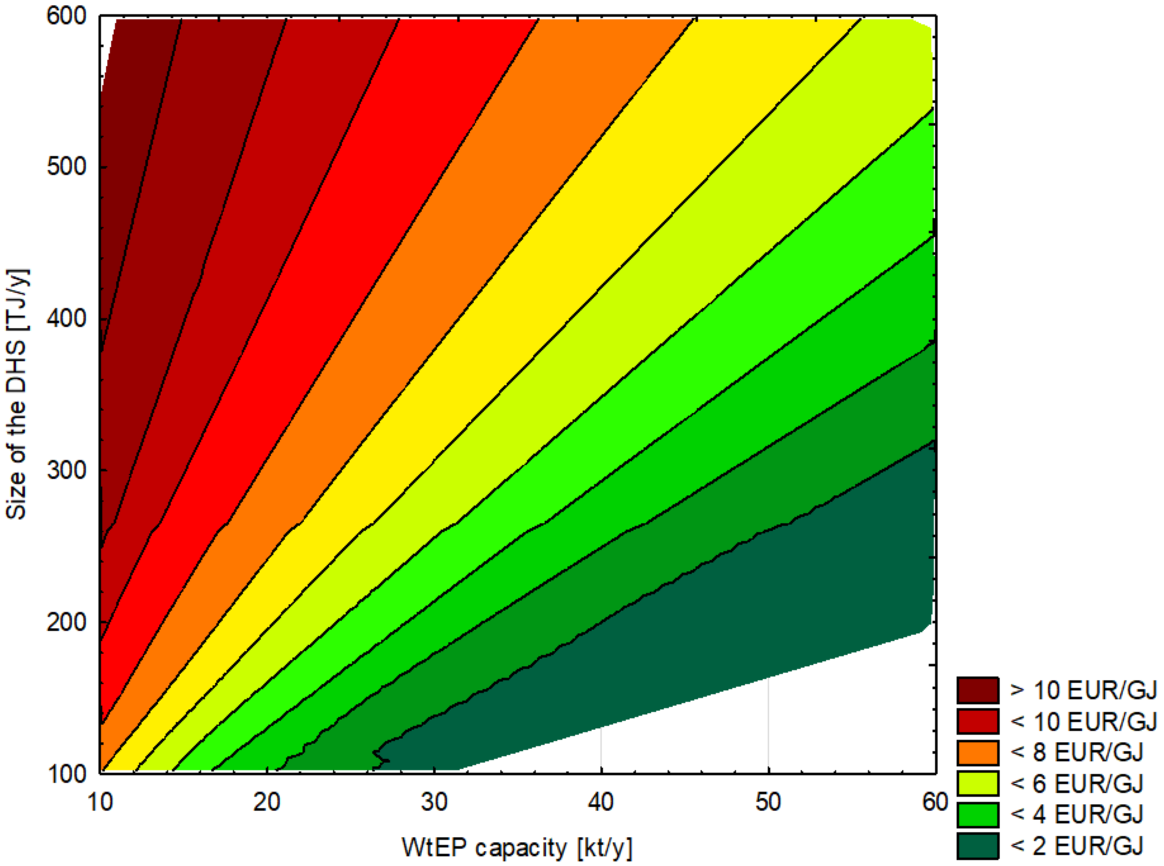

Figure 2 Dependence of additional costs of supplied heat on DHS size and WtEP output

Results were later used as input data for the techno-economic model of WtEP. This TE model is described in more detail in (Janošťák et al., 2016). The technical solution is discussed in Introduction and concerns processing of residual solid waste (RSW). More specifically, the solution entails a WtEP of low capacity with grate combustion and production of 220 °C and 13 bar steam in a boiler using simple expansion modulefor electricity production. The steam condensates beyond the turbine in a heat exchanger designated for heating of water for the purposes of DHS. If the heat demand is low, the excess heat is wasted in air-cooled chillers. Flue gas cleaning system should employ the so called dry cleaning method. This method consists of spraying the flue gas stream with sorbents and adsorbents which are later filtrated.

Owner of the WtEP and GFBS is considered to be one entity, and profits from sale of heat depend only on size of DHS network and price of heat at the entrance to the DHS. In other words, heat demand in the WtEP model is always fully covered, regardless of the thermal output of the WtEP. Heat supplied from GFBS is reflected in the model in the form of costs of running the GFBS (see Figure 2). These costs were obtained using a 2D linear regression method.

As mentioned above, profits from waste processing and sale of heat are crucial factors affecting economy of small WtE projects. Price of waste processing depends on many circumstances that are hard to predict. Ferdan et al. (2015) employed stochastic optimization method to describe the way of estimating the price depending on capacity of the plant. The waste processing prices in the model were fixed for all plant capacities at 90 EUR/t for the installation year (2025). The cost of transporting the waste are relatively low (Gregor et al., 2016) and therefore it was not considered. This means that the constant gate-fee is assumed, regardless on the capacity of the plant. The gate-fee may be further specified and refined so that it is possible to assess a concrete site.

Regarding the acceptable heat prices at the entrance to the DHS network, these depend on several factors, such as technical condition and age of the DHS, heat losses. Wahlroos et al. (2017) present different heat prices throughout the year in Scandinavian countries where prices significantly drop during the summer.

Ten thousand calculations for various combinations of WtEP capacity and DHS size were performed. According to the Czech Energy Regulatory Office, the heat prices at the outlet from secondary pipes of larger DHSs reached ca. 22 EUR/GJ on average, including taxation, and ca. 16 EUR/GJ at the outlet from primary pipes. The price of heat leaving WtEP (and entering DHS) is estimated at ca. 10-12 EUR/GJ, including distribution costs. Project's investors, upon considering the concrete conditions of the project's site, may prefer the heat prices to be lower for final customers and prices of waste processing higher, or the other way around.

Success of the project may be assessed by several criteria. Some of the most common criteria include return on investments (ROI), net present value (NPV) and internal rate of return (IRR). ROI may be easily calculated but it doesn't concern cash flow in any given year (only profits of the project) and therefore fails to account for differences in value of money over time. Most authors decide to work with IRR or NPV instead. Weber, 2014 comments on differences between NPV and IRR. Profitability of the project described in this paper was evaluated using IRR.

3. Results

Figure 3 illustrates final dependence of IRR on capacity of five different DHS networks with different heat demand. Price of heat entering DHS is set at 11 EUR/GJ. Capacity restrictions are obvious. In case of small DHS networks, capacity of WtEP is limited from above by low efficiency R1. On the other hand, smaller capacities result in low IRR, which is caused by high specific costs for covering remaining heat demand from GFBS.

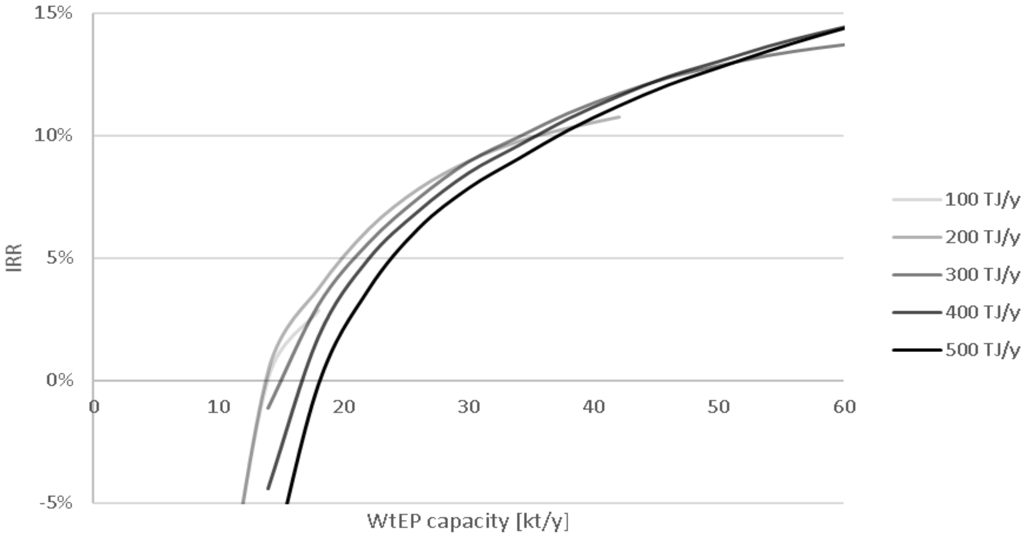

Figure 3 Dependence of IRR on WtEP capacity for various DHS sizes, heat price: 11 EUR/GJ

Minimal IRR depends on requirements and type of an investor. Sufficient values of IRR for a municipal project may be as low as 6% but a private investor will most likely require a much higher minimum IRR. It is clear that size of DHS doesn't play a big role up to a certain WtEP capacity. In case of small DHS networks, IRR steeply rises along with WtEP capacity thanks to a drop of specific investment and operating costs but before IRR reaches a plausible value, it drops below required level of efficiency R1. In case of DHS with heat demand of 300 TJ, efficiency R1 attains sufficient levels for the whole spectrum of assessed capacities. In general, the results clearly show that maximum profitability of the project is always associated with maximum capacity, provided that the requirements on efficiency R1 are met. Profitability of the project rises more or less constantly until almost the whole heat demand is covered from WtEP; further increase in capacity provides little space for savings of variable costs for GFBS. Recommended capacity is therefore close to the maximum capacity which is restricted by R1 factor.

Higher prices of heat entering DHS which exceed costs of the heat production in GFBS may be compensated by bigger DHS network. It may not always be true that the larger DHS is better for the project economy. Especially if the acceptable heat price is low and WtEP's capacity is limited for some reason (e.g. lack of waste, legislative or technological constraints), higher IRR can be achieved in a smaller DHS.

If the DHSs are large and heat prices are low, low capacity WtE projects may become economically unsustainable.

Results further prove that profitability of the project, depending on the network size and measured as IRR equal to 6%, starts at capacity of 22-25 kt/y for the estimated prices of heat, entering DHS, of 11 EUR/GJ. IRR for capacities of 10-60 kt/y may reach up to 15% provided that the DHS is of sufficient size and heat prices are at

11 EUR/GJ. Heat price significantly impacts IRR. As of now, it's not possible to precisely state how much IRR will change if heat prices rise/drop. Value of IRR depends on many factors but in general, we may conclude that WtE projects in large DHS with low capacity are more susceptible to changes of heat prices. For example, if heat prices drop by 1 EUR/GJ, WtEP with 30 kt/y waste processing capacity and DHS with heat demand of 400 TJ/y experience a drop of IRR by 2%; WtEP with 60 kt/y capacity and DHS with heat demand of 200 TJ/y experience drop of IRR only by 0.6%.

4. Conclusions

Results of the analysis prove that replacement of the original heat source in the WtEP and GFBS is economically sustainable. Economy of these projects heavily depends on prices of waste processing which is in turn dependent on competition within the relevant area and acceptable heat prices. Heat prices depend on distribution costs and limit prices for final customers. If this limit price is exceeded, there is a risk of collective disconnection of the customers and consequent disintegration of the DHS.

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