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Energy Dispatch Model for Integrated Waste-to-Energy Plant

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Waste management currently is a much-discussed topic. Waste should be treated in accordance with EU Directive 2008/98 EC. However, material recycling cannot be applied to all waste generated. It is not only for this reason that the construction of new waste-to-energy plants (WtEP) is being considered in many countries with high landfilling shares. When designing WtE projects, it is essential to assess their economic sustainability with regard to local conditions. Revenues from the sale of heat are one of the most important parameters for the economy of these facilities in the climatic conditions of Central Europe. This often involves the need to supply heat to an existing central district heating system (DHS). The paper presents a complex mathematical optimisation tool for integrated WtE assessment. It is a multi-period model, where the annual operation is analysed in 365 days. It is able to simulate the simultaneous operation of several heat sources (gas or coal boilers coupled with turbines), while respecting their design constraints and operation economy, such as the power range of individual boilers, turbines, variable operating costs and efficiency, etc. The tool is able to refine the estimate of the acceptable heat price and its amount from the WtEP through the change in the variable costs of heat production before and after the integration of the new WtEP. This is a key benefit compared to commonly used techno and economic models of WtEPs, which in most cases work with a simplified assumption that all heat produced can be utilised if its monthly output is lower than total demand in the DHS. As a result, the calculation of the minimum gate-fee or profitability of the project will be improved. The whole problem is the task of linear integer programming and is implemented in GAMS programming environment with the use of MS Excel for a user-friendly interface. The software functionality is presented in the second part of the paper on a real example of WtEP integration into existing DHS.

1. Introduction

Nowadays, the whole world is struggling with waste disposal. According to Sabki et al. (2017), approximately 1.3 x 10^9 t of MSW per year is produced worldwide and this will be up to 2.2 x 10^9 t by 2025.
The European Directive 2008/98/EC defines the waste hierarchy, which prioritises prevention methods of waste recovery and recycling. However, waste production cannot be completely prevented, reuse is also limited, and recycling is currently only suitable for some types of materials, whether due to inappropriate technology or costs. In terms of sustainable development and the principle of the circular economy, energy use seems to be a viable option (Malinauskaite et al., 2017). This leads to the creation of new WtEP construction projects. For example, Taib et al. (2017) describes a project WtEP in Malaysia.
The main theme of the article is the problem of accurate economic models WtEP projects in terms of utilization of the produced heat. For economic and legislative reasons, WtEP is, if possible, integrated into DHSs. The construction is thus often considered in the area of an existing heating plant. This will result in a moderate reduction in investment cost (partial technology sharing), while at the same time ensures demand for heat energy, which is an important part of the WtEP's economy. However, an important prerequisite for integration is the mutual symbiosis dealt by Aziz and Hashim (2019) describing a water regeneration system. This article presents a tool for planning the integration of a WtEP into a DHS involving both construction and subsequent operation.
In the model case, WtEP technology is considered to have a back-pressure steam turbine and subsequent heat utilisation for the purposes of district heating. It can be characterised as a combined heat and power plant

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(CHPP). As described in Bischi et al. (2014), in general, the optimisation of the operation of CHPP is the role of mixed integer non-linear programming (MINLP), since operation planning must include information about individual equipment (boilers, turbo-generators). In particular, these are performance curves, maximum and minimum allowable loads, shutdown options, etc. The integer part of programming is hidden in the on/off variables and nonlinearity occur in performance curves. The problem of MINLP itself is difficult to solve even for the most recent optimisation software, so MINLP is retreating and there are many integer linear programming (MILP) techniques that convert the problem to MILP.

One example that modifies the problem to MILP is described by Thorin et al. (2005), who deals with the design for long-term optimisation of cogeneration systems. His approach is based on a combination of MILP and Lagrangian relaxation. However, when selecting a time step length of one hour, the authors are already in trouble with solvability if they want to optimise the time period of several months. A similar time-consuming problem is also described in Piacentiono and Cardona (2008), which also approaches hourly-based modelling and, with its model, begins to have a significant increase in computing time for task dealing over 40 d. Rong and Lahdelma (2007) also define the model on an hourly basis. It works with the idea that cost-effective CHPP operation can be planned with optimisation models. Using various decomposition techniques, the mid to long term planning model can be divided into hourly models that can be more or less independently resolved depending on the algorithm used.

Most of the above mentioned were classified as short-term models, with operation optimisation only within hours, days or weeks. The long-term goal is to simulate at least one year or the entire life of the facility. Depending on the time horizon, the appropriate time step must be chosen. For short-term, even hour-based optimisation can be performed, but the hour-based calculation for several years of plant's lifetime is no longer possible. For a long-term model, a month or a year time step is usually used.

One such case is Buoro et al. (2013), which, however, made it more difficult to incorporate environmental aspects. Thus, it receives a multi-objective task that includes both investment and operation of the entire plant. One year is chosen as a time step. The same approach uses Fazlollahi et al. (2012), who defines the role of MILP in his work, which he further develops and proposes to solve it using an evolutionary algorithm. The parallel calculation approach is used to save computational time. Fazlollahi et al. (2014) proposes to reduce the computational time using cluster analysis. Here the problem is to optimise a district heating system. This leads to a multi-year model that will work on an hourly basis. The number of variables with the size of the task is growing rapidly, and the model of the MILP character is becoming unsolvable.

From the perspective of research to date, it can be seen that the models that deal with the optimisation of CHPP construction and operation, which includes WtEP, face the problem of computational complexity. Usually, it is solved by extending the calculation time step to month or year. However, by neglecting the daily or hourly effects of variables over time, they introduce significant errors in the calculation. This problem for heat demand is described in Putna et al. (2018). The aim of this article is to design a tool to simulate the operation of CHPP over its lifetime, which works on a daily basis, and for this reason, adequately describes the variables over time.

2. Problem description and methodology

The tool presented in this article specialises in integrating WtEP into DHS. The tool includes a comprehensive assessment of the potential for heat production from a WtEP, which is closely linked to the economy of these plants and to the energy efficiency achieved. The heat demand is given in the form of daily averages, so the annual profile represents 365 values that change over the years. At the same time, the tool contains all technical and economic parameters including investment costs.

Given the fact that the WtEP is connected to the DHS, the calculation of the existing heat source, which had previously been supplied DHS itself, must be included. This tool analyses the mode of operation of the original heat source and then assesses how this mode will change after connecting a WtEP with different processing capacity or in the form of output heat provided while minimizing heat production costs. The result is an acceptable WtEP heat price, its economically viable amount and the profitability of the construction project itself. The profitability of the project is assessed here from the point of view of the internal rate of return (IRR), which is appropriate for this issue, see (Weber, 2014).

2.1 Mathematical model

The whole model works on a daily basis and can be divided into two parts. In the first part scenarios of indeterminate parameters and their expected development are defined, namely (i) the price of electricity exported to the system, (ii) gate-fee, (iii) lower heating value (LHV) of the processed waste, (iv) heat demand.

The estimated price and LHV of the incinerated waste at a given processing capacity is the subject of NERUDA optimisation tool (Šomplák et al., 2014) and JUSTINE (Pavlas et al., 2017). The scenarios of these two parameters, as well as electricity prices, are set in the form of anticipated future developments, and their change

over time is included for subsequent years. Heat demand scenarios are entered in the form of daily averages at individual output levels. If daily averages are not available, the heat demand can be entered in the form of monthly averages. The daily averages are then automatically generated using a suitable statistical distribution based on an analysis of heat demand fluctuations during the year from other locations.
The second part of the model is shown in the schematic in Figure 1. The parameters of individual boilers and turbines, heat demand at each level and possible energy flows in the technology are entered into the user interface.

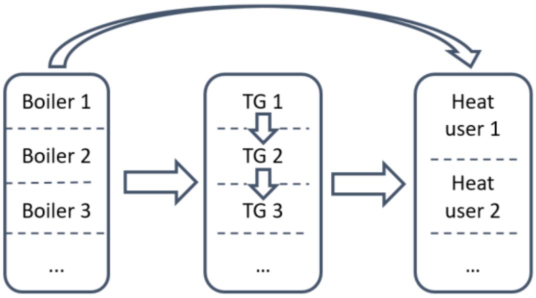

Figure 1: Scheme of the second part of the model

Up to eight boilers can be entered in total. For each boiler, parameters of the steam produced, output range, feedwater parameters, variable operating costs (e.g. fuel costs), boiler efficiency, the percentage of heat consumption for technology and shutdown options are specified. For example, it is possible to prohibit the shutdown of some boilers for operational reasons. Potential consumers of heat produced are further entered for each boiler, which in this case can be turbines or direct heat export to DHS.
Turbines are entered in a similar way to boilers. For each turbine, a possible input energy range is set. The electromechanical efficiency of the turbine and as with boilers, the possibility of a shutdown is set. The internal thermodynamic efficiency of the turbines is determined by the regression coefficients a, b. The consumption of heat for electricity generation is then described by the function:

$$P_{el} = a \cdot P_{th} + b, \tag{1}$$

where P_{el} is the heat consumption for electricity generation, a, b are regression coefficients and P_{th} is the heat input. In this way, it is possible to take into account the decrease in efficiency when the steam input is changed, and the model's linearity is maintained. Possible energy flows from individual turbines are entered again in the same way as for boilers. It is considered that steam from the turbine continues either to another turbine, or to a condensing stage of the turbine or is directly used in the DHS. If a condensing extraction turbine is installed in the technology, its individual stages are modelled as separate turbines, with the condition that all its stages must be simultaneously in operation (or shut down). The tool can calculate up to eight turbines, respectively turbine stages.
The second part of the tool is calculated in two phases. In the first phase, for the current scenario from the first part and for each day, the optimum mode of operation of the heating plant is found from the point of view of the minimum heat production costs without considering the WtEP. The objective function, in this case, has the form:

$$Z = \sum C_{fuel} + \sum C_{emi} + \sum C_{res} + \sum C_{lim} + \sum C_{oth} - \sum R_{el}, \tag{2}$$

where Z is the difference between variable costs and revenues for heat generation, $\sum C_{fuel}$ is the sum of fuel costs for all the boilers, $\sum C_{emi}$ is the sum of the cost of emission allowances for all the boilers, $\sum C_{res}$ is the sum of the cost of handling residues for all the boilers, $\sum C_{lim}$ is the sum of limestone costs for desulphurisation, $\sum C_{oth}$ is the sum of other variable costs for all considered boilers, $\sum R_{el}$ is the sum of revenue from the sale of electricity from all turbo-generators.
In this optimisation calculation, certain boundary conditions have to be respected. Specifically, it is to respect the performance range of the boilers. Each boiler has to be operated at either the set power interval or it has to be shut down if this is possible. These conditions are also determined for turbo-generators. The total sum of the energy flows at the boiler or turbine outlet must correspond to the total output heat output and the total heat demand must be satisfied.
As mentioned previously, this optimisation calculation (first phase) results in variable heat production costs in the heating plant in an economically optimal mode of operation. In the second phase of the calculation, WtEP

integration is considered. In this case, it is assumed that all heat produced in the WtEP is bought at different levels by the heating plant, which either uses it (e.g. to generate electricity or for technological purposes), sells it to the DHS or dissipates it.

From the calculation point of view, WtEP is modelled as an additional boiler with zero operating costs, the performance of which is consistent with the intended capacity of the plant. Possible energy flows are set depending on the location.

In the second phase, the calculation is performed again, this time with the WtEP (another virtual boiler). The resulting heat production cost is lower. The resulting cost savings compared to the initial state divided by the amount of heat supplied by the WtEP in the economically optimal mode of operation in the second phase of the calculation corresponds to the acceptable specific heat price that the CHP can afford to offer to the WtEP while maintaining the original profitability.

It should be noted that there may be a situation where there are infinitely many optimal solutions. For example, when a boiler with a high minimum output and a WtEP using a back-pressure turbine deliver heat to the DHS, whose performance is not sufficient to meet the current heat demand. It is necessary to operate the boiler at its minimum power output and the WtEP performance is not suitable for economic reasons (waste processing revenues) to be limited. So there will be a surplus of heat produced, part of which must be dissipated, and it does not matter from the model's point of view whether it comes from the CHPP's boiler or from the WtEP. As a result, delivering more heat from WtEP at a lower price or, on the contrary, supplying less heat from WtEP at a higher price could be calculated as the optimal solution, with total heat revenues being the same. In order to better interpret the results, such a situation is dealt with in such a way that the delivery from the CHPP is always preferred.

This principle is graphically represented in Figure 2. Since the fixed costs of the CHPP and its profit are considered constant before and after the integration of the WtEP, there is no need to consider them in the model. The loss represents a possible fall in electricity sales, with a total decline in performance after WtEP integration.

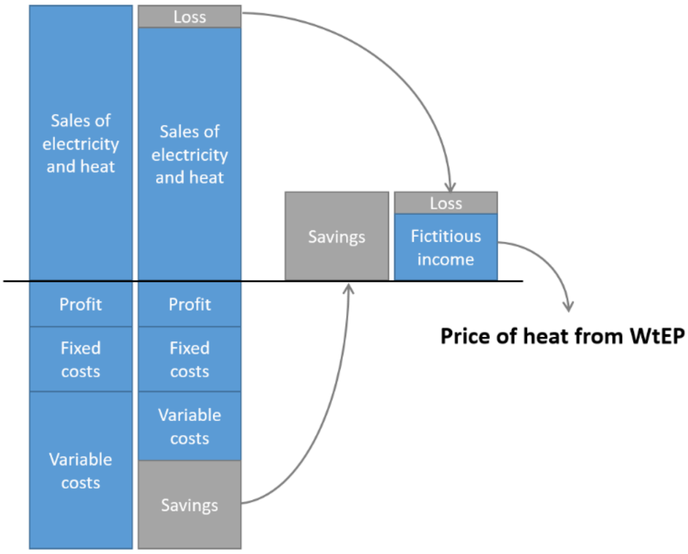

Figure 2: The principle of calculating the heat price from the WtEP

The secondary output is also the amount of electricity exported from WtEP. This quantity must also be based on optimisation because when using extraction turbine, the electrical power is directly dependent on the heat export.

3. Case study and results

Software functions are presented on a case study of existing DHSs in the Czech Republic with a proposal of possible changes (construction of a WtEP, interconnection of DHSs). These are two separate DHSs with their own heat sources and with similar overall annual heat demand (approx. 600 MJ/y). These systems are currently connected by an unused steam pipeline. The first system (A) has a heating system with 2 coal boilers (2x32.9 MW_t), one gas boiler (14.9 MW_t) and an extraction turbine with three stages (20 MW_e). Heat is supplied as hot water, high pressure and low-pressure steam. In the second system (B), the CHPP uses 3 liquid fuel

boilers. (78.7 MW_t, 2x17.2 MW_t), one gas boiler (24.2 MW_t), one coal boiler (71 MW_t) and 2 turbines (9 MW_e, 8 MW_e), of which one is a two-stage condensing extraction turbine and the other is a back-pressure turbine. The heat is supplied in the form of hot water and low-pressure steam.
In this paper, two basic scenarios have been analysed. The first is the construction of a WtEP with a capacity of 10-40 kt/y, which can supply thermal energy in the form of steam and hot water. The second is the possibility of connecting the DHSs so that system A can supply low-pressure steam to system B.
On the basis of the parameters of the CHPP in both systems and their technological possibilities, the optimal operation of the current state was calculated, which serves as a starting point and from which the profit or loss of the potential solution is determined. Table 1 summarises the status of the WtEP integration into system A without interconnection with system B within one year.
The "Heat from WtEP" column characterises the amount of heat the WtEP has supplied as hot water or steam. Savings of the system represent a decrease in the Z variable described above. "Cost of heat from WtEP" expresses the money that WtEP needs to be passed on in order to have a chosen IRR of 10% (assuming the gate fee is 88 EUR/t). The "Total savings" column then defines the total savings that network A has experienced by changing the operation (WtEP integration). Under the given conditions, the most advantageous option is the WtEP with a capacity of 40 kt/y. The other scenario is to connect the systems without WtEP and then with it, see Table 2.
Compared to the previous table, a column "Savings of system B" has been added, which analogously describes the savings of the system B owner. Also, the costs of the connection of the systems have been added to the column "Costs for heat from WtEP". It can be seen from the results that the interconnection of networks itself seems to be a suitable option, which will bring total annual savings of approximately 293 kEUR, which can be distributed between the systems as profit from the point of view of the WtEP construction, the most suitable option again is the capacity of 40 kt/y, which would bring total savings of approximately 874 kEUR.

Table 1: Economic evaluation - separate DHS

	WtEP capacity [kt/y]	Heat from WtEP [GJ/y]	Savings of system A [kEUR/y]	Costs of heat from WtEP [kEUR/y]	Total savings [kEUR/y]
Heat delivery	10	78,615	484.85	1,424.58	-939.74
	20	157,226	969.69	1,510.05	-540.36
	30	234,897	1,448.81	1,387.18	61.63
	40	301,323	1,858.63	1,209.93	648.69
Hot water delivery	10	45,160	278.61	1,324.97	-1,046.36
	20	57,774	356.49	1,310.87	-954.38
	30	60,136	371.09	1,088.35	-717.26
	40	45,160	371,29	811.53	-440.24

Table 2: Economic evaluation - connected DHS

	WtEP capacity [kt/y]	Heat from WtEP [GJ/y]	Savings of system A [kEUR/y]	Savings of system B [kEUR/y]	Transported heat [TJ/y]	Costs for heat from WtEP and connection DHS [kEUR/y]	Total savings [kEUR/y]
		-	-673.55	1,030.62	109	64.24	292.79
Heat delivery	10	78615	-188.74	1,030.62	109	1,488.82	-646.94
	20	157231	296.14	1,030.62	109	1,574.33	-247.57
	30	235846	781.03	1,030.62	109	1,451.46	360.19
	40	314461	1,265.41	1,030.62	109	1,274.17	1,021.82
Hot water delivery	10	45160	-394.94	1,030.62	109	1,389.21	-753.72
	20	57774	-317.06	1,030.62	109	1,375.11	-661.75
	30	60136	-302,45	1,030.62	109	1,152.63	-424.46
	40	60136	-302,45	1,030.62	109	875.77	-147.60

4. Conclusions

In the paper, a tool for optimising several heat sources was introduced, at least one of which is a WtEP. The principle of the tool has been illustrated for two examples at a specific location in the Czech Republic. The first

deals with the integration of WtEP (capacity between 10-40 kt/y) to the existing DHS A. The WtEP with a capacity 40 kt/y is the most suitable option. With a 10% return (IRR) on the WtEP project, system A achieved a saving of 208 kEUR/y. A second example is the integration of WtEP under the interconnection of A and B networks by steam piping. WtEP with a capacity of 40 kt/y appears to be the most suitable option again. This brings to the systems A and B a total saving of 874 kEUR/y. The interconnection of A and B systems without WtEP is also an option that saves about 293 kEUR/y.
The selected heating system included a total of 8 combustion boilers, 3 turbo-generators and 5 levels of heat supply in the form of hot water or steam. It was a very complex system, so simplification had to be considered in the calculation. Thanks to these simplifications, the problem could be solved on a daily basis, with which most of the previous work has a problem. This prevented significant inaccuracies due to fluctuations in heat demand. \The removal of some simplifications and the extension by the environmental aspect (Fan et al., 2019) is the subject of future work.

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