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Short-time Fluctuations and Their Impact on Waste-to-Energy Conceptual Design Optimized by Multi-Stage Stochastic Model

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The paper focuses on the development of a computational tool for effective investment planning in the field of waste-to-energy. The expected return on investment is only achieved if the plant operates successfully in the future. Generally, the operation of any plant can be analysed at various levels of detail, which differ in the basic time step. We may distinguish short-term, mid-term and long-term operation planning.
The construction period of any waste-to-energy plant, including legislative processes usually lasts 5 to 10 y. The following operation is planned for next 20 - 30 y. Such a long project duration requires a robust design with low sensitivity to future changes in the key parameters. So here, multi-stage optimization model, which proposes a conceptual design of the plant based on plant's performance under different future scenarios can serve as an effective support tool. So future operation modelling represents an integral part of such a tool.
The objective of the paper is to discuss a proper time interval in the context of the complex multi-stage model and the influence of different time steps. The proper length of the time step varies depending on the required accuracy of the model. This paper aims to determine the susceptibility of different models depending on the time step. Correction coefficients for a more accurate model, which take into account the fluctuation of the data on the shorter time intervals, are proposed.
The paper reviews aspects, which substantially fluctuate and vary with time and thus their prediction for long periods of time is very difficult, e.g. heat demand or waste supply. They are described and classified and their influence on the future economy of the plant is analysed. Data analysis of these parameters over shorter periods of time can also help to include auxiliary equipment such as heat accumulators or reserve gas or coal-fired boilers into the investment planning phase.
Given the scope of the model is to design a new project, which uses data on an annual basis. For a more realistic model outputs, daily fluctuations in many parameters should be mentioned as well. For this purpose system of correction coefficients is proposed where applicable.

1. Introduction

It is necessary to consider the life cycle of about 25 y in the waste-to-energy (WtE) project planning. There are important parameters for assessing the economics of the project and operation planning, which vary with time and which are difficult to predict accurately in the long-term and even short-term period. A two stages model for WtE conceptual design was presented by Šomplák et al. (2013). It assesses the suitability of the WtE project investment while some uncertain circumstances regarding the future operation are considered. In other words, accuracy of the second stage model (future operation with fixed plant design) is essential. In this contribution, we will focus on the second stage of the model to investigate the effect of various "interval length" on the results. A stochastic model for electricity production planning in the waste-to-energy plant (WtEP) based on operational data, which reflects uncertain input parameters, has been presented by Tous et al. (2015). In practice, techno and economic models for the design of the basic parameters of the technology on a monthly basis are often used. Generally, this period is assumed to be sufficiently accurate, while it is still

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possible to predict the unknown parameters relatively reliably at this level of detail. The paper attempts to point out the consequences of such simplification.

Considering heat utilization strategy three types of WtE concepts may be distinguished – power, heat oriented and combined heat and power production (CHP). Second and last option is applicable to localities, where district heating system (DHS) or industrial heat supply is available. In this paper district heating is considered, since significant fluctuations in heat demand may occur there. This is a typical case in the Czech Republic, where DHS are very common. However, a variation in demand could be defined as well for power (e.g. price variation due to the seasonal character of renewable sources etc.). The proposed methodology is applicable for power-oriented waste-based production. In this context, focusing on electricity demand variation, Chang et al. (2016) examined the effect of short-term temperature fluctuations in the demand for electricity. Salgado and Pedrero (2008) described the ways of electricity and heat production planning in different time horizons.

Generally, the authors can say that the heat demand depends mainly on the ambient temperature. In the Czech Republic, it varies periodically both in the course of the year and during the day. For heat supply to the industry, specifics of the particular industrial plant play a significant role.

There are reasons why the heat demand may change in a long-time horizon. Heat demand reduction may be caused e.g. by improving of thermal insulation or decentralization of DHS. On the other hand, connection of new customers can increase the demand.

The authors dispose of a complex techno and economic model, used in the design of optimum parameters of an integrated WtEP. Integrated here stands for simultaneous delivery of heat into a common DHS by WtEP and another heat source (e.g. heating plant or gas-fired boiler). In this respect, the main aim of the paper is to analyse, what error occurs while simplifying the model calculated in terms of the length of basic time intervals, where the heat and mass balance and financial incomes and outcomes are calculated. Another object was to estimate the calculation time requirements for models with different time intervals and to discuss about the ideal compromise. Finally, "error-correction coefficients" which allow to increase the accuracy of the model while keeping the monthly calculation interval, are introduced.

In the following section, a DHS used later on in the calculation is described. Consequences of neglect of the heat demand fluctuations at different time levels are identified with use of a simple techno and economic model of integrated WtEP. In the next section, a novel approach employing error-correction coefficients is presented. The effect on model accuracy and computational time is analysed. In the end a much more complex model, which raises other research challenges, is introduced.

2. Used computation data

Heat demand for steam and hot water was assumed in the modelled locality. Real data from existing district heating plant were used and real demand profile during the year, as well as all short-term fluctuations in demand were analysed. The heat demand data are summarized in Table 1. There is a shutdown of the entire heating plant for a period of 58 d in summer. The total annual heat supply is 190 TJ.

Table 1: Heat demand data

Month	1	2	3	4	5	6	7	8	9	10	11	12
Total heat supply [TJ]	31.8	26.7	21.9	14.9	11.8	6.1	0.1	0.6	9.3	15.6	22.0	28.9
Average heat supply [GJ/h]	42.7	39.7	29.4	20.7	15.9	8.4	0.2	0.7	12.9	21.0	30.5	38.9
Standard deviation of hour averages [GJ/h]	10.3	10.8	10.8	7.3	6.1	2.1	1.0	2.3	4.0	9.9	8.9	10.7

Figure 1 shows the demand in one month (April) in more details. The hourly averages, which are considered as the shortest time interval, considerably fluctuate and cannot be overlooked and. neglected when modelling the operation of WtEP. The effect of neglect of these variations will be shown on the following model of an integrated WtEP introduced in the next section.

A simple techno and economic model was created for this integrated WtEP/WtEP depicted in Figure 2. Among others, operation cost for natural gas (7.9 EUR/GJ) and revenues for waste treatment (65 EUR/t) and sold power (45.5 EUR/MWh) and heat (7.5 EUR/GJ) are taken into account. The main result from the model is annual profit. The WtEP of the small capacity of 40 kt/y with a single turbo-generator (TG) and connection to the central heating is considered. The WtEP has an additional gas-fired boiler for topping peaks in demand. Heat demand was modelled using data from the previous section.

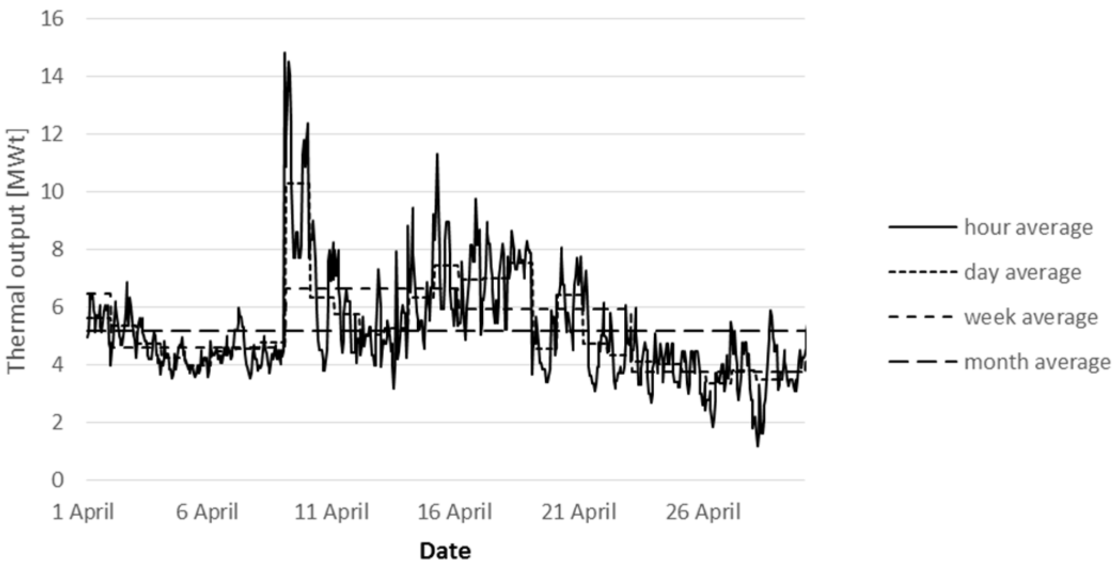

Figure 1: Heat demand on different time intervals in April

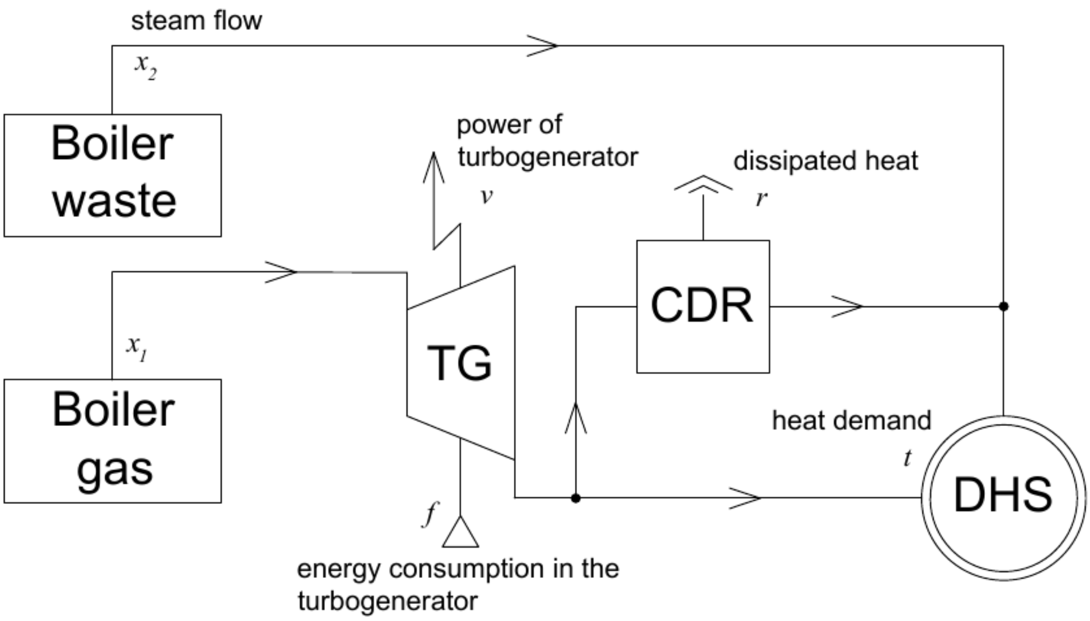

Figure 2: Scheme of WtEP

The waste is incinerated in a furnace. Steam generated in the boiler continues to back-pressure turbo-generator and after that is used for district heating or flows to condenser (CDR) depending on current heat demand. When the demand exceeds the capacity of the boiler, there is a possibility of using a gas-fired boiler. All relations can be described by similar equations like in the paper Janošťák et al. (2016). The results are shown in the following table depending on the length of used time step.

Table 2: Year profit of WtEP

Time step	Hour	Day	Week	Month	Year
Profit [k-EUR]	1,619.9	1,672.7	1,675.8	1,690.8	1,862.4

As can be seen from the results, the biggest leap in calculated profit occurs between hourly and daily time interval. The results between weekly and daily interval approach are not very different. Another leap occurs between approach of weekly and monthly basis.
The results show that it is useful to consider the model on an hourly basis. Due to lack of the data or the complexity of the model (high computational times), it is not always possible. The problem can be partially solved by using error-correction coefficients described in the next section.

3. Error-correction coefficients

There may be different kinds of correction coefficients for different applications. In this case a coefficient, which virtually decreases maximum heat output of the WtEP according to the following Eq(1) was used:

$$P'_{max} = P_{max} \cdot C \tag{1}$$

Where P'_{max} is the plant's corrected maximum heat output, P_{max} is actual maximum heat output and C is the fluctuation coefficient of heat supply (FCHS). The principle of this coefficient is explained in Figure 3. An extreme case is shown, since the maximum thermal output from the WtEP corresponds to the average monthly demand, so the influence of the peaks is highest. The figure shows real satisfaction of the heat demand by both WtEP and gas-fired boiler. The WtEP with a maximum thermal output P_{max} of 5.22 GJ/h (corresponding to the capacity of 10 kt/y, lower heating value of waste 9 MJ/kg and boiler efficiency 80 %) will supply in total 3.26 TJ of heat. The remaining heat (0.5 TJ) has to be supplied from the gas-fired boiler with more expensive operating costs. These values, i.e. 3.26 TJ and 0.5 TJ (areas above and bellow P_{max} line) must be maintained as much as possible while using a simplified model on a monthly basis. This is achieved by using FCHS with value of 0.87. This means, that the maximum heat output after the correction P'_{max} equals 4.54 GJ/h. The use of FCHS allows performing the calculation on a monthly basis, while maintaining real heat supply potential.

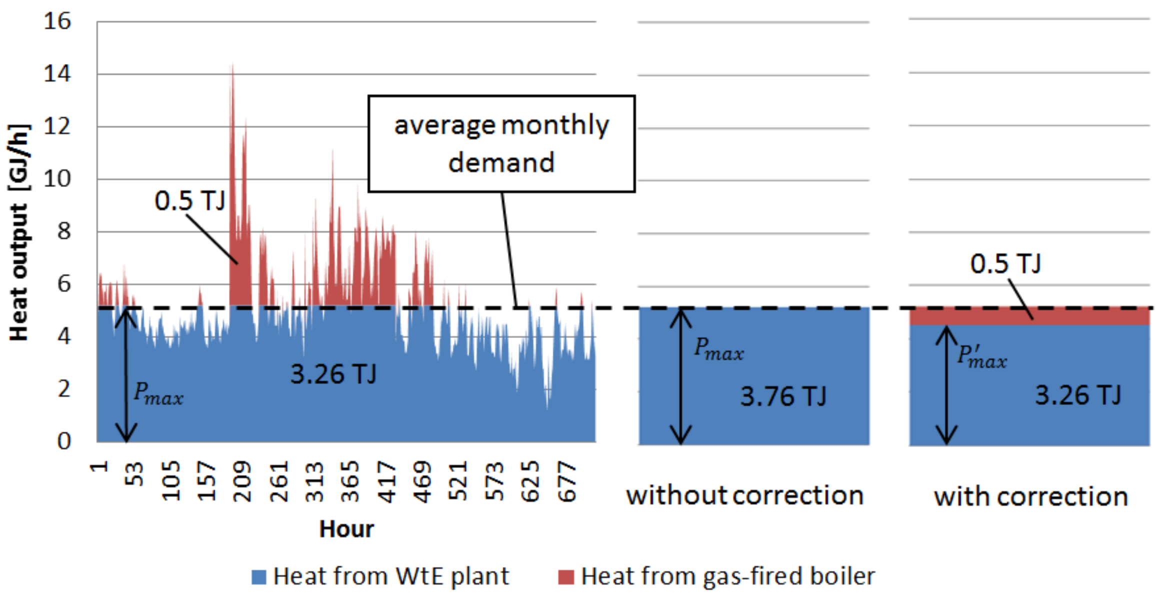

Figure 3: The principle of error-correction coefficients

The example shows, that without using the FCHS the heat supply would be by 15.4 % higher than in reality. In other words, there will be a need of satisfying of 13.3 % of heat supply from another heat source, which worsens the economy contrary to expectations. If the calculation would be performed on a weekly or daily basis, the error would be reduced to 4.4 % or 2.2 %.
In similar way, C may be defined for various months and capacities of WtEP. A dependence of FCHS on a ratio of average monthly heat demand and maximum heat output of the plant P_{max} was found.
The values of individual FCHS obtained from actual operational data of seven existing heating plants in the Czech Republic are shown in Figure 4. Their dependence on the mentioned ratio with linear approximation is shown. FCHS for the assessed locality (see Table 1) are highlighted.

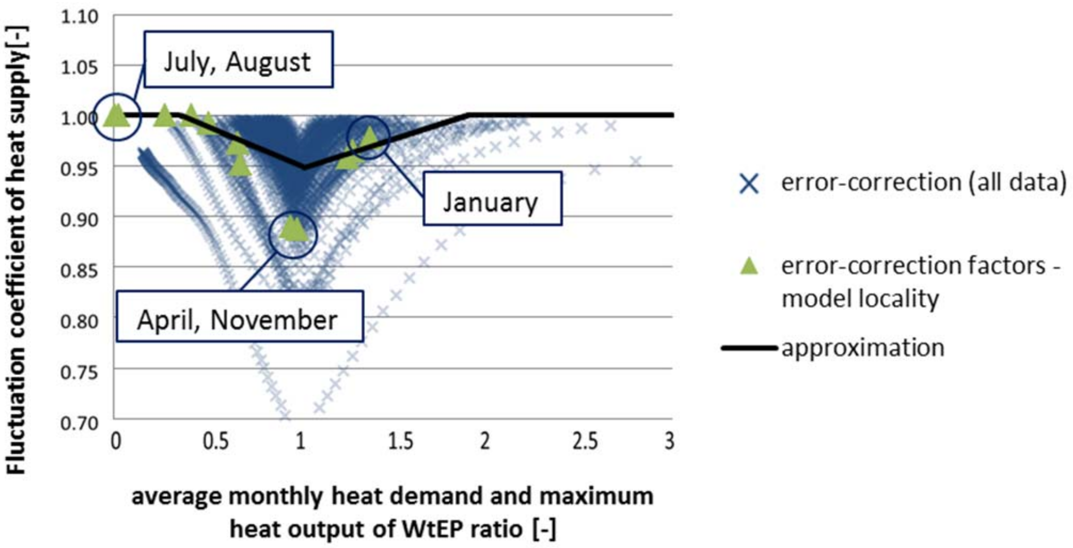

Figure 4: Fluctuation coefficient of heat supply

The calculation of the model described in section 2 was performed once again with the data on monthly basis. This time FCHS were employed. The calculated annual profit was 1,643.3 EUR, which corresponds to the accuracy of hourly or daily basis calculation (see Table 2).

4. Techno and economic model of complex Integrated system

Many new construction projects WtEP are currently planned in the Czech Republic. In terms of capital and operational costs the construction of WtEP by existing heating plants is favourable because of possibility of use of existing technology or employees sharing and proximity of DHS. Therefore, we consider cooperation between WtEP and combined heat and power plant (CHPP) in the following example meaning much more complex model.

In the model example, the construction of WtEP with low processing capacity was considered in a locality with both steam and hot water DHS described in the previous section. Part of the heat supply is taken by WtEP, and operating cost savings for existing heating plant arises, which would be reflected in the price of heat supplied from WtEP. The used model and description of the site were presented by Janošťák et al. (2016). The primary source of heat is CHPP plant with two coal-fired fluidised-bed boilers and two steam turbines TG1 and TG2. A possibility of heat supply from WtEP directly into hot water or steam distribution is considered, the steam can be alternatively used to drive TG2 in so-called “summer mode”.

The main income affecting the economy of WtEP projects include incomes for waste processing (65 EUR/t) and sale of heat (7.5 EUR/GJ). The key outcome of the model is profit of WtEP in optimal mode of operation (same as the mentioned model). In general, optimization of operation of cogeneration systems was dealt by Narang et al. (2017) or Nazari-Heris et al. (2017).

The original model, published by Janošťák et al. (2016), has worked on a monthly basis, i.e. 12 time intervals were considered to describe operation during the year. Recasting the model to an hourly basis led to insolvability. In simplicity, it becomes so large MILP problem (over 420,000 binary variables). Therefore, few simplifying changes are made.

- Capacity of WtEP determined before calculation (fixed capacity)
- Power output as a function of steam throughput on TG1 and TG2 was described by linear equation
- Binary variables were removed, i.e. model was decomposed into the subtasks (winter mode with CHPP on, winter mode with CHPP off, summer mode with CHPP on, summer mode with CHPP off)

Individual subtasks have linear character. The ideal operating conditions are determined by analysing the results of individual subtasks. Simplification and only one month considered allowed the calculation to be performed on hourly basis. Results for different time intervals are shown in the following Table 3.

The results show that fluctuations in hourly demand are very important also in this case. For accurate estimates they should be included in the model. However, the computational time is enormous and its limits the model applicability for real case studies. Consequently month interval revels as reasonable compromise, when similar corrections as mentioned in section 3 are implemented.

Table 3: Profit of WtEP in April and calculation time

Model time interval	Hour	Day	Week	Month	Year
Profit per month [thous. EUR]	165.6	180.4	178.1	186.7	193.2
Computational time [s]	Over 1,500	51.9	9.7	5.4	5.4

5. Conclusions

The influence of short-time fluctuations of heat demand on accuracy of techno and economic models was analysed in this paper. The differences among obtained results (profit of the plant) were compared using two models. The first one was a simple model of WtEP and peak-time gas-fired boiler. The second one was a complex model of integrated WtEP and CHPP. The most accurate input data on hourly basis was replaced by daily, weekly, monthly or yearly averages. This measure is often necessary, because computational time would be untenable.

There are several reasons, why neglect of the fluctuations distorts the results. The first one is represented by peaks of heat demand. These peaks must be satisfied from another heat source. On the other hand, the dips mean decrease of the applicable heat and cause reduction of heat recovery potential. This problem can be partially eliminated by applying FCHS, which was introduced in section 3. Through FCHS the accuracy of the model was significantly improved.

Another reason is the possibility of shutdown of additional heat source with certain minimum performance (heating plants, gas-fired boiler etc.) when heat demand is low enough. If the calculation is performed on monthly basis, the shutdown is not usually proposed for proper period. Further off, for instance when a peak heat source is sized, maximum heat demand is important. This aspect is neglected again if monthly averages are used. These examples indicate that other “error-correction coefficients” can be effectively used, which will be a part of future work in this area.

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