Energy 90 (2015) 137–147

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Combined heat and power production planning in a waste-to-energy plant on a short-term basis

Michal Touš [a, *], Martin Pavlas [a], Ondřej Putna [a], Petr Stehlík [a], Lukáš Crha [b]

[a] Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology (UPEI VUT), Technická 2896/2, 616 69 Brno, Czech Republic
[b] Pražské služby a.s. - ZEVO, Průmyslová 615/32, 10800 Praha, Czech Republic

ARTICLE INFO

*Article history:*
Received 24 December 2014
Received in revised form
15 May 2015
Accepted 24 May 2015
Available online 30 June 2015

*Keywords:*
Waste-to-energy
Short-term
Combined heat and power
Black-box modelling
Planning
Stochastic simulation

ABSTRACT

In many cases, WtE (waste-to-energy) plants are CHP (combined heat and power) producers. They are often integrated into a central heating system and they also export electricity to the grid. Therefore, they have to plan their operation on a long-term basis (months, years) as well as on a short-term basis (hours, days). Simulation models can effectively support decision making in CHP production planning.

In general, CHP production planning on a short-term basis is a challenging task for WtE plants. This article presents a simulation based support. It is demonstrated on an example involving a real WtE plant. Most of the models of relevant WtE sub-systems (boilers, steam turbine) are developed using operational data and applying linear regression and artificial neural network technique. The process randomness given mainly by fluctuating heating value of waste leads to uncertainty in a calculation of CHP production and a stochastic approach is appropriate. The models of the sub-systems are, therefore, extended of a stochastic part and Monte-Carlo simulation is applied.

Compared to the current planning strategy in the involved WtE plant, the stochastic simulation based planning provides increased CHP production resulting in better net thermal efficiency and increased revenue. This is demonstrated through a comparison using real operational data.



## 1. Introduction

This work was motivated by the need to improve how energy is managed in a plant for energy recovery from waste, also called WtE (waste-to-energy). Greater efficiency and increased revenue are the two goals for improving the planning of energy production in the plant. In this contribution, we present a planning approach based on black-box modelling and sequential stochastic simulation.

The WtE facility concerned in this paper is located in Prague, the Czech Republic. Its simplified flow-sheet is in Fig. 1. Its processing capacity is 300 kt/y. It was put into operation in 1998 and consists of four lines with a processing capacity of 15 t/h of waste per line. The corresponding production of steam in one boiler is 36 t/h at a pressure of 1.37 MPa and temperature of 235 °C. Since the WtE facility was originally assumed to deliver heat only for a DHS (district heating system), the steam parameters at the boiler outlet were designed specifically with this in mind. No steam turbine was installed in its original arrangement and so it was run without electricity production. Although the facility was a minor heat supplier within the DHS, the lack of heat demand, especially during the summer, caused its limited performance.

In 2009, the plant underwent massive modernization. Its flue gas treatment system was expanded with DeNOx/DeDiox technology, which is a combined process for the catalytic removal of nitrogen oxides and dioxins from flue gas [1]. At the same time, a new condensing steam turbine, with a nominal output of 16 MW, with one uncontrolled extraction was installed. Since then, it has been simultaneously producing heat and electricity, i.e. it became a CHP (combined heat and power) producer. However, there were no changes implemented on the boilers to increase steam parameters. Regarding the current state-of-the art, the steam parameters are low compared to other WtE plants. Typical values for a plant of this type are 4 MPa and 400 °C or more [2]. In addition to heat from CHP production, there is also a live steam supply as a utility for

* Corresponding author. Tel.: +420 541 144 961.
*E-mail addresses:* tous@fme.vutbr.cz (M. Touš), pavlas@fme.vutbr.cz (M. Pavlas), putna@upei.fme.vutbr.cz (O. Putna), stehlik@fme.vutbr.cz (P. Stehlík), crha@psas.cz (L. Crha).

http://dx.doi.org/10.1016/j.energy.2015.05.077

**Nomenclature**

*Variables*

| | |
|---|---|
| $m_{st}$ | steam production in boilers (t/h) |
| $\Delta m_{st}$ | an increment in steam production in boilers (t/h) |
| $\Delta m_{st,\ max}$ | a reference value for a decision if an increment in steam production is large or not (t/h) |
| $m_{st,\ bo}$ | the flow rate of steam for boilers' blow off (t/h) |
| $m_{st,\ da}$ | the flow rate of steam to deaerator (t/h) |
| $m_{st,\ ec}$ | the flow rate of steam to external consumer (t/h) |
| $m_{st,\ TG}$ | the flow rate of steam to the steam turbine (t/h) |
| $m_{st,\ bp}$ | the flow rate of by-passed steam (t/h) |
| $m_{st,\ ex}$ | the flow rate of extraction steam (t/h) |
| $m_{st,\ ex,\ DHS}$ | the flow rate of steam for district heating (t/h) |
| $m_{st,\ ex,\ sc}$ | the flow rate of steam for self-consumption (t/h) |
| $p_{st,\ ex}$ | the pressure of extraction steam (kPa) |
| $T_{st,\ ex}$ | the temperature of extraction steam (°C) |
| $T_{st,\ ex\ +\ bp}$ | the temperature of extraction and by-passed steam mixture (°C) |
| $T_{min}$ | the minimum temperature required at the inlet of the district heating heat exchanger (°C) |
| $h_{st,\ ex}$ | the specific enthalpy of extraction steam (kJ/kg) |
| $h_{st}$ | the specific enthalpy of steam produced in the boilers (kJ/kg) |
| $h_{st,\ ex\ +\ bp}$ | the specific enthalpy of extraction and by-passed steam mixture (kJ/kg) |
| $h_{st,\ ex/ex\ +\ bp,\ T\ =\ 70\ ^{\circ}C}$ | the specific enthalpy of condensate at the outlet of the district heating heat exchanger with the outlet temperature of 70 °C (kJ/kg) |
| $W_{TG}$ | steam turbine electricity output (MW) |
| $W_{TG,\ exp}$ | electricity export (MW) |
| $W^{0}_{TG,\ exp}$ | calculated electricity export with zero by-pass and planned heat delivery (MW) |
| $Q_{DHS}$ | heat delivery to a district heating system (MW) |
| $Q_{st,\ TG\ +\ bp}$ | heat content in steam before by-pass (MW) |
| $\mu_{th}$ | net thermal efficiency (%) |
| $d$ | drift of mean (t/h) |
| $\xi,\ \omega$ | random numbers (−) |

*Superscript*

| | |
|---|---|
| $t$ | time parameter |

*Parameters*

| | |
|---|---|
| $H$ | hour in a day |
| $D$ | day in a week |
| $NB$ | number of boilers in operation |

*Abbreviations*

| | |
|---|---|
| WtE | waste-to-energy plant |
| CHP | combined heat and power |
| DHS | district heating system |
| MC | Monte-Carlo simulation |
| PC | plan confidence |
| LR | linear regression model |
| ANN | artificial neural network model |
| LHVW | lower heating value of waste |
| FRW | the waste flow rate |
| MAE | mean absolute error |
| MRAE | mean relative absolute error |

industrial heating. This steam is supplied according to current demand which is not regular and is difficult to predict.

The new plant arrangement brought with it more flexibility but, at the same time, an increased need for energy management. CHP production is governed by contracts on heat and electricity delivery. These contracts specify things such as amount of heat/electricity, prices, penalties, and so on.

The amount of heat delivered in a year is specified and then distributed into months (higher in winter, lower in summer). A month's delivery is uniformly distributed into days in the month and a day's delivery uniformly into hours. A delivery deviation within a specific range from the planned amount is feasible (given by a contract), otherwise there are penalties.

Furthermore, the facility has a contract on electricity delivery. The electricity is offered to a retailer, after which, the retailer takes it to the electricity market. The same rule of delivery deviation from the planned amount holds. The electricity delivery has to be kept within a specific range from the planned amount, otherwise there are penalties.

The contract's conditions, together with WtE plant's actual performance, govern the planning of heat and electricity delivery on an hourly basis for the next day. The goal of planning is to prepare a balanced production plan where the plant's performance is maximized from an economic point of view. To summarise, the plant's efficiency and risk of not-meeting the plan should be addressed at the same time.

In general, WtE heat and electricity planning is a challenging task, especially due to inhomogeneous waste. The properties (composition and lower heating value) fluctuate over the time. In addition, the WtE plant delivers live steam to the external consumer. However, the steam demand is strongly irregular and significantly contributes to uneasy operation planning. The external consumer is a facility producing dairy products and the irregularity is due to variable production.

Considering the operation of a WtE plant in general, there are three situations which may occur in relation to a proposed production plan (see Fig. 2):

- First, a plan underestimates a plant's actual performance, the amount of steam leaving the boiler house and entering the turbine house is higher than expected. More heat and power could be produced. Penalties are accepted and/or part of energy has to be wasted to meet the plan (e.g. turbine bypassing or heat releasing into environment). This leads to a financial loss or loss in CHP efficiency, respectively.
- Second, a plan overestimates a plant's performance. This may cause an inability to satisfy the planned delivery which leads to penalties or high operation cost by utilizing natural gas to increase steam production.
- Third, a plan reflects a plant's actual performance within common fluctuations, which leads to an uncomplicated operation with maximized financial effect and CHP production.

Clearly, a balanced plan represents an ideal situation and is preferred whenever possible. Underestimating represents a conservative approach and overestimating may be observed when an unexpected drop in steam production appears. We want to avoid underestimating and overestimating as much as possible.