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Effective biomass integration into existing combustion plant

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Fossil fuels such as coal still dominate in current energy production plants. However due to large carbon footprint, rising prices and unclear availability of fossil fuels, increasing interest in renewable and alternative fuels is observable. The optimization approach introduced in this paper supports sustainable biomass-based fuels integration into existing large energy system. The plant involved in the case study produces approximately 3400 TJ of heat and 460 GWh of power per annum. It secures delivery of heat to residential areas, public institutions and industrial enterprises. There are three boilers installed in the boiler house and two of them are fired by coal and biomass.
By implementing mid-term operation planning (one year, time step of one month) procedure the conditions for effective biomass utilization are identified first (optimum amount of fuels burned in every boiler with maximum profit with respect to export limitation).
The plant model was built using real operation data and therefore is supposed to be as close to real plant as possible. A limited resource of various types of biomass over a year represents typical inventory type constraints and makes the problem multi-period. Since some of the transformation functions (e.g. input-output model of boiler and turbine) in the model are nonlinear, it is non-linear programming problem (NLP).
The model is implemented in GAMS (General Algebraic Modeling System) optimization tool and solved using included solvers for NLP problems (MINOS, CONOPT). Excel interface was developed for user-friendly and comfortable work with GAMS and better result presentation. Sensitivity analysis of parameters such as fuel prices, etc. is performed and results are presented and discussed.

1. Introduction

In the recent years, the use of renewable energy sources (RES) has been discussed a lot. The use of fossil fuels has a negative impact on the environment due to mining, processing and pollutants released during their combustion. Moreover, fossil fuels are not inexhaustible. Utilization of RES is the option to partially reduce dependence on fossil fuels. By 2020, renewable energy should account for 20 % of the EU's final

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energy consumption in order to reduce CO_2 emissions and other negative impacts on the environment. Co-firing fossil and biomass-based fuels represents a low-cost, short-development-time method (compared to other renewable options) how to achieve this target (Baxter 2005). The important factors are technical potential, biomass availability and last but not least economy related aspects.
Works dealing with minimizing the environmental impact of biofuels supply chain have been recently published (Lam et al. 2009). This paper contributes to research on economically effective biomass utilization in combustion plants and is related to previous works of Drápela et al. (2009) and Popela et al. (2009). The optimization procedure proposed supports decisions related to substitution of fossil fuels with renewable and alternative fuels in mid-term horizon in energy producing systems. Many papers deal with optimal operation planning for energy systems, e.g. Oh et al. (2007), but only few of them consider biomass co-firing, e.g. Ko and Chang 2008.

2. General mathematical model

The objective was to design general mathematical model of a plant utilizing more fuels (one primary fossil an few other biomass-based). The model is based on the analysis of a real heating plant in the Czech Republic but is also applicable for other plants. There are five sets representing key parts of the model.
The set of periods T may include months in a year, years 2010 up to 2020, etc. The set of fuels J includes all types of fuels that are used in operation such as coal, wood chips and other biomass-based fuels. Elements of the sets of boilers K and turbines I are obvious. The set of energy types M contains just two elements: electricity and heat. According to the particular needs, subsets of these basic sets, that will define more specific area of the elements of the basic sets, may be created.

2.1 Boilers

The key parts of the boiler model are depicted in Tab. 1. The first step is evaluation of calorific value of the fuels using vector function $\mathbf{u} = \mathbf{f}(\mathbf{x}, \boldsymbol{\xi})$. Then the energy transferred to water/steam is evaluated using vector function $\mathbf{v} = \mathbf{g}(\mathbf{u}, \boldsymbol{\eta})$. The process of steam production has to be supplied with constrains representing fuels availability and boiler

Table 1 Overview of key components

Denote	Description
$\mathbf{x} = (x_{j,k,t})_{j\in J, k\in K, t\in T}$	amount of fuels introduced into each boilers in each period
$\boldsymbol{\xi} = (\xi_{j,t})_{j\in J, t\in T}$	lower heating value of fuels in each period
$\mathbf{u} = (u_{j,k,t})_{j\in J, k\in K, t\in T}$	calorific value of fuels in each boiler and each period
$\boldsymbol{\eta} = (\eta_k)_{k\in K}$	thermal efficiency of each boiler
$\mathbf{v} = (v_{j,k,t})_{j\in J, k\in K, t\in T}$	energy transferred into water/steam in each boiler and period
$\mathbf{a} = (a_{j,t})_{j\in J, t\in T}$	available amount of fuels
$\mathbf{b} = (b_{k,t})_{k\in K, t\in T}$	boiler capacity

capacity $\sum_k x_{j,k,t} \le a_{j,t}$ a $\sum_j u_{j,k,t} = b_{k,t}$.

Turbines

The key parts of the turbine model are depicted in Tab. 2. The first step is the evaluation of the energy transported (in the form of steam) from boiler house to turbine house $\sum_j \sum_k v_{j,k,t} = \sum_i w_{i,t}$. Energy production is represented by vector function $\mathbf{y} = \mathbf{h}(\mathbf{w}, \boldsymbol{\gamma})$. Waste heat and energy losses are calculated using expression $w_{i,t} = \sum_m y_{i,m,t} + y^-_{i,t}$. There are also constrains on turbines: turbine capacity $w_{i,t} \le c_{i,t}$ and operation area of the turbine $o\left(y_{i,m=teplo,t}\right)_i \le y_{i,m=electricity,t} \le p\left(y_{i,m=teplo,t}\right)_i$.

Table 2 Overview of key components

Denote	Description
$\mathbf{w} = \left(w_{i,t}\right)_{,i\in I,t\in T}$	energy (in the form of steam) on turbines in each period
$\boldsymbol{\gamma} = (\gamma_i)_{,i\in I}$	thermodynamic efficiency of each turbine
$\mathbf{y} = \left(y_{i,m,t}\right)_{,i\in I,m\in M,t\in T}$	energy produced on each turbine in each period
$\mathbf{y}^- = \left(y^-_{i,t}\right)_{,i\in I,t\in T}$	waste heat and energy losses
	turbine capacity
$\mathbf{up} = \left(o(y_{i,m,t})_i\right)_{,i\in I,m=heat,t\in T}$	vector of functions *o* representing upper bound function of turbines operation area
$\mathbf{lo} = \left(p(y_{i,m,t})_i\right)_{,i\in I,m=heat,t\in T}$	vector of functions *p* representing lower bound function of turbines operation area

3. Optimization

The optimization of a plant operation can be performed using the model. The objective is to find optimal operation plan providing maximal profit. The objective function consists of:

incomes from:

- heat and electricity export
- subsidies for electricity from renewable energy sources (RES-E)
- CO_2 allowances trading
- bonus on electricity from cogeneration (CHP)

costs of:

- fuel purchasing
- ash disposal
- flue gas desulphurization

The government subsidies for RES-E and cogeneration bonus are governed by national legislation harmonized with EU directives on renewable energy and cogeneration.
The decision variables representing operation parameters are:

- amounts of fuels introduced into every boiler $\mathbf{x} = \left(x_{j,k,t}\right)_{,j\in J,k\in K,t\in T}$
- heat and electricity production $\mathbf{y} = \left(y_{i,m,t}\right)_{,i\in I,m\in M,t\in T}$

4. Case study

The case study has been done using data from a real heating plant in the Czech Republic. The plant provides heat and electricity to residential areas, public institutions and industrial enterprises. Block diagram of the heating plant with process streams is shown in Fig. 1. An overview of key components of the heating plant is depicted in Tab. 3. Biomass-based fuels are introduced in boiler houses II and III with technical limit 10 % by mass flow rate and 40% by heat content respectively.

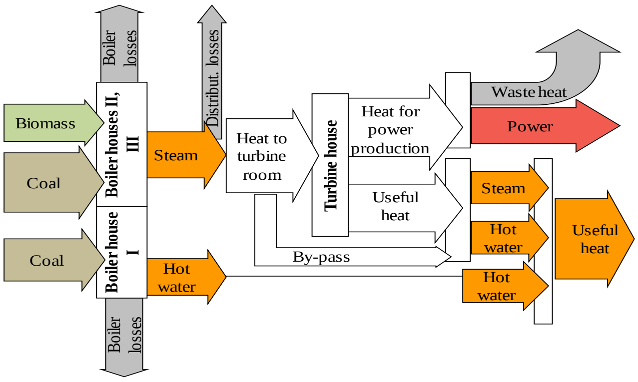

Figure 1: Block diagram of the heating plant

Table 3 Overview of key components

Component	Description
Boiler house I	2 hot-water boilers with capacity 35 MW
Boiler house II	2 granulation powder steam boilers with capacity of 128 MW each
Boiler house III	1 fluidized bed steam boiler with capacity of 135 MW each
Turbine house	1 back-pressure turbine 70 MW, 1 condensing extraction turbine 67 MW

There are six biomass-based fuels available in the plant's location and assumed in the case study: wooden chips, spent grain (residue from beer production), sugar beet pulp (residue from sugar production), rape-cake and sunflower-cake (both residues from oil production), and fine bark (residue from mulch bark production).

The objective is to find optimal amounts of fuels utilized in this heating plant all year round regarding maximum annual profit with respect to heat and electricity demand (Fig. 2). The most important factors are the economic ones: fuels prices (see Fig. 3) and level of subsidy for RES-E. The level is the same for the most considered biomass-based fuels excepting the fine bark, for which it is 14 times lower. Fuels' availability limit has to be considered as well (see Fig. 3). The results of the optimization are shown in Fig. 4. Biomass-based fuels are preferred mainly in cold months. It is due to calculation of RES-E according to legislation in the Czech Republic, where the waste heat extracted from turbine condenser negatively influences biomass-based fuels profitability. Increased use of condensing turbine in summer months means less RES-E calculated.

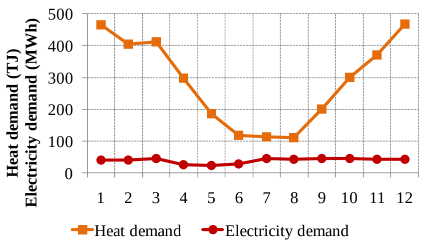

Figure 2: Heat and electricity demand

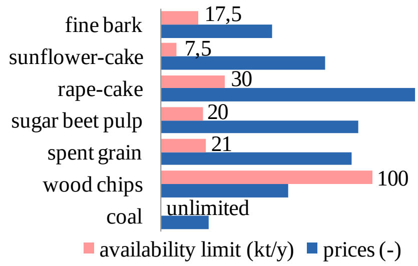

Figure 3: prices and availability limit of fuels

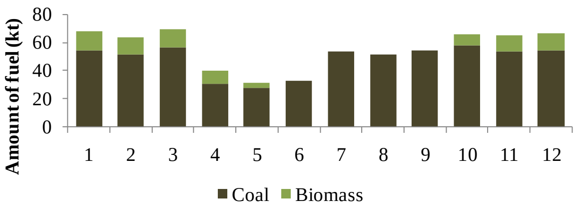

Figure 4: Optimal amount of fuels

To investigate the influence of some economic parameters the sensitivity analyses have been performed. Currently, biomass-based fuels are more expensive than coal. Due to limited coal reserves in the Czech Republic the coal price is expected to increase. Therefore influence of coal price on fuels utilization has been investigated. Results are summarized in Tab. 4.

Table 4 The fuels utilization for increased coal prices (CP – current price of coal)

	CP	1.44·CP	1.89·CP	3.33·CP	3.89·CP
Coal (kt/y)	580	532	504	454	450
Wooden chips (kt/y)	80	80	80	80	80
Spent grain (kt/y)	0	20	21	21	21
Sugar beet pulp (kt/y)	0	0	20	20	20
Rape-cake (kt/y)	0	0	0	18	20
Sunflower-cake (kt/y)	3	7.5	7.5	7.5	7.5
Fine bark (kt/y)	0	17.5	17.5	17.5	17.5

Considering current coal price (see column CP), wooden chips and sunflower-cake are beneficial. As the coal price increases other biomass-based fuels get beneficial as well. When the coal price is 1.89 times higher, then spent grain, fine bark and sugar beet pulp are utilized. Rape-cake gets beneficial only when the coal price is much higher than current price. Since biomass is more expensive than coal its utilization for purposes of energy production has to be financially supported. Therefore influence of level of subsidy for RES-E on fuels utilization has been investigated. Results are summarized in Tab. 5. When the level of subsidies reaches up to 150 % of current level only wooden chips and sunflower-cake are beneficial. Further increase makes the spent grain and sugar beet pulp profitable. However, increasing the current level of subsidy twice is still not enough to make rape-cake and fine bark beneficial.

Table 5 Fuels utilization for increased level of subsidy for RES-E (CL - current level)

	1·CL	1.3·CL	1.5·CL	1.7·CL	2·CL
Coal (kt/y)	580	577	573	548	531
Wooden chips (kt/y)	80	80	80	80	80
Spent grain (kt/y)	0	0	0	18	21
Sugar beet pulp (kt/y)	0	0	0	0	11.5
Rape-cake (kt/y)	0	0	0	0	0
Sunflower-cake (kt/y)	3	7.5	7.5	7.5	7.5
Fine bark (kt/y)	0	0	0	0	0

5. Conclusion

The mathematical model of a heating plant and optimization procedure with the objective of maximum annual profit has been proposed. The optimization has been performed to find optimum amounts of fuels used during the year. Then sensitivity analysis has been performed to investigate influence of coal prices and level of subsidy for RES-E.

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