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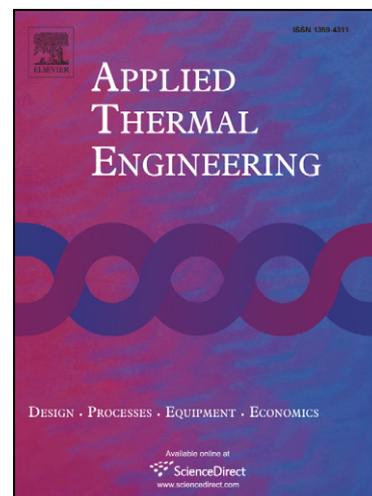
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# Energy Saving Opportunities in Heat Integrated Beverage Plant Retrofit

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## Abstract

This paper presents practical applications of mathematical programming for energy integration in a large beverage plant. The opportunities of heat integration between batch operations were analysed by a Mixed Integer Linear Programming (MILP) model, which was slightly modified by considering specific industrial circumstances. The feasibility of combined electricity, heating and cooling production was studied using a simplified MILP model, developed for the selection of an optimal polygeneration system. The superstructure includes cogeneration systems with different prime movers (steam turbine and gas turbine), and a trigeneration system with a back-pressure steam turbine. The proposed heat integration scheme and the selected cogeneration system may improve a company's economic performance and reduce its environmental impact.

**Keywords:** heat integration, polygeneration, batch processes, retrofit, industrial application.

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## 1. Introduction

The current drive towards environmental sustainability and the rising costs of utilities has forced process industries to search for additional opportunities regarding energy savings in existing plants, by using process integration. This includes heat integration of existing operations as well as installation of more efficient systems for the production of several energy forms, from a single primary energy source.

Earlier heat integration studies of batch processes relied on methods developed for continuous processes. The Time Average Model assumes that the streams exist simultaneously as if the process were continuous, i.e. the time schedule is ignored and the heat flows are averaged over the batch cycle time [1]. The time dependence of batch processes is included in later studies, by dividing the time horizon into time intervals [2]. Time Pinch Analysis treats time as the primary constraint, while temperature driving forces are treated as secondary constraints [3]. The concept of Pinch Analysis in combination with energy storage system design was used for thermal integration of batch processes applying time decomposition approach [4]. Lee and Reklaitis [5] developed a mixed integer linear programming (MILP) mathematical model for the maximisation of heat recovery in batch processes involving no intermediate storage (NIS). This model assumes cyclically operated single-product campaigns and one-to-one matches between streams. Further development in the heat integration of cyclically operated batch processes was based on cascade analysis and includes the NIS policy with residence time, in the case of multiple streams matching [6]. Mathematical model for detailed design of multipurpose batch process facilities was developed as MILP program with incorporated heat integration [7]. The continuous-time mathematical formulation was used for

optimization of direct heat integration in cases of variable and fixed batch sizes [8]. A mathematical programming approach based on the superstructure was developed for design and optimization of indirect thermal storage systems in order to minimize the consumption of external utility [9]. An evolutionary process integration technique was developed for synthesizing a cost optimal heat exchanger network for batch processes including minimum unit targeting [10]. In general, mathematical models assume that the production scheduling is known and optimal. In open literature, a small number of articles consider the scheduling and heat integration in batch processes, simultaneously [11].

On the other hand, a great number of articles deal with the design and analysis of polygeneration systems [12-17], along with their influence on the environment [18, 19]. International projects, e.g. EDUCOGEN, OPTYPOLYEN etc., provide valuable information about technical data, the production parameters of polygeneration systems, and the data bases of existing polygeneration systems [20]. Combined heat and power integration in batch and semi-continuous processes was also presented in the literature [21] including a general procedure for utility generation and utility system design optimization by means of mixed integer nonlinear programming problem (MINLP).

In this paper, a large beverage plant has been studied in order to analyse the possibilities: 1) of heat integration between batch operations in order to maximize heat recovery and, 2) installation of a polygeneration system in order to produce electricity, and heating and cooling at the site. In order to achieve the first goal, a MILP mathematical model for the heat integration of batch processes [5] was applied and

slightly modified, in order to fit with specific industrial conditions. Secondly, a simplified MILP model was developed for selection between several polygeneration options.

## **2. Heat integration retrofit**

MILP formulation for the heat integration of cyclically operating single-product campaigns, with nonzero holding time and no intermediate storage [5] was chosen as a basic mathematical model. Cocurrent contacting was assumed between the batch units as in the process under study, the batches must remain in their tanks during heat exchange. This article assumes the reader is familiar with the basic model and, therefore, only the modifications of this model are briefly described in the next section.

### **2.1. Mathematical model for heat integration retrofit**

Selected MILP formulation determines the operating schedule for maximum heat integration between the batch units. Heat integration is performed simultaneously by rescheduling the initial operating schedule, which is determined by the linear programming problem. The minimum cycle time without considering heat integration is the upper bound for the cycle time of the final schedule. This enables an adjustment of the schedule of batch processes without increasing the production time. The selected model was applied almost straightforwardly for retrofitting the existing process, only three small modifications were introduced.

## a) Operations without heat transfer

Several operations in the studied plant are carried out without temperature change (e.g. lautering process). These operations were included in the model along with the heat transfer operations, in order to fit the existing operating schedule.

## b) One-to-two matches

In the process under study, heat integration is desired between one unit operating in an in-phase manner and several other units. As the basic model allows only one-to-one matches, the option of multiple integration of such units was introduced by dividing the operation into two out-of-phase stages inside the in-phase stage, as shown in Figure 1.

The ending time of the first out-of-phase operating unit,  $t_{E_{i,j+1}}$  /h, is equal to the input time of the second one,  $t_{I_{i,j+2}}$ . They are defined by equation:

$$t_{I_{i,j+2}} = t_{I_{i,j+1}} + t_{P_{j+1}} = t_{E_{i,j+1}} \quad i = 1, \dots, N; \quad j \in J_{IP} \quad (1)$$

where  $t_{I_{i,j+1}}$  /h is the starting time at which batch  $i$  enters out-of-phase unit  $j+1$ ,  $t_{P_{j+1}}$  /h is the fixed processing time of out-of-phase unit  $j+1$ ,  $N$  is the number of batches over which heat integration is considered, and  $J_{IP}$  is a set of input streams of the first units on in-phase stages. In the case studied brewery, vapour generation during boiling process represents such in-phase unit. One part of vapour stream is used for preheating the next batch through thermal storage system while the unused part is rejected despite of its heating potential. Vapour generation was thus divided into two out-of-phase operations. Heat integration opportunities of unused vapour stream were explored by including Eq. 1 into original mathematical model for cocurrent heat exchange.

## c) Economic objective function

In the basic formulation [5], the objective function is defined as a fraction of the utility savings to the utility required per individual batch without heat integration. In order to introduce an economic trade-off between the utility savings and investment costs of the heat exchanger's area, the objective function was transformed into a net present value function which includes annual savings in utility costs, and the annual investment cost of the heat exchangers.

The area of the heat exchanger is defined by equation:

$$A_{j,k} \geq \frac{\phi_{i,j,k}}{U_{j,k} \cdot \ln T_{j,k}} \quad (2)$$

where  $\phi_{i,j,k}$  /kW is the amount of heat exchange between unit  $j$  in  $i$ -th batch and unit  $k$  in the first batch,  $A_{j,k}$  /m<sup>2</sup> is the heat exchange area,  $U_{j,k}$  /kW/(m<sup>2</sup>·K) is the overall heat transfer coefficient, and  $\ln T_{j,k}$  /K is the logarithmic mean temperature difference [22].

In the retrofit study, the existing process places some additional restrictions on the predicted matches. The calculated heat exchange area is limited by the size of the production vessel on which a jacket or half-pipe coil jacket could be installed.

$$A_{j,k} \leq A^{\text{VESSEL}} \quad (3)$$

where  $A^{\text{VESSEL}}$  /m<sup>2</sup> is the available heat transfer area of the jacketed vessel.

The investment of the heat exchanger is calculated from equation:

$$I_{j,k} = r \cdot A_{j,k} + s \cdot \sum_i Y_{i,j,k} \quad (4)$$

where  $I_{j,k}$  /EUR is investment in heat exchanger,  $r$  and  $s$  are the variable and fixed parameters, respectively, of the heat exchanger investment cost.  $Y_{i,j,k}$  is a binary variable

for existence of match between unit  $j$  in  $i$ -th batch and unit  $k$  in the first batch. The sum of  $Y_{i,j,k}$  in the original model is set to one, therefore, fixed costs are accounted only once. Equation 4 represents linear investment cost approximation which was derived from the regression of the installed cost data obtained by Aspen Icarus [23] for the exchanger area within the range 20 m<sup>2</sup>–60 m<sup>2</sup>.

The differential cash flow of retrofitted solution is defined by equation:

$$F_C = (1-r_t) \cdot \left( P^{\text{HU}} \cdot \sum_{i,j,k} \phi_{i,j,k}^{\text{H}} + P^{\text{CU}} \cdot \sum_{i,j,k} \phi_{i,j,k}^{\text{C}} \right) + r_t \cdot \sum_{j,k} I_{j,k} \cdot \left[ \frac{(1+r_d)^n - 1}{r_d \cdot (1+r_d)^n} \right]^{-1} \quad (5)$$

where  $F_C$ /(EUR/year) is the differential cash flow,  $P^{\text{HU}}$  and  $P^{\text{CU}}$ /(EUR/kW year) are the prices of hot and cold utilities, respectively,  $\phi_{i,j,k}^{\text{H}}$ /kW and  $\phi_{i,j,k}^{\text{C}}$ /kW represent decreases in hot and cold utility consumptions,  $r_d$  is a discount rate,  $n$  is the depreciation period, and  $r_t$  is the tax rate. The objective function,  $F_{\text{obj}}$ , maximizes the net present value of the invested capital for heat integration retrofit:

$$F_{\text{obj}} = -\sum_{j,k} I_{j,k} + F_C \cdot \left[ \frac{r_d \cdot (1+r_d)^n}{(1+r_d)^n - 1} \right]^{-1} \quad (6)$$

## 2.2. Results of heat integration retrofit

In the studied beverage plant, the specific heat consumption per m<sup>3</sup> of beer sold is 1.17 GJ/m<sup>3</sup>. According to the Reference Document on Best Available Techniques in the Food, Drink and Milk Industries [24], the specific heat consumption needs to be within the range 0.85–1.20 GJ/ m<sup>3</sup>, which indicates the need for additional energy savings.

A heat integration study was performed in the brewhouse, which is the largest heat consumer in the plant. Figure 2a presents a block diagram of production in the

brewhouse. Processes in the brewhouse mainly consume heat energy. The mashing process consists of several precisely defined heating and holding steps, during which the starch converts to fermentable sugar. Wort boiling is the largest consumer of heat. The hops and trub are separated from the wort in the whirlpool, and the wort is then cooled down to fermentation temperature. In the studied beverage plant, part of the waste vapour formed during boiling is used for the production of hot water, which is stored in an intermediate storage tank and used for wort preheating in the next batch (dashed line in Figure 2a). The remaining vapour is discharged. Heat released during the cooling process is used to prepare process water for the next batch.

In the first step, data acquisition and adjustment were performed in order to obtain suitable information for the applied mathematical formulation. Each temperature increase was defined as a specific stage. Altogether, the single-product batch process in this study consisted of 19 units, from which three parallel units were used in mixed, in-phase and out-of-phase manner. The minimum cycle time obtained by the linear programming problem was 3.33 h, which coincided well with the existing production (3.75 h to 4 h, depending on the season).

Processes in the brewhouse are based on sensible biotransformations with a precisely defined processing time, and the batches must remain within their vessels during heat exchange. Therefore, in the second step, optimal heat integration was studied using the mathematical model for cocurrent heat exchange, which was accomplished by heating and cooling media. The price of hot utility was  $P^{\text{HU}} = 183$  EUR/kW year and price of cold utility  $P^{\text{CU}} = 63$  EUR/kW year. The variable parameter of the exchanger investment cost was  $r = 91.4$  and the fixed parameter  $s = 7,183$ .

The size of the applied MILP model was app. 6,700 constraints, 5,000 continuous variables and 1,200 binary variables. The model was solved by GAMS solver Cplex [25], using 1 s of CPU time at the PC (P4, 2.6 GHz and 512 MB RAM). The integrality gap was 7.69 %.

Two matches were predicted by the optimization model: 1) heating the adjunct mash by the waste vapour produced during boiling and 2) heating the mash by the heat released during wort clarification in whirlpool (dotted lines in Figure 2b). The heat exchange of the first match can be accomplished by a half-pipe coil jacket on the adjunct mash tun. This would result in utility savings of 434,690 EUR/year. The required heat exchange area was estimated to be 59 m<sup>2</sup>, and the corresponding investment cost amounted to 12 590 EUR. The net present value is positive at discount rate of 10 %, and the payback period is very low, around 11 days.

The heat transfer of the second match could be accomplished by the heat transfer fluid (water) in the jacketed mash tun, however, the available heat exchange area of the tank's jacket is insufficient for the required heat transfer. The maximum available area would suffice for preheating the mash by hot water, while further heating during processing stage should be accomplished by the steam supplied to the jacketed bottom. The additional utility saving would be 175,471 EUR/year, nevertheless, the second match was rejected by the company, because it can not satisfy the total heat demand of the mashing stage and operation splitting is not allowed. At the moment, low temperature utility produced by whirlpooling can not be used elsewhere during production. An increase in the exchange time is impossible, because rescheduling is disallowed. The final schedule and repeated heat integration pattern are shown in Figure 3.

On the level of the entire company, the overall specific heat consumption would be reduced from 1.17 GJ/m<sup>3</sup> to 1.15 GJ/ m<sup>3</sup> with the proposed heat integration match in the brewhouse. This indicates that high level of heat integration is already achieved in this section, and therefore, it could not contribute significantly to the reduction of overall heat consumption below the upper BAT level. In fact, the actual technology for beer production does not allow significant savings, because the main part of the vapour generated during boiling process is already integrated within the process. Recently, research is under way to analyze heat integration potential in another section of the company, i.e. the packaging area, which should indicate whether specific the heat consumption could be further reduced.

### **3. Polygeneration**

Polygeneration is a combined production of mechanical or electrical, thermal, and cooling energy using the same primary energy source. This enables remarkable energy savings and more efficient operation compared to those systems which produce electricity, heat, and cooling energy, separately. In addition to decreased fuel consumption, polygeneration results in a decrease of pollutant emissions (carbon dioxide, sulphur dioxide, and oxides of nitrogen). Currently available prime movers for polygeneration systems include: steam turbines, gas turbines, combined cycle gas/steam turbines, reciprocating internal combustion engines, stirling engines, and fuel cells.

#### **3.1. Mathematical model for polygeneration**

The industrial plant being studied produces single product with significant seasonal variations in demand. The plant is a large consumer of low pressure steam which is

produced in a conventional manner (steam boilers). However, there is an intention to produce electricity and cooling energy besides the thermal energy at the site, as the brewery consumes all three.

The superstructure of alternative polygeneration systems (Figure 4) includes a cogeneration with a back-pressure steam turbine at three pressure levels ( $i = 1, 2, 3$ ), and a cogeneration system with back-pressure steam turbine at three pressure levels, and higher heat production during heating season ( $i = 4, 5, 6$ ). In this way, the influence of inlet pressure and steam flow rate on electricity production in the cogeneration system with a steam turbine is taken into account. The model also includes a cogeneration system with a gas turbine ( $i = 7$ ) and a trigeneration system with a back-pressure steam turbine at three inlet pressure levels ( $i = 8, 9, 10$ ). It should be noted that steam production in options  $i = 1-3$  and  $7-10$  should exactly fulfil the current demand of heat in the factory, while the additional production of heat is optimized in the options  $i = 4, 5, 6$  assuming regular demand of external consumers.

The optimal polygeneration system is selected by maximizing the net present value:

$$F_{\text{obj}} = \sum_{i=1}^{10} V_{\text{NP}i} \quad (7)$$

where  $F_{\text{obj}}$  /EUR represents the objective function,  $V_{\text{NP}i}$  /EUR is the net present value of polygeneration system  $i$ . The net present value of alternative  $i$  is calculated by equation:

$$V_{\text{NP}i} = -I_i + F_{\text{Ci}} \cdot \left[ \frac{r_d \cdot (1+r_d)^n}{(1+r_d)^n - 1} \right]^{-1} \quad i = 1, \dots, 10; \quad (8)$$

where  $I_i$ /EUR is investment in polygeneration system  $i$ ,  $F_{Ci}$ /(EUR/year) is differential cash flow. The logical constraint for the selection of optimal polygeneration system is:

$$\sum_{i=1}^{10} Y_i = 1 \quad (9)$$

where  $Y_i$  is a binary variable for selection of the optimal polygeneration system for the company. Additional economic criteria were calculated for the alternatives after optimization. Internal rate of return,  $r_{IRR_i}$ , is defined by equation, from which it is calculated iteratively:

$$\frac{I_i}{F_{Ci}} = \left[ \frac{r_{IRR_i} \cdot (1 + r_{IRR_i})^n}{(1 + r_{IRR_i})^n - 1} \right]^{-1} \quad i = 1, \dots, 10; \quad (10)$$

Payback period,  $t_{PB_i}$ /year, is defined as:

$$t_{PB_i} = \frac{I_i}{F_{Ci}} \quad i = 1, \dots, 10; \quad (11)$$

The constraints of the mathematical model describing different polygeneration systems are presented in the continuation.

#### ***a) Cogeneration system with back-pressure steam turbine***

The cogeneration system with back-pressure turbine has the simplest configuration (Figure 5). The electricity produced depends on steam pressure reduction through the turbine. The higher the turbine inlet pressure, the greater the electricity output. The actual outlet steam condition is dictated by the required temperature during the process.

According to the highest steam flow rate, as measured in the studied brewery, the following pressure levels were selected: 42.4 bar, 59.7 bar and, 101 bar. Because of

seasonal production, index  $j$  is introduced to define monthly productions of heat and electricity. The latter is calculated based on the current heat consumption:

$$E_{i,j}^P = Q_j \cdot c_i \cdot Y_i \quad j = 1, 2, \dots, 12; \quad i = 1, 2, 3; \quad (12)$$

where  $E_{i,j}^P$ /(kW h) is the monthly electricity production in polygeneration system  $i$ ,  $Q_j$ /GJ is monthly heat consumption and  $c_i$ /((kW h)/GJ) is a conversion factor for electricity production by the polygeneration system  $i$ . As already mentioned above, heat production is constant for options  $i=1, 2, 3$ . The annual electricity production,  $E_i^{P,a}$ /(kW h)/year), is:

$$E_i^{P,a} = \sum_{j=1}^{12} E_{i,j}^P \quad i = 1, 2, 3; \quad (13)$$

The annual heat consumption,  $q^a$ /(kW h)/year) is defined by equation:

$$q^a = \sum_{j=1}^{12} q_j \quad (14)$$

where  $q_j$ /(kW h) is the heat consumption in month  $j$ .

The fuel consumption (natural gas) in polygeneration systems is higher compared to the conventional heating system because of additional electricity production. Increase in fuel consumption is presented by the factor for fuel consumption increase:

$$F_i^{ADD} = \frac{(f_i \cdot E_i^{P,a} + Y_i \cdot q^a) \cdot F}{q^a} - F \cdot Y_i \quad i = 1, 2, 3; \quad (15)$$

where  $F_i^{ADD}$ /(m<sup>3</sup>/year) represents the additional annual fuel consumption for polygeneration system  $i$ ,  $F$ /(m<sup>3</sup>/year) is the current fuel consumption and

$f_i / (\text{kW h})_{\text{th}} / (\text{kW h})_e$  is factor for fuel consumption increase, where subscript  $th$  refers to the thermal energy, and subscript  $e$  to electricity.

Companies that invest in polygeneration systems are eligible for tax relief on the reduced carbon dioxide emission. The latter is calculated as a difference between CO<sub>2</sub> released before and after polygeneration installation:

$$m_{\text{CO}_2,i} = u^{\text{C}} \cdot Y_i \cdot q^{\text{a}} - u^{\text{CG}} \cdot E_i^{\text{P,a}} \quad i = 1, 2, 3; \quad (16)$$

where  $m_{\text{CO}_2,i} / (\text{g/year})$  is the annual decrease in carbon dioxide emission for polygeneration system  $i$ ,  $u^{\text{C}} / (\text{g}/(\text{kW h})_{\text{th}})$  is the specific emission of carbon dioxide from industrial steam boilers, and  $u^{\text{CG}} / (\text{g}/(\text{kW h})_e)$  is the specific emission of carbon dioxide from the polygeneration system with steam turbine.

The cash flow is defined by equation:

$$F_{\text{Ci}} = (1 - r_t) \cdot \left( E_i^{\text{P,a}} \cdot P^{\text{E}} + m_{\text{CO}_2,i} \cdot P^{\text{EN}} - E_i^{\text{P,a}} \cdot P^{\text{M}} - F_i^{\text{ADD}} \cdot P^{\text{F}} \right) + r_t \cdot I_i \cdot \left[ \frac{(1 + r_d)^n - 1}{r_d \cdot (1 + r_d)^n} \right]^{-1} \quad i = 1, 2, 3; \quad (17)$$

where  $P^{\text{E}} / (\text{EUR}/(\text{kW h}))$  is the price of electricity,  $P^{\text{EN}} / (\text{EUR}/\text{g})$  is the carbon dioxide emission tax,  $P^{\text{M}} / (\text{EUR}/(\text{kW h}))$  is the price of maintenance, and  $P^{\text{F}} / (\text{EUR}/\text{m}^3)$  is the price of natural gas.

The investment in polygeneration systems is calculated from equation:

$$I_i = K_i \cdot \Phi^{\text{MAX}} \cdot c_i \cdot Y_i \quad i = 1, 2, 3; \quad (18)$$

where  $K_i/(\text{EUR}/\text{kW})_e$  is the investment parameter for polygeneration system  $i$ , and  $\Phi^{\text{MAX}}/(\text{GJ}/\text{h})$  is the maximum heat flow rate required in the plant. The latter is calculated from the maximum mass flow rate of steam, measured at the boiler's outlet.

***b) Cogeneration system with back-pressure steam turbine - increased heat production during heating season***

Besides the inlet pressure, electricity production can also be increased by increasing the steam mass flow rate and, thus, increasing heat production. In the studied brewery plant it was estimated that the maximum allowable increase in steam production during the heating season is 50 % above the current production level. The monthly electricity production during the heating-season months is limited by constraint:

$$Q_j \cdot c_i \cdot Y_i \leq E_{i,j}^{\text{P}} \leq Q_j \cdot c_i \cdot f_i^{\text{ADD, HEAT}} \quad i = 4, 5, 6; \quad j \in JH = 1, 2, 10, 11, 12; \quad (19)$$

where  $f_i^{\text{ADD, HEAT}}$  is the optimization variable of heat production increase and  $JH$  is the set of heating-season months. The upper bound of this increase is determined by inequality:

$$f_i^{\text{ADD, HEAT}} \leq Y_i \cdot f_i^{\text{ADD, HEAT, UP}} \quad i = 4, 5, 6; \quad (20)$$

where  $f_i^{\text{ADD, HEAT, UP}}$  is the maximum allowable increase in heat production, which is defined by the company according to identified outside consumers of heat energy and amounted to 1.5. The differential cash flow in this case is defined by equation:

$$F_{Ci} = (1 - r_t) \cdot \left( \begin{aligned} & E_i^{\text{P,a}} \cdot P^{\text{E}} + P^{\text{H}} \cdot (f_i^{\text{ADD, HEAT}} - Y_i) \cdot \sum_{j \in JH} q_j + \\ & m_{\text{CO}_2, i} \cdot P^{\text{EN}} - E_i^{\text{P,a}} \cdot P^{\text{M}} - F_i^{\text{ADD}} \cdot P^{\text{F}} \end{aligned} \right) + r_t \cdot I_i \cdot \left[ \frac{(1 + r_d)^n - 1}{r_d \cdot (1 + r_d)^n} \right]^{-1} \quad i = 4, 5, 6; \quad (21)$$

where  $P^H$ /(EUR/(kW h)) is the price of heating for external consumers.

Investment in the polygeneration system is defined by:

$$I_i = K_i \cdot \Phi^{\text{MAX}} \cdot f_i^{\text{ADD,HEAT}} \cdot c_i \cdot Y_i \quad i = 4, 5, 6; \quad (22)$$

Equations 13–16 remain unchanged.

### c) Cogeneration system with open-cycle gas turbine

The cogeneration systems with gas turbines produce electricity primarily, and secondarily the heat from the hot gases by a heat recovery system, Figure 6. The electricity production would exceed the company's current demand by applying the cogeneration system with a gas turbine at the current steam production level. The surplus energy could be sold as “green energy” into the public electricity network at the, so called, feed-in tariffs.

$$E_i^S = Y_i \cdot \sum_{j=1}^{12} (E_{i,j}^P - E_j^D) \quad i = 7; \quad (23)$$

where  $E_i^S$ /(kW h/year) is the annual electricity for sale and  $E_j^D$ /(kW h) is the monthly electricity consumption of the company. The differential cash flow in this case is defined by equation:

$$F_{Ci} = (1 - r_t) \cdot (E_i^D \cdot P^E + E_i^S \cdot P^{\text{GE}} - E_i^{\text{P,a}} \cdot P^{\text{M}} - F_i^{\text{ADD}} \cdot P^{\text{F}}) + r_t \cdot I_i \cdot \left[ \frac{(1 + r_d)^n - 1}{r_d \cdot (1 + r_d)^n} \right]^{-1} \quad i = 7; \quad (24)$$

where  $P^{\text{GE}}$ /(EUR/(kW h)) represents the price of “green energy”. High additional fuel consumption prevents tax relief on carbon dioxide emissions. Equations 12–15 and 18 remain unchanged.

*d) Trigeneration system with back-pressure steam turbine*

In the case of the trigeneration system, cooling energy is produced along with heat and electricity. According to the classical concept of trigeneration, the heat is transformed into cooling energy by an absorption chiller during summer, when there is no need for heating. This concept can not be applied in the studied plant because of simultaneous consumptions of heat and cooling energy. Peak season production takes place during the summer, when the demands for both, heating and cooling, are the highest. Yet another possibility is to connect the refrigeration compressors to the steam turbine, thus avoiding the transformation of energy from mechanical work to electricity (Figure 7). In this case, the steam turbine operates over a speed range, depending on the compressor's load.

The equations are the same as for the cogeneration system with the back-pressure steam turbine 12–18, with the exception of the conversion factors for electricity production, (Table 1).

### **3.2. Results of polygeneration**

In the case studied Brewery the annual heat consumption was 127.2 MJ and the annual electricity consumption 13.58 GW h. The Brewery generates steam for its own needs using a conventional boiler, while electricity is purchased from the vendors. The wort preparation process is the largest consumer of heat, while the highest need for cooling energy is during fermentation and maturation operations.

Equations 7–24 represent a MILP model for selecting the optimal polygeneration system. The parameters of the model are given in Table 1. The model selects the optimal polygeneration system based on the economic objective function. In addition, the increase

in heat production during the heating season is optimized for alternatives  $i = 4, 5, 6$ . The results of analysis are shown in Table 2.

The size of the applied model is app. 200 constraints, 200 continuous variables and 10 binary variables. The CPU time was less than 1 s.

It is evident from Table 2, that electricity production increases with inlet pressure in cogeneration system with a back-pressure steam turbine ( $i=1, 2, 3$ ). The highest electricity production would be achieved at an inlet pressure of 101 bar ( $i=3$ ),  $E_3^P = 7.59$  GW h, which represents 56 % of current electricity consumption. However, the net present value, the internal rate of return, and the payback period decrease with the pressure level, as the investment, maintenance costs and fuel consumption increase.

In the case of higher heat production during the heating season by cogeneration system with back-pressure steam turbine ( $i=4, 5, 6$ ), the highest electricity production would also be achieved at an inlet pressure of 101 bar, ( $i=6$ ),  $E_6^P = 9.10$  GW h or 67 % of the current company's demand. The optimal heat production during the heating season is 50 % higher than the current consumption, which represents the upper limit approved by the Brewery. From the economic point of view, the cogeneration systems with back-pressure steam turbine and additional heat production during heating season is the most favourable option. The net present value and the internal rate of return are higher and the payback period shorter, but the company would become dependent on outside consumers.

Electricity production by the cogeneration system with open-cycle gas turbine ( $i=7$ ) would exceed the current electricity demand by 9.03 GW h. The electricity surplus could be sold in public electricity network as a "green energy". In spite of these results, this

cogeneration system is unacceptable for this brewery. The net present value is negative because of an overdimensioned cogeneration system induced by low steam production.

In the case of trigeneration systems with a back-pressure steam turbine ( $i=8, 9, 10$ ), the highest electricity production is  $E_{10}^P = 8.20$  GW h or 60 % of the current electricity consumption. No additional compressors were assumed in the economic analysis. If the new compressors were installed, the net present value would become negative, because of high investment costs (estimated at 1,173,600 EUR).

The optimal solution selected by the model is the cogeneration system with back-pressure steam turbine at the pressure level of 42.4 bar ( $i=4$ ). During the heating season, heat production should increase by 50 % above the current level. Electricity production would cover 42 % of the company's requirements. The net present value is 934,467 EUR and the payback period 3.2 years. The disadvantage of this solution is that the brewery would become dependent on smaller consumers of surplus heat.

It should be noted, that economic calculations were based on the electricity price negotiated on a long-term basis between the Brewery and electricity distributor. However, the economics of polygeneration systems is quite sensitive on changes in electricity prices, e.g. an increase of 10 % would increase the optimal net present value by 18 %, and reduce the optimal payback period from 3.2 years to 2.9 years. As electricity prices are expected to increase in the future, polygeneration technology would become even more favourable.

## 4. Conclusions

Possibilities of heat integration, and combined electricity, heating, and cooling production in a beverage plant were analysed by application of mathematical programming optimization models. The mathematical model for the heat integration of batch processes [5] was slightly modified in order to correspond to industrial circumstances. Two matches were predicted in the brewhouse by this model. The first one is between waste vapour from wort boiling and adjunct mash heating processes. The second match integrates the heat released at wort clarification with the mash heating process. The resulting savings on utilities would be significant, however, only the first match was acceptable to the company. The second match supplies only part of the heat required by the mash heating process and was, therefore, rejected.

A simplified MILP model was developed for the feasibility analysis and selection of the optimal system for combined electricity, heating, and cooling production in the plant with significant seasonal variations in demand. The set of alternatives included steam and gas turbines at three pressure levels, and a trigeneration system with a back-pressure steam turbine. The option of heat production increase above the company's demand was optimized. The optimal polygeneration system for the brewery was selected according to the economic criteria considering the company's constraints. The cogeneration system with a back-pressure steam turbine at a pressure level of 42.4 bar has the highest net present value. Heat production would be increased during the heating season by 50 %. Electricity production would cover 42.5 % of the current brewery's consumption. The net present value is positive and the payback period is 3.2 years. The disadvantage of this

solution is that the plant would become dependent on external consumers of surplus heat energy.

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## 5. Nomenclature

### Sets and indices

$i$	index of batch or polygeneration systems
$j$	index of units or months
$JH$	set of heating-season months
$J_{IP}$	set of input streams of the first units of in-phase stages
$k$	index of units of the first batch

### Parameters

$A^{\text{VESSEL}}$	available heat exchange area on the production vessel, m <sup>2</sup>
$c_i$	conversion factor for electricity production by polygeneration system $i$ , (kW h)/GJ
$E_j^D$	electricity consumption in month $j$ , kW h
$F$	current fuel consumption, m <sup>3</sup> /year
$f_i$	factor for fuel consumption increase for polygeneration system $i$ , (kW h) <sub>th</sub> /(kW h) <sub>e</sub>
$K_i$	investment parameter for cogeneration system $i$ , EUR/kW <sub>e</sub>
$\ln T_{j,k}$	logarithmic mean temperature difference for streams $j$ and $k$ , K
$N$	number of batches over which heat integration is considered
$n$	depreciation period, year
$P^{\text{CU}}$	price of cold utility, EUR/(kW year)

$P^E$	price of electricity, EUR/(kW h)
$P^{EN}$	carbon dioxide emission tax, EUR/g
$P^F$	price of natural gas, EUR/m <sup>3</sup>
$P^{GE}$	price of “green energy”, EUR/(kW h)
$P^H$	price of heating, EUR/(kW h)
$P^{HU}$	price of hot utility, EUR/(kW year)
$P^M$	price of maintenance, EUR/(kW h)
$r$	variable parameter for heat exchanger investment cost
$r_d$	discount rate, -
$r_t$	tax rate, -
$s$	fixed parameter for heat exchanger investment cost
$U_{j,k}$	overall heat transfer coefficient between units $j$ and $k$ , kW/(m <sup>2</sup> ·K)
$u^C$	specific emission of carbon dioxide from industrial steam boilers, g/(kW h) <sub>th</sub>
$u^{CG}$	specific emission of carbon dioxide from polygeneration system with steam turbine, g/(kW h) <sub>e</sub>
$Q_j$	monthly heat production, GJ
$q_j$	heat consumption in month $j$ , kW h
$q^a$	annual heat consumption, (kW h)/year
$\Phi^{MAX}$	maximum heat flow rate, GJ/h

**Variables**

$A_{j,k}$	heat exchange area for match between units $j$ and $k$ , m <sup>2</sup>
$E_{i,j}^P$	monthly electricity production by polygeneration system $i$ , kW h
$E_i^{P,a}$	annual electricity production by polygeneration system $i$ , kW h/year
$E_i^S$	electricity for sale in case of polygeneration system $i$ , kW h/year
$F_C$	cash flow for heat integration retrofit, EUR/year
$F_{Ci}$	cash flow for polygeneration system $i$ , EUR/year
$F_i^{ADD}$	additional fuel consumption for polygeneration system $i$ , m <sup>3</sup>
$F_{obj}$	objective function, EUR
$f_i^{ADD,HEAT}$	factor of heat production increase for polygeneration system $i$
$f_i^{ADD,HEAT,UP}$	upper bound of factor for heat production increase
$I_i$	investment in polygeneration system $i$ , EUR
$I_{j,k}$	investment in heat exchanger for match between units $j$ and $k$ , EUR
$m_{CO_2}$	annual decrease of carbon dioxide emission, g/year
$r_{IRR_i}$	internal rate of return for polygeneration system $i$ , -
$t_{PB_i}$	payback period for polygeneration system $i$ , year
$t_{i,j}$	time at which batch $i$ enters unit $j$ , h
$t_{E_{i,j}}$	exit time of each unit $j$ of batch $i$ , h
$t_{P_j}$	fixed processing time in unit $j$ , h
$V_{NP_i}$	net present value for polygeneration system $i$ , EUR

$\phi_{i,j,k}$  heat exchanged between the unit  $j$  in batch  $i$  and unit  $k$ , kW

$\phi_{i,j,k}^C$  decrease of cold utility consumption, kW

$\phi_{i,j,k}^H$  decrease of hot utility consumption, kW

### Binary variables

$Y_i$  binary variable for selection of optimal polygeneration system

$Y_{i,j,k}$  binary variable for match between unit  $j$  in batch  $i$  and unit  $k$

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Figure captions:

Figure 1. Schematic diagram of in-phase and out-of-phase manner operating units.

Figure 2. Schematic diagram of production in the brewhouse before heat integration retrofit a) and after retrofit b).

Figure 3. Result of heat integration in the brewhouse.

Figure 4. Superstructure of mathematical model for selecting the optimal polygeneration system.

Figure 5. Cogeneration system with back-pressure steam turbine.

Figure 6. Cogeneration system with open-cycle gas turbine.

Figure 7. Trigeneration system with back-pressure steam turbine.

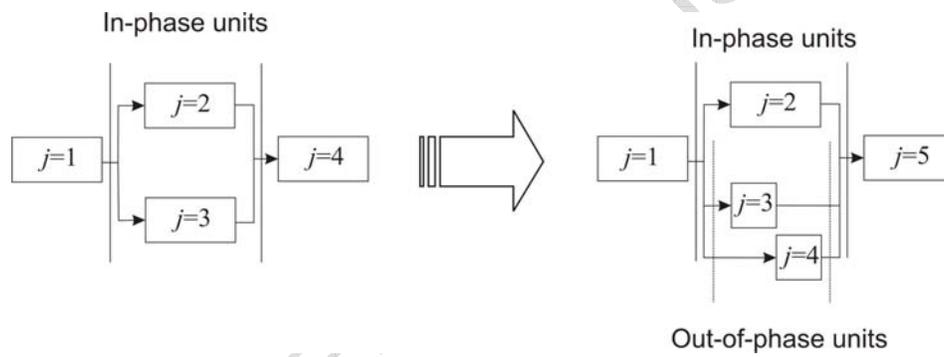


Figure 1. Schematic diagram of in-phase and out-of-phase manner operating units.

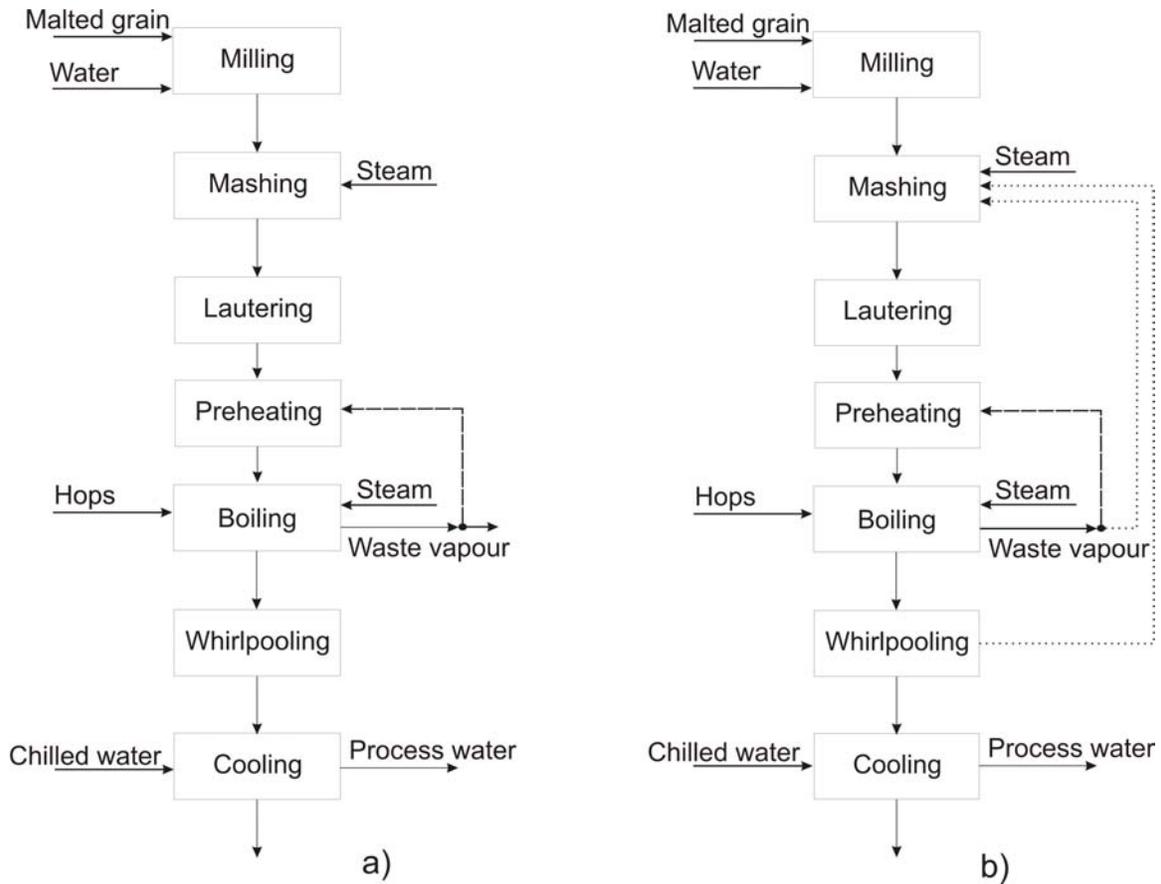


Figure 2. Schematic diagram of production in the brewhouse before heat integration retrofit a) and after retrofit b).

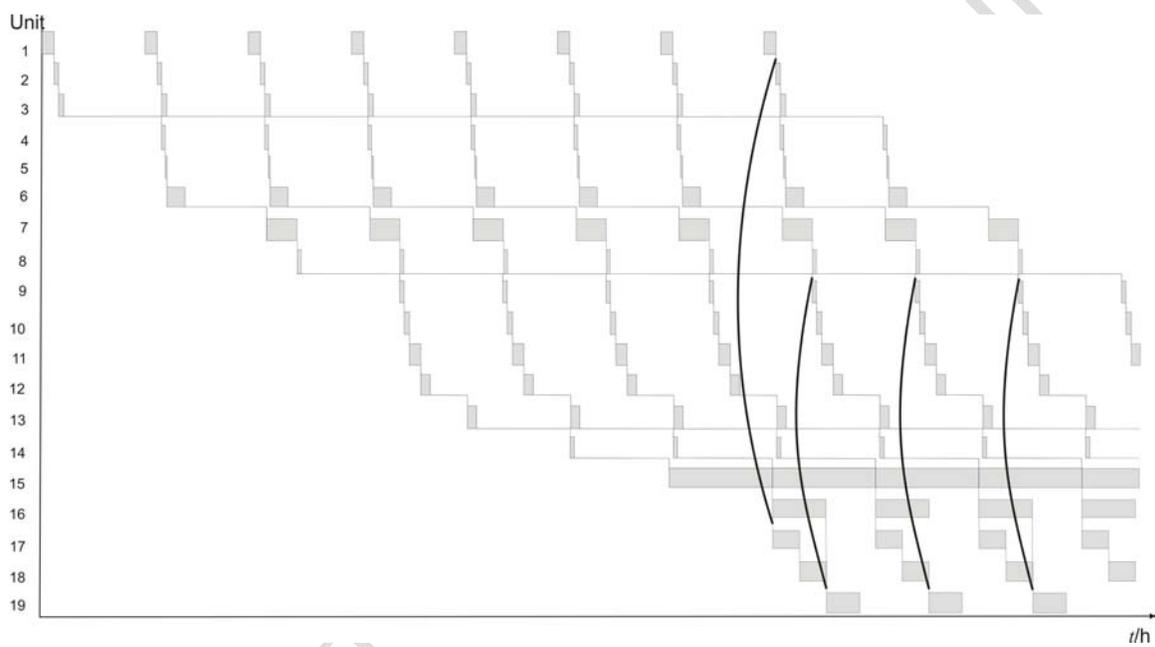


Figure 3. Result of heat integration in the brewhouse.

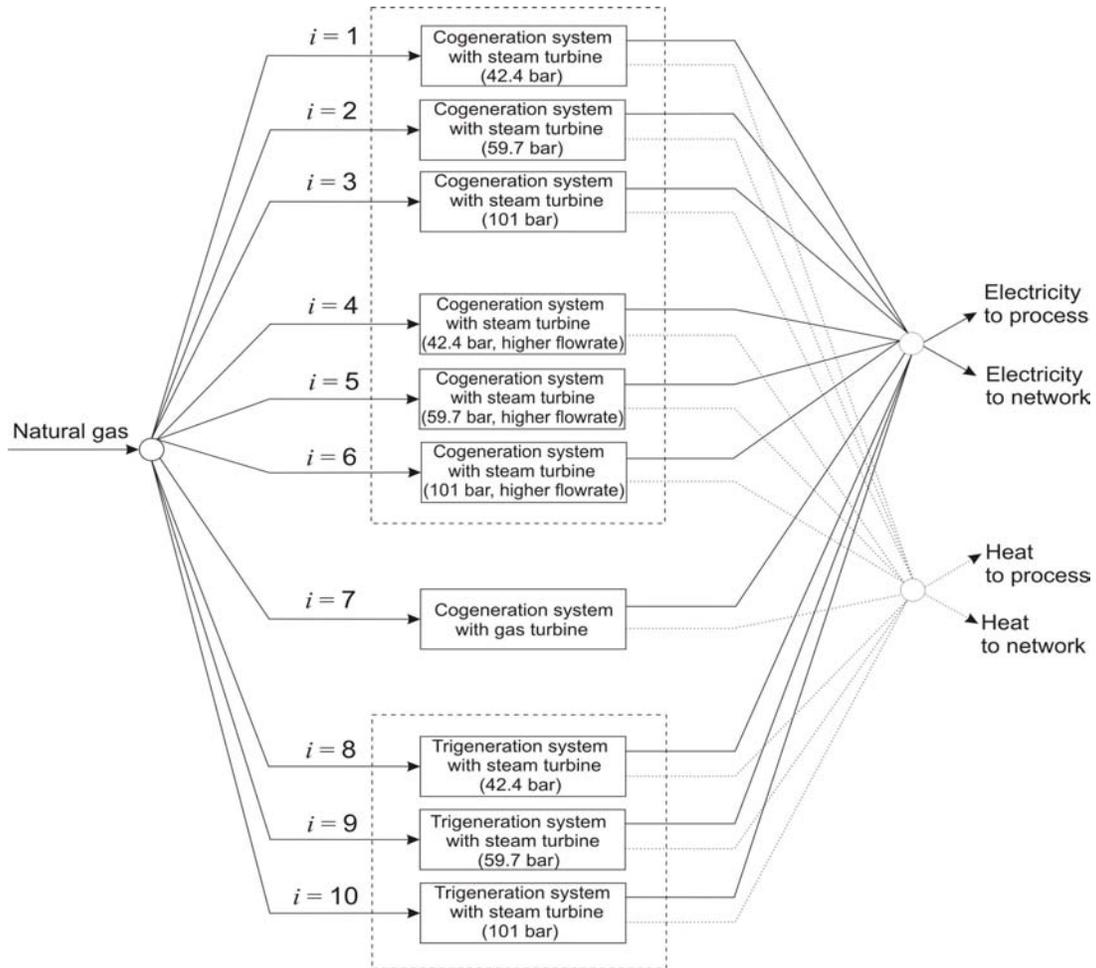


Figure 4. Superstructure of mathematical model for selecting the optimal polygeneration system.

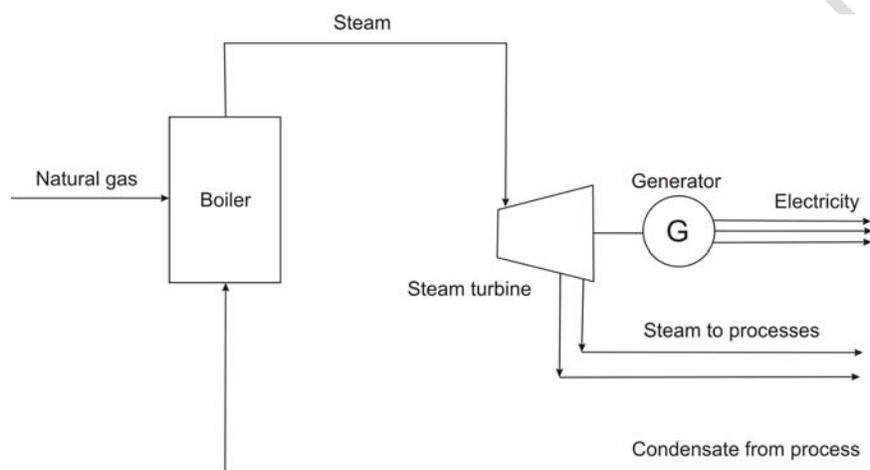


Figure 5. Cogeneration system with back-pressure steam turbine.

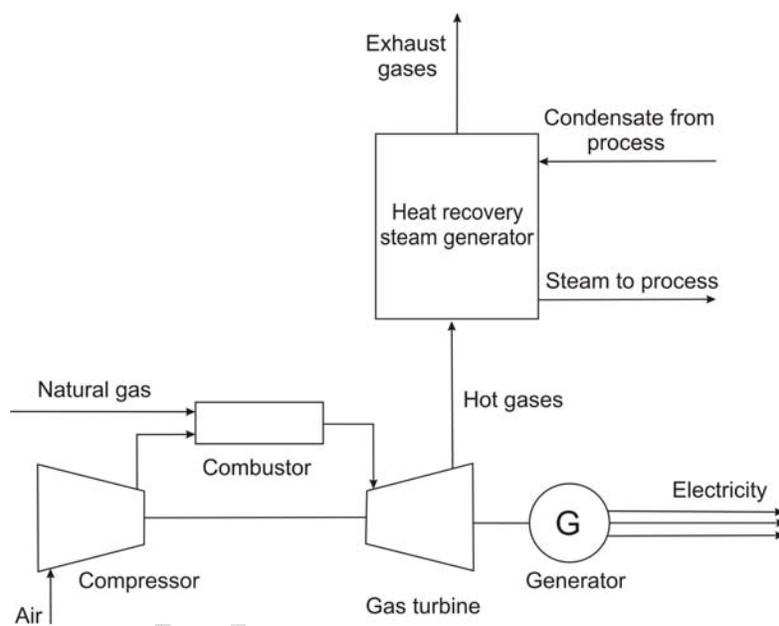


Figure 6. Cogeneration system with open-cycle gas turbine.

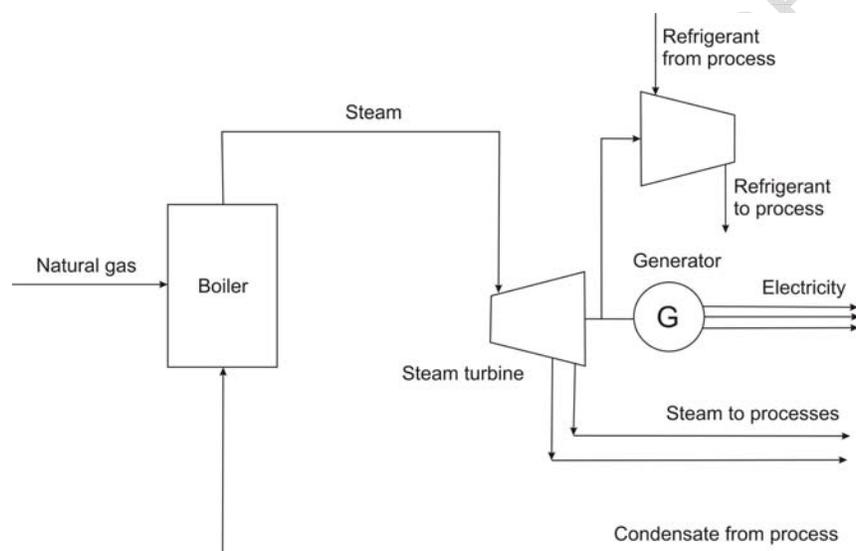


Figure 7. Trigeneration system with back-pressure steam turbine.

Table captions:

Table 1. Data for the industrial case study.

Table 2. Results for polygeneration.

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Table 1. Data for the industrial case study.

Model parameters		
Conversion factor (kW h/GJ) [21]	$c_i = 36.96$	$i = 1, 4$ (42.4 bar)
	$c_i = 44.55$	$i = 2, 5$ (59.7 bar)
	$c_i = 59.71$	$i = 3, 6$ (101 bar)
	$c_i = 177.77$	$i = 7$
	$c_i = 39.92$	$i = 8$ (42.4 bar)
	$c_i = 48.11$	$i = 9$ (59.7 bar)
	$c_i = 64.49$	$i = 10$ (101 bar)
Factor of fuel consumption increase (kW h) <sub>th</sub> / (kW h) <sub>e</sub> [27]	$f_i = 1.2$	$i = 1, \dots, 10, i \neq 7$
	$f_i = 1.7$	$i = 7$
Specific emission of carbon dioxide from industrial steam boiler (g/(kW h) <sub>th</sub> ) [28]	$u^C = 225.55$	
Specific emission of carbon dioxide from polygeneration system (g/(kW h) <sub>e</sub> ) [28]	$u^{CG} = 808.16$	
Economic data		
Price of electricity (EUR/kW h)	$P^E = 0.06468$	
Price of “green energy” (EUR/kW h)	$P^{GE} = 0.07094$	
Price of natural gas (EUR/m <sup>3</sup> )	$P^F = 0.291$	
Price of heat (EUR/kW h)	$P^H = 0.025$	
Price of maintenance (EUR/kW h) [26]	$P^M_i = 0.003$	$i = 1, \dots, 10, i \neq 7$
	$P^M_i = 0.005$	$i = 7$
CO <sub>2</sub> emission tax (EUR/g)	$P^{EN} = 0.0000125$	
Investment parameter [26]	$K_i = 800$	$i = 1, \dots, 10, i \neq 7$
	$K_i = 600$	$i = 7$

Table 2. Results for polygeneration.

Polygeneration system, <i>i</i>	<i>i</i> = 1	<i>i</i> = 2	<i>i</i> = 3	<i>i</i> = 4	<i>i</i> = 5
Pressure level (bar)	42.4	59.7	101.0	42.4	59.7
Annual electricity production (kW h)	4,701,732	5,667,266	7,595,791	5,635,133	6,792,348
Savings by electricity production (EUR/year)	304,108	366,559	491,296	364,480	439,329
Saving by additional heat energy production (EUR/year)	0	0	0	175,328	175,328
Investment (EUR)	680,064	819,720	1,098,664	1,020,096	1,229,580
Maintenance cost (EUR/year)	14,105	17,002	22,787	16,905	20,377
Additional fuel consumption cost (EUR/year)	174,151	209,914	281,346	208,724	251,587
Savings by relief on CO <sub>2</sub> emission tax (EUR/year)	64,027	54,268	34,775	54,593	42,896
Payback period (year)	4.2	4.6	5.2	3.2	3.6
Net present value (EUR)	318,900	278,822	198,772	934,467	854,755
Internal rate of return (%)	18.86	16.13	12.63	27.74	23.44

Polygeneration system, <i>i</i>	<i>i</i> = 6	<i>i</i> = 7	<i>i</i> = 8	<i>i</i> = 9	<i>i</i> = 10
Pressure level (bar)	101.0	11.4	42.4	59.7	101.0
Annual electricity production (kW h)	9,103,728	22,614,365	5,078,278	6,120,139	8,203,861
Savings by electricity production (EUR/year)	588,829	1,519,213	328,463	395,850	530,626
Saving by additional heat energy production (EUR/year)	175,328	0	0	0	0
Investment (EUR)	1,647,996	2,453,226	734,528	885,224	1,186,616
Maintenance cost (EUR/year)	27,311	113,072	15,234	18,360	24,611
Additional fuel consumption cost (EUR/year)	337,200	1,116,841	188,098	226,688	303,869
Savings by relief on CO <sub>2</sub> emission tax (EUR/year)	19,534	0	60,221	49,690	28,629
Payback period (year)	4.2	–	4.3	4.7	5.3
Net present value (EUR)	695,741	<0	303,270	260,024	173,532
Internal rate of return (%)	17.88	–	17.68	15.13	11.84