Model-Based Evaluation of Opportunities for Implementation of Small-Scale CHP Systems in the Industrial Facilities

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Abstract – **This paper dials with an approach based on the development and use of simulation models and techniques on the stage of pre-feasibility studies, related to implementation of small-scale CHP units in the industrial facilities. For modeling of the operational modes before and after improvements, the proven energy balance software is used. The ability for assessment of different technical options and subsequent economic appraisal is demonstrated by means of case studies for specific industrial facilities.**
Keywords – **Simulation, Energy balance modeling, Combined Heat and Power**

I. Introduction

The principle of combined heat and power production (CHP) is well known and widely used technology due to its technical, economic and environmental benefits, which provides highly efficient and therefore cost-effective exploitation of primary energy sources.

Power generation in the industrial facilities is possible with gas turbines or gas engines and depending of the specific industry requirements can be combined with production of process steam, hot water or combination of both of them.

The demand for thermal energy (with process steam or hot water) vary from facility to facility in correspondence to the specific conditions and existing production cycles, but in most cases can be considered to be continuous over the day and year. In the same time electricity consumed by the plant's equipment is purchased from the Regional Electricity Distribution Companies (REDC) on the basis of three tariff zones (peak, day and night).

The last changes in the Bulgarian legislation in respect to the electricity production from CHP units together with its technological advances making such option more attractive for industrial facilities in the future. On the other hand the vide spectrum of conditions, under which these facilities have to operate need a detail technical and economic assessment for identification of the most suitable and profitable solution. This paper demonstrates an approach dealing with development and use of simulation models and techniques to match the above stated requirements on the stage of pre-feasibility studies related to implementation of small-scale CHP units in the industrial facilities.

II. Plants description

Typically, the energy facilities in the industrial plants consist of steam or hot water boilers with capacity designed to cover thermal demands with process steam or hot water at different operational conditions over the year. To ensure the reliable heat supply and thus to secure the production cycle an additional boiler is normally installed and used as reserve. An auxiliary components, like de-aerators, control valves, pipes, heat exchangers etc. are also part of the plant's equipment and can also be subject of assessment, when increase of efficiency or reduction of the production costs is investigated. In most of the cases, the main fuel is natural gas which lead to an overall plant efficiency in the range of 0.9 – 0.92.

III. Models description

For this study the commercially available simulation software GateCycle-5.4 [3] has been used for the simulation of operational modes of energy facility in the industrial plants. The existing state and future improvements based on the implementation of gas turbine or gas engine and HRSG is estimated. Simulation environment uses detailed mathematical models of different energy conversion plant components for calculation of their performance. There is also a possibility for extension of the existing database for gas turbines by using user-defined characteristics. A Microsoft Excel interface – *Cycle Link* was used to automatically generate a number of simulation runs associated with estimated variants and cases.

For assessment of the benefits resulted from implementation of small-scale CHP modules in the industrial facilities two-step approach is proposed and used. The first step is directed to the proper definition of the so-called *base case*, representing the typical plant modes, including equipment in operation, thermal and electricity demands. The second step deals with formulation of different investment options or *variants* in respect to the type of the CHP module, thermal and electricity production as well as type of the heat carrier used for technology.

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Above-mentioned approach is demonstrated on the basis of case study for industrial facility with thermal demand in the range 4 - 16 t/h process steam and electricity consumption between 450.0 and 1150.00 kW. The needed steam is generated by two steam boilers KM-12 and KM-4 while another one (KM-12) is used as reserve.

Simulation of the *base case* represents the mutual operation of the equipment at the present operational conditions and includes the models of following components: steam boilers, de-aerator, pumps, headers, pressure reduction valves and consumers. From the common head the de-aerated water is entered steam boilers where saturated steam with parameters p=9.0 bar and T=185°C is generated and from the common head at the boilers outlet through the number of pressure reductions is distributed to the consumers with different requirements. For modeling of steam boilers "*Efficiency-Capacity*" characteristic and resistance of boilers are used. Pumps can be described by means of η – Q and H-Q characteristics for detail calculations or only defining the duty point if no precise data available. The water flow at the de-aerator inlet is composed from the feed water and returned condensate flows. Last one can be defined as percentage of the steam supply to the consumers.

Options corresponding to the implementation of CHP units in the industrial facilities are divided generally in two main variants: a) installation of gas turbine plus HRSG (fig.1) and installation of Gas Engine plus HRSG (fig.2). For the first variant a number of cases can be evaluated in respect to the type of the turbine, installed capacity, possibilities for supplementary firing etc.

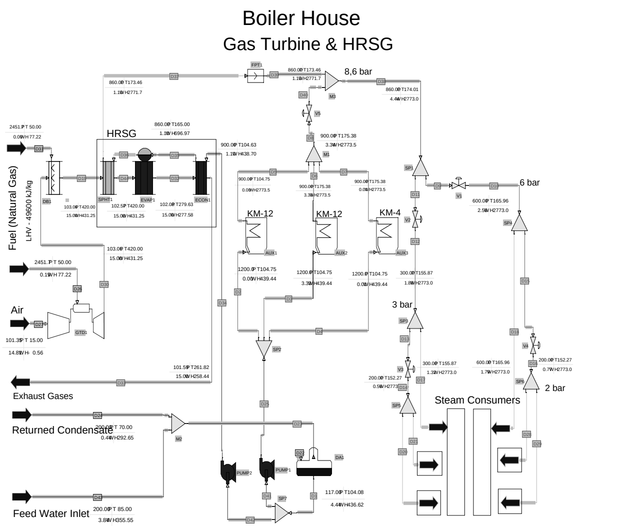

Fig.1. CHP model including Gas Turbine and HRSG

The CHP model with gas turbine consists of single stage gas turbine system and HRSG that uses the hot exhaust gases to generate saturated or superheated steam, which is directed to the common head after the steam boilers. For simulation of turbine operation two type of manufacturer's characteristics are used: *Output Power – Inlet Air Temperature* and *Heat Rate – Inlet Air Temperature*. The HRSG is modeled with predefined components from simulation environment, including: *Economizer*, *Evaporator* and *Superheater*. Additionally the gas turbine model was extended with *Duct Burner* and thus supplementary firing was possible to be simulated.

The CHP model with Gas Engine (fig.2) consists of gas engine HRSG, which utilizes the heat from the exhaust gases for steam production, while in the same time the hot water is produced from the machine cooling circuits. As calculation method the *Specify Heat Rate* method was selected.

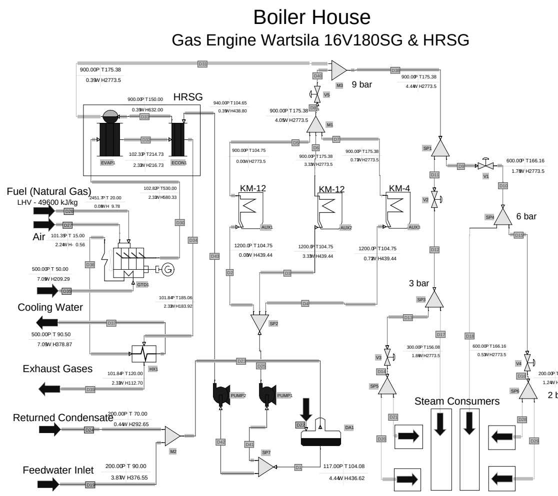

Fig.2. CHP model, including Gas Engine and HRSG

IV. Simulation Results

Based on the above described models and using an actual manufacturers data a number of cases are defined and assessed to identified the most profitable solution at the existing operational and economic conditions for different kind of industrial facilities. For variant 1 two options in respect to gas turbine are investigated: Saturn 20 PG and GTES-2.5 (Russian maid aviation gas engine).

The first option is selected in a way to cover max. electricity consumption of the plant and to be able to simulate the process steam production without and with supplementary firing. The last one resulted in the shut-down of the steam boilers and increase of overall system efficiency (heat and electricity production up to 92%). The simulation results for this option are shown in the tables 1 and 2.

The second option is characterized with electricity production more than plant's own needs, so the difference is assumed to be sale to REDC. The results from simulation runs for two cases – corresponding to different thermal demands with process steam are presented in the table.3.

For variant 2 also two possible alternatives are considered: using the gas engine for simultaneous generation of steam and hot water – option 1and only hot water production – option 2. The engines performance was simulated in correspondence with the Technical data sheets provided from manufactures – WARTSILA and JENBACHER for option 1 and 2 respectively. The results from simulation runs with steam and hot water production are presented in the table 4. For all three cases it is assumed that thermal energy with the hot water is sold to the consumers nearby the industrial facility. A situation referring to the facility with thermal demand of hot water only is investigated in the option 2. In both cases shown in table 5

TABLE 1
SATURN 20 PG PLUS HRSG
WITHOUT SUPPLEMENTARY FIRING

Description	Dim	Case1	Case2	Case3
Heat carrier		steam	steam	steam
Electricity demand	KW	469	995	1150
Process heat	KW	2592	4996	10364
Electrical output	KW	1210	1210	1210
Thermal output	KW	2592	2592	2592
Boiler house output	KW	-	2404	7772
Purchased electricity	KW	-	-	-
Sold electricity	KW	741	215	60

TABLE 2
SATURN 20 PG PLUS HRSG
WITH SUPPLEMENTARY FIRING

Description	Dim	Case2	Case3
Heat carrier		steam	steam
Electricity demand	KW	995	1150
Process heat	KW	4997	10367
Electrical output	KW	1210	1210
Thermal output	KW	4997	10367
Boiler house output	KW	-	-
Purchased electricity	KW	-	-
Sold electricity	KW	215	60

TABLE 3
GTES 2.5 WITH HRSG

Description	Dim	Case2	Case3
Heat carrier		steam	steam
Electricity demand	KW	995	1150
Process heat	KW	5185	10553
Electrical output	KW	2500	2500
Thermal output	KW	4204	4204
Boiler house output*	KW	1038	6406
Purchased electricity	KW	-	-
Sold electricity	KW	1505	1350

TABLE 4
WARTSILA 16V180SG – STEAM AND HOT WATER

Description	Dim	Case1	Case2	Case3
Heat carrier		steam water	steam water	steam water
Electricity demand	KW	469	995	1150
Process heat	KW	2638	5043	10411
Electrical output	KW	1360	1360	1360
Thermal output	KW	958	958	958
Boiler house output	KW	1680	4085	9453
Purchased electricity	KW	-	-	-
Sold electricity	KW	891	365	210
Sold hot water	KW	1038	1038	1038

TABLE 5
GAS ENGINES WITH THERMAL OUTPUT – HOT WATER

Description	Dim	Wartsila	Jenbacher
Heat carrier		hot water	hot water
Electricity demand	KW	1740	1740
Process heat	KW	2001	2001
Electrical output	KW	1360	660
Thermal output	KW	2001	873
Boiler house output	KW	-	1128
Purchased electricity	KW	380	1080
Sold electricity	KW	-	-

Comparable economic assessments are difficult to be done in the field of cogeneration, because every plant is complex and built to meet the specific needs. However the majority of industrial thermal and power facilities have one think of common: their main product is heat or steam. Electrical energy can almost always be obtained from a power utility, but steam cannot. Therefore, in the industrial plant at least as much fuel is required as is consumed by a steam boilers for generation of process steam. The additional fuel that is necessary corresponds to the difference between the fuel consumption on the CHP unit and that of the steam boilers. The efficiency of the power generation can be therefore defined as follows [1]:

$$\eta_P = \frac{P}{P_{FUEL} - \dfrac{H}{\eta_{HP}}} \qquad (1)$$

Defined in such a way the efficacy can be used after that in the equation presented bellow for calculation of the power production cost in case of power generation in the industrial facilities, taking into account the capital and investment costs:

$$Y_P = \frac{I_{CHP}}{P}\frac{\Psi}{EN} + \frac{Y_{FUEL}}{\eta_P} + \frac{U_{CHP}}{P\,EN} + u_{CHP} \qquad (2)$$

where:

Y_P - cost of electricity generation [currency unit/kWh]
Y_F - fuel costs [currency unit/kWh];
I - capital costs [currency unit];
EN - equivalent utilization period [h/y];
Ψ - annual amortization [%];
u - variable operating costs [currency unit/kWh];
U - fixed operating costs, including personnel costs [currency unit/a]
η_P - efficiency of power generation

The cost of electricity generation is key parameter for the economic model presented in [2], because this figure influences the incomes in case of electricity sale and can serve as indicator for the feasibility of the proposed solution in comparison to waited average price of electricity purchased by the plant.

The overall economic benefit of the energy facility in the industrial plant after improvements therefore can be assessed, by combining the results achieved through above described models with the methods from engineering economics and realistic investment cost estimation. The economic indices like Net Present Value, Internal Rate of Return, Profitability Index and related payback period have been calculated for all cases described above taking into account the following economic assumptions:

Total capital investments [BGL]
Operating and maintenance costs [BGL]
Average inflation rate [%]
Price of natural gas [BGL/th.nm3]
Economic life of the equipment [years]
Price of purchased electricity [BGL/kWh]
Annual amortization [%]

For the most feasible cases – Gas engine with thermal output – hot water and Saturn Gas turbine with HRSG and supplementary firing additional sensitivity analysis was conducted. The results are shown on fig.3 and 4.

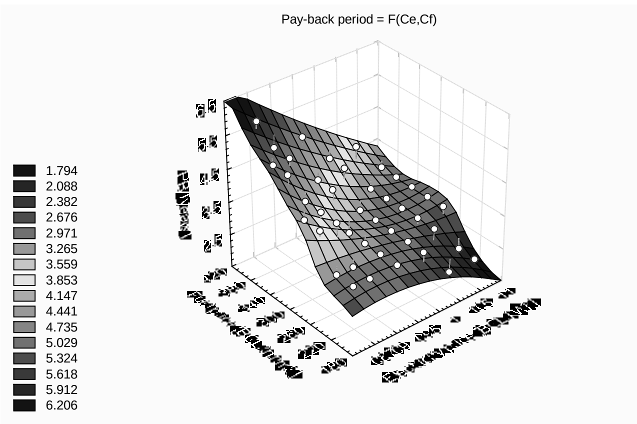

Fig.3. Estimated payback period for CHP with Gas engine and hot water as thermal demand

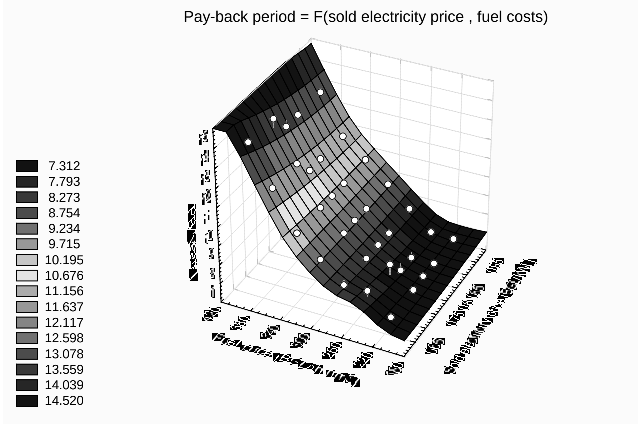

Fig.4. Estimated payback period for CHP with Gas turbine and thermal demand – process steam

V. CONCLUSION

From the results of a sensitivity analysis (fig.3 and fig.4) it can be seen that fuel cost and price of electricity have the most significant influence on the production cost of electricity generated by the CHP module and thus to the pay-back period for plants with steam as heat carrier.

The implementation of small-scale CHP modules in the industrial facilities with steam as heat carrier is very sensitive to the ratio: price of electricity / fuel cost. Additional key factor is this case is the thermal demand covered by the module. The better operational performance and lower production cost of electricity can be achieved if the HRSG is combined with supplementary firing and thus to reach overall efficiency up to 92% (for steam production of 16 t/h).

When the process heat required is produced with hot water as heat carrier and total amount of electricity generated by the CHP module is used for own needs only, the situation is going to be better. The difference between production cost of electricity and waited average price of this purchased from the REDC formed the basis for increase of operational cash flow and reduction of the payback period.

VI. REFERENCES

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