INDUSTRIAL GAS TURBINE OPERATION PROCEDURE IMPROVEMENT

by

Dušan D. GVOZDENAC*, Jovan R. PETROVIĆ, and Branka D. GVOZDENAC-UROŠEVIĆ

Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Original scientific paper
UDC: 662.76.035/.036
DOI: 10.2298/TSCI100516012G

In technical respect, co-generation is well studied technology but it is sometimes not used in an optimum way in practice. Factors affecting operating economics of this technology in practice are very similar to other industrial technologies although the degree of their influence may vary. When co-generation is concerned, the decisive importance lies on the parity between prices of electricity and driving fuel and reliability of concurrent utilization of generated heat and power. In this paper, a realistic case of real industrial co-generation plant operations is analyzed in details and it is pointed out to the necessity of optimizing operations of the plant as a whole.

Key words: *co-generation, gas turbine, drying kiln*

Introduction

Although numerous papers have dealt with co-generation technologies, there are not many devoted to their practical applications. This paper analyzes in detail operations of a gas turbine which is an integral part of gypsum boards drying technology. However, the manner of using gas turbine in the drying process is rather different and may vary from 100% up to 0% of its utilization. This possibility, as well as the distinctive impact of frequently changing prices of energy carriers on the operating economics of the plant requires optimization of the plant's operating regime.

All advantages and disadvantages of co-generation technologies are elaborated in details in [1-9] and without any doubts, it can be said that due to their higher energy efficiency these technologies definitely have future [10-13]. However, it is obvious that co-generation gives two "products" whose relevance is mutually dependent. This dependence requires special analysis in practice since demand of heat and power may vary considerably [14, 15].

Parallel with the development of co-generation technologies, it was necessary to develop accompanying regulations. The essence of regulations is contained in [6, 16]. Since the relation between the price of electricity and driving fuel has a decisive impact on the economics of co-generation in practice, all the countries have created mechanisms achieving stimulating conditions to employ co-generation technologies irrespective of the parity price.

* Corresponding author; e-mail: gvozden@uns.ac.rs

Facts on analyzed co-generation plant

This real life example refers to the factory for the production of gypsum boards (35,664,000 m^2 per year). The factory employs around 200 workers and it operates 7488 hours per year. The overall annual expenses of the company for energy are 2.45 million US$.

The detailed energy audit (DEA) itself will not be discussed here; however, some of the data will be used for analyzing one of recognized energy conservation opportunities. This is the case of a drying kiln which is used for drying gypsum boards. This is the largest single energy cost center (ECC) in the factory. Specifically, the DEA defined the system's boundaries for several ECC which have been separately analyzed and which have been submitted to surveying and controlling of energy performances.

Figure 1 presents gas consumption (without consumption for running the gas turbine) and overall consumption of electrical energy depending on the monthly production in the factory. The gas turbine is an integral part of the drying kiln and it is used for improving energy efficiency of the drying process. Namely, the drying kiln is driven by natural gas (NG). This natural gas is partly used for driving the turbine and partly for the production of heat energy directly. Exhaust gases from the turbine are directly mixed with gasses from independent combustion chambers. Gases prepared in this way are introduced into the drying kiln. The maximum turbine output power at the generator terminal is 7,000 kW$_e$ (–40 °C ambient temperature, see level). However, ever since the factory commenced with work, the gas turbine has been operating with considerably lower power than possible under given circumstances. Normal operating procedure of this co-generation plant has been to cover factory electrical energy consumption with about 90-95%.

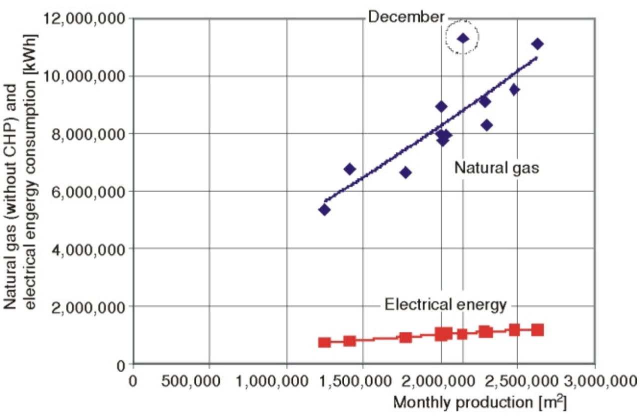

Figure 1. Natural gas and electrical energy consumption *vs.* production

Let us now go back to the fig. 1. It can easily be noticed that one point, which indicates natural gas consumption in the process, considerably deviates from other eleven points. In that month and each December in a year, the general overhaul of the turbine is carried out. It is obvious that in that period a considerable increase of gas consumption occurs in the drying kiln, and that there is no substantial increase of electricity consumption. During the turbine's overhaul, required electricity is completely taken over from the local electric grid and the process in the drying kiln is carried out undisturbed with the utilization of two existing combustion chambers. This and some other facts have definitely indicated the need to optimize operating procedure with an aim to reduce electricity costs and perform detailed check of the current manner of utilization of the co-generation plant, as well to examine possibilities and financial conditions for permanent and extensive production of electricity for the local distribution company. During the DEA and related to this ECC, the above stated has been the primary plan and this is what this paper is concerned with.

12 months operation data

Here are some basic data related to the analyzed ECC.

– Total factory energy cost per year (TEC):	2,445,738 US$/a
– Number of operating hours (NOH):	7,448 h/a
– Analyzing period:	April 1-March 31 next year
– Total 12 months electricity consumption (EC):	12,292,700 kWh/a
(*Generated by co-generation plant (ECC*):	*10,378,700 kWh/a*
(*Purchased from local grid (ECG*):	*1,914,000 kWh/a*
(*Purchased from local grid during shut-down of gas turbine*)	*949,520 kWh/a*
– Average purchased electricity cost:	0.0825 US$/kWh
– Average unit price of electricity produced by co-generation plant (only cost of NG is calculated)	0.0781 US$/kWh
– Average price of electricity paid by local electricity authority to the company	0.0363 US$/kWh
– Total annual NG consumption (NGC):	161,114,988 kWh/a
– Annual NG consumption for co-generation only (NGCG):	57,080,000 kWh/a
– Average unit NG cost (NGP):	0.0142 US$/kWh
– Annual average ambient temperature (T_a):	30 °C

Kiln description

The simplified scheme of the drying kiln is presented in fig. 2. Only energy aspects of drying process will be analyzed. There are two consumers of NG: (1) gas turbine and (2) two additional combustion chambers for hot gas generation and direct supplying of the kiln. The proper temperatures of drying fluids are controlled by mixing the flue gases from the turbine exhaust, flue gases from combustion chambers and fresh air.

In the scheme, the circles designate measuring points which have been used for measuring parameters of the whole plant within DEA. The majority of these measuring points have also been used in the regular monitoring and control of the process. Measurements have been mostly executed with the existing (built in) measuring equipment.

The main designed data for the relevant gas turbine are:

Power (ISO: 15 °C, sea level, no inlet or exhaust losses; relative humidity 60%; NCV = 31.5 to 43.3 MJ/nm^3)	5,200 kW$_e$
– Fuel rate	17,200 kW$_{NG}$
– Exhaust flow	78,800 kg/h
– Temperature (turbine inlet)	1,010 °C
– Temperature (turbine outlet)	485 °C
– Electrical efficiency	30.2%
– Compressor discharge pressure	10.8 barg
– Heat-to-power ratio (exhaust temperature 156.3 °C)	1.45

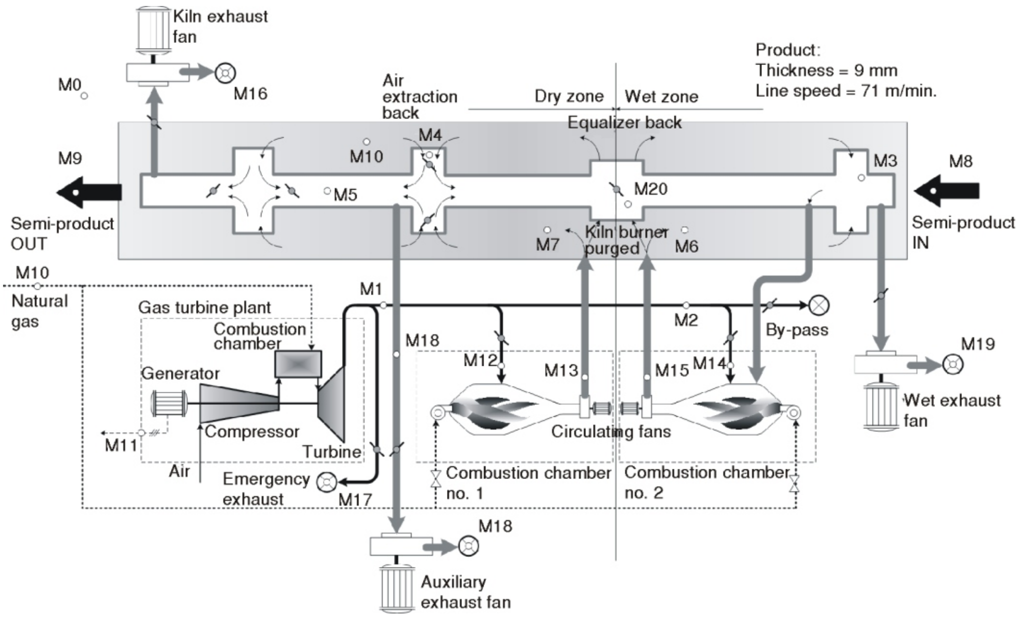

Figure 2. Drying kiln and waste heat recovery unit (circles denote measuring points; measurements are given in tab. 1)

Figure 3 shows the dependence between output power at generator terminal and exhaust temperature and fuel flow rate of natural gas for the average annual ambient temperature of 30 °C. This diagram and other technical data of the given turbine have been used for further calculations.

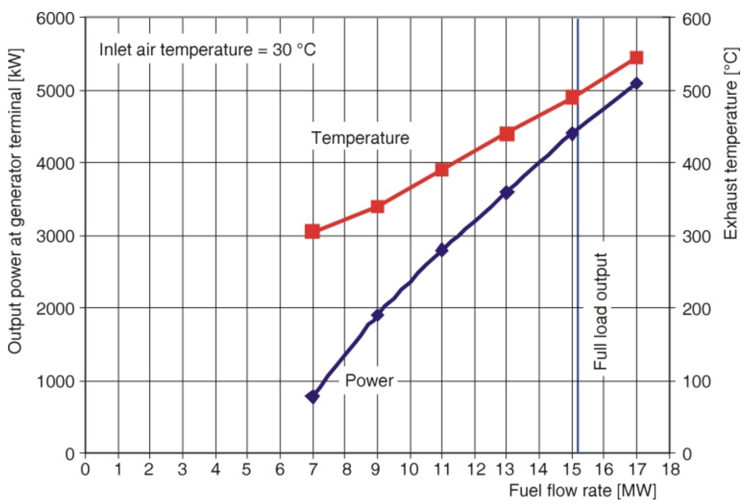

Figure 3. Output power and exhaust temperature *vs.* fuel flow rate

Objectives of analysis

Preliminary analysis of gathered information, processed data referring to the whole factory (overall production, specific consumptions, *etc*.) and preliminary data for the defined ECC – drying kiln have enabled identifying objectives and the development of a working plan within the DEA.

The relation between the cost of electricity and gas is as much as 5.81 (0.0825/0.0142). Such a relation has existed for several previous years. This is extremely favorable for the maximum production of electrical energy. However, in negotiations with the local electricity distribution company (EDC), a very low price for buying up produced electrical energy has been offered. This price has been only 0.0363 US$/kWh. However, an advantage concerns the fact that the delivery of excess electrical energy to the local grid has not been conditioned by delivery periods (peak on, partial peak or peak off). The medium price which the factory pays to the local EDC was in the analyzed period equal to 0.0825 US$/kWh (this unit price is calculated according to monthly invoices and consumed active energy). Also, the price of produced electrical energy in the co-generation plant is calculated and amounted to 0.0781 US$/kWh (the calculation is performed only on the basis of gas consumed for its production). The review of daily and monthly log sheets of the plant's operations enabled conclusion that the average power of the turbine is chiefly around 1,500 kW.

As shown in fig. 3, the existing turbine can achieve a much higher power at working temperature of intake air of around 30 °C.

The above mentioned facts have induced us to propose to the factory's management to give up previous operation procedure of meeting only own consumption needs and to take up an operation procedure which implies maximum production of electrical energy and sale of surplus electricity to the local EDC. Considering the consumption of the heat energy in the drying kiln, there have been no doubts that all available waste heat from the turbine will be absorbed in it.

The inspection of fans, exhaust gases ducts, dumpers and controlling equipment has indicated that such a change of the operation procedure can be implemented without any need for modifications.

We will deal now with measurement results and technical estimations which have been used to assess expected effects of the suggested energy conservation measure.

Measurement, technical calculation, and analysis

Results of measurement are presented in tab. 1. Some measured values have been recalculated in previously used units. On the basis of measured values, it is possible to calculate the degree of the turbine's efficiency. It is equal to 26.0% (2112/8118). The turbine's exhaust gasses temperature was 348.3 °C during measurements. By comparing other measured values with those established for the technological procedure for making of gypsum boards, we have concluded that they are all within allowed ranges.

The co-generation plant worked within all analyzed period (except during annual maintenance period of the gas turbine in December (it lasted 21 days or NOH_{SD} = 504 hours). Average annual generating power (P_e) for gas turbine operating hours NOH_{GT} = 7,448 – 504 = 6,994 h is:

$$P_e \quad \frac{E_e}{NOH_{GT}} \quad 1{,}495\ \mathrm{kW} \tag{1}$$

Average consumption of natural gas for the generation of average electrical power of 1,495 kW is equal to 8.22 × (7,448 – 504) = 57,080 MWh. Power of natural gas for gas turbine only ($P_{NG,Cogen}$ = 8.22 MW) is determined from fig. 3 for average electrical power.

Table 1. Measurements report: Product dimensions: 9 mm SC × 1200 mm; Line speed: 71 m/min.; October 14th

Point	Description	Name	Unit	Result
M0	Ambient	Temperature	°C	32.7
		Relative humidity	%	57.9
M1	Turbine supply to kiln	Temperature	°C	348.3
M2	Turbine supply to wet zone burner	Pressure	mWC	–0.82
M3	Wet zone – returned gas	Temperature	°C	177.1
		Pressure	mWC	0.02
M4	Air extraction	Temperature	°C	121.5
		Dumper position	%	59.1
M5	Dry zone – waste gas	Temperature	°C	95.4
		Pressure	mWC	0.05
		Dumper position	%	39.8
M6	Wet zone	Temperature	°C	237.3
M7	Dry zone	Temperature	°C	147.8
M8	Product – inlet	Moisture	%	40.82
M9	Product – outlet	Moisture	%	13.04
M10	NG consumption	NG power	MW	8.12
M11	Electricity production	Energy	kWh	2112
M12	Turbine supply to dry zone combustion	Dumper position	%	96
M13	Combustion chamber supply to dry zone	Dumper position	%	0
M14	Turbine supply to wet zone combustion	Dumper position	%	100
M15	Combustion chamber supply to wet zone	Dumper position	%	54.3
M16	Kiln exhaust fan	Temperature	°C	103
		Dumper position	%	47.5
		Flow rate	m^3/h	56,520

M17	Emergency exhaust	Temperature	°C	–
		Dumper position	%	0
		Flow rate	m^3/h	0
M18	Auxiliary exhaust fan	Temperature	°C	87
		Dumper position	%	–
		Flow rate	m^3/h	33,840
M19	Wet exhaust fan	Temperature	°C	155
		Dumper position	%	34.6
		Flow rate	m^3/h	43,920
M20	Equalizer back	Dumper position	%	100

Useful heat power, which is used in the kiln, at average output temperature of gases from the kiln of 117 °C, is equal to:

$$Q_{\mathrm{Cogen}} = m_{\mathrm{eg}} \bar{c}_{\mathrm{p,eg}} (T_{\mathrm{eg}} - \bar{T}_{\mathrm{kiln}}) = 4.376 \text{ kJ/s (or kW)} \tag{2}$$

Average output gases temperature from the turbine is 325 °C for average annual power of the turbine of 1,495 kW (fig. 3). Exhaust gases mass flow rate is 72,000 kg/h and is practically constant for all operational loads.

Useful heat energy of the turbine's exhaust gasses is as follows:

$$\dot{Q}_{\mathrm{Cogen}} = 30{,}386{,}944 \text{ kWh (30,387 MWh)} \tag{3}$$

The overall efficiency of the co-generation plant can be found as follows:

$$\eta = \frac{P_{\mathrm{e}} + Q_{\mathrm{Cogen}}}{P_{\mathrm{NG.Cogen}}} 100 = 71.4\% \tag{4}$$

For driving the co-generation plant during the analyzed period of twelve months, the following NG energy was used:

$$\Sigma NG_{\mathrm{Cogen}} = 57{,}079{,}680 \text{ kWh (57,080 MWh)} \tag{5}$$

This, at prices valid at that time, was worth 810,531 US$.

During that period, 10,378 MWh of electrical energy was produced, as well as 30,387 MWh of useful heat energy.

The turbine's waste energy was used together with hot gases made by two combustion chambers (see fig. 2). Total average annual NG power of both turbine and combustion chambers was 14.7 MW. This value is calculated as mean monthly consumption which is measured regularly. Total annual NG consumption for drying kiln was as follows:

$$\Sigma NG_{\mathrm{Kiln}} = 102{,}076{,}800 \text{ kWh (102,077 MWh)} \tag{6}$$

This was worth 1,449,491 US$.

It is now possible to calculate the quantity of consumed gas only for combustion chambers. It is equal to:

$$\Sigma NG_{\mathrm{CC}} = \Sigma NG_{\mathrm{KILN}} - \Sigma NG_{\mathrm{Cogen}} = 44{,}997{,}120 \text{ kWh } (44{,}997 \text{ MWh}) \tag{7}$$

The average power of combustion chambers burners is:

$$NG_{\mathrm{CC}} \quad \frac{\Sigma NG_{\mathrm{CC}}}{NOH_{\mathrm{GT}}} \quad 6{,}480 \text{ kW} \tag{8}$$

If the efficiency of combustion in chambers is equal to $\eta_{\mathrm{CC}} = 0.90$, then the useful heat introduced into the kiln, but only from combustion chambers, equals 0.9 × 44,997,120 = = 40,497,408 kWh. It is now possible to estimate totally delivered heat energy into the drying kiln. It equals Q_{DK} = 40,497,408 + 30,386,944 = 70,884,352 kWh (70,884 MWh). The participation of heat from the co-generation plant is 42.3 %.

During the turbine's overhaul, the production process does not stop, however the consumption of gas in combustion chambers is increased. The power of natural gas during this period can be estimated on the basis of the totally required heat energy, which has just been calculated. Thus:

$$NG_{\mathrm{CC\ \ SD}} \quad \frac{Q_{\mathrm{DK}}}{NOH_{\mathrm{GT}}} \frac{1}{\eta_{\mathrm{CC}}} \quad 11{,}342 \text{ kW} \tag{9}$$

The increased consumption of gas for driving the kiln during the overhaul of the turbine equals to:

$$\Sigma NG_{\mathrm{CC\text{-}SD}} = (NG_{\mathrm{CC\text{-}SD}} - NG_{\mathrm{CC}}) NOH_{\mathrm{SD}} = 2{,}441{,}376 \text{ kWh} \tag{10}$$

This increase can easily be noticed in fig. 1 in the month of December when overhauling was usually performed. However, it should be pointed out that the turbine's overhaul is a very complex operation and it cannot be performed during the factory's short shut-downs.

The energy performance improvements

The suggested measure implies the following:
(a) the drive of the co-generation plant with maximum capacity (with consequential increase of the NG consumption),
(b) complete supply of the factory with electrical energy, and
(c) the sale of surplus electrical energy to local EDC at previously contracted price without preconditions regarding time and quantity of deliveries.

This measure does not require additional investments as it has already been mentioned above because the existing control system enables transfer to the new operation procedure without any limitations.

The turbine's operational parameters at the maximum load can be read from fig. 3. The flow of the turbine's exhaust gases practically does not change with varied loads. The new operational parameters of the turbine at the full load are as follows:

Generated output power:	$P_{\mathrm{e,new}} = 4{,}485$ kW
NG consumption:	$P_{\mathrm{NG,new}} = 15.2$ MW
Exhaust gas temperature:	$T_{\mathrm{eg,new}} = 493$ °C
Exhaust gas flow rate:	$m_{\mathrm{eg,new}} = 72{,}000$ kg/h

Available waste heat energy from the co-generation plant for the kiln (for average temperature of the exhaust gasses from the kiln is as follows (this is the value that has been measured and confirmed by reviewing daily log sheets):

$$Q_{\text{Cogen, new}} = m_{\text{eg}} \bar{c}_{\text{p,eg}} (T_{\text{eg}} - \bar{T}_{\text{kiln}}) = 7{,}911\,\text{kJ/s (kW)} \tag{11}$$

As opposed to the previous case, the output gases temperature from the turbine is now 493 °C.

Annual useful heat of the co-generation plant is:

$$\dot{Q}_{\text{Cogen, new}} = 55{,}498{,}504\,\text{kWh (55,499 MWh)} \tag{12}$$

The power of the natural gas required for producing 5,485 kW of electrical power and useful heat power of 7,911 kW is equal to 15.22 MW (fig. 3).

The efficiency of this co-generation process is:

$$\eta_{\text{new}} = \frac{P_{\text{e, new}} + Q_{\text{Cogen, new}}}{P_{\text{NG, new}}} 100 = 81.4\% \tag{13}$$

It can be noticed that the efficiency of the co-generation plant has been significantly improved. It used to be 71.4% and now expectations can be as much as 81.4%.

The load duration curves for current and proposed operating procedure of this co-generation plant are presented in fig. 4. It has already been pointed out and can easily be noticed that the plant operated under significantly lower load than the load which is possible under given circumstance. This caused the overall efficiency to be 10% lower than the optimum one.

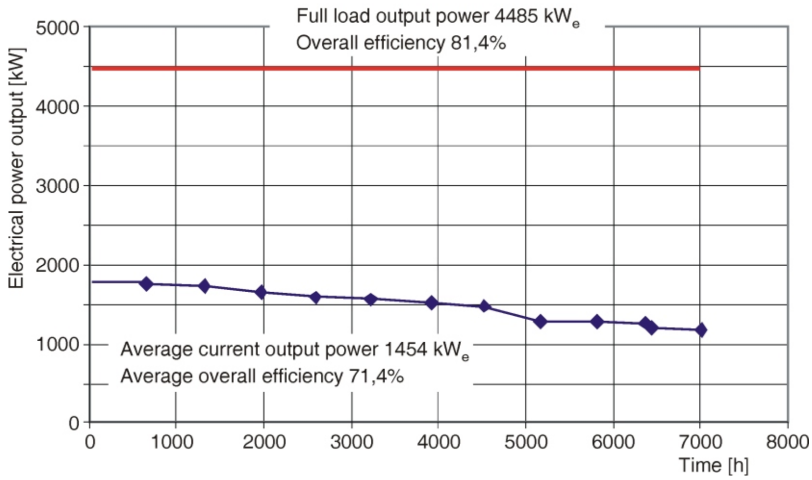

Figure 4. Load duration curve

The gas consumption for driving the turbine in the new regime is as follows:

$$\Sigma NG_{\text{Cogen,new}} = 105{,}548{,}800\,\text{kWh (105,549 MWh)} \tag{14}$$

The required heat energy for driving the drying kiln from combustion chambers can be determined as we know totally required heat energy for running the process and heat energy released under the turbine's full load. In this manner, it is obtained that additional heat energy is required, which is equal to:

$$\dot{Q}_{\mathrm{CC,\,new}} \quad 15{,}394{,}560\ \mathrm{kWh}\ (15{,}395\ \mathrm{MWh}) \tag{15}$$

and gas consumption for driving combustion chambers is:

$$\Sigma NG_{\mathrm{CC,\,new}} \quad \frac{\dot{Q}_{\mathrm{CC,\,new}}}{\eta_{\mathrm{CC}}} \quad 17{,}105{,}067\ \mathrm{kWh}\ (17{,}105\ \mathrm{MWh}) \tag{16}$$

Now, it is possible to estimate overall consumption of NG under the full load of the gas turbine which produced surplus electrical energy. Thus:

$$\Sigma NG_{\mathrm{KILN,\,new}} = 122{,}653{,}867\ \mathrm{kWh}\ (122{,}654\ \mathrm{MWh}) \tag{17}$$

This quantity of gas is worth 1,741,685 US$ (for current regime it is 1,449,491 US$). The increased expense for purchasing gas is 292,194 US$. However, the produced electrical energy is equal to:

$$E_{\mathrm{Cogen,\,new}} = 31{,}143{,}840\ \mathrm{kWh}\ (31{,}144\ \mathrm{MWh}) \tag{18}$$

The overall consumption of electrical energy in the whole factory is 12,292,700 kWh. Energy purchased from the local grid during the shut-down of the gas turbine is 949,520 kWh. This means that it is possible to deliver 31,143,840 – (12,292,700 – 949,520) = 19,800,660 kWh (19,801 MWh). At the price of 0.0363 US$/kWh the worth of electrical energy is 718,764 US$.

Finally, it is possible to calculate ultimate benefit achieved by introducing this simple and no cost energy conservation measure. The following is obtained:

$$\text{Expected benefit} = 718{,}764 - 292{,}194 = 426{,}570\ \text{US\$}\ (0.43\ \text{million US\$}) \tag{19}$$

This saving amounts to as much as 17.4% of the overall expense for energy existent at that time.

Environmental impact

As it has already been mentioned, it is very difficult to estimate the environmental impact of any energy conservation measure as precise standards do not exist. One of the most serious issues involves the lack of reliable data concerning emissions of large plants for the production of electrical energy which are usually parts of national energy systems.

In this given case the consumption of the NG has been increased from the current 102,076,800 kWh to 122,653,867 kWh (20.2%), but the production of electrical energy in the same plant has been increased for almost 200% (from 10,378,700 to 31,143,840 kWh), and the production of heat energy has been increased for 82.6% (from 30,386,944 to 55,498,504 kWh). At the same time, the consumption of NG in combustion chambers has been reduced for 62.0% (from 44,997,120 to 15,394,560 kWh).

By using data concerning emissions of certain plants [17], it is possible to establish the balance of CO_2 emissions for observed plants (tab. 2). We have not performed estimates of real emissions of certain exhaust gases as this requires proper chemical composition of fuels (NG) and measured data of exhaust gases. We have used estimates given in the above mentioned tables. The increased production of electrical energy in the new operation procedure has been expressed by the production of electrical energy in central power plants fired by coal, heavy fuel oil (HFO) and NG. It is obvious that results are different in these three cases. However, it is evident that there is a significantly reduced emission of CO_2 in the case of the suggested solution. Valuation of this positive effect varies in different countries, but it is possible to say that presently generally accepted valuation of this effect does not exist. The same is with the emission of other gases and particles.

General conclusion is that by applying this measure, it is possible to achieve significant reduction of harmful emissions.

Table 2. CO_2 balance

	Current	New
Co-generation plant	10,378,700 × 808.16 = 8,388 t/a	31,143,840 × 808.16 = 25,169 t/a
Combustion chamber	44,997,120 × 252.55 = 11,364 t/a	15,394,560 × 252.55 = 3,888 t/a
Electrical energy generated somewhere else	31,143,840 – 10,378,700 = 20,765,140 Coal: 20,765,140 × 1134.20 = 23,552 t/a HFO: 20,765,140 × 887.06 = 18,420 t/a NG: 20,765,140 × 594.24 = 12,335 t/a	
Total	Coal: 43,303 t/a HFO: 38,172 t/a NG: 32,087 t/a	29,057 t/a

Conclusions

It is quite rare that in real conditions a plant or a facility operates under design parameters. In the project design stage, operating conditions which are at that time known are adopted, as well as legal regulations and economic parameters (energy prices, interest rates, *etc*.). Even at the very moment when the plant is put into operations, these conditions can be substantially different. For that reason, it is necessary to perform constant audits of operation procedure and carry out permanent optimization of the plant's operations in line with previously established criteria. It is typical for co-generation plants that they are very sensitive to changes of these relevant parameters and the need for this type of optimization is even more pronounced. The reason for that is the existence of two mutually "dependent" outputs (electricity and heat) and relatively high investment in relation to classical plants for the production of electricity and heat. Namely, electricity is bought from the public grid and heat is generated in relatively cheap boilers.

This paper analyzes real life example of the gas turbine operation in the drying kiln. The gas turbine is not a necessary part of the drying process but with its construction the drying kiln was given an opportunity to increase energy efficiency of the whole process. Since the drying process in the gypsum factory represents the single largest energy consumption, optimization of the drying kiln operations certainly affects the factory's economics. Although this paper shows one case which does not refer to optimal, it provides a solution for changing the process management procedure which may lead to considerable energy, environmental and financial effects.

From practical experience, we can say that many plants which have been adjusted once do not undergo any checks relevant to applied operational procedure irrespective of the fact that there has been a disruption in relevant parameters. All this is the task of energy management which must continually optimize all energy flows. Further investigations should primarily cover the assessment of potentials of such a measure in increasing energy efficiency on plant, regional and national levels. In technical sense, these measures are very simple and cheap and require good knowledge of the process which operational procedure has to be managed.

References

[1] Griffiths, R. T., Combined Heat and Power, Energy Publications, ISBN 1-874334-04-8, 1995
[2] Brown, K., Minett, S., History of CHP Developments and Current Trends, *Applied Energy, 53* (1996), 1-2, pp. 11-22
[3] Brown, M., Minett, S., Market Study on Industrial Energy Outsourcing, Undertaken by Delta Energy & Environment for the European Bank for Reconstruction and Development, 2003, http://www.ebrd.com
[4] ***, CHP Resource Guide, Oak Ridge National Laboratory, 2003
[5] ***, Cogen 3: Proven, Clean & Efficient Biomass, Coal and Gas Co-Generation, Cal Bro Intelligent Solution, 2004
[6] Holcomb, F. H., Binder, M. J., Taylor, W. R., Co-Generation Case Studies of the DoD Fuel Cell Demonstration Program, Presented at the IQPC F-CELLS Stationary Conference, London, 2000
[7] ***, Roadmapping of the Paths for the Introduction of Distributed Generation in Europe, http://www.dgfer.org
[8] Gvozdenac, D., *et al*., Assessment of Potential for Natural Gas-Based Co-Generation in Thailand, *Energy*, *34* (2009), 4, pp. 465-475
[9] Moravy, Z., Gvozdenac, D., Applied Industrial Energy and Environment Management, John Wiley and Sons, N. Y., USA, 2008
[10] Cullen, J. M., Allwood, J. M., Theoretical Efficiency Limits for Energy Conversion Devices, *Energy, 35* (2010), 5, pp. 2059-2069
[11] Kimberly, C. M., Curran, L. M., Perspective: REDD Pilot Project Scenarios: Are Costs and Benefits Altered by Spatial Scale? *Environmental Research Letters, 4* (2009), 3, pp. 031003-031006
[12] Polyzakis, A. L., *et al*., Long-Term Optimization Case Studies for Combined Heat and Power System, *Thermal Science, 13* (2009), 4, pp. 49-60
[13] Ferdelji, N., Galović, A., Guzović, Z., Exergy Analysis of a Co-Generation Plant, *Thermal Science, 12* (2008), 4, pp. 75-88
[14] Ravi Kumar, N., Rama Krishna, K., Sita Rama Raju, A.V., Thermodynamic Analysis of Heat Recovery Steam Generator in Combined Cycle Power Plant, *Thermal Science, 12* (2008), 4, pp. 143-156
[15] Smolen, S., Budnik-Rodz, M., Technical and Economic Aspects of Waste Heat Utilization, *Thermal Science, 11* (2007), 3, pp. 165-172
[16] ***, Directive 2004/8/EC of the European Parliament and the Council, 2004
[17] ***, Guidelines for the Measurements and Reporting of Emissions in the UK Emission Trading Scheme, http://www.actionenergy.org.uk

Paper submitted: Maj 16, 2010
Paper revised: June 27, 2010
Paper accepted: June 29, 2010