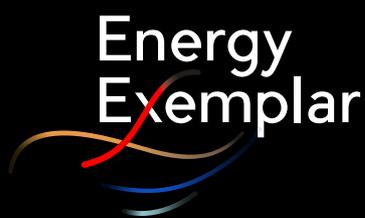


# OPTIMIZING THE OPERATION OF COGENERATION PLANTS IN A COMMON MODEL OF POWER AND GAS SYSTEMS



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# OPTIMIZING THE OPERATION OF COGENERATION PLANTS IN A COMMON MODEL OF POWER AND GAS SYSTEMS

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## Abstract

The interaction between different energy markets, such as natural gas or coal, and electricity markets is increasingly present in the energy sector. By reducing available reserves, dependence on imported gas in the future will surely rise, and this is a challenge that will require new solutions to maintain the safety of power system. Renewable energy sources' share of power system production already plays a significant role, and according to many forecasts, a tendency for further growth is anticipated. Considering their volatility and impact on electricity market prices, it is clear that plant optimization will be more complex.

The primary objective of optimization is to meet the demand for heat energy but also to minimize fuel costs and include revenue from the sale of electricity and heat. The higher price of natural gas or lower electricity prices in the market is analysed long with the extent of their impact on the engagement of modelled power plants. The impact on the use of the gas system unit includes the supply of natural gas from gas pipelines to gas pipeline transport and the use of gas storage facilities.

The work includes the modelling of thermal power plants and cogenerations plants in the PLEXOS programming tool.

The model of cogeneration plants and gas system enables co-optimization of the gas and power system. Primarily, this option is used when connecting power plants that use natural gas as fuel directly to the gas grid. It is possible to consider the prices in the electricity market and the natural gas market, which definitely increase the range of possible solutions in model optimization.

The model was applied in the case of the Republic of Croatia and the work includes the modelling of thermal and cogenerations power plants in the HEP production d.o.o. The model and simulations contain units that are still in the construction and design phase. With this, the results of the budget show how the unit engagement would take place if all were built and run in the time observed in the simulations. In the gas system of the Republic of Croatia, the transport system and the underground gas storage is modelled with the most important characteristics: maximum and minimum capacity of injection and withdrawal.

**Keywords:** PLEXOS, gas system, thermal power plant, energy market, cogeneration

# 1. INTRODUCTION

During the last decade, the world electricity sector has been undergoing drastic changes. The integration of a large number of renewable energy sources (RES), mostly wind power plants, into the systems poses many challenges. One of the most significant is the system security maintenance considering the volatility of newly installed RES capacities. Namely, the energy supplied by such sources varies from hour to hour, which makes a new phenomenon when compared to the conventional power plants, such as coal or nuclear, upon which the past power sector was based.

The battery storage facilities have not yet made enough technological advancements to provide effective and economically profitable storage of the residue energy in the periods when the energy consumption is low, i.e., discharging stored energy when consumption is increased or is lacking energy in the system. Power plants that use natural gas as a fuel are considered as a transition towards the higher integration of RES.

The ability for a quick start of the natural gas power plants is certainly the feature that responds to the above RES volatility challenge. Also, natural gas power plants are distinct to the coal power plants due to the lower emission of pollution gasses, which is in line with low-carbon future goals. Another positive feature of gas turbine power plants is their ability to build a cogeneration system for satisfying electricity and heat demand.

This study includes modelling of thermal power plants (TPPs) and heating plants (HPs) in the portfolio of HEP Generation Ltd. using the PLEXOS software tool. The model and simulations contain the units that are still under the building and design phases. Consequently, the results of calculations show how the units would be engaged as if they were already built and in operation mode at the observed time in the simulations.

## 2. NATURAL GAS SYSTEM OF THE REPUBLIC OF CROATIA

The Republic of Croatia exploits the natural gas from 17 exploitation fields onshore (Pannonian Basin System) and three offshore (North Adriatic see) what covers 63,1% of domestic consumption. The natural gas production from the Pannonian basin is slightly higher compared to the Adriatic (see gas production). Most of the Pannonian reserves come from the reservoirs at Molve, Kalinovac and Gola. In recent years, observations showed the continuous decrease of the production and decrease of the reserves of natural gas in Republic of Croatia. In combination with the increase of gas consumption, Croatia will become increasingly dependent on imported gas, which gives rise to the need for diversification of the imported gas to enable competitive prices and decrease the dependency on natural gas from Russia.

### 2.1. Transport system

The natural gas transport system is regulated energy activity, which is performed as a public service. The company PLINACRO Ltd. is the owner and operator of the gas transportation system, consisting of the international, magistral, regional and separated gas pipelines and objects on the pipelines, measurement reduction stations (MRS) of various capacities and systems that enable reliable and safe operation.

### 2.2. Underground gas storage Okoli

The underground gas storage (UGS) Okoli is located at Velika Ludina in the Sisak-Moslavina County. It includes the so-called seasonal storage facilities as it has the possibility of storing large amounts of gas and regulation of the production and injection cycle within one calendar year. The maximum designed storage volume is 553 million m<sup>3</sup>[1]. The storage process takes place in two cycles: injection (April – October) and production (October – April). The most important technical characteristics are:

- Maximum injection capacity: 4.32 mil. m<sup>3</sup>/day, 180,000 m<sup>3</sup>/h
- Maximum production capacity: 5.76 mil. m<sup>3</sup>/day, 240,000 m<sup>3</sup>/day
- Minimum injection capacity: 30,000 m<sup>3</sup>/h
- Minimum production capacity: 20,000 m<sup>3</sup>/h

### 3. DESCRIPTION OF THE EXISTING HEATING PLANTS AND THERMAL POWER PLANTS IN THE HEP GENERATION LTD. PORTFOLIO

#### 3.1. About the Croatian power system

The electricity production capacities of the HEP Group include 17 large hydropower plants, seven TPPs and half of the installed capacity in the nuclear power plant (NPP) Krško. TPP Plomin d.o.o. is using the coal for its electricity production. At the Croatian territory, the total installed capacity is 4,105 MW (without NPP Krško) with the total electricity production of 9,536 GWh in 2016. With an additional 50% of the power production of the NPP Krško, the total installed capacity increases to 4,453 MW with another 2,715 GWh of electricity production.

Among other installed capacities that are not within the HEP Group, the most significant are the wind power plants with total installed capacity of 483 MW and electricity production of 1,014.2 GWh in 2016.

The HEP Group portfolio also includes cogeneration (CHP) plants: TE-TO Zagreb, EL-TO Zagreb, TE-TO Osijek and TE-TO Sisak.

### 4. THE MODEL OF THE COGENERATION POWER PLANTS AND GAS SYSTEM

#### 4.1. Description of the PLEXOS software

The optimisation model was created with the software tool *PLEXOS* by *Energy Exemplar*. The PLEXOS tool is a simulation-optimisation software, which can make models, simulations and analysis of the energy systems and markets [2]. The data that includes techno-economic parameters of all TPP and HP units in the model is provided by the HEP Group. Some of the main characteristics are:

- Maximum capacity of generator and boiler [MW]
- Technical minimum of the generator [MW]
- Specific fuel expenses depending on the amount of produced energy [GJ/MWh]
- Initial costs [€]
- Costs of ramp up and ramp down [MW/min]

This study includes the development of a gas model, which can be integrated with the power system into one unit. The model requires a large amount of input data of the heat demand (heat and process steam) which was also provided by the HEP Group. As HPs and TPPs are most often used for satisfying the heat demand, the model does not include electricity consumption, but it is sold out on the market.

The optimisation algorithm, as mentioned before, has been made for satisfying the heat and process steam demand. Therefore, the goal is to maximise operative profit which depends on variable expenses of the units and revenues from the sale of electricity and heat:

$$\max \sum_{h=1}^n \sum_{u=1}^m P_{EE,h} \times Q_{E,h,u} + P_h \times Q_{H,h,u} + P_s \times Q_{S,h,u} - P_{G,h} \times F_{G,h,u} - P_{EM} \times Q_{EM,h,u} \quad (1)$$

where:

- $P_{EE}$  – electricity price
- $Q_{E,u}$  – amounts of produced electricity of the u-unit
- $P_h$  – heat price
- $Q_{H,u}$  – amount of the heat of the u-unit
- $P_s$  – process steam price
- $Q_{S,u}$  – amount of the process steam of the u-unit
- $P_G$  – price of the natural gas
- $F_{G,u}$  – amount of the natural gas of the u-unit
- $P_{EM}$  – price of the emission units
- $Q_{EM,u}$  – amount of the emissions of the u-unit
- $h$  – time (hour or day)

<sup>1</sup> The information provided in this chapter is taken from the documents "Energy in Croatia 2016"(EIHP and MZOIE) [7], "Optimisation of gas thermal power plants and thermal power plants in Croatian electrical energy system"(EIHP)[8], HEP d.o.o. [9] and the resulting model in PLEXOS.

## 4.2. Natural gas model

PLEXOS software includes a modelling option of the gas system, which can be used for the short-term or long-term simulations. An additional feature is a co-optimisation of the gas and power system which provides numerous additional modelling options. Primarily, this possibility is used to connect power plants that use natural gas as fuel directly to the gas pipeline network. Following that, the electricity market prices and gas market prices can be taken into account. That extends a range of possible solutions for the model optimisation. The basic principle of the gas system connection is depicted in the Figure 1.

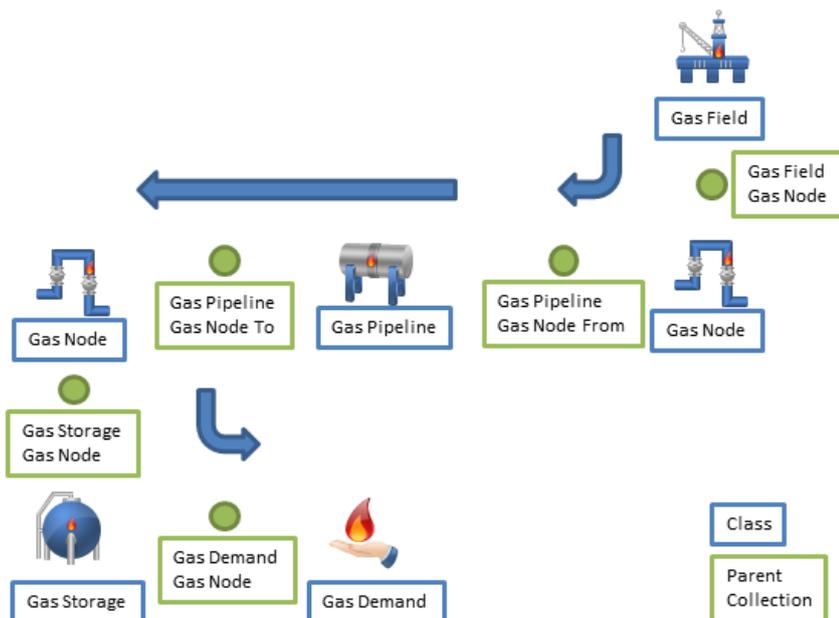


Figure 1: Model of the natural gas system in the PLEXOS software

As with the power model, it is possible to assign any rule via constraints, decision variables and conditional clauses.

## 4.3. Power and natural gas model

Integration of the power and natural gas systems can be made by connecting generators on a gas node while simultaneously connecting the fuel on the same gas node, meaning it is necessary to achieve the membership between generator and fuel; generator and gas node and fuel and gas node.

### 4.3.1. Input data of the gas model

The main elements of the gas system and the appearance of the model are shown in Figure 2. Natural gas at the area of the Republic of Croatia is modelled with object Gas Field, including parameters:

- Initial volume: 513,550 TJ (total reserves in 2016)
- Cost: 5.55 €/GJ (transport costs included)

Daily production has been taken from the web page of the PLINACRO Ltd. [4], but it is important to note that only 20% of the daily domestic production could be used for the HPs and TPPs of the HEP group due to the distribution obligations.

The gas trade market is modelled with the object *Market* connected on the gas node "AU exchange". The prices on the market have been entered according to the data from Middle Europe gas node "CEGH" provided by the HEP Inc.

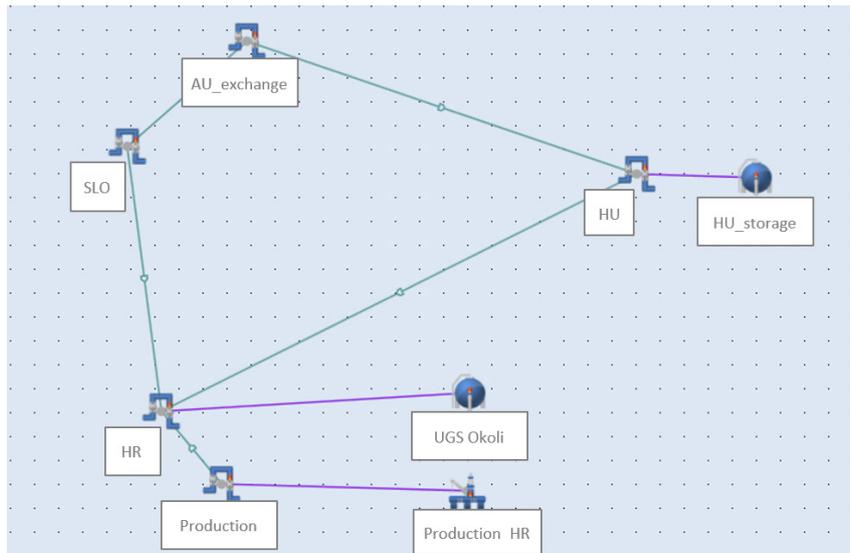


Figure 2: Model of the natural gas system modelled in the PLEXOS software

An important relation to the gas system is *tariffs* of gas passing through the transport system of the countries included in the transport. Gas is traded on the Austrian market and, depending on the transport prices, passes through Slovenia and Hungary. Regarding simplicity, the tariff prices are modelled daily according to the achieved agreement of the transport amounts on a fixed price.

The prices of the storage are defined according to the prices defined by law and published in *Official Gazette* [5].

Hungarian gas storages are gathered to one object. Technical data are taken from the webpage of the gas infrastructure of Europe . The prices are defined according to the equation [6]:

$$TM = 0,3337 \times \left[ \text{MAX}\left(1; 133,33 \times \frac{B}{M}; 70,31 \times \frac{K}{M}\right) + \frac{133,33}{\text{MIN}\left(133,33; \frac{M}{B}\right)} + \frac{70,31}{\text{MIN}\left(70,31; \frac{M}{K}\right)} \right] \quad (2)$$

where:

- TM – storage tariff (HUF/kWh/year)
- M – total leased capacity (kWh)
- B – leased capacity of the gas injection (kWh/day)
- K – leased capacity of the gas production (kWh/day)

<sup>2</sup> Gas Infrastructure Europe; <https://agsi.gie.eu/>

## 4.4. Thermal power plants and heat plants models

The optimisation model with the technical parameters of the EPP-HP Zagreb, HP-TPP Zagreb, HP-TPP Osijek, HP-TPP Sisak are provided by the HEP d.d. The model includes current units which are the same as the ones in the building and project phase mentioned in chapter 4.

### 4.4.1. Modelling of combined heat and power plant (CHP)

On the Figure 3, the combined cycle CHP (CCGT-CHP) principal model is depicted which was used in this study. The first part is comprised of a gas turbine (GT), which is using gas as a fuel, and in combination with the generator generates electricity, which is being delivered to the consumers. Waste heat from the gas turbine is discharged to the waste heat boiler (KNOT) and two additional virtual units are defined (KNOT heat and KNOT steam) which are using the virtual fuel.

KNOT heat takes some of the heat out of the boiler and immediately delivers it according to the heat demand. The second part consists of virtual steam subtraction units (there are two subtractions in the shown case) and a steam turbine. The amount of produced steam for the second part of the model is required for satisfying the energy needs that have to be equal to the amount of the steam generated by "KNOT steam".

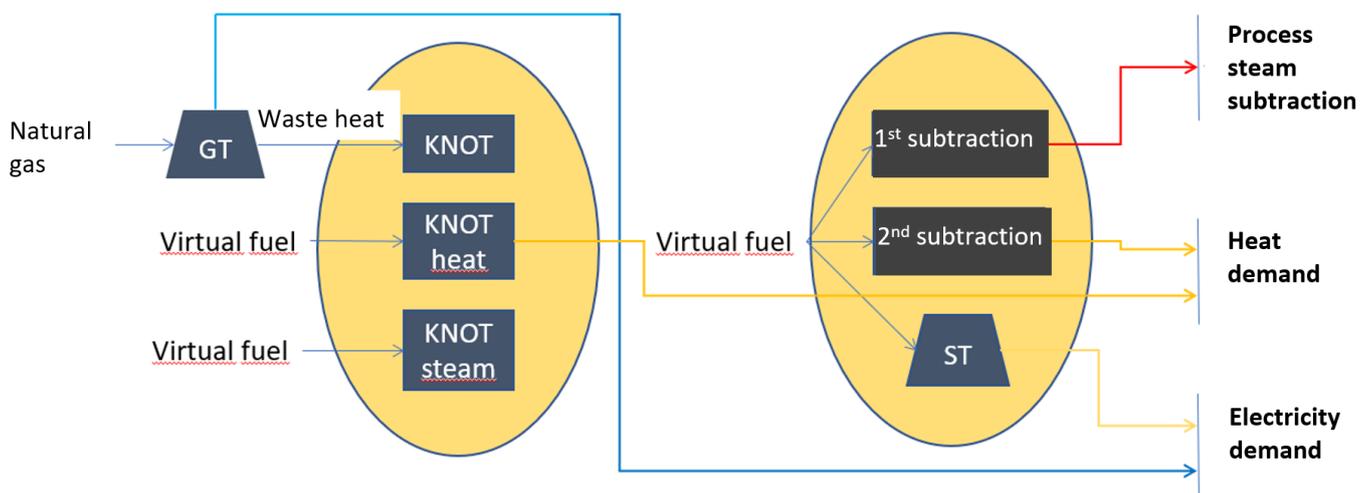


Figure 3: Model of the CCGT-CHP plant

## 4.5. Other input data

The simulation requires additional inputs without which it is impossible to start a calculation. That includes:

- Hourly electricity prices
- Hourly rates of heat demand for each plant
- Hourly rates of technological steam demand for each plant
- Costs of units: 8.5 [€/t]
- Sales price of heat: 45.06 [€/MWh]
- Sales price of process steam: 31.79 [€/MWh]

Data for all the mentioned items were provided by HEP d.d.

## 5. SIMULATION RESULTS

The results of all calculations are based on the mid-term simulations (MT Schedule).

## 5.1. Baseline scenario

Due to the optimization of operation of gas storage facilities in which gas injection and withdrawal take place in two cycles per year, a minimum period of two years should be taken. Therefore, years 2015 and 2016 were selected for the Baseline scenario. It is important to note that the simulation results also include units that are still under construction or in the design phase and thus the data obtained will not fully correspond to the actual values recorded for the observed period.

### 5.1.1. EL-TO Zagreb

The demand curves for heat and process steam for EL-TO Zagreb are shown on the Figure 4. It is clearly shown that due to the high temperatures, the demand for heat falls to about 10 percent of winter values in the summer. Because technological steam is used in the industry, changes in the summer are not as significant as they are for heat, but there is also a decline in demand.

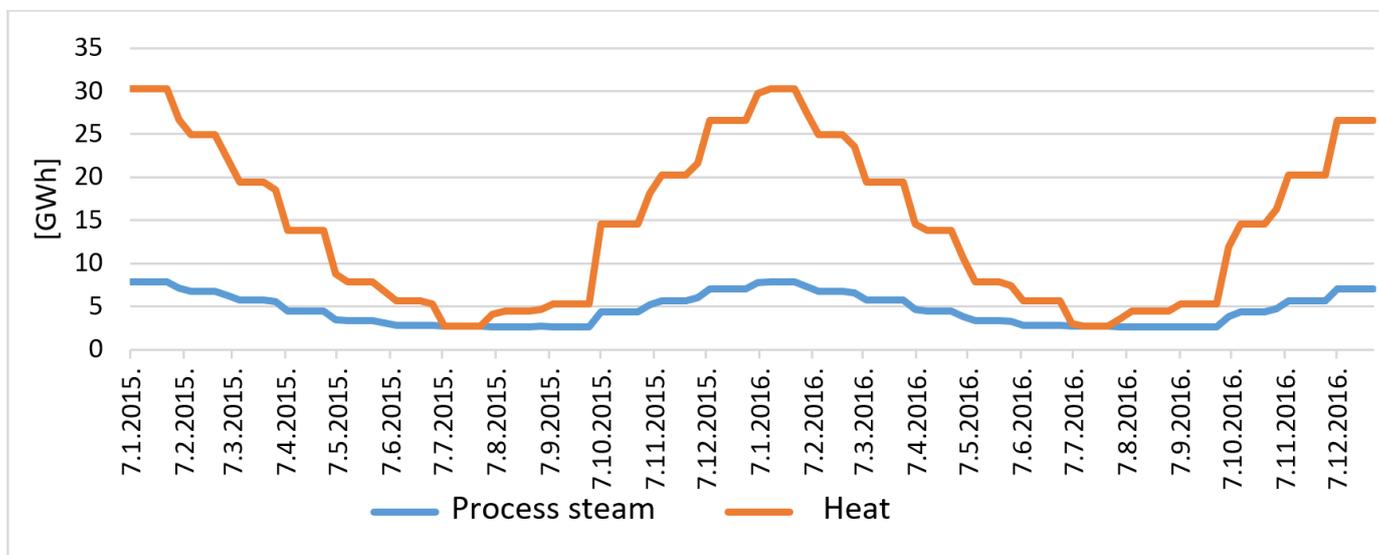


Figure 4: Weekly demand for technological steam and heat for the facility EL-TO Zagreb

Figure 5 also shows that the electricity productions of units H and J in the summer are almost zero. This is because, in the absence of heat demand, the cogeneration units H and J are too expensive to be deployed.

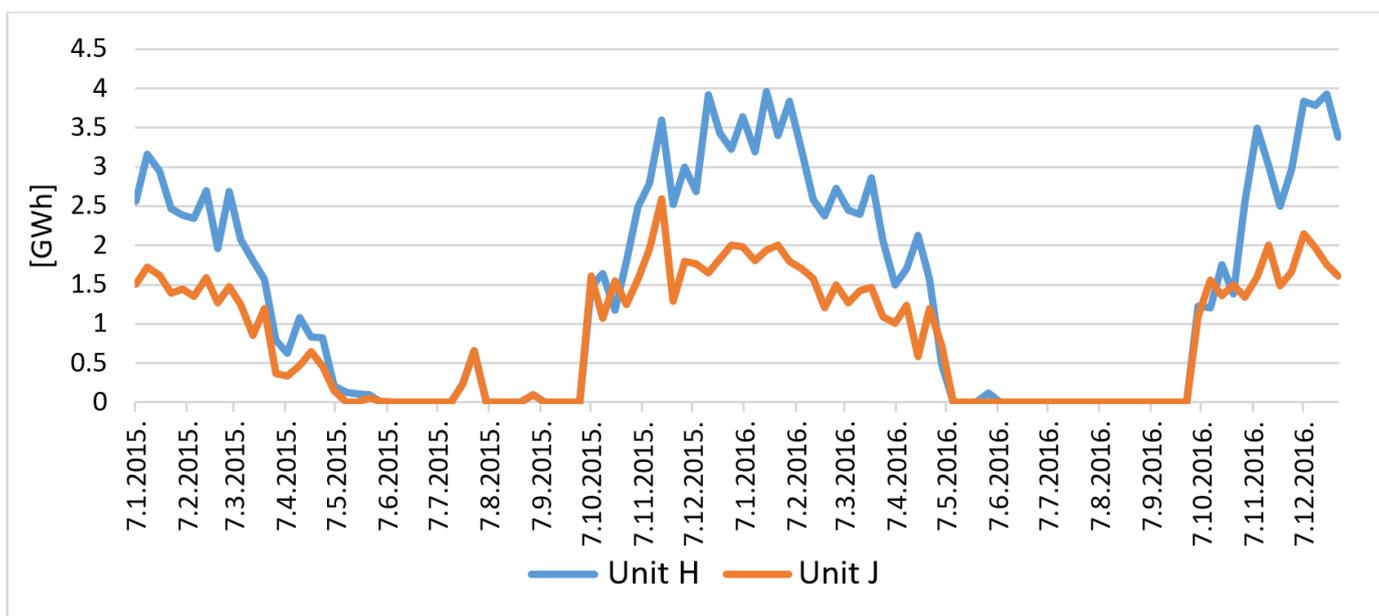


Figure 5: Electricity production of the blocks H and J of the facility EL-TO Zagreb

### 5.1.2. TE-TO Zagreb

The demand curves for process steam and heat are shown in Figure 6. As in the case of EL-TO Zagreb, a characteristic decrease in heat demand during the summer months is also visible for TE-TO Zagreb.

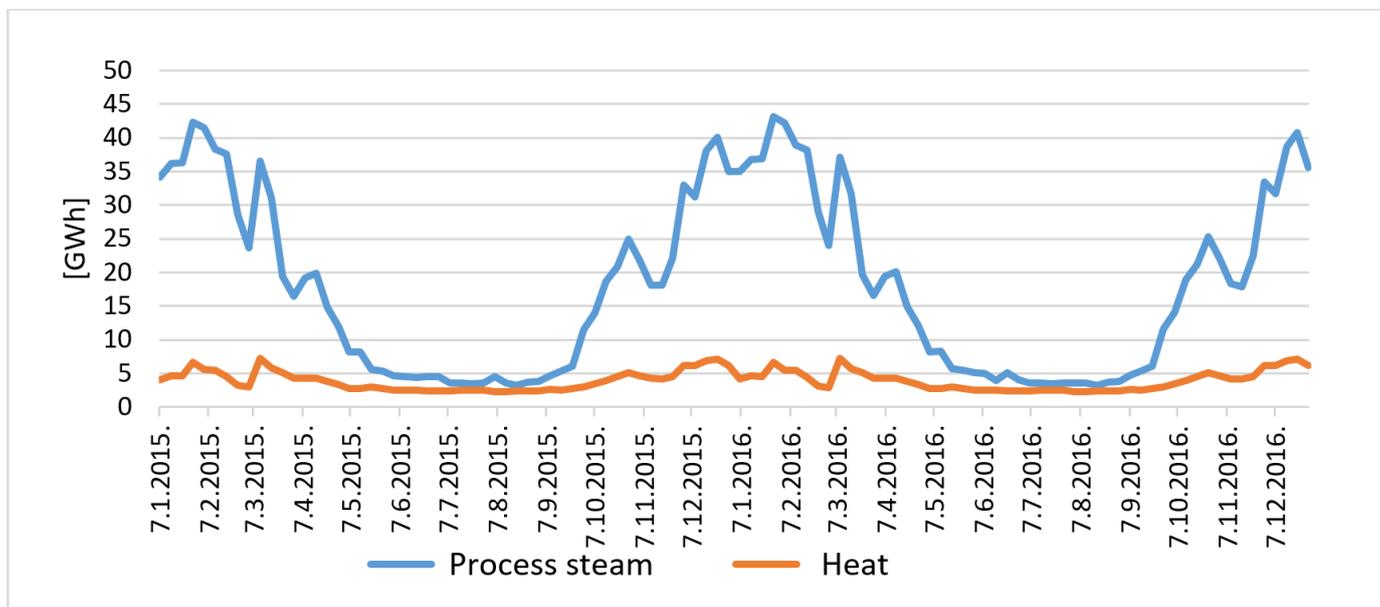


Figure 6: Weekly demand for process steam and heat for the facility TE-TO Zagreb

### 5.1.3. TE-TO Sisak

Process steam is the only form of heat demand (shown on the Figure 7) for the facility TE-TO Sisak.

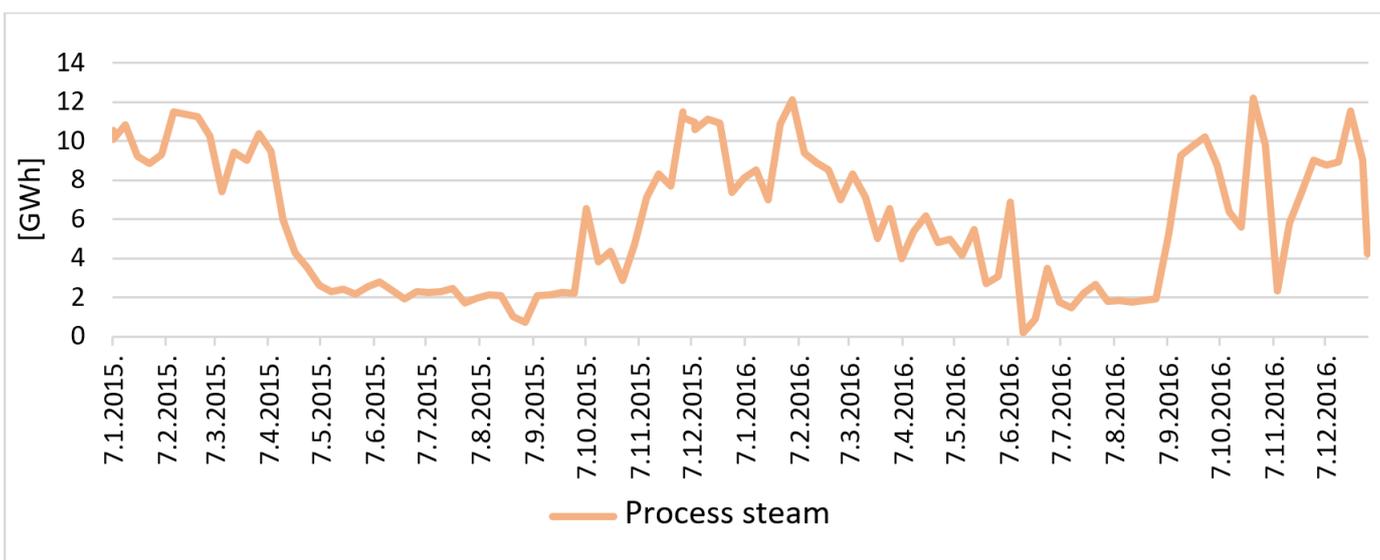


Figure 7: Weekly demand for technological heat for the facility TE-TO Sisak

Due to the preferential price of the biomass-fired CHP plant (BE-TO Sisak), it produces maximum power throughout the whole year and participates with 3 percent of total production of the TE-TO Sisak.

The heat demand for the TE-TO Osijek plant drops to zero during the summer months and steam boilers are used only to meet the demand for process steam (Figure 8). Due to the preferential price (same as BE-TO Sisak), BE-TO Osijek produces maximum power throughout the year and accounts for six percent of total electricity production in 2015 and five percent in 2016. The new block B produces the rest of the EE and is characterized by a much lower fuel cost.

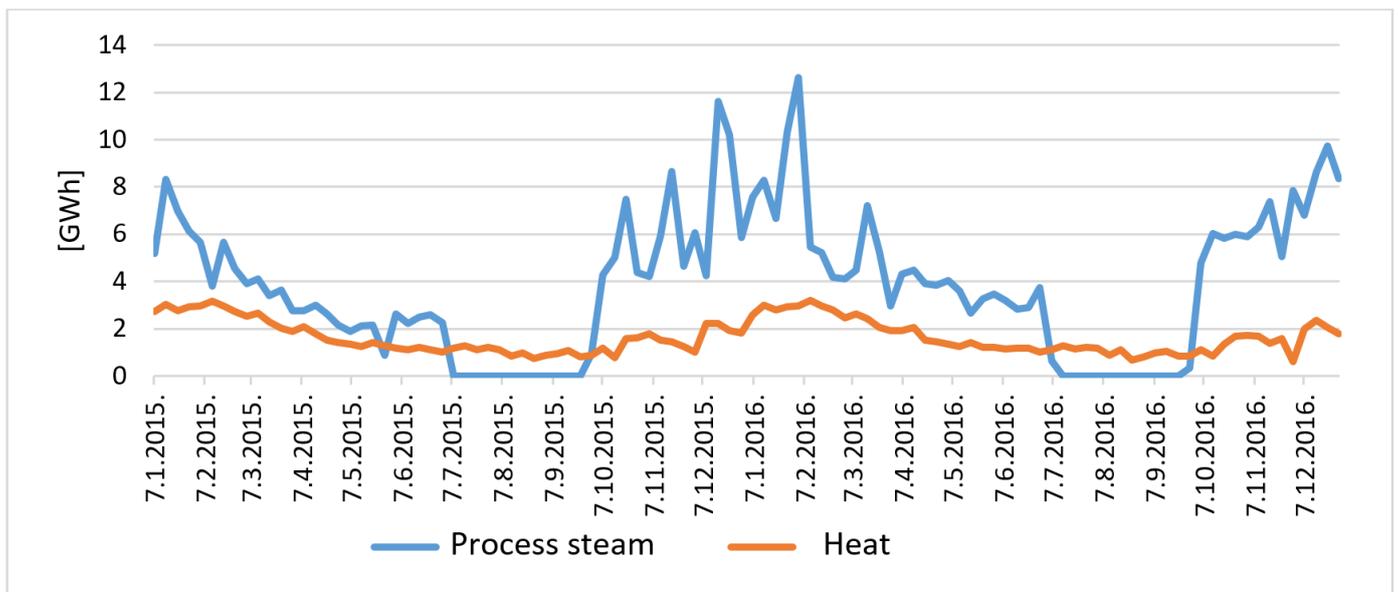


Figure 8: Weekly demand for process steam and heat for the facility TE-TO Osijek

### 5.1.4. Natural gas

The gas needs of the model are met by purchasing on the gas market located in Austria and through domestic production from gas fields in the Republic of Croatia. In 2015, a total of 8,335.15 TJ of natural gas was supplied from the gas fields of the Republic of Croatia, while in 2016 domestic gas was not used at all for the operation of units. This is due to the lower gas prices on the market shown in Figure 9. Since the price of natural gas from the Republic of Croatia is € 5.55 / GJ, it is more worthwhile to buy gas on the market and thus meet the needs of the plant.

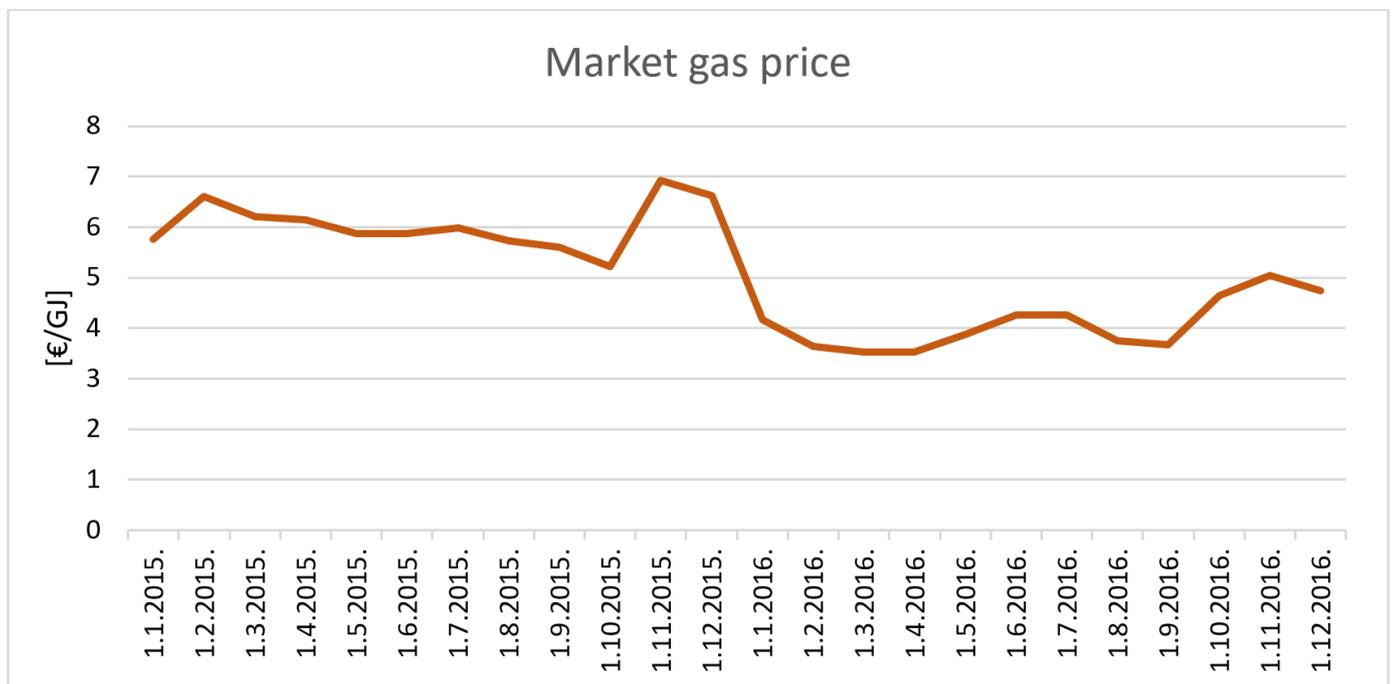


Figure 9: Average monthly market prices

Transport of gas from the market in Austria is mainly made through Slovenia. Sixty-two percent of total gas consumption in 2015 was transported through pipelines through Slovenia, and in 2016 that share rose to as much as 82 percent of total consumption. Gas pipelines through Hungary delivered two percent of gas in 2015, while in 2016 that share rose to 18 percent – primarily due to the use of gas storage facilities.

The use of gas storage is much more pronounced in 2016 (Table 1). This is due to lower natural gas prices on the market.

Table 1: Gas storage in Baseline scenario

Gas storages	2015	2016
HU_storages (TJ)	504.79	2,946.84
PSP Okoli (TJ)	469.65	5,896.80
Cost HU_storages (€)	431,544	2,519,257
Cost PSP Okoli (€)	461,604	5,795,797
Total cost of storing (€)	893,148	8,315,054

## 5.2. Scenario of increased cost of gas on the market ("Expensive gas")

The purpose of a scenario with 10 percent cost appreciation of natural gas is to show the impact of fuel prices on the engagement of electricity and gas system units, and on the value of total costs and revenues covered by the model. The increase was modelled by simply raising the daily price values in the base case market by 10 percent, as shown in Figure 10. Other inputs are the same as in the case of the baseline scenario.

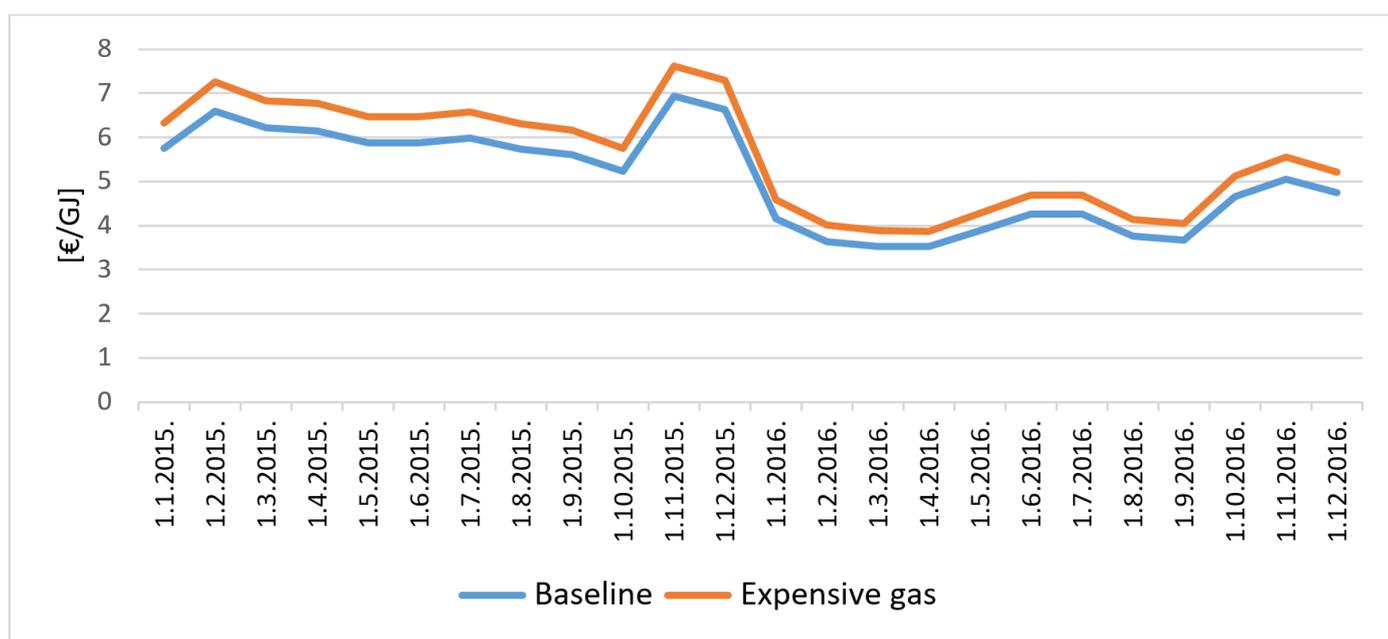


Figure 10: Average monthly costs of natural gas (Baseline scenario and Expensive gas scenario)

### 5.2.1. Scenario comparison – gas system

The supply of natural gas from the Republic of Croatia for the first year of simulations is almost equal in both scenarios. The difference is observed in the second year of the simulation, where in the baseline scenario there has no supply at all from the Republic of Croatia, while in the gas price scenario there is a supply of 1,282.96 TJ. The total percentage increase from the base year is 19.9 percent.

Higher market prices for natural gas result in lower gas supply from the market itself. Interestingly, a 10 percent increase in prices results in as much as 26.8 percent less transport through Hungary, and 17 percent less transport through Slovenia. The reduction in transportation costs is proportional to the reduction in transport due to the unique cost of passing through gas transmission systems during the year.

The use of gas storage facilities, as well as gas transportation, are reduced in the Expensive gas scenario. Table 2 shows a greater decrease in the use of Hungarian gas storage facilities. The biggest reason for this is of course the tariffs of transport systems. As gas storage tariffs are the same throughout the year, there is a proportional reduction in gas storage costs.

Table 2: Gas storage (Baseline scenario and Expensive gas scenario)

Gas storages	Baseline scenario	Expensive gas scenario	Difference (%)
HU_storages (TJ)	3,451.63	2,538.22	-26.5
PSP Okoli (TJ)	6,366.45	5,960.77	-6.4
Cost HU_storages (€)	2,950,801	2,169,928	-26.5
Cost PSP Okoli (€)	6,257,401	5,858,675	-6.4
Total cost of storage (€)	9,208,202	8,028,603	-12.8

## 5.2.2. Scenario comparison – power system

Input data on heat demand are the same for both scenarios. As the satisfaction of thermal consumption is the primary task of modelled thermal power plants, changes in the Expensive gas scenario are related to the production of electricity. The decrease in electricity production for the Expensive gas scenario is 14.8 percent (Table 3), while the total gas consumption is lower by 15.2 percent. It is interesting to note that although total costs fell by 8.8 percent, EE sales revenue fell by as much as 12.8 percent. This certainly shows how important it is to monitor prices in both the EE and natural gas markets.

Table 3: Power system (Baseline scenario and Expensive gas scenario)

	Baseline scenario	Expensive gas scenario	Difference (%)
Total electricity production (GWh)	6,375.62	5,431.58	-14.8
Total natural gas consumption (TJ)	52,778.05	44,741.90	-15.2
Fuel costs (€)	295,239,689	270,814,292	-8.3
Emissions costs (€)	25,167,212	21,335,175	-15.2
Total costs (€)	320,406,901	292,149,467	-8.8
Revenue from the sale of electricity (€)	292,913,185	256,596,023	-12.4

## 5.3. Scenario of lower costs of electricity on the market ("Cheaper electricity scenario")

Similarly, as with the gas price scenario, the Cheaper electricity scenario demonstrates the impact of market electricity prices on the employment of electricity and gas units, as well as on the value of total costs and revenues covered by the model. Daily price values are lowered by 10 percent compared to the baseline scenario (Figure 11). Other inputs are the same as in the baseline scenario.

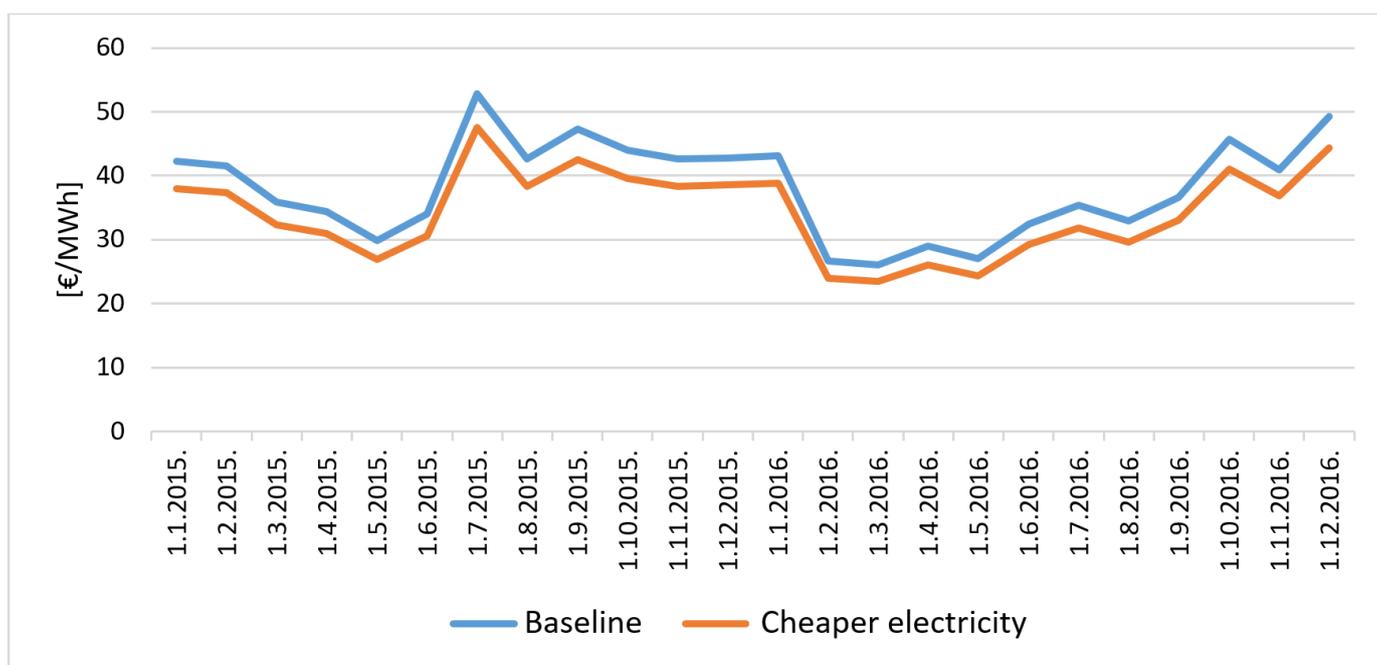


Figure 11: Average monthly electricity prices (Baseline scenario and Cheaper electricity scenario)

### 5.3.1. Scenario comparison – gas system

Due to the equal prices of gas on the market in both scenarios, supply from the Republic of Croatia has not changed: in both cases the value is 8,335.15 TJ. Values of gas transported through pipelines and transportation costs are shown in Table 4. Cheaper electricity on the market causes lower electricity production from thermal power plants because the total cost of production exceeds the market price. Lower demand for gas causes a reduction in gas transportation through the pipelines, resulting in lower transport costs.

Table 4: Gas transport (Baseline and Cheaper Electricity scenario)

Natural gas supply routes	Baseline scen.	Cheaper Electricity scen.	Difference (%)
Production in RH (TJ)	8,335.15	8,335.15	0
AT→HU→RH (TJ)	5,772.75	4,367.01	-24.4
AT→SLO→RH (TJ)	38,670.15	31,515.61	-18.5
Gas transportation costs AT→HU→RH (€)	3,982,301	3,012,562	-24.4
Gas transportation costs AT→SLO→RH (€)	26,492,474	21,590,980	-18.5
Total transportation costs (€)	30,474,775	24,603,542	-19.3

The values related to the use of gas storage in the cheaper EE scenario are shown in Table 5. It is interesting to note that the total amount of stored gas in the case of Hungarian storage is lower by 20.3 percent, while in the case of PSP Okoli the reduction is only 1.4 percent. This is because natural gas prices have remained the same on the market, but as gas demand decreases, it is more worthwhile to transport gas through Slovenia and store it at PSP Okoli rather than use Hungarian warehouses and pay more expensive transport tariffs.

Table 5: Gas storage (Baseline and Cheaper Electricity scenario)

Gas storages	Baseline scen.	Cheaper Electricity scen.	Difference (%)
HU_storages (TJ)	3,451.63	2,751.85	-20.3
PSP Okoli (TJ)	6,366.45	6,275.91	-1.4
Cost HU_storages (€)	2,950,801	2,352,553	-20.3
Cost PSP Okoli (€)	6,257,401	6,168,411	-1.4
Total storage costs (€)	9,208,202	8,520,964	-7.5

### 5.3.2. Scenario comparison – power system

The generation of electricity in the scenario of 10 percent lower prices of electricity in the market is 19.9 percent lower than in the Baseline scenario (Table 6). Even more interesting is that EE's sales fell 24.1 percent, more than double the market price drop.

Table 6: EES (Baseline and Cheaper Electricity scenario)

	Baseline scen.	Cheaper Electricity scen.	Difference (%)
Total electricity production (GWh)	6,375.62	5,120.62	-19.9
Total gas consumption (TJ)	52,778.05	44,217.77	-16.2
Fuel costs (€)	295,239,689	248,421,074	-15.9
Emission costs (€)	25,167,212	21,085,245	-16.2
Total costs (€)	320,406,901	292,149,467	-15.9
Revenues from the electricity sales (€)	292,913,185	222,296,424	-24.1

## 6. CONCLUSION

The interaction of different energy markets, such as natural gas or coal, and the electricity market is increasingly present in the energy sector. By reducing the available reserves, Croatia's dependence on imported gas will surely grow in the future, and this is a challenge that will require new solutions to maintain the security of the electricity system. The share of RES in the production of electricity is already playing a significant role and according to many forecasts the tendency is for further growth.

The PLEXOS program can capture many inputs and model the energy sector units in very small detail. Market models are an added advantage of PLEXOS, in addition to the technical and economic characteristics of the units and power sector. Using energy-economic models is the approach for finding solutions to all the challenges ahead.

Model upgrading is possible in many segments, primarily related to more accurate modelling of gas pipeline tariffs and gas storage tariffs. In addition, much more complex analysis is needed to accurately represent future market prices. A modelling approach involving the integration of gas and power systems represents a step forward in optimizing the facility operation and opens the possibility of simulating a number of scenarios that could be realized in the future.

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