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Techno-Economic Analysis of Common Work of Wind and Combined Cycle Gas Turbine Power Plant by Offering Continuous Level of Power to Electricity Market

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ABSTRACT

Wind power varies over time and variations occur on all time scales, mainly under the influence of meteorological fluctuations. Understanding these variations and their predictability is of key importance for integration and optimal utilisation of wind in the power system. There are two major attributes of variable renewable generation that notably impact the participation on power exchanges: variability and uncertainty. Due to variability and uncertainty, wind plants cannot participate in the electricity market, especially on the power exchanges. This paper will present a techno-economic analysis of work of wind plants together with a combined cycle gas turbine power plant as support for offering continuous power to the electricity market. This work presents a model of electricity production from wind farms and a combined cycle gas turbine power plant developed in the programming tool called PLEXOS. Real hourly input data and all characteristics of combined cycle gas turbine power plant were used in the model. A detailed analysis of techno-economic characteristics of ramp rates and different types of starts and stops of the plant was made. The main motivation for this analysis is to investigate both technical and economical possibilities for an investor to participate in the power exchanges by offering continuous guaranteed power from wind plants by backing them up with a combined cycle gas turbine power plant.

KEYWORDS

Combined cycle gas turbine plant, Wind plant, Wind power balancing, PLEXOS model, Power plant ramp rate, Power plant start-up regime, Optimisation time resolution.

INTRODUCTION

Investing in new sources of energy represents a great challenge for investors because of the high risk caused by uncertainty in the electricity market. The goal of the power

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system is to cover a given load at any point of time, however, technology also needs to cover the initial investment and earn a profit in order to survive in the electricity market. Introduction of renewable technologies, especially wind and solar, has caused some unexpected issues in the power systems because of randomly variable production. The unpredictability of wind has a negative impact on the participation of wind power plants in the market because of its uneven production and geographical distribution. Nevertheless, energy strategies across Europe and the world encourage the development of renewable technologies under the pressure of climate change agreements. Sustainable development, as an important factor for the further advancement of mankind, is defined as: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1] and dictates the development of the present energy industry. People's present lifestyle has a big impact on the future. The Kyoto protocol introduced internationally binding emission reduction targets [2], but it only requires developed countries to take action, which is its main weakness. A new global agreement has been reached in 2015 named the Paris Agreement and its main elements are: long-term goal, contributions, ambition, transparency and solidarity. The goal is to limit global warming below 2 °C and it covers the period from 2020 onward. The goal for the European Union (EU) is to have a low-carbon economy, which is more climate-friendly and less energy-consuming. It includes the following important guidelines:

- Cut emissions to 80% below 1990 levels by 2050;
- 40% emissions cuts by 2030 and 60% by 2040;
- Contribution of all sectors;
- Feasible and affordable low-carbon transition [3].

In order to meet the obligations under the United Nations Framework Convention on Climate Change (UNFCCC), Croatia has developed a low-carbon development strategy which dictates the development of the energy sector in Croatia by 2050. Croatia has already accomplished the 5% reduction targets set by the UNFCCC [2].

Obligations under the EU and the UNFCCC encourage the introduction of green energy sources (wind, offshore wind, solar, hydroelectric, geothermal, tidal, wave) and decommission of fossil fuel power plants across countries. But most of renewable energy sources have a variable and/or an unpredictable nature. According to some studies [4, 5], participation of wind energy on the spot market reduces the price of electricity and the attractiveness for the investment in natural gas power stations. In Croatia, as well as in some other countries, like Germany, Denmark, Spain, the Netherlands, France and Portugal, the price of electricity produced from wind is determined by feed-in tariffs. The transmission system and distribution system operators have an obligation to connect privileged producers to the network, to buy electricity from renewable energy sources and to apply the Tariff System for the electricity produced in plants using renewable energy sources [6]. An increased share of wind (as well as other green energy sources) in the power system requires balancing when conditions are not as expected. This highlights the problem of the day-ahead forecasts, which would significantly improve the position of wind power on the electricity market, more details in [7]. The existing regulatory framework enables investors in renewable energy technologies to have a good position on the market. The introduction of feed-in tariffs in the Croatian power system has had a positive impact on investors in renewable energy technologies. There are many other support schemes for wind energy production as explained in [8]. Without forecast methods of extreme quality, systems need other options for balancing, considering that today it is not possible to have a 100% predicted production of wind at any point of time. This is important for peaks and gaps in the electricity production, especially when wind production is less than anticipated. The priority is system stability – equality of production and consumption at any point of time. Some ways of providing peaking power for power systems are: energy storages, pumped hydro power plants, Open Cycle Gas Turbines (OCGT) and Combined Cycle Gas Turbines (CCGT) [9]. According to some considerations and taking into account the levelized cost of peak generation [10], pumped hydro plants have certain advantages over OCGT and CCGT, while CCGT still has some advantages over OCGT. According to Ela *et al.* [11], the total system benefits will always increase with increased storage, but the benefits per unit of storage size will decrease. This means there is a point beyond which increasing the storage system's size would be counterproductive in today's market. The option considered in this article is the CCGT-Wind combination. Today's systems and markets do not allow CCGT to work in optimal conditions at nominal power. Frequent changes of the load consequently cause changes of fuel consumption and emission levels. These changes in the operating modes have a significant effect on the Operation and Maintenance (O&M) costs of conventional technologies, which should not be ignored in long-term planning and investment costs. Their impact is discussed in [12, 13]. It is important to consider restrictions such as minimum power output, rate of increase and decrease of power, interdependence between starting time and previous operating condition of the plant and all associated costs. Sustained levels of electricity offered on the market, created as a result of the CCGT-Wind combination, would allow wind to offer to the electricity market a certain amount of energy with absolute certainty, and its variation in production (less or more produced energy) would be covered by the CCGT. On the contrary, in order to be a back-up source for the wind, for a CCGT power plant it means an additional amount of revenue in the market where one conventional power plant can have difficultly breaking through and achieving sufficient revenue to cover the initial investment and earn a profit. Gas power plants represent a cost-competitive option from the perspective of investing in new power plants. CCGT power plants have significantly lower total costs of covering the peak load in the system compared to other power plants. According to [14], gas will play a key role in the transition process, and with it, the replacement of coal with gas can mean a reduction of emissions with existing technologies by 2030 or 2035. Therefore, CCGT power plants have a certain advantage compared to other electricity generation technologies. CCGT power plants use a gas turbine. An air-fuel mixture moves through the gas turbine, the Heat Recovery Steam Generator (HRSG) captures heat from the gas turbine and produces steam, which is delivered to the steam turbine. Both the gas turbine and the steam turbine convert spinning energy into electricity. This combined production increases the production of electricity by up to 50% with the same fuel cost as traditional gas power plants. There are several ways a CCGT plant can perform depending on the number of axles (for gas and steam turbine) which can optimise the production output of the plant. By including more axles, the investment costs are increasing, however the flexibility, which is an extremely important factor for a CCGT power plant, enables covering wind production gaps in the required point of time. Numerous papers [15-17] are focused on thermo-economic optimisation of the CCGT, recognising great opportunities in these areas for the competitiveness of CCGT power plants by finding a set of optimal solutions in moments when the load is variable. These specifications make CCGT one of the most flexible ways of balancing the unpredictable wind power and provide great market opportunities for mutual cooperation of wind and CCGT. Variable demand/production has a huge impact on profitability and sustainability of CCGT power plants on the market. In the previous year, many articles tried to determine the impact of wind power on the gas market and gas power plants, especially CCGT power plants. Keyaerts *et al.* [18] presents a wind and CCGT power plant model in order to investigate the demanded level of flexibility. The impact of the variable demand upon the performances of a 800 MW CCGT power plant is presented in Bass *et al.* [13] and the impact of step changes, conditional modulation and hot/cold starts of the plant are considered. The operating parameters of the CCGT systems in Italy between 2011 and

2013 are presented in Prina *et al.* [19]. High penetration of renewable sources and its influence on the CO_2 emissions and costs are also considered.

The rest of this paper is organized as follows: Section 2 describes the outline of the problem and methods used and the technical aspects of CCGT power plants, while Section 3 presents the description of the model. In this section, the optimization tool PLEXOS is described. Section 4 is a case study with two cases presented. Section 5 describes results obtained using CPLEX solver under the PLEXOS tool. The conclusion of this paper is presented in Section 6.

OUTLINE OF THE PROBLEM AND METHODS

The objective of this paper is to examine the technical and economic indicators of a CCGT power plant in balancing or stabilising variable electricity production from wind. For this purpose, a model is made in the programming tool PLEXOS. Description of the model and the software can be found further in this paper.

Technical aspects of Combined Cycle Gas Turbine power plant

The first part of the analysis is related to the technical ability, i.e., flexibility, of CCGT power plants to follow variable production from wind. Considering that CCGT production depends on the nature of the wind in the area, frequent switching of the CCGT plant and associated high costs are expected [20]. Therefore, two cases are examined.

In the first case, CCGT and wind offer a fixed amount of power in an all-time interval and that amount is equivalent to an installed capacity of wind which uses a CCGT power plant for back-up. In this case, frequent start-ups and shutdowns of the CCGT are expected, as well as significant associated costs since the CCGT has a certain minimum stable power output (power output does not vary from 0 to P_{max} but from P_{min} to P_{max}). In the second case, it is assumed that CCGT and wind offer a fixed amount of power which is greater than the total installed wind power capacity for the amount that is greater than the minimum stable power output of the CCGT. This prevents frequent start-ups and shutdowns and should reduce specific operating costs of the CCGT power plant.

In the technical part of the analysis, the goal is to compare the flexibility of CCGT power plants in monitoring the variable production of wind in different time resolutions of the optimization process for both cases. It is expected that, with the increase of the resolution (using one minute resolution instead one hour), the effort from the CCGT power plant, from a technical perspective, becomes increasingly higher. Corresponding total and specific operating costs of a CCGT plant are determined.

Market perspective of the common offering of Combined Cycle Gas Turbine and wind power plant

In the second part of the analysis of the current market position of wind energy, in which the incentive price in the Feed-in system guarantees the purchase of the entire produced electricity, it is open to full exposure to market conditions. In other words, wind farm is exposed to the electricity market price and should take the entire responsibility for the deviation between the planned and actual wind farm production of electricity (balancing energy).

Because of insufficiently accurate and reliable methods of wind production forecasting [21-23], the system is forced to find an appropriate way of balancing in real time. This paper is guided by the assumption that the stated balance is achieved just by using the CCGT power plant.

The goal is to determine the competitiveness of the CCGT power plant in contrast to an electricity market based on the model which takes into account all the necessary parameters of a wind and CCGT power plant.

Since most of the variable costs of production of a CCGT power plant are related to fuel costs, several scenarios of different gas prices will be examined in the analysis. Thereby, in this part of the analysis temporal resolution of the optimization process will not vary (resolution will invariably be 1 h). More on this in the case study chapter.

DESCRIPTION OF THE MODEL

The optimization tool PLEXOS, which is more fully described below, does not have a simple object for modelling a CCGT power plant since the concept of a CCGT power plant, in terms of modelling, is significantly much more complex than the concept of traditional power plants. However, PLEXOS is a highly effective way for modelling CCGT power plants.

PLEXOS is a software tool for modelling and simulating relations on the electricity market with prominent comprehensive range of features delivered through a simple interface. The tool was developed by Energy Exemplar. It is a general simulation tool based on object modelling which defines a hierarchical set of classes, while the user of the simulator creates parts or an entire system by designing the instances of objects. The definition of the class describes which collections may belong to objects of a particular class and how they act according to the objects of the same or different type.

After entering the required system parameters and defining scenarios and determining the planning period, PLEXOS runs a specialized program for solving mathematical optimization problems. It is possible to use several commercially available solvers in PLEXOS: MOSEK, Gurobi, Xpress-MP and CPLEX. Upon solving mathematical problems, PLEXOS obtains prepared data from solutions in order to review and analyse them in the users interface.

PLEXOS model of the Combined Cycle Gas Turbine power plant

The following approach is used for modelling a CCGT power plant in PLEXOS. The recommended strategy is to create links between the waste heat of one or more generating units and the energy input of production units on the next level. Production units, with waste heat used for the next stage, are gas turbines of the CCGT power plant and production units in the next stage of the electricity production, which take advantage of the waste heat, are steam turbines of the real CCGT power plant. Each production unit, either gas turbine (or turbines) or steam turbine (usually only one) are modelled by using an object “Generator”. It is possible to define a unique object “Fuel” and a separate heat rate curve for each steam turbine. Connecting the waste heat of an object “Generator” with PLEXOS automatically enables modelling of the economizer and other possible components of the steam part of the CCGT power plant (e.g. an additional combustion chamber, etc.). The object “Generator”, which represents a steam turbine, needs not to be linked with an object “Fuel” because it uses waste heat from the gas turbine, which uses energy of combustion of the associated fuel.

Gross amount of energy that is transferred to the steam turbine is equal to the sum of the waste heat of the gas turbines of the CCGT power plant. The waste heat of the gas turbine is equal to the difference of energy of fuel and generated electricity. This heat comes to the boiler in the steam cycle which has a separately defined efficiency. Accordingly, the net overall heat that comes through the steam turbine is equal to the total waste heat multiplied with efficiency of the boiler. Output electricity of the steam turbine is defined by the description of the heat rate in the steam cycle.

The presented method can give an accurate model for the real CCGT power plant since PLEXOS tools automatically take into account all the characteristics of a CCGT power plant, such as the restriction that prevents the work of the steam turbine if none of the gas turbines work. It is also possible to define some specific limits using an object “Constraint”.

Following characteristics are used for the purpose of creating a detailed model of a CCGT power plant according to the given input data:

- Number of units of gas and steam turbines;
- Installed capacity – maximum;
- Minimum stable power;
- Detailed heat rate curves;
- FO&M fee;
- VO&M fee;
- Start-up costs for multiple start profiles;
- Start-up time for multiple start profiles;
- Rate of power increase at the start for multiple start profiles;
- Rate of power increase in operating mode;
- Rate of power decrease in operating mode;
- Motor fuel;
- Fuel used at start-up;
- Fuel consumption at the start for multiple start profiles;
- Fuel prices;
- Production emissions;
- Price of emissions;
- Limitation of production;
- Limitation of the start;
- Auxiliary consumption of the power plant;
- Others.

Model of the environment of the Combined Cycle Gas Turbine power plant in PLEXOS tool

Electricity market. The external electricity market model is developed according to a sample of historical electricity prices from the analysed markets, described in the case study section.

Specificity in terms of modelling of renewables. There are data available of the wind power plants production in Croatia, in hourly resolution, for electricity from wind power plants. Based on these data, basic statistical parameters are used for the modelling of the output power of wind in PLEXOS as a stochastic variable with default parameters. In order to take into account interdependence of certain wind speeds in neighbouring hours, ARIMA modelling approach is used for modelling variable output power of wind [24-27].

Modelling of the power consumption. Since only the coordination of the wind and CCGT power plant is analysed, the consumption of a particular region is not modelled. Consumption is a fixed amount which is equal throughout the entire optimisation period.

Modelling of the dummy power plant. Dummy power plant is a super flexible power plant in which marginal cost and cost of launching are significantly higher than the marginal cost of CCGT heating units, but significantly lower than in the model defined Value of Lost Load (VoLL). A Dummy power plant covers the imbalance that a CCGT power plant cannot cover. When a Dummy power plant has a larger production, it means less technical capabilities and flexibility of the CCGT power plant in monitoring variable production of the wind.

CASE STUDY

This part of the paper describes the details of the CCGT model and its environment, especially the electricity market and the residual consumption curve.

Combined Cycle Gas Turbine model

The basic data of CCGT are shown in Table 1 and Table 2. Sources for the given data can be found in [28-34].

Table 1. Input data for gas and steam turbine

	Max cap. [MW]	Min. stable level [MW]	VO&M [EUR/MWh]		FO&M [EUR/kW/year]
GT	307	61.4	3.22		20
ST	138	27.6	3.22		20
	Aux [MW]	Ramp rate [MW/min]	Eff. 100% [%]	Eff. 80% [%]	Eff. 20% [%]
GT	10	15.35	40	38	23
ST	4	6.9	31.17	31.17	31.17

Table 2. CCGT start profile data

Start	Idle time [hrs]	Fuel offtake [GJ]	Start cost [EUR]	Start time [min]
Hot	8	89.2	10,235	30
Warm	48	93.9	14,685	90
Cold	96	112.67	20,025	190

Electricity market model

The electricity market is created with the object “Market” in the PLEXOS tool. There are no constraints in the form of maximum amounts that can be sold or bought from the market. Prices are taken from the stock exchange EPEX for the year 2014.

Wind model

As noted in the description of the problem and the methods, wind is modelled using stochastic variables and the ARIMA approach. The data used to model the variables, which represent the output power of wind power plant, can be found in Table 3. ARIMA parameters are determined by trial and error process until they achieved the patterns of wind power output similar to the real ones. The same data are used independently of the time resolution of the optimization procedure.

Table 3. Wind power output stochastic parameters

Case	Min. value [MW]	Max. value [MW]	Mean. value [MW]	Std. dev. [MW]	ARIMA a	ARIMA b	ARIMA d
Case 1	0	400	102	97	0.5	1	0.5
Case 2	0	280	71	68	0.5	1	0.5

Data in Table 3 are scaled on the basis of the calculated statistical data for the output of wind power in Croatia, according to the maximum output power of wind. It is assumed that the relationship between the expected value, the expected error and the maximum amount are fixed compared to the capacity of the wind.

Data from Table 3 is used to model the generator object in PLEXOS that represents existing wind farms in Croatia. It is assumed that the operation cost of this generator is zero and that there are no constraints on ramp up and down limits due to the fact that stochastic output data are modelled based on real wind farms output data.

Dummy generator model

The Dummy generator is modelled in case that a CCGT power plant cannot, in some moments, cover the residual consumption due to technical capabilities. Dummy generator is a super flexible generator for starting and lifting power. Its operating costs are significantly higher than the costs of the CCGT, so the Dummy generator is activated only in cases when a CCGT power plant achieves technical limits. For the purpose of the analysis, the modelled Dummy generator has the max capacity of 500 MW and VO&M cost of 5,000 EUR/MWh. It should be noted that the amount of VoLL in the model is fixed on 100,000 EUR/MWh to ensure activation of the Dummy generator only in case of an emergency and the generator activation price is EUR 1,000,000.

Electricity consumption model

The consumption of electricity is 400 MW in each time period (according to the maximum wind power capacity in Case 1). It is important to note that this consumption is not actually the consumption of some specific region, but instead the load that is covered by the combination of CCGT and wind farms. The authors purposely wanted to conduct a conservative analysis from the CCGT perspective. Namely, it is assumed that there is no prediction for wind farm production in order to help with the planning of operation. Therefore, it is considered as worst case scenario from a CCGT point of view due to the fact that wind farm errors (and burden on CCGT) are highest in this case.

RESULTS AND DISCUSSION

The presented results were obtained on a 3.6 GHz based processor with a 32 GB RAM using CPLEX solver under PLEXOS® 7.

Because of the complexity of the model and many technical constraints, and in order to keep the same wind power output profile (for easier and more reliable comparisons of the results), for all analysed time resolutions in individual cases, the duration of optimisation is set according to a set time resolution of simulation, so that the total number of analysed time intervals is constant (in this case 60), according to Table 4.

Table 4. Optimization time horizon data

Time resolution [min]	1	5	10	60
Total optimization duration [h]	1	5	10	60

Technical limitations of the Combined Cycle Gas Turbine power plant

In the section ‘Description of the problem and methods’ the results are shown in two cases as follows.

Case 1. Production of wind power in intervals in Case 1 (independent of time resolution) is shown in Figure 1.

Results of the optimisation analysis which have a different length but the same number of time intervals (60) will be compared. Instead of comparing undelivered energy, undelivered power between the analysed cases will be compared. Figure 2 shows the comparison of undelivered power of the CCGT power plant for Case 1 in different time resolutions.

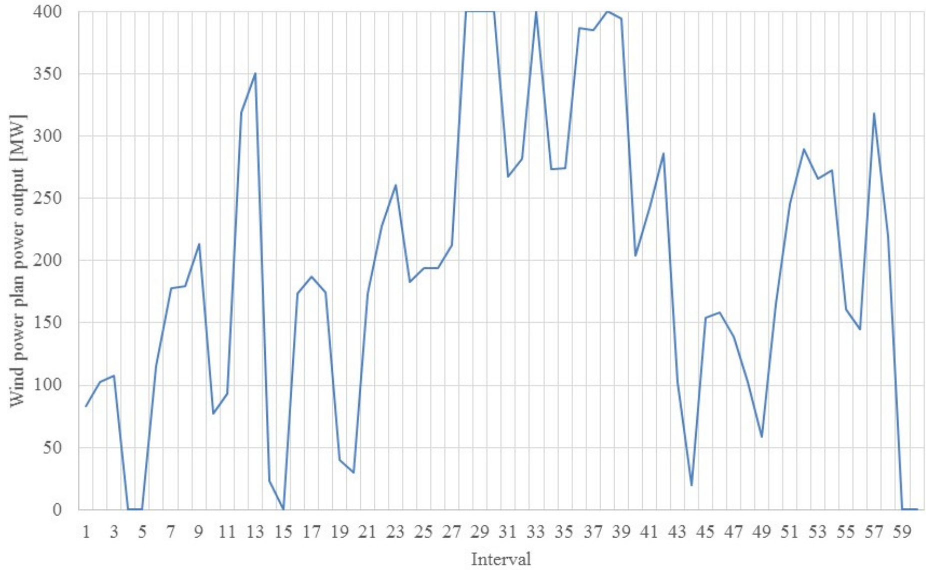

Figure 1. Wind power plant power output in Case 1

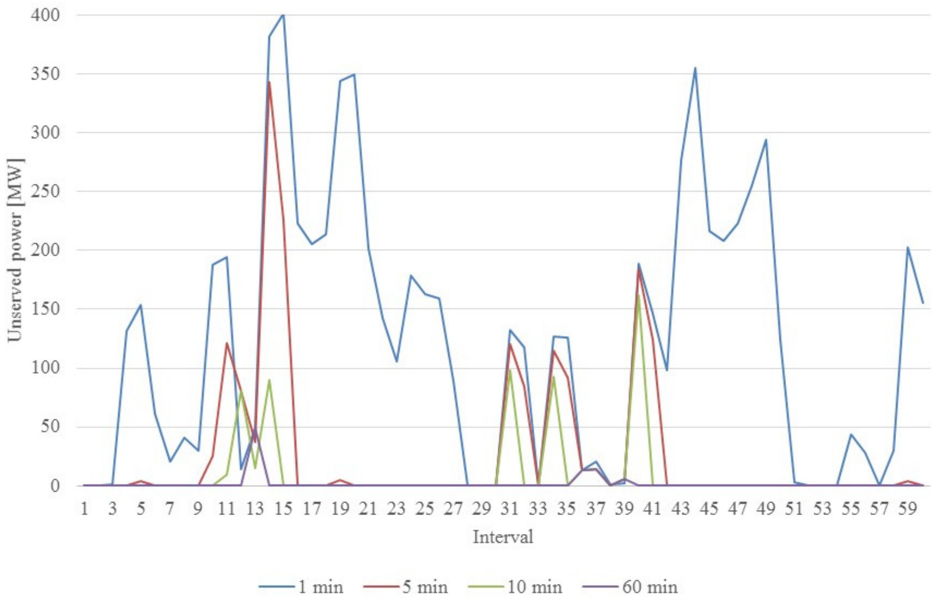

Figure 2. CCGT unserved power (Case 1)

The average undelivered power per hour is drastically different depending on time resolution of optimisation. For the time resolution of 1 min the average undelivered power is 123.8 MW, for the time resolution of 5 min undelivered power is 26.6 MW, for 10 min 9.7 MW, for 60 min is only 1.4 MW. The reason for the large differences of undelivered power is in the speed of power changes and limit in starting of the CCGT power plant. Those limits become more frequent when resolution time of the optimisation process is shorter (shorter time interval). When resolution time is 60 min neither of these limits is reached within the time interval (too rough resolution). But even in the resolution time, certain level of non-supplied power (purple line) can be noticed. In this case, the limit of the minimum working point of a CCGT plant leads to the unmet need for power. In cases where the difference between total demand (400 MW) and power output of the wind is less than the minimum stable level of the CCGT power plant, CCGT will not be able to meet the necessary difference. In Case 2, this occurrence is avoided and it is possible to compare purely technical limitations related to the speed of increasing power of the CCGT in normal operation.

Case 2. Production of wind power in intervals in Case 2 (independent of time resolution) is shown in Figure 3.

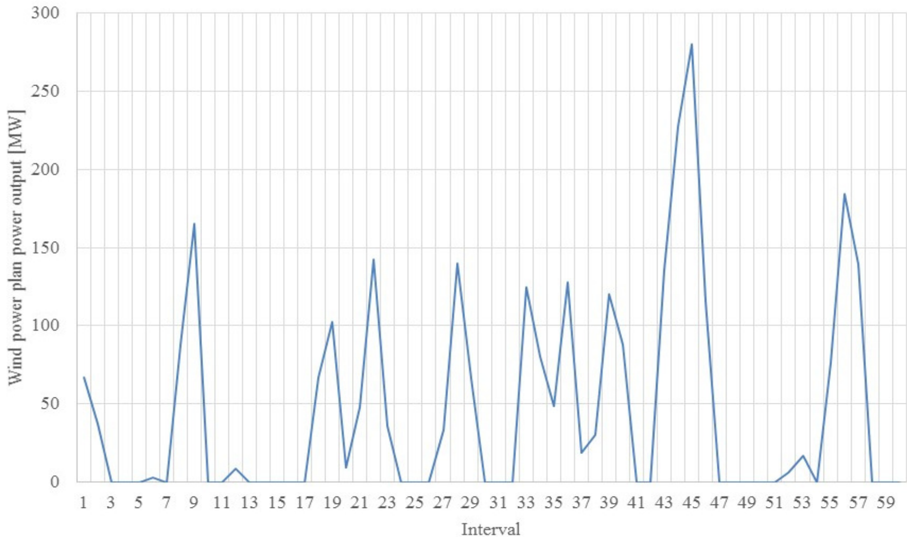

Figure 3. Wind power plant power output in Case 2

Same as in Case 1, undelivered power between the analysed cases will be compared. Figure 4 shows comparison between undelivered power in different time resolutions for Case 2.

Because of the possibility that CCGT power plant works continuously (does not have to go through slow starts) and because there are more adequate wind characteristics than in Case 1, undelivered power is significantly lower than in Case 1. The average undelivered power per hour for a time resolution of 1 min is 66.5 MW, for 5 min is 3.1 MW, while for 10 min and 60 min resolution undelivered power isn't recorded. By comparing Case 1 and Case 2, it is possible to conclude that the CCGT power plant monitors wind power significantly better when it is not forced to frequent switching.

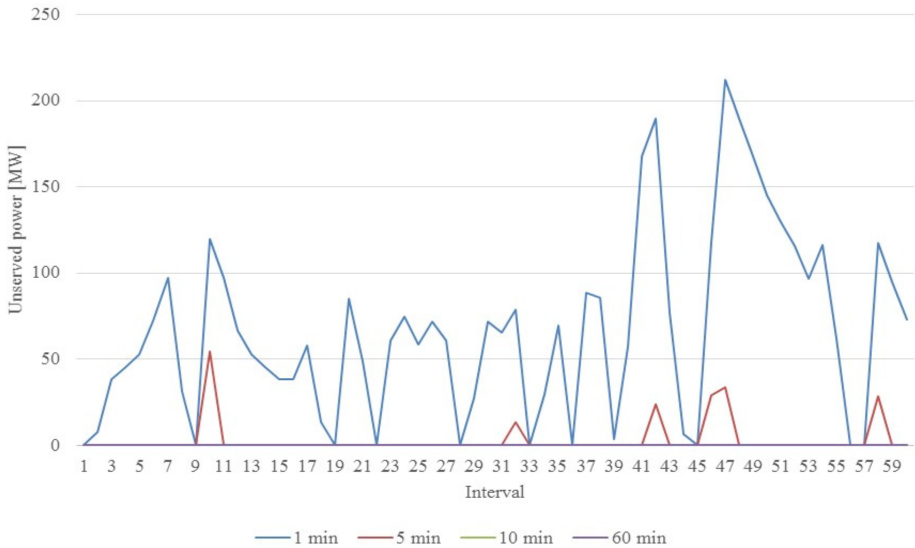

Figure 4. CCGT unserved power (Case 2)

Market perspective

The question is: Whether and under what conditions a CCGT power plant, as a supplement for the production from a wind power plant, is more competitive than buying electricity on the electricity market. Since the price of gas is the most influential factor for the production cost of CCGT power plants, the gas prices in this analysis vary between 2 EUR/GJ and 8 EUR/GJ by increments of 2 EUR/GJ for any individual cost. An optimisation procedure is performed for all costs, as well as an analysis of the amount of energy produced by the CCGT and the amount of energy which was bought in the electricity market. Consumption is again fixed at 400 MW.

The period of one month is analysed with stochastic parameters of wind as in Table 3 for Case 2. The prices of electricity are taken from the stock exchange EPEX for January 2014 (Figure 5).

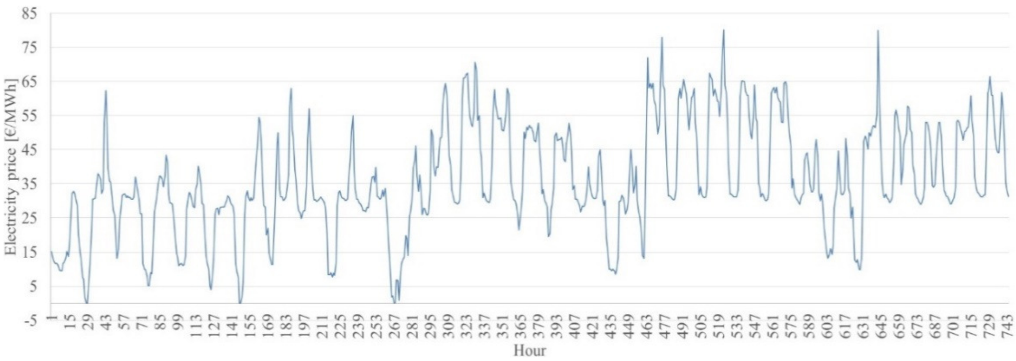

Figure 5. Electricity price (EPEX, January 2014)

Figure 6 shows wind power generation for the same period on the basis of random variables.

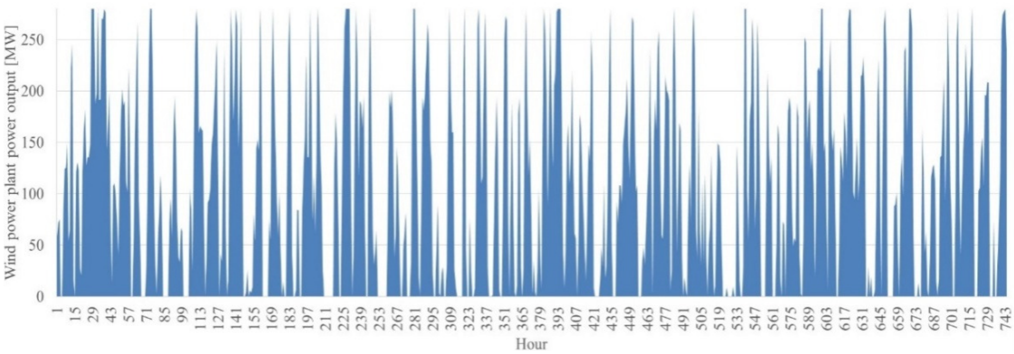

Figure 6. Wind power plant power output in market environment

Figures 7, 8 and 9 show the production of CCGT in the observed period for gas prices of 2.4 and 6 EUR/GJ. An interesting fact is that with gas price of 8 EUR/GJ CCGT, in the observed period, power plant did not work a single hour.

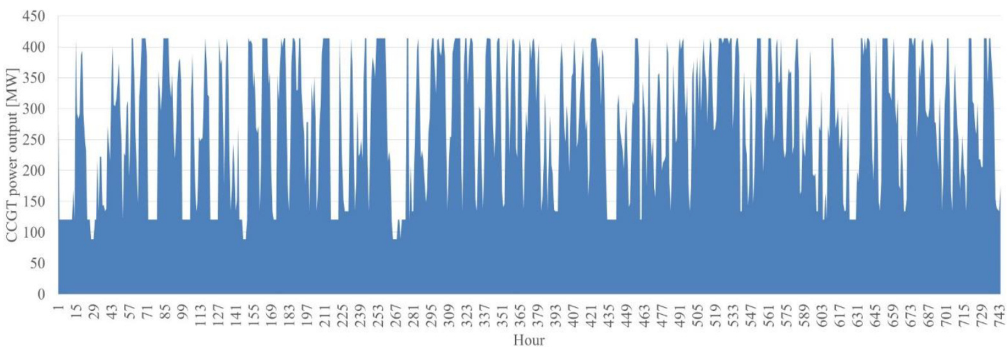

Figure 7. CCGT power output in market environment (Gas price 2 EUR/GJ)

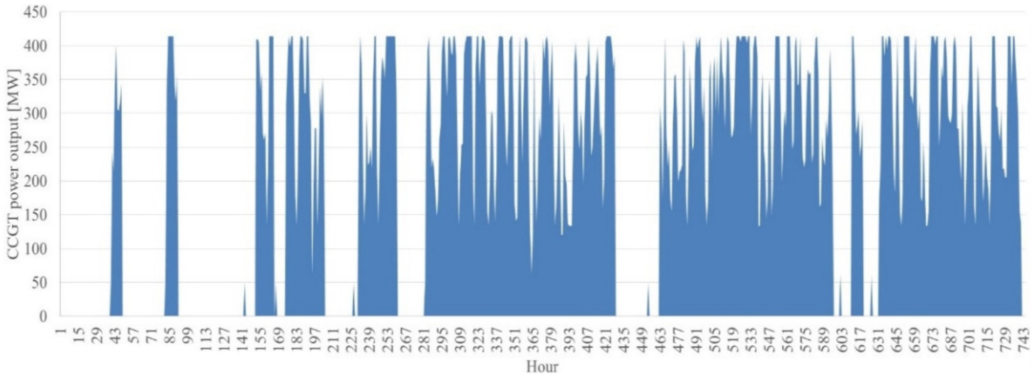

Figure 8. CCGT power output in market environment (Gas price 4 EUR/GJ)

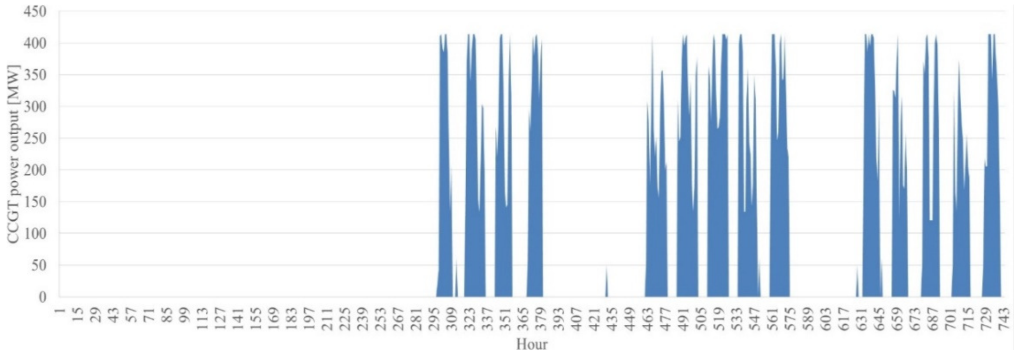

Figure 9. CCGT power output in market environment (Gas price 6 EUR/GJ)

In the previous figures, it can be clearly seen that the increase in the gas price has drastic consequences in terms of reducing production of a CCGT power plant. And it is clearly evident that the production of the CCGT is the highest in periods when the price of electricity is the highest. The average price of electricity on the market in the analysed period was 35.8 EUR/MWh. Total demand for electricity was 297.6 GWh. Wind covers 81.55 GWh or 27.4% of the demand. The rest of the demand is covered by CCGT and electricity market in different proportions depending on the gas price. Table 5 shows the contribution of each source of electricity depending on the gas price.

Table 5. Share of each electricity source for different gas prices

Fuel price [EUR/GJ]	Share of wind farm [%]	Share of CCGT [%]	Share of market [%]
2	27.4	70.1	2.5
4	27.4	51.3	21.3
6	27.4	20.2	52.4
8	27.4	0	72.6

With the very low cost of gas of 2 EUR/GJ, the modelled CCGT is almost invariably more competitive than the electricity market. With 4 EUR/GJ (equivalent to the price of gas on the EPEX Stock Exchange on July 20, 2016) ratio of CCGT production and market purchase is 2.5 in favour of the CCGT. The situation is exactly opposite when the gas price is 6 EUR/GJ, but for the gas price of 8 EUR/GJ, in the observed period, CCGT did not run a single hour.

CONCLUSION

This paper is focused on the techno-economic analysis of the possibilities of balancing the volatile nature of the wind with CCGT power plants. Technical characteristics of the CCGT power plant provide balance for the wind, but also have certain limitations. The limitations are especially evident in the limited speed of increasing power in CCGT and limited speed for the start of CCGT. In order to avoid restrictions associated with the start of the CCGT power plant, it is desirable for CCGT to constantly work on the power above the minimum stable level. Therefore, a fixed amount which is jointly offered by wind and CCGT in an observed period should be equal to, or greater than, the sum of the expected maximum power output of the wind and min stable level of the CCGT power plant. This paper shows how the variability of the wind affects the reaching of the technical limitation of CCGT power plant through optimization in different time resolutions. It is shown that, with the same variability of the wind in the optimization with higher time resolution, real technical limitations of CCGT power plants come better to the fore, especially in terms of the speed of increasing and decreasing output power. Therefore, with this kind of analysis it is necessary to collect quality data at the best possible resolution and then adequately model the wind power plants and adjust resolution time in the optimization process in order to get meaningful and usable results. The paper also shows how the use of statistical data in hourly resolution in the optimization process with significantly higher resolution, e.g., 1 min, results in significantly higher demands on the CCGT power plant. This reaffirms the need to coordinate the resolution time of the input data on which the stochastic modelling of the wind is based and the resolution time (interval) of the optimization, as well as similar problems.

In terms of economic feasibility, balancing of wind power output with CCGT power plants (in the optimisation model in hourly resolution) is compared to the competitiveness of the CCGT plant in relation to the electricity market as an alternative to balancing. It is proved that the greatest impact on competitiveness or production costs of the CCGT power plant has the price of fuel – natural gas. It turned out that, in the case of gas prices that are half of what they are today, CCGT is almost always the cost effective option. On the other hand, the prices that are twice of what they are today, external market completely dominates and CCGT does not record any production in the considered case. At current gas prices, which are about 4 EUR/GJ, CCGT is more competitive than the external market. It is necessary to emphasize that the results depend on the electricity prices and the stock market from which the same are taken. Recommendation for further research is to put an emphasis on variability and expected movement trends in electricity prices in the market.

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