

An approach to optimize the cycling operation of conventional combined heat and power plants

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The implementation of the market mechanism, which includes electricity price fluctuation, and a wide integration of intermittent generation, namely solar PV and wind energy, in energy production have changed the role and operation manner of conventional generation. It is partly or not at all adapted to new running conditions. Therefore, the efficiency and flexibility of conventional generation has to be improved. The numerical approach is developed in the context of combined cycle gas turbine (CCGT) technology to adapt its running conditions to the electricity market mechanism. The developed approach was verified on a case study of the Baltic States (Latvia) examples in a multi-paradigm numerical computing environment *MATLab*. The obtained results show that the added profit is gained through production of supplementary electricity, and the impact of cycling operation is reduced through the decrease of cycling operation ranges numbers and the substitution of start-up with a less adverse one from a technical and economical point of view. The developed approach can be adapted to various technologies and situations by adding appropriate characteristics and constraints of technology.

Keywords: conventional generation, cycling operation, electricity market, start-up, shutdown

INTRODUCTION

Combined heat and power (CHP) systems seem to be attractive because they can deliver a variety of energy, environmental, and economic benefits. Moreover, CHP applications produce energy where it is needed, avoid wasted heat, and reduce transmission and distribution network and other energy losses [1, 2].

The issue is that the implementation of market mechanisms, large-scale integration of intermittent generation in the energy production process and feed-in tariffs for renewable energy sources have changed [3–6]:

- the conventional generation's running conditions, i.e. the shifting from base load operation to cycling operation. It is an operation in line with availability of intermitted generation or fluctuation of the electricity price instead of heat energy demand. This has led to the efficiency decrease of conventional generation and more frequent trips and outages, because it is partly or not at all adapted to the cycling operation;
- the role of conventional generation, i.e. the secure integration of renewable energy sources in the energy production process and provision of regulation service to the transmission system operator instead of heat energy supply in line

with its demand. This promotes the mass closing or mothballing of conventional generation due to surplus of generation and in turn threatens the security of energy supply.

In [7], S. Lüdge stated, “The economic situation for conventional power plants is so bad that a lot of them will have to shut down permanently in the coming years and naturally there won’t be any new projects within this framework. Flexibility, especially from fossil fuel fired power plants is not only needed but is a success factor for the whole energy turn around.”

The flexibilisation of conventional generation is needed not only today, but also within the next decades [2, 7, 8]:

- To adapt existing generation to new running conditions and provide their efficient, flexible and profitable operation;
- To ensure the secure integration of intermittent generation in the energy production process and to ensure a stable energy system;
- To achieve the goal of European Commission concerning renewable energy sources and energy efficiency.

There are different ways to increase flexibility of conventional generation, which were grouped by authors in [9]. Much attention is paid to transient modes, especially to the start-ups. Firstly, they are adverse from an economical, technical and environmental point of view [10, 11]. Secondly, they provide the main key to increase flexibility of the production unit. Thirdly, the enhancement of power plant flexibility through the start-ups optimization generally is not a cost-based measure [3].

There are a lot of academic papers where the cycling operation of conventional power plants is optimized taken into account the transient modes (start-up, shutdown, warm state preservation). The papers differ in the rate of transient modes’ consideration. For example, in [12] and [13] the objective function of the power plant (profit maximization and minimization of production costs) includes costs of transient modes, but their features (type, time, trajectory, etc.) are omitted. However, there are scientific papers where the significant attention is devoted to the features of transient modes. For instance, in [14–16] the start-ups are considered taking into account the preceding offline time of the unit. It was complicated by limiting the temperature increase and the heating speed

[17], ramping constraints, including start-up, shut-down production trajectory, ramp rate and ramp down constraints [18–20], and the change of thermal stress of the main equipment [21].

The rate of transient mode consideration differs from the content of academic paper. For instance, the consideration of transient modes is important where the CHP operation is studied in portfolio with intermitted generation [22, 23] or where different activities are provided with transient modes to optimise the power plant operation as it is presented in this paper.

The authors developed an approach which optimizes the cycling operation of combined cycle gas turbine technology in line with electricity market conditions, i.e. the recovery of additional profit from added produced electricity and the reduction of cycling operation on the equipment technical resource (reduction of start-ups numbers and change of their type to less adverse) by extending the cycling operation range, i.e. shifting shutdown “*forward*” and start-up “*backward*”. The developed approach is approbated on the example of Riga CHP-2. It can be used to plan the optimal CHP plant generation scheduling to obtain maximum profit or decrease the effect of cycling operation on equipment technical resource in day-ahead and intra-day markets. Also, it can be used in balancing market to evaluate the possibility of added energy production where energy deficit is observed.

THE DEVELOPED APPROACH

The presented approach is developed for combined cycle gas turbine technology with the aim to optimize its cycling operation in electricity market conditions. The principle of the approach is usable for other technologies and situations as well. It consists of two models: evaluation model (EM) and optimization model (OM). The EM processes the production data of the power plant and consequently determines the cycling characteristics of the power plant and input for the OM. The OM ensures the extension of the cycling operation range by shifting shutdown “*forward*” and start-up “*backward*” and hence the supplementary electricity is produced; the numbers of cycling periods are reduced and start-ups are replaced with less adverse ones.

The input parameters of the EM (Fig. 1) are: produced electrical power (P), heat power (Q)

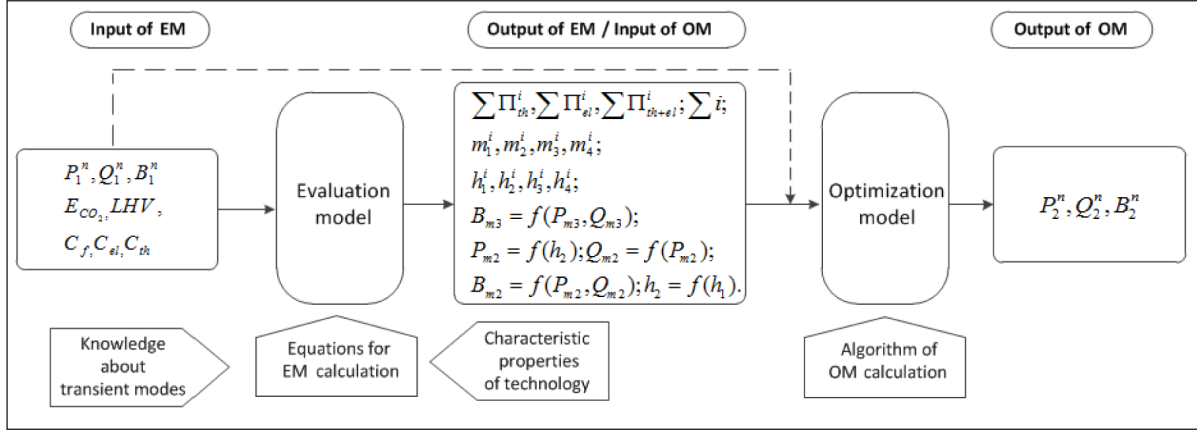


Fig. 1. The flow chart of the developed approach

and fuel consumption (B), price of heat (C_{th}), electricity (C_{el}) and fuel (C_f), emission factor (E_{CO_2}) of fuel and its low heat value (LHV). The equations of the evaluation model are presented in Table 1. The output of the EM provides information about the amount of cycling operation ranges ($\sum i$) and its periods (m_1, m_2, m_3, m_4), the duration of transient mode (h_1, h_2, h_3, h_4) and the type of start-ups, the obtained profit from electricity and heat production ($\sum \Pi_{th}, \sum \Pi_{el}, \sum \Pi_{th+el}$) and characteristics, which are in detail shown in Table 1 and Table 2.

The input of the OM is an output of the EM (obtained characteristics and values of parameters)

and the values of EM input parameters describe the initial situation in the optimization model. The calculation of the OM is based on the algorithm presented in Section 2.2. The outputs of the OM are the new values of electrical power (P_2^n), heat power (Q_2^n), and consumed fuel (B_2^n).

Development of the evaluation model

The cycling operation range (i) contains these four periods: warm state-preservation (m_1), start-up (m_2), operation above technical minimum (m_3), and shutdown (m_4), whose duration is h_1, h_2, h_3, h_4 respectively (Fig. 2).

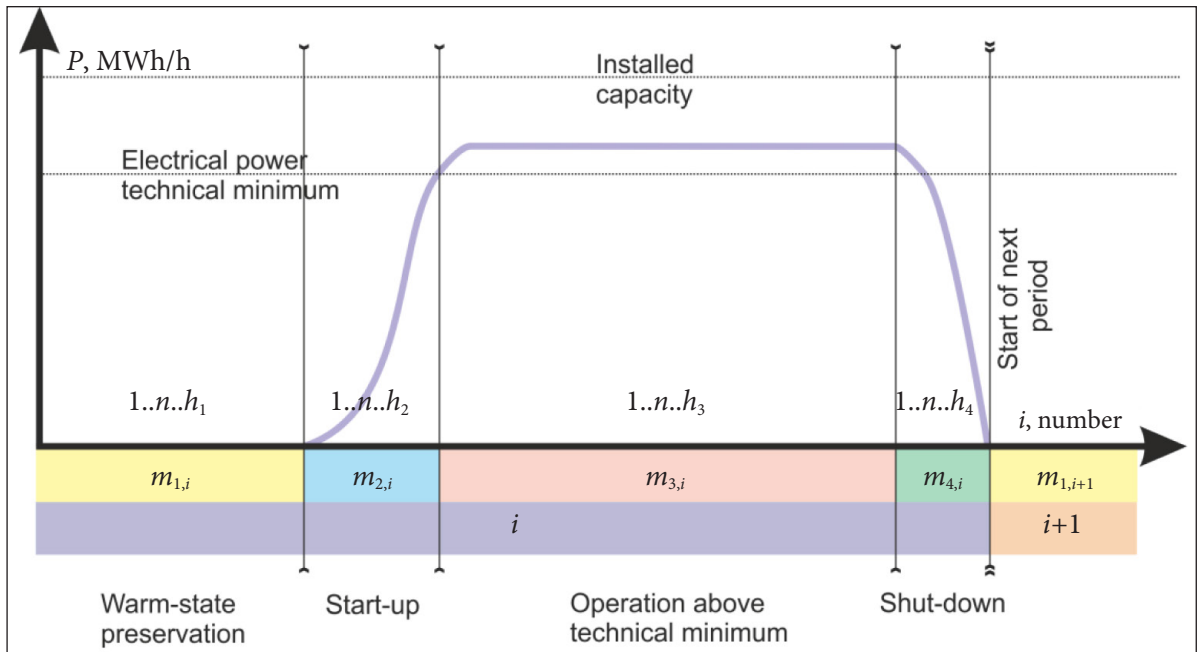


Fig. 2. The model of the cycling operation range (i)

The duration of h_1 determines the type of start-up. There are three start-up types: hot (if $h_1 \leq 12$), warm ($12 < h_1 \leq 72$), and cold (if $h_1 > 72$). The duration of warm state preservation (h_2) defines the continuation of start-up (h_2), i.e. for cold start-up $h_2 > 5$ hours, for warm start-up $2 < h_2 \leq 5$ hours, and for hot start-up $h_2 \leq 2$. The changes of electrical power (P),

heat power (Q), fuel consumption (B) during the cycling operation range are illustrated in Fig. 3.

The equations (1–9) of the EM (Table 1) are developed based on information in Fig. 2 and previously obtained knowledge about transient modes and characteristic properties of combined cycle turbine technology in [24, 25].

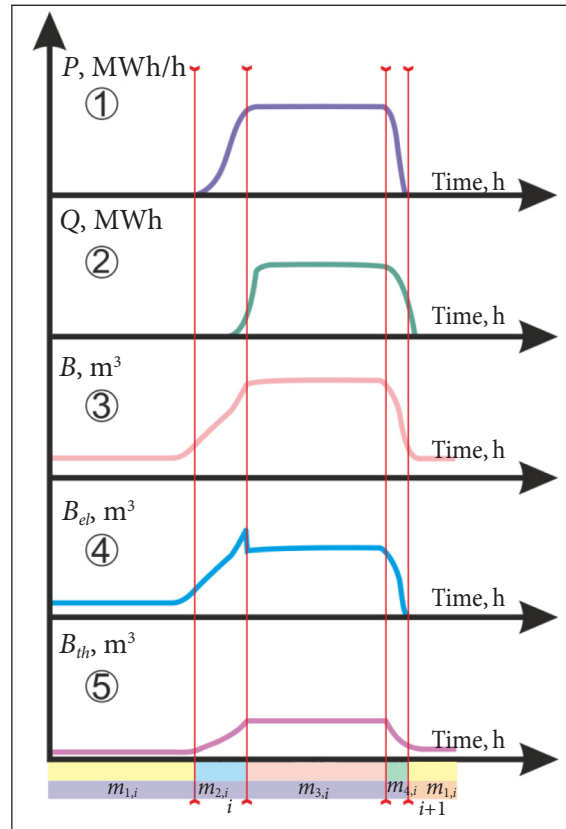


Fig. 3. The schematic change of electricity, heat and fuel during the cycling operation range "i"

Remarks:

- ① The change of electrical power is taken as a reference point, i.e. the division of the cycling operation range to $m_{1,i}$, $m_{2,i}$, $m_{3,i}$ and $m_{4,i}$.
- ② Heat power falls behind electrical power in $m_{2,i}$ and $m_{3,i}$. At the end of $m_{4,i}$ and at the beginning of $m_{1,i+1}$ heat power is greater than zero and electrical power is equal to zero. The value of heat power in $m_{1,i+1}$ is shifted to the warm state preservation of a new cycling operation range, i.e. $i+1$.
- ③ Fuel is consumed, when the unit is out of operation, to preserve the warm state of the unit. If the outage is too long, then the warm state is not preserved. Also, the total consumed natural gas for electricity and heat production is taken as an input data in a mathematical model of cycling operation range evaluation.
- ④⑤ Natural gas for heat and electricity production in $m_{3,i}$ and $m_{4,i}$ was calculated by equation (1) and (2), correspondingly. Due to a short duration of $m_{4,i}$ (less than 30 minutes) the consumption of fuel is calculated for both periods simultaneously. Fuel consumption for heat and electricity production in $m_{1,i}$ and $m_{2,i}$ is calculated proportionally to the produced heat and electricity in $m_{1,i}$ and $m_{2,i}$. It is done by equations (3–4). The $Q_{m_{1,i}} = Q_{m_{1,i+1}}$ due to the fact that at the end of $m_{4,i}$ and at the beginning of $m_{1,i+1}$ heat power is greater than zero and electrical power is equal to zero.

Table 1. Equations of the evaluation model

Equation	Unit	Meaning	Eq. No.
$B_{th_{n,m}^{3..4}}^i = \frac{Q_{n,m}^{3..4}}{0.93 \times LHV}$	[m ³ /h]	The consumption of fuel for heat production in periods: operation above technical minimum and shutdown (Coefficient 0.93 describes the efficiency of heat production in cogeneration mode)	(1)
$B_{el_{n,m}^{3..4}}^i = B_{n,m}^{3..4} - B_{th_{n,m}^{3..4}}^i$	[m ³ /h]	The natural gas consumption for electricity production in periods is: operation above technical minimum and shutdown	(2)
$B_{th_{n,m}^{1..2}}^i = B_{n,m}^{1..2} \times \frac{\sum_{m_1}^{m_2} \sum_{n=1}^{n=N} Q_{n,m}^i}{\sum_{m_1}^{m_2} \sum_{n=1}^{n=N} P_{n,m}^i}$	[m ³ /h]	The consumption of natural gas for heat production in periods: warm state preservation and start-up	(3)
$B_{el_{n,m}^{1..2}}^i = B_{n,m}^{1..2} - B_{th_{n,m}^{1..2}}^i$	[m ³ /h]	The natural gas consumption for electricity production, when cogeneration unit is in warm state preservation or is started-up	(4)
$MC_{el_{avg}^{n,m}}^i = \frac{\sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (B_{el_{n,m}}^i \times C_{f_{n,m}}^i + B_{el_{n,m}}^i \times LHV \times E_{CO_2} \times C_{CO_2}^i)}{\sum_{m_2}^{m_1} \sum_{n=1}^{n=N} P_{n,m}^i}$	[€/MWh]	The average marginal cost of electricity per cycling operation range	(5)
$MC_{th_{avg}^{n,m}}^i = \frac{\sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (B_{th_{n,m}}^i \times C_{f_{n,m}}^i + B_{th_{n,m}}^i \times LHV \times E_{CO_2} \times C_{CO_2}^i)}{\sum_{m_2}^{m_1} \sum_{n=1}^{n=N} Q_{n,m}^i}$	[€/MWh]	The average marginal cost of heat per cycling operation range	(6)
$\Pi_{th}^i = \sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (C_{th_{n,m}}^i \times Q_{n,m}^i - B_{th_{n,m}}^i (C_{f_{n,m}}^i + LHV \times E_{CO_2} \times C_{CO_2}^i))$	[€]	The profit of produced heat in cycling operation ranges per year	(7)
$\Pi_e^i = \sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (C_{e_{n,m}}^i \times P_{n,m}^i - B_{e_{n,m}}^i (C_{f_{n,m}}^i + LHV \times E_{CO_2} \times C_{CO_2}^i))$	[€]	The profit of produced electricity in cycling operation ranges per year	(8)
$\Pi^i = \Pi_e^i + \Pi_{th}^i$	[€]	The total profit of heat and electricity production in cycling operation ranges per year	(9)

Figure 4 illustrates the simultaneous change of three parameters: natural gas consumption, heat power, and electrical power. Equation 10 presents the mathematical relation of these parameters; it is used as an input of the OM:

$$B_{m_3} = a_1 \times P_{m_3} + a_2 \times Q_{m_3} + a_3 \quad [m^3] \quad (10)$$

Table 2 reflects the obtained start-ups characteristics of CCGT technology. They are:

- the duration of start-up from the continuation of warm state preservation $h_2 = f(h_1)$;
- the consumed fuel for production of electricity and heat $B_{m_2} = f(P_{m_2}, Q_{m_2})$ during start-up (m_2);
- the change of electrical power during start-up from start-up type $P_{m_2} = f(h_2)$;
- the change of heat power from electrical power $Q_{m_2} = f(P_{m_2})$ during start-up (m_2).

The fitness of mathematical relations (Table 2), i.e. coefficient of determination (R-squared) and

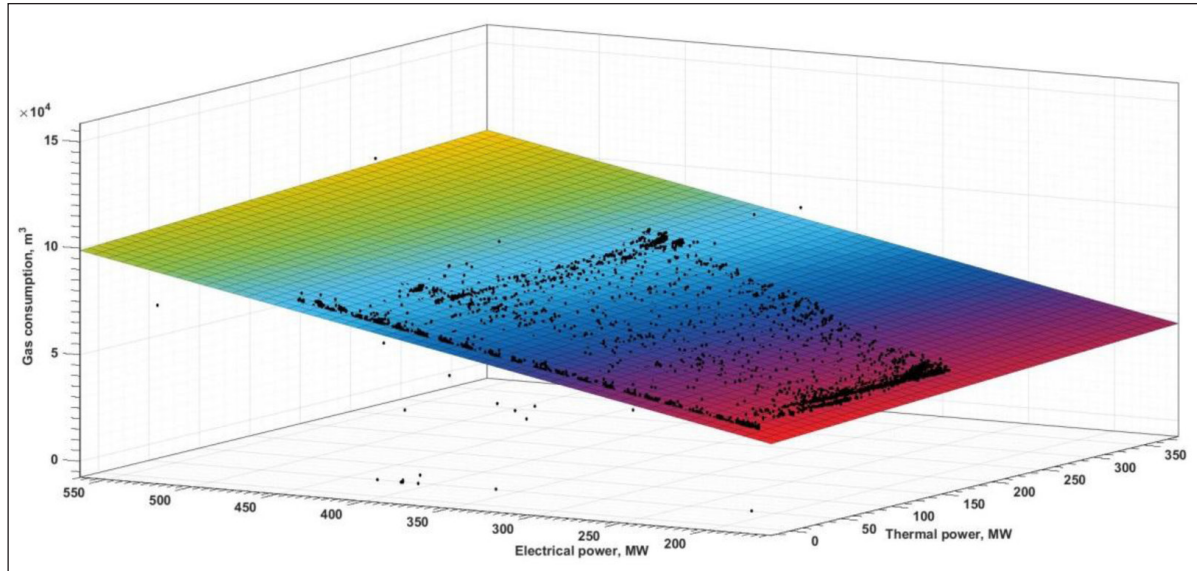


Fig. 4. Natural gas consumption as a function of electrical and heat power

Table 2. Start-up characteristics of CCGT technology

Start-up type	Function	Fitness
All	$h_2 = a_1 \times h_1 + a_0$	R-square: 0.9904; RMSE: 0.1757
Cold	$B_{m_2} = b_1 \times P_{m_2} + b_1' \times Q_{m_2} + b_0$	R-square: 0.9655 & RMSE: 1097
	$P_{m_2} = c_2 \times h_2^2 + c_1 \times h_2 + c_0$	R-square: 0.9415; RMSE: 12.67
	$Q_{m_2} = d_3 \times P_{m_2}^3 + d_2 \times P_{m_2}^2 + d_1 \times P_{m_2} + d_0$	R-square: 0.7916 & RMSE: 11.06
Warm	$B_{m_2} = u_1 \times P_{m_2} + u_1' \times Q_{m_2} + u_0$	R-square: 0.9833 & RMSE: 1099
	$P_{m_2} = k_1 \times h_2 + k_0$	R-square: 0.9393 & RMSE: 13.21
	$Q_{m_2} = l_2 \times P_{m_2}^2 + l_1 \times P_{m_2} + l_0$	R-square: 0.8364 & RMSE: 9.581
Hot	$B_{m_2} = r_1 \times P_{m_2} + r_1' \times Q_{m_2} + r_0$	R-square: 0.9739 & RMSE: 1015
	$P_{m_2} = v_1 \times h_2 + v_0$	R-square: 0.7361 & RMSE: 19.7
	$Q_{m_2} = z_2 \times P_{m_2}^2 + z_1 \times P_{m_2} + z_0$	R-square: 0.9006 & RMSE: 9.566

root-mean-square error (RMSE), reflects a good correlation among the parameters.

Development of the optimization model

The proposed principle of the optimization model can be used in day-ahead and intra-day markets to ensure more profitable operation of a thermal power plant. Also, it can be used in balancing market to evaluate the possibility of producing additional energy when power deficit is observed. The information about Nord Pool physical markets can be found in [26, 27]. The developed optimization

model can be integrated in the unit commitment (UC) model to take into consideration the cycling operation of thermal power plants and increase the accuracy of the UC model. If the introduced optimization model is not going to be integrated into the UC model, then additional calculations are needed to check the influence of additionally produced energy on the generation portfolio. In this article, the concept of optimization task (Fig. 5) and its calculation algorithm (Fig. 6) are based on the principles of the Nord Pool intra-day physical market when the UC model results are

known. The developed approach is verified omitting the fact that additionally produced energy influences other energy sources.

According to the developed approach, the optimization of cycling operation is achieved through the extension of the cycling operation range (Fig. 5). The optimization time interval is limited to 24 hours, i.e. $\sum h_{1,2,3,4} = 24$. It is expected to gain added profit from the additionally produced energy in the market and decrease the adverse influence of cycling operation on equipment technical resource through the reduction of start-ups and change of their types to the less adverse ones. The last is taken for granted without numerical evidence based on literature [4, 11, 28, 29] and know-how.

The situation is variable at the electricity market, for instance, in the first additional hour of operation the profit is $\Pi_1 > 0$, in the second – $\Pi_2 < 0$, but $\sum \Pi_{1,2} > 0$, because $\Pi_1 \gg \sum \Pi_{1,2}$. In the third added hour the profit is $\Pi_3 > 0$, but $\sum \Pi_{1,2,3} < \Pi_1$, because $\Pi_1 \gg \Pi_3$. The dilemma rose, i.e. the maximum profit was obtained in the first hour, but the probability to reduce the adverse influence of cycling operation of equipment technical resource is smaller than in the second and third hours. However, the total gain profit for the first and second or for the first, second and third hours is positive, but is less than in the first additional hour. That is why the optimization task can be implemented in two ways: refer to the maximum profit (Optimization No. 1) or refer to the positive profit and reduction of the cycling operation negative impact on equip-

ment technical resource by maximizing the hours in operation (n) under condition that gained profit must be positive (Optimization No. 2). It is expressed through the maximization of operation hours (n).

The objective function for Optimization No. 1 is as follows:

$$\sum_i [\sum_{m_1}^{m_1} \sum_{n=1}^{n=N} (C_{e_{n,m}}^i \times P_{n,m}^i - B_{e_{n,m}}^i (C_{f_{n,m}}^i + LHV \times E_{CO_2} \times C_{CO_2_{n,m}}^i)) + \sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (C_{th_{n,m}}^i \times Q_{n,m}^i - B_{th_{n,m}}^i (C_{f_{n,m}}^i + LHV \times E_{CO_2} \times C_{CO_2_{n,m}}^i))] \rightarrow \max \Pi$$

Subject to

$$i = 1, \dots, I, i \in Z_+$$

$$n = 1, \dots, N, n \in Z_+$$

$$N \leq 24$$

$$\begin{cases} P = 0 \\ Q = 0 \end{cases} \text{ if } m = m_1$$

$$\begin{cases} 0 < P \leq P_{m_2} \\ 0 < Q \leq Q_{m_2} \end{cases} \text{ if } m = m_2$$

$$\begin{cases} P^{\min} < P \leq P^{\max} \\ Q^{\min} < Q \leq Q^{\max} \end{cases} \text{ if } m = m_3, m_4$$

The objective function for Optimization No. 2 is as follows:

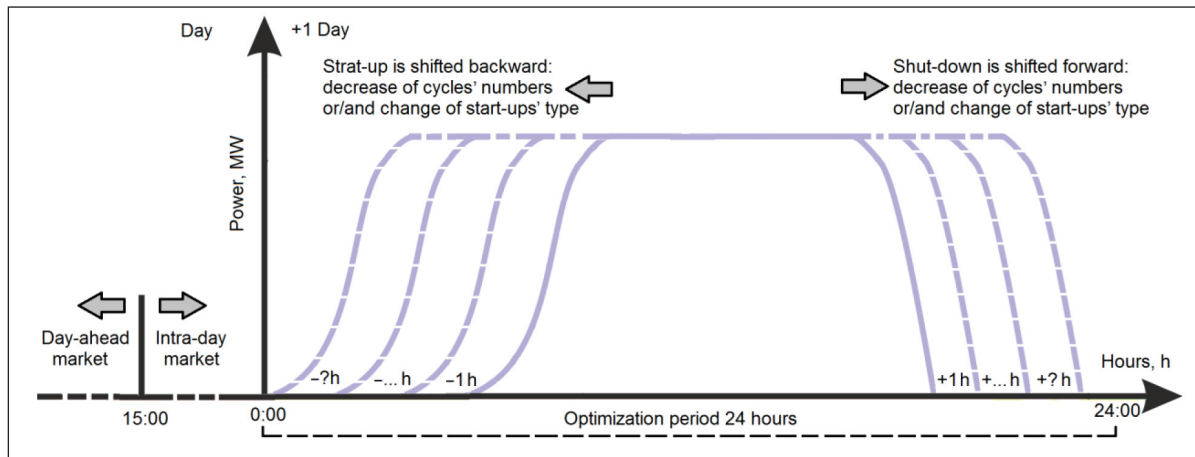


Fig. 5. A classic example of optimization task concept

$$\sum_i \left[\sum_{m_1}^{m_4} \sum_{n=1}^{n=N} (C_{n,m}^i \times P_{n,m}^i - B_{n,m}^i (C_{f,n,m}^i + LHV \times E_{CO_2} \times C_{CO_2,n,m}^i)) \right. \\ \left. + \sum_{m_1}^{m_2} \sum_{n=1}^{n=N} (C_{h,n,m}^i \times Q_{n,m}^i - B_{h,n,m}^i (C_{f,n,m}^i + LHV \times E_{CO_2} \times C_{CO_2,n,m}^i)) \right] \rightarrow \max \Pi$$

Subject to

$$i = 1, \dots, I, i \in Z_+$$

$$n = 1, \dots, N, n \in Z_+$$

$$N \leq 24$$

$$\begin{cases} P = 0 \\ Q = 0 \end{cases} \text{ if } m = m_1$$

$$\begin{cases} 0 < P \leq P_{m2} \\ 0 < Q \leq Q_{m2} \end{cases} \text{ if } m = m_2$$

$$\begin{cases} P^{\min} < P \leq P^{\max} \\ Q^{\min} < Q \leq Q^{\max} \end{cases} \text{ if } m = m_3, m_4$$

$$\Pi > 0, \Pi \in R_+$$

The input of OM algorithm (Fig. 6) is the production data of technologies (P , Q , B , etc.) and obtained characteristics in Table 2. Initially, the calculation day is identified in line with Nord Pool market principles (the total number of days is 365/366). After the extension of technology, the working time is calculated for each identified day by shifting shutdown “forward” and start-up “backward” until the optimal solution is achieved in line with Optimization No. 1 and 2. The obtained results are accumulated while

the calculations for all days of the year are done. After they are finished, the appropriate solution is found.

CASE STUDY: APPLICATION OF THE DEVELOPED APPROACH IN RIGA CHP-2

Investigated object: Riga CHP-2

After Latvia has joined the Nord Pool electricity market in June 2013, the production unit Riga CHP-2 started to operate in line with electricity market conditions. The power plant is in operation if its production costs are less than the electricity price at the market and is stopped if its marginal costs are higher than the electricity price. The Riga CHP-2 power plant is not fully adapted to the cycling modes. Moreover, taken into account the significance of CHP-2 in the Baltic States, the negative consequences may arise, which are described in detail with calculus in [30], if flexibility and efficiency of the cogeneration power plant will not be sustained. That is why Riga CHP-2 has been chosen as an investigated object to verify the developed approach in Section 2 and provide recommendations for the CHP-2 plant in line with the developed approach.

Briefly, the CHP-2 power plant is located in Acone, i.e. 28 km from Riga (the capital of Latvia). It is a base load power plant. CHP-2 consists of two combined cycle gas turbine units, CCGT-2/1 ($P = 413$ MW and $Q = 274$ MW) and CCGT-2/2 ($P = 419$ MW and $Q = 270$ MW), and five heat

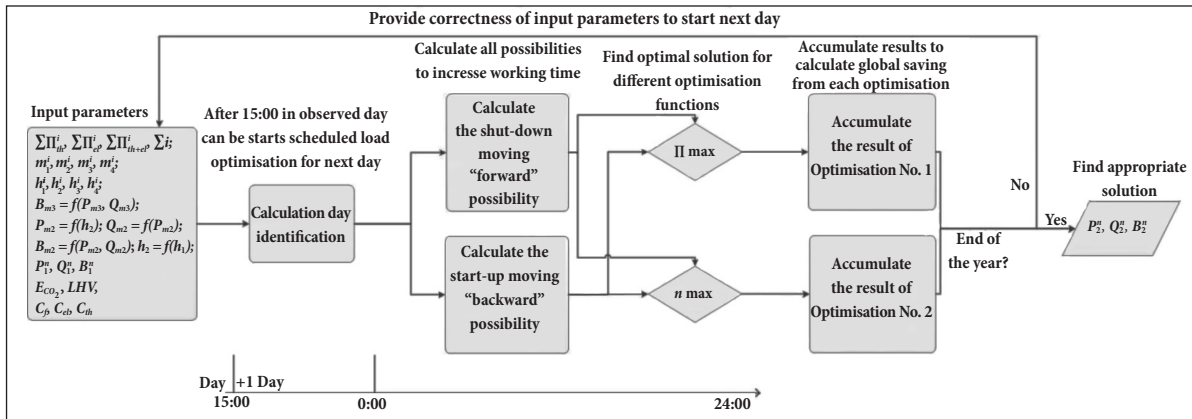


Fig. 6. The algorithm for optimization model calculation

only boilers ($Q = 5 \times 116$ MW). Natural gas is used as a primary fuel, and diesel as emergency fuel. Cogeneration units (CCGT-2/1 and CCGT-2/2) are identical, that is why further the operation features and developed approach approbation are shown on the example of CCGT-2/1. The cogeneration unit operates in these three modes:

- cogeneration and condensation ($P_{\text{cog. \& cond.}} = 190\text{--}413$ MW and $Q_{\text{cog. \& cond.}} = 60\text{--}180$ MW);
- pure cogeneration ($P_{\text{pure cog.}} = 190\text{--}413$ and $Q_{\text{pure cog.}} = 180\text{--}274$ MW);
- pure condensation ($P_{\text{pure cond.}} = 190\text{--}442$ MW and $Q_{\text{pure cond.}} = 0$ MW).

Figure 7 reflects the CCGT-2/1 operation area (modes) and operation statistics for three years (2014–2016). The shifting from efficient modes (pure cogeneration) to inefficient operation conditions (cogeneration and condensing) can be noticed. For example, the operation in pure cogeneration mode was 44.09% in 2014, 1.14% in 2015, and 16.88% in 2016. In turn, the operation in cogeneration and condensation mode increased from 31.7% (in 2014) to 48.37% (in 2016). The running conditions were determined by ambient temperature, electricity price, and natural gas price. The cogeneration unit was operated mainly in pure condensation mode (84%) in 2015 due to a low heat energy demand, low natural gas price, and high electricity price. How-

ever, the pure condensation in 2014 and 2016 was 24.22% and 34.74%, respectively.

Results of model evaluation

The CCGT-1 cycling operation range was analysed for 2016 in line with the approach introduced in Section 2.1. There were 57 start-ups or *i* cycling operation range: 15 hot start-ups, 19 warm start-ups, and 23 cold start-ups.

The cold start-up was 2 times longer than the warm start-up and 4 times longer than the hot start-up. The average duration of the cold start-up was more than 4 hours (Fig. 8).

During the cold start-up, approximately 2 times more natural gas was consumed than for the warm start-up and approximately 3 times more than for the hot start-up. The average consumed natural gas for the cold start-up was 9.8×10^4 m³ (Fig. 9).

In 2016, the longest cycling operation range was 448 hours, and the shortest 8 hours. The average duration of the cycling operation range was 45 hours (Fig. 10). The maximum values of benefit from electricity and heat realization were 3.2×10^6 € and 175.4×10^3 €, respectively. The maximum values of losses from electricity and heat productions were 140×10^3 € and 8.5×10^3 €, correspondingly. The profit from electricity and heat realization of CCGT-2/1 was

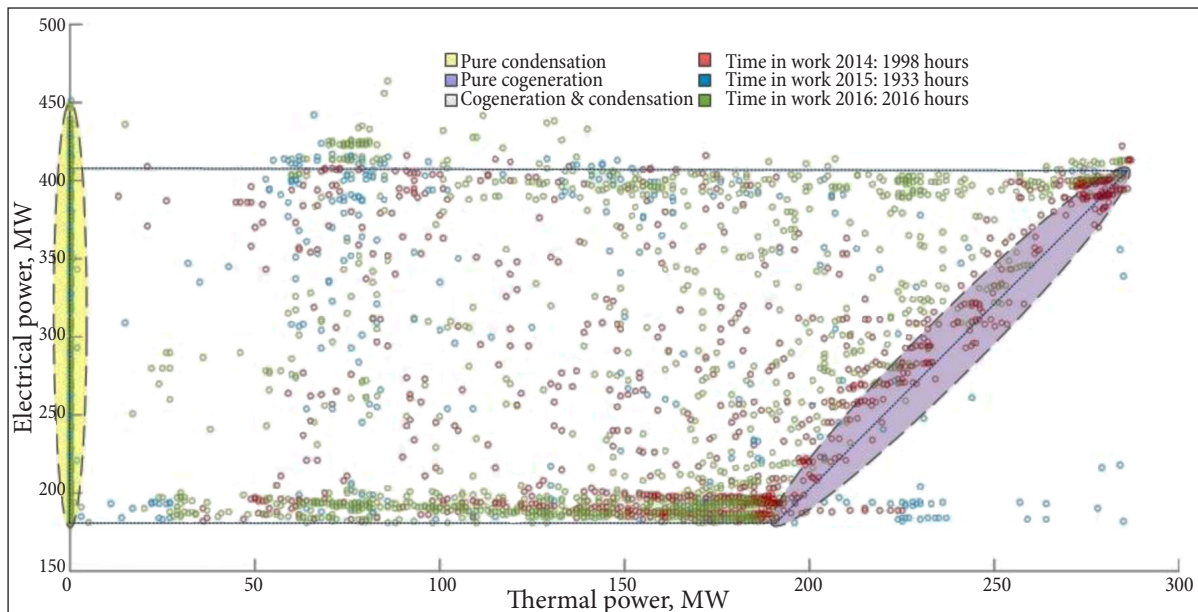


Fig. 7. CCGT-2/1 operation area and operation statistics

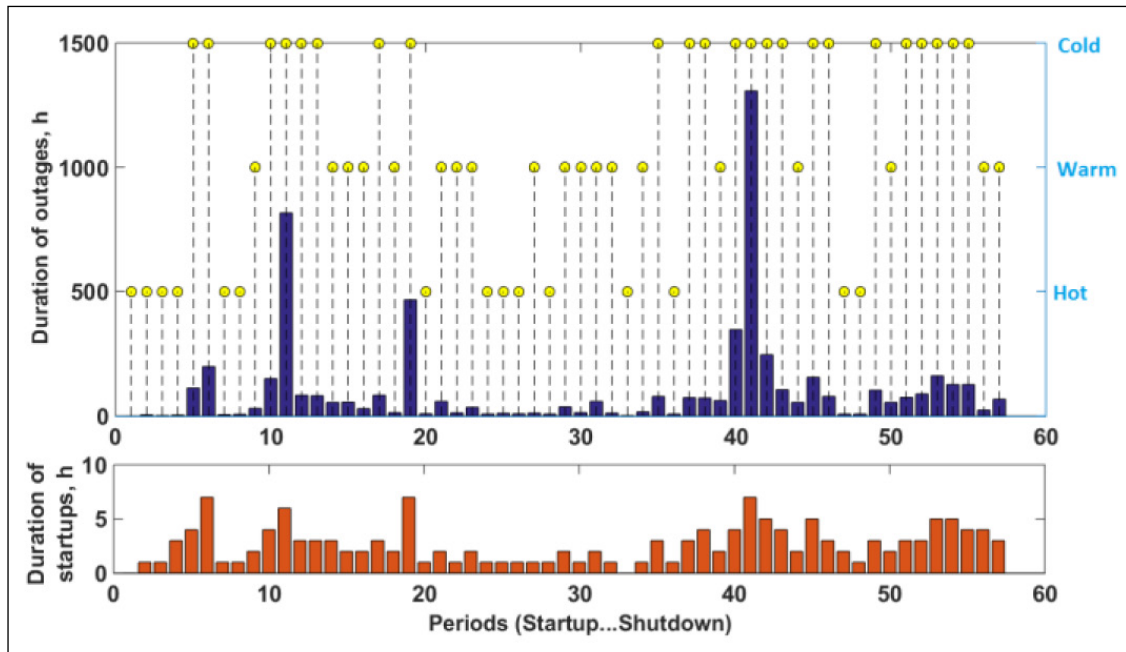


Fig. 8. Types of start-ups, duration of start-ups and outages

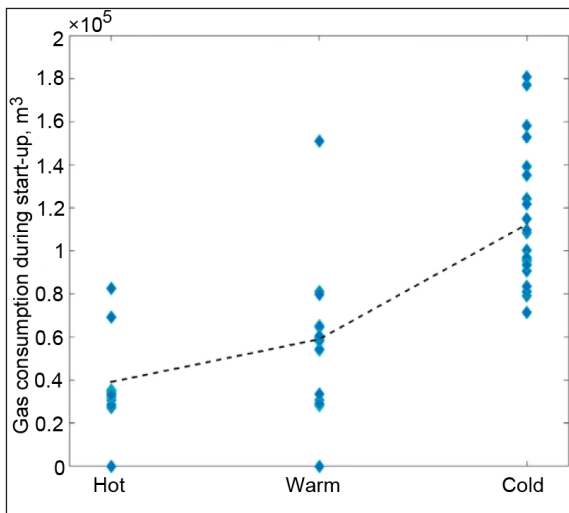


Fig. 9. Gas consumption versus start-up time

6.0×10^6 € and 400.0×10^3 € per 2016. The obtained results indicate that the realization of electricity provides higher profit for the power plant than the realization of heat energy. The total profit from heat and electricity realization of CCGT-2/1 was 6.4×10^6 € in 2016.

Results of the optimization model

Table 3 shows the results of shifting shutdown “forward” and start-up “backward” by extension of the cycling operation range for two optimization tasks: $\Pi \rightarrow \max$ and $n \rightarrow \max$.

The results of Optimization No. 1 demonstrate that the number of operation ranges stays the same, i.e. 57. The amount of the warm start-up and cold start-ups reduced by 4 and 2, respectively, that is why the hot start-ups increased by 6. The increment of operation hours is 228 hours, and of added profit is 1.42 M€. The results of Optimization No. 2 reflect that the number of warm and cold start-ups reduces by 4 and 2, respectively, but hot start-ups increase by 2 due to the reduction of cycling operation from 57 to 53. The increment of operation hours is 275 hours, and of profit is 1.27 M€.

After the results of two optimization tasks had been compared, the authors concluded that Optimization No. 1 ensured a higher profit than Optimization No. 2, i.e. 1.42 M€ and 1.27 M€, respectively. The difference is insignificant, approximately 150 k€. In turn, the results of Optimization No. 2 demonstrated the decrease of cycling operation ranges by four cycles, whereas Optimization No. 1 did not. The optimization under condition $n \rightarrow \max$ is preferable.

For instance, Fig. 11 represents a graphical illustration of changes in CCGT-2/1 operation (the probability of start-up and shutdown) before (the dash red and blue line) and after (the solid red and blue line) Optimization No. 2. The red lines describe the duration of outages, and blue lines characterise the duration of

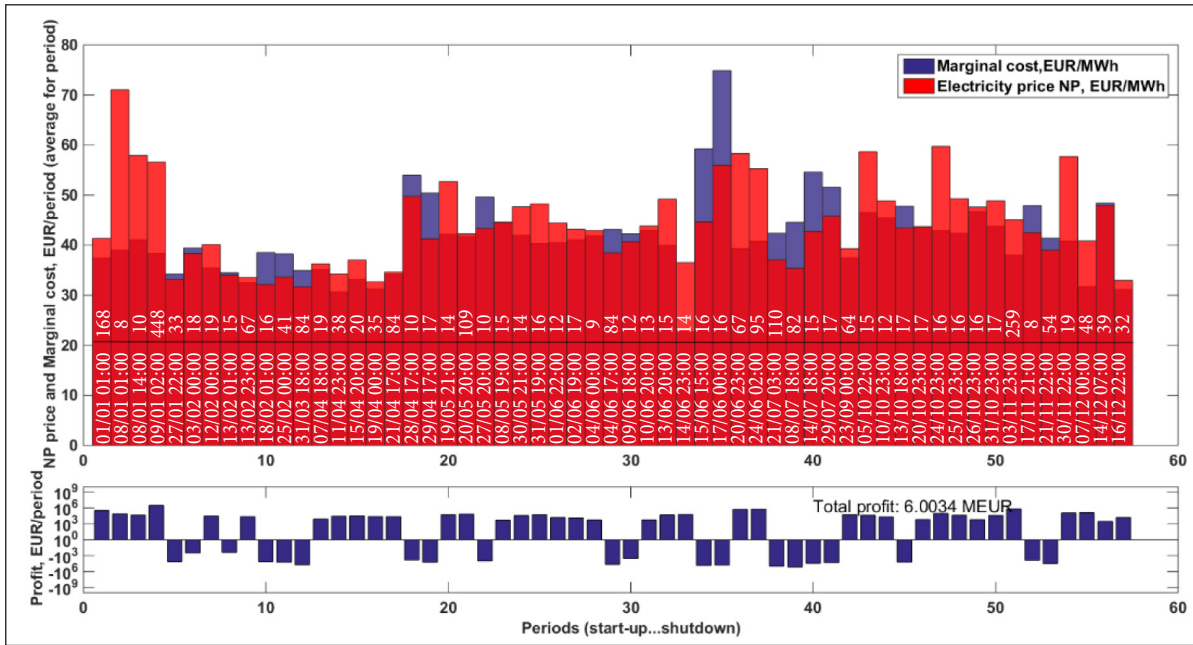


Fig. 10. Average Nord Pool price, average electricity marginal cost and profit from electricity realization in cycling operation ranges “r”

Table 3. The results of optimization tasks

	Profit, [M€]	Σj , [number]	Operation hours, [h]	Amount of hot start-ups, [h]	Amount of warm start-ups, [h]	Amount of cold start-ups, [h]
Before optimization	6	57	2571	15	19	23
Optimization No. 1 ($\Pi \rightarrow \max$)	7.42	57	2799	21	15	21
Optimization No. 2 ($n \rightarrow \max$)	7.27	53	2846	17	15	21

cycling operation. The continuance of cycling operation ranges became longer, i.e. the blue solid line under the dash blue line or the shifting of

blue dash line to the right is observed in Fig. 11. In turn, the duration of outages became rarer and shorter, i.e. mainly the red solid line is under

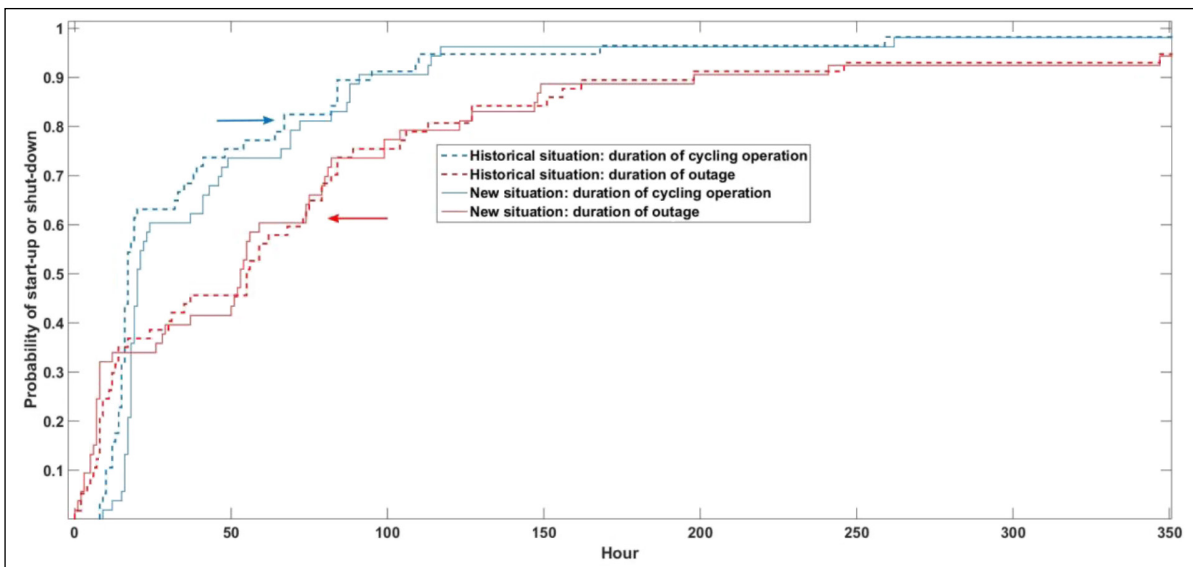


Fig. 11. Probability of start-ups and shutdowns before (historical situation) and after (new situation) Optimization No. 2

the dash red line or the shifting of red dash line to the left is noticed in Fig. 11.

DISCUSSIONS AND FUTURE WORK

In this article, an approach has been developed for the combined cycle gas turbine power plant, which operates in the electricity market on the example of the Nord Pool intra-day physical market to ensure its operation in a more flexible, efficient and profitable way. The approach has been realized in a multi – paradigm numerical computing environment *MATLab*. The results from a real-life case study have shown that the developed approach is accurate and computationally efficient.

It is recommended to incorporate the developed approach in the generation portfolio of Riga CHP-2. The obtained results ensure that the use of this approach ensures the additional profit and the reduction of cycling operation negative impact on equipment technical resource (Optimization No. 2).

The presented concept of the developed approach can be adapted to various technology and physical markets by changing the characteristics and principles, respectively. It can be integrated into the unit commitment model and used as a corrective block for thermal power plants which take into account the features of cycling operation.

Directions for future research would include: (1) further improvement of the developed approach, e.g. time step minimization to the minute or second, the supplementation of the optimization model with the ramp rate of technology, heat load forecasting when the extension of the cycling operation range occurs; (2) the provision of numerical evidence that the achieved decrease of start-up numbers and the change of start-up types to the less adverse have the positive effect on a thermal power plant from an economical, technical and environmental point of view; (3) integration of the developed approach in the unit commitment model and making a conclusion on the usefulness of UC supplement with the developed approach.

Received 15 November 2017

Accepted 15 December 2017

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CIKLINIO EKSPLOATAVIMO OPTIMIZAVIMO METODAS TRADICINĒMS KOGENERACINĒMS JĒGAINĒMS

Santrauka

Rinkos mehānismu īgyvendināmas, apimantis elektros enerģijas kainu svāriumus ir plataus atsānujānanču enerģijas išteklju (saulis ir vjo enerģijas) integrāvu i elektros enerģijas gamybu, pakeitē tradicinis

enerģijas gamybos vaidmenj ir veikimā. Tai is dalies arba is viso nira pritaikyta naujoms eksploatavimo salygoms, todrl reikia tobulinti tradicinis elektros gamybos efektyvumā ir lankstumā. Kombinutojo ciklo duju turbinu (angl. CCGT) tehnologiju pagrindu sukurtas skaitmeninis metodas siekiant pritaikyti ju veikimo salygas elektros enerģijos rinkai. Sukurtas metodas buvo patvirtintas MATLAB skaičiavimo aplinkoje Baltijos saliu (Latvijos) atvejo analize. Gauti rezultatai rodo, kad papildomas pelnas yra gaunamas gaminant daugiau elektros enerģijos, o ciklinis eksploatacijos poveikis sumažija mažinant ciklu skaičiu ir pakeičiant paleidimus palankesniu techniniu ir ekonominiu režimu. Sukurtas metodas gali būti pritaikytas įvairioms tehnologijoms ir situacijoms papildant atitinkamas technologines charakteristikas ir ribojimus.

Raktažodžiai: tradicinė gamyba, ciklinė eksploatacija, elektros rinka, paleidimas, stabdymas