Modernization of a combined-cycle gas turbine unit for operation in the dynamic district heating mode

Vladimir Sednin[1,*], *Alexei* Sednin[2], and *Sergei* Rumyantsev[1]

[1]Belarussian National Technical University, Industrial Thermal Power Engineering department, Minsk, Belarus
[2]Belarussian National Technical University, Research and Innovation Center "Automated Control Systems in Thermal Power Engineering and Industry" Minsk, Belarus

Abstract. The ongoing changes in the unified power system of Republic of Belarus require cost-efficient technical solutions to increase flexibility and reliability of electricity supply. Expected power generation mix and plant load factor of the newly constructed sources give limited possibilities of cost-efficient and reliable operation. The paper introduces the optimization of peaking and reserve energy source constructed newly at site of the existing power plant. Transferring the existing combined-cycle gas turbine into a dynamic district heating mode enhances the operational and financial flexibility of total system in a long-term prospective.

1 Introduction

When organizing power supply systems for the industrial and residential sectors, the physical characteristics of electricity as a commodity must be taken into account. Namely, at any specified time there must be a balance between electricity production and consumption. This, together with the technical limitations of generating equipment, economic and legal limitations, forms one of the most inportant problem of power system regulation - providing consumers with the required amount of electricity at any given time. The consideration and reserches regarding the above-mentioned problem were previously carried out in both technical and economical fields [1,2].

A main trend of the development of energy systems around the world are the significant changes resulting from the introduction of distributed energy resources: integration of energy sector with related industries, increasing availability of cheap variable renewable energy sources (hereinafter - RES), advances in digitalization, growing electrification capabilities and a number of other factors specific to individual countries.

RES has become the second largest source of electricity in the world. In 2018, they accounted about 25% of global electric power generation. It is more than traditional sources as natural gas, nuclear power and oil products, and less only than coal-fired generation. This became possible due to the reduction in the cost of generating capacity and the policies of developed countries that support the development of RES. The integration of higher shares of variable renewable energy sources (hereinafter - VES) such as wind and solar photovoltaics technologies into energy systems is important to decarbonize the energy sector while continuing to meet the growing demand for energy. However, the inherent variability of wind and solar photovoltaic generation creates challenges for energy system operators and regulators. Therefore, the growing importance of VES is one of the most important factors in the transformation of energy systems around the world. However, energy systems in which a high share of installed capacities must operate in baseload mode, face the similar problems as well.

The development of the energy sector has taken place in Belarus in three main directions: significant re-equipment through the introduction of combined-cycle technologies using natural gas mainly, construction of a nuclear power plant and expansion of the use of local and renewable fuels. Thus, nuclear fuel and renewable energy sources, such as solar energy, wind, liquid biofuels, biogas, and renewable municipal waste are added to the traditional natural gas. Abovementioned rapid changes caused large disbalances in local energy system and put in front of the new challenges. While growing influence of VRE can be limited by administrative limitations, the issue of integration of the Belarussian nuclear power plant (hereinafter - BelNPP) into the unified energy system of the country is more serious and comprehensive problem. Commissioning of the nuclear power plant with capacity of 2 400 MW (about 20% of the installed capacity of the energy system) is the main disturbing factor, which determines changes of modes of operation of the Belarusian energy system. Commissioning of the first from two planned 1200 MW units is carried out in 2021. Therefore, the problem of balancing the generation and consumption of energy, as well as the organization of the operational reserve of generating capacity is an urgent problem for the energy system of Belarus.

* Corresponding author: vsednin@mai.ru

Abovementioned changes require increasing flexibility of the unified power system and taking measures to support the integration of nuclear power and RES, including VES. Flexibility in this case refers to the ability of the power system to maintain uninterrupted saturating the consumers' needs in electricity during periods of rapid and large fluctuations in consumption and generation, regardless of its reasons. Flexibility has always been an important requirement for power systems because of contingencies, such as outages of power plants and transmission lines, but in this situation this requirement comes to the fore.

One of the measures taken to increase the flexibility of the power system and to increase the operational capacity reserve is the construction of peaking and reserve energy sources (hereinafter - PRES) with a total capacity of ~ 800 MW [3]. At the sites of the four existing power plants are constructed respectively: 300 MW of gas turbine capacities - at Minsk CHP-5 (currently operating in condensing mode), located about 30 km away from Minsk, 250 MW at Berezovskaya Regional power station (less than 20 km from the nearest regional center), 150 MW at Lukomlskaya Regional power station (the most distant station from significant heat consumers, about 100 km from Orsha and Vitebsk) and 100 MW at Novopolotsk CHP. The first three plants are now equipped with 400 MW el. combined cycle gas turbines (hereinafter – CCGT-400). At Minsk CHP-5 a 270 MW M701F gas turbine (Dongfang Turbine Co. Ltd. together with MHI); a 129,6 MW steam turbine (Dongfang) and a 445 MW electric generator are applied. All the PRES stations are equipped with Siemens SGT-800 gas turbine units. Their core engines are gas turbine engines of single-shaft design with 15-stage compressor, 3-stage turbine and low-emission combustion chamber with technology of dry emission suppression (DLE) [4]. Natural gas is used as the main fuel of the PRES, while light fuel oil is used as backup and emergency fuel.

According to the preliminary estimations the PRES will operate at full power output approximately 700 h/year (2 h/day). In the existing conditions at the market of energy resources, it is impossible to achieve any parameters of operation, allowing payback of this technical solution in the based-planned option. In this regard, minimization of the final costs can only be discussed.

Assessment of possible losses due to NPP unit shutdown or insurance risks of NPP operation is a separate problem, requiring special knowledge and qualification. Nevertheless, comparing the corresponding availability factors of NPP units published by the IAEA [5], it can be noticed that the actual values differ from the planned ones, and also differ even at reactors of the same type located in one country. This is due to the objective limits of predictability of availability of such a complex technical facility, and this discrepancy cannot characterize the quality of performance of the NPP unit itself. However, because of the significant capacity of BelNPP units (up to 25% of the base load of the power system and about 15-20% of the peak load[a]), the discrepancy between the predicted and actual availability of BelNPP can have a significant impact on the balance of the power system.

Therefore in the common practice, the payback of such kind of projects is provided through the introduction the higher rates for reserve capacity. In Belarus this aproach is used by the application of a differentiated rates for energy, introduced in Belarus by the Decree of the Council of Ministers of the Republic of Belarus of July, 1st , 2019 № 442 "On Amendments to the Decree of the Council of Ministers of the Republic of Belarus of December, 30th , 2013 № 1166".

There is a conseusis that the most effective way to regulate consumption is considered the transition from monopoly to market pricing for electricity in the common case [6]. This method ultimately allows to find a mutually satisfactory solution to the problem - smoothing of peaks and dips in consumption. Introduction of differentiated tariffs by time intervals can be considered as a special case of such approach.

As follows from markets data [7,8], the price of electricity is determined by the balance of supply and demand, and the technical side of the issue of energy production and supply (which directly affects the cost) remains the choice and responsibility of the generating organization. In this case, the prices of electricity produced in the base mode are quite low. At the same time, prices for peaking and reserve generation, are mainly higher than the average daily prices, and during unplanned or emergency situations (e.g. emergency shutdown of a large source), may exceed the average daily prices by tens of times.

In Belarus, where energy tariffs are controlled by the government, such transition is not considered. However, the natural monopoly approach can give an advantage of possibility of cooperation between significant economical entities that reduces final operational costs for the total system.

One of the apparent technical solutions is turning the PRES in to "dynamic district heating" mode [9], [10]. The structural optimization of 250 MW PRES with CCGT-400 in cogeneration mode according to Minsk CHP-5 conditions was presented in [11]. Fig. 4 presents a process chart of the integrated unit.

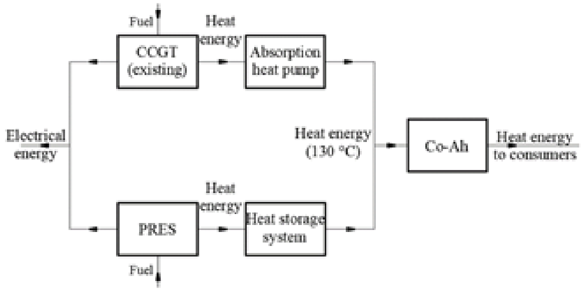

Fig. 4. Process chart of integrated unit.

[a] According to the Concept of development of electric generating capacities and electric networks for the period up to 2030 (Annex to the Resolution of the Ministry of Energy of the Republic of Belarus, February, 25th, 2020 № 7).

A special aspect is the application of long-distance heat supply technology of so-called "Co-Ah" type [12] that utilizes the absorption heat pumps both on the side at the power plant and on the side of heat consumers. Application of Co-Ah technology at the heat source and heat substation at the input to the distribution network (in this case – at peaking boiler house) based on absorption heat pumps can significantly enhance the capacity of main heat pipelines and reduce the costs of heat transport.

Previous numerical study [11] assumes that turning PRES to the dynamic district heading mode leading positive payback period. Payback of simple cycle plants is possible only at prices for peak and reserve generation will be more than 0.15 $/kWh, which corresponds to 80% increase of the existing rate. At the same time, for the cogeneration modes the payback is possible even when the electricity price is 0.07$/kWh. At the same time the increase of natural gas price makes cogeneration schemes more preferrable, and reduce the economical values of the simple-cycle schemes.

Since the total capacity of the newly constructed PRES will be about 8% of the installed generating capacity of the power system after the commissioning of BelNPP both reactors, and the designed lifecycle of this type of equipment is about 30 years, it worth to continue the investigations of the use of RPES in the dynamic district heating mode, taking into account the uncertainty of such factors as fuel price and electricity tariff to determine the dependence of economical efficiency of the integrated plant from this variable factors.

Resulting from the applied changes in power system in Belarus, an expected scenario is an outage of hughly-efficient combined-cycle gas turbines (as 400 MW el. unit at Minsk CHP-5) and holding them in non-spinning recerve mode. More optimistic scenario is transferring such units from baseload operation to variable load, but the possibilities of such operation and its efficiency remains uncertain. In any case it is obvious that all of this scenarios will lead to decreasing a plant load factor and increace a total costs, comparing with existing conditions.

In addition, outage of a combined-cycle gas turbines that operates in cogeneration mode will cause heat demant that will have to be covered by a direct fired boilers or electrical boilers. Both of the solutions have nothing similar with energy efficiensy and will bring only the additional costs increasing caused by transferring from coreneration to separate generation of energy.

2 Materials and methods

As a structural optimization of PRES the authors propose the utilizing of PRES in the periods of peak loads of the power grid torether with transferring the CCGT-400 to a cogeneration mode with the lowest possible steam flow to the condencer (maximum steam flow is directed to the selection). Tab. 1 shows CCGT-400 performance data at partial loads.

Table 1. CCGT-400 performance data [11, 12].

Gas turbine load, %	Exhaust gases flow rate, kg/s	Exhaust gases temp.,ºC	Combine-cycle power output, MW el.	Combined-cycle electrical efficiency, %
100	710	585	385.5	50.6%
90	670	580	349.7	50.0%
80	620	570	311.9	48.7%
70	570	570	276.2	47.8%
60	530	570	241.7	46.2%

Fig. 5 shows the process chart of integrated (structially optimized) unit. Table 2 lists the performance data of the integrated unit.

Table 2. Integrated unit performance data (CCGT 400 MW el. + 300 MW el. PRES in dymamic district heating mode) [11].

Elecrtical power output, MW el	564.5	MW el.
Inclusing PRES	318	MW el.
Heat power output @ PRES opetation. h/day:		
1	193.8	MW th.
2	210.3	MW th.
3	226.7	MW th.
4	243.2	MW th.
5	259.7	MW th.
6	276.0	MW th.

In this paper, the PRES with a heat recovery system for district heating up to 95 °C. In the process of operation of the PRES the primary heating network (hereinafter - PHN) water obtains heat from the exhaust gases and is supplied into the district heating network. The excesses of heated PHN water are accumulated in the heat storage tank, which is discharged gradually and evenly during the day. The PHN water with a temperature of 95 °C from the PRES mixes with the PHN return water heated in the absorption heat pump installed at CHP, to a temperature of 85 °C and further it is supplied to the steam-water heat exchanger, where obtains the heat from selection steam and heated to a temperature of 130 °C. The remaining part of the steam, that directed to the heating selection (2.5 barG) of the steam turbine, is used for heating the water directly in the steam-water heat exchanger from 25 to 130 °C.

From the CHP steam-water heat exchangers the PHN supply water is supplied by pipeline to the peaking boiler house, located in the heat load zone, where the absorption heat pump and the heat exchanger are installed as a single system, called "Co-Ah" [13]. PHN supply water with a temperature of 130 ° C enters the heat pump as a drive and leaves the it with a temperature of 90 ° C and then passes to the heat exchanger, where it heats the secondary heating network (SHN) water from 50 to 85 ° C. Then the PHN water with temperature of about 55 °C is directed back to the heat pump, but as a low-potential flow. The heated flow in the heat pump is SHN water.

From the results of the study [10], which shows the effect of changes in a number of factors (fuel price, number of PRES operation hours, the price of electricity) on the financial performance of the project with different

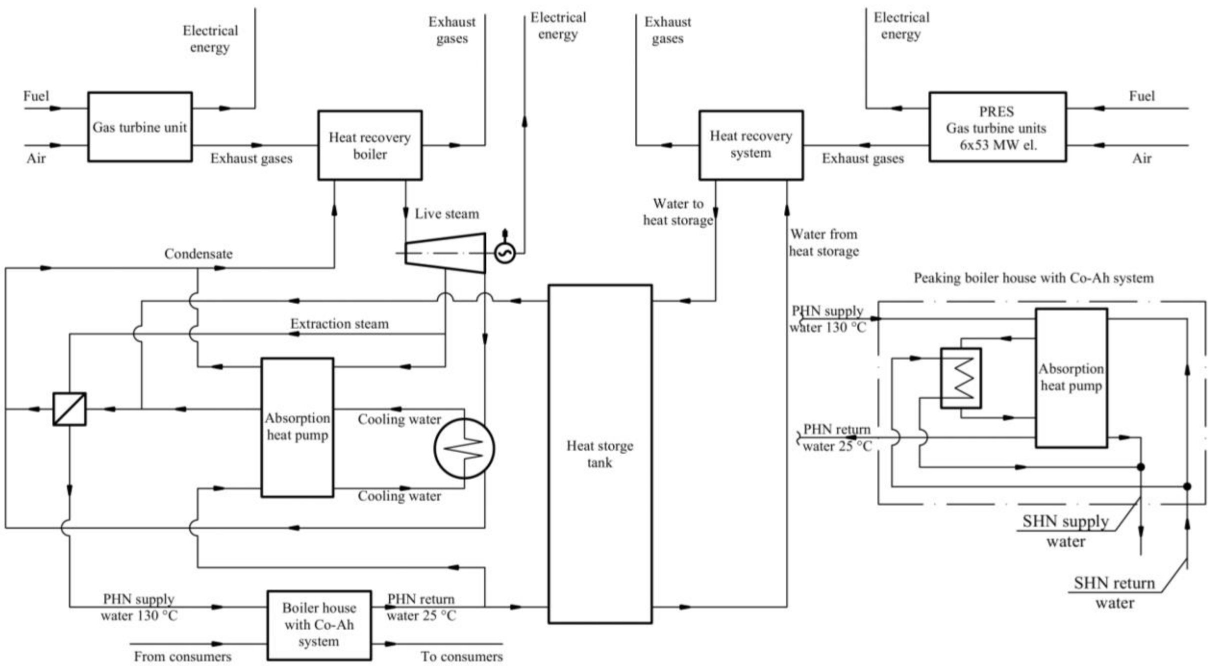

Fig. 5. Process chart of the integrated unit of CCGT-400 and PRES of 300 MW el.

options of PRES equipment, it follows that the practical interest is not in the extremum of the target function, but in the conditions under which break-even operation (NPV=0).

The macro-level mathematical model [14,15] developed earlier was used for this study. That allows considering a various combinations of operation modes of the PRES and CCGT with unloading of the latter to the minimum capacity, providing economically efficient performance. Equipping of the PRES with the heat accumulation system will allow the integrated power plant to operate efficiently following the electric loads of the system.

The net present value (NPV) for the PRES estimated lifecycle, reduced to the initial period, was taken as the target function (TF). This parameter clearly indicates economical efficiency of the project - its positive value or the position of the graph above the abscissa clearly indicates the payback period. NPV is defined as:

$$\text{TF=NPV=}\sum_{t=0}^{T_{serv}}\frac{\text{K}_i\text{-E}_i}{(1+r)^t},\ \text{mln. \$}$$

where K_i is the single period (i) investments, estimated on the major Components characteristics, determined by process chart calculation; E_i is economic effect during single period (i), mln. $, determined as difference between revenue received from electricity and heat sale and fuel and maintenance costs; T_{serv} is PRES estimated lifetime, years; r is discount rate; t is number of period (years).

To determine the parameters of break-even point operation of PRES the authors propose a method of determining the relation of NPV fron a number of factors. The costs of generated electricity T_{el} and fuel C_f are considered as the determining factors, and PRES operating hours τ as a function (response). The results matrix of numerical experiment with the proposed mathematical model, performed in specified parameters area, is used as the initial basis:

- electricity cost – from 0.07 to 0.15 $/kWh;
- fuel cost (natural gas) – from 100 to 225 $/th.m^3;
- PRES operating hours per day, from 1 to 6.

Using the data obtained from the numerical study of the mathematical model by identifying the target function (NPV) in the state corresponding to the break-even point of operation.

The common form of the required relation is:

$$\text{NPV} = f\left(T_{\text{el}}, C_f, \tau_{\min}\right) = 0,$$

Using the equation for linear approximation, it can be writen as:

$$\text{NPV}(\tau_{\min}) = NPV(\tau_1) + \frac{\text{NPV}(\tau_2) - \text{NPV}(\tau_1)}{\tau_2 - \tau_1}\cdot\left(\tau_{\min} - \tau_1\right) = 0$$

Converting the abovementioned equation in relation to the PRES operation time, the equation for determination of the required parameter (in this case, the minimum PRES operation time) corresponding to the break-even point can be written as:

$$\tau_{\min} = \tau_1 + \text{NPV}(\tau_1)\cdot\frac{\tau_2 - \tau_1}{\text{NPV}(\tau_2) - \text{NPV}(\tau_1)},\ \text{h/day}$$

By a defined values the relation of a PRES minimal operation time $\tau_{\min}$ from peaking generation price T_{el} is approximated to a second-degree polynom as following:

$$\tau_{\min}\left(T_{\text{el}}\right)=a_0+a_1\cdot T_{\text{el}}+a_2\cdot T_{\text{el}}^2,\ \text{h/day},$$

Taking into account a form of the abovementioned relation, the polynom coefficients can be found using three points from the matrix of numerical simulation results by solving the system of equations:

$$\begin{cases}\tau_{\min}\left(T_{1\text{el}}\right)=a_0+a_1\cdot T_{1\text{el}}+a_2\cdot T_{1\text{el}}^2\\ \tau_{\min}\left(T_{2\text{el}}\right)=a_0+a_1\cdot T_{2\text{el}}+a_2\cdot T_{2\text{el}}^2\\ \tau_{\min}\left(T_{3\text{el}}\right)=a_0+a_1\cdot T_{3\text{el}}+a_2\cdot T_{3\text{el}}^2\end{cases},$$

Similary, the relation $a_i=f\left(C_f\right)$ is determined.

By combining the determined relations, a generalized relation of the PRES minimum operating time from the parameters, at which cost-effective will be ensured can be given as:

$$\tau_{\min}\left(T_{el},C_f\right)=\sum_{\substack{(i=0)\\ j=0}}^{2} b_{ij}\left(T_{\text{el}}\right)+\sum_{\substack{(i=1)\\ j=0}}^{2} b_{ij}\left(T_{\text{el}}\right)C_{\text{f}}+\sum_{\substack{(i=2)\\ j=0}}^{2} b_{ij}\left(T_{\text{el}}\right)C_{\text{f}}^2,\ \text{h/day} \quad (1)$$

Using the data of the numerical investigation for the basic option and the integrating cogeneration unit (optimized option), the coefficients of equation (1) were obtained. Tab. 3, Tab. 4. and Fig. 6 show the dependence of the break-even PRES operation time for a simple-cycle operation (basic option) and in cogeneration mode (optimized option).

Table 3. Coefficients of the equation (1) for basic option.

j	b_{0j}	b_{1j}	b_{2j}
0	7.05	$-2.43\cdot10^{-1}$	$2.06\cdot10^{-3}$
1	$2.45\cdot10^{-2}$	$-2.92\cdot10^{-3}$	$6.97\cdot10^{-5}$
2	$8.61\cdot10^{-5}$	$-2.29\cdot10^{-6}$	$-1.18\cdot10^{-8}$

Table 4. Coefficients of the equation (1) for proposed optimized option.

j	b_{0j}	b_{1j}	b_{2j}
0	5.02	$1.19\cdot10^{-1}$	$-6.79\cdot10^{-3}$
1	$4.75\cdot10^{-2}$	$-4.91\cdot10^{-3}$	$1.08\cdot10^{-4}$
2	$-6.39\cdot10^{-5}$	$5.91\cdot10^{-6}$	$-1.28\cdot10^{-7}$

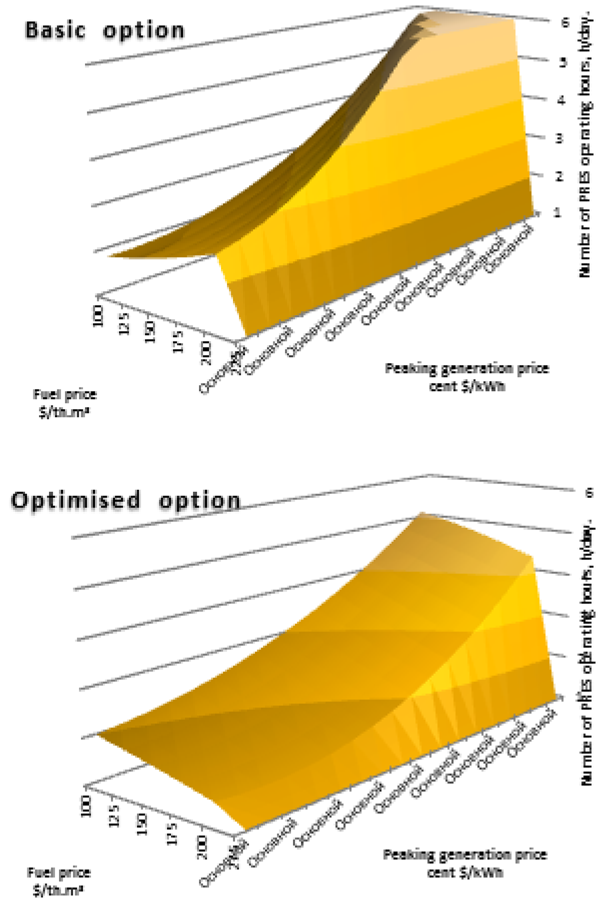

Fig. 6. Trend of change of the break-even PRES operation time from the price of peaking generation and the price of natural gas.

3 Results

The paper analyses the problem of improvement of the efficiency of the PRES operation in regard of associated with changes in the modes of operation of the unified energy system of Belarus. The authors propose a technical solution: to convert the operation of power plants from a simple cycle to a combined dynamic district heating mode.

A special aspect of this solution is the combination of the power generating equipment of PRES into an integrated unit together with the existing combined-cycle gas turbine, and the application of long-distance heat supply technology.

The numerical study proves the prospections the proposed solution. In order to simplify the economic analysis of the efficiency of PRES operation, the authors propose a method for identifying relations for determining the break-even conditions of power plant operation. Use of these equations significantly simplifies the solution of the problem of determining the break-even operation of power generating equipment in conditions of uncertainty of the initial information during design and for the prediction and optimization of modes of its operation during the operational campaign.

4 Discussion

The current investigation theoretically proves the possibility of creating conditions for break-even operation of PRES with low plant load factor - less than 1000 hours per year. PRES scheme is optimized by creating a dynamic district heating integrated plant and the use of long-distance heat supply technology based on the use of absorption heat pumps on both the heat source and the heat consumer side.

The main risks of implementation of concidered technical solution are the uncertainty of economic factors (the price of fuel, electricity and heat tariffs, maintenance cost of core equipment). Thus it is important to have a tool to quickly assess the effectiveness of construction and operation of dynamic district heating systems.

Additional risks may be the instability of heating loads, because heat energy is transmitted to the nearest settlement, where there are existing district heating systems, which may be excessive in terms of installed capacity for existing residential sector.

At the same time to the main positive factors should be attributed increase of flexibility of operation in terms of increase of maneuverability of both equipment newly constructed PRES and existing combined-cycle gas turbine integrated with it. It is also important to note the fact that the growth of fuel cost increases the efficiency of the proposed technical solution, while to ensure payback of the basic option will require a significant increase in prices for peaking and reserve generation (or covering the increased costs by a related industries), or, otherwise, taking the attempts of reduction the price of imported fuel using administrative forces. Both of this ways are much more risky in long-term prospective either for business or for administrative independence of the country itself.

5 Conclusions

The paper shows the problem of PRES efficiency increasing with integration of a high-capacity inflexible power (nuclear power plant) into power grid of the Republic of Belarus. It proposed to combine existing CCGT-400 power unit and newly constructed PRES based on gas turbines and turn it into district heating mode.

The results show that the break-even point of proposed system is possible with wider range gas and electricity costs, as compared to basic option. It was further shown that within the range of peak electricity generation costs from 7 to 15 cent $/kWh an fuel cost from 100 to 225 $/th.m^3 the operation hours of break-even does not exceed 5 hours per day.

Simplified interpolation relations for estimation analysis and cost-efficient planning the operational modes of generating equipment were obtained by processing the results of numerical simulation.

The article was issued by the authors as a part of the governmental research program of "Industrial Heat Power and Thermal Power Engineering" department of the Belarusian National Technical University on the thesis «Applied problems of the development of heat technologies and energy supply systems in the context of the digitalization of the economy» and corresponds to the priority directions of scientific, technical and innovation activities in the Republic of Belarus for 2021-2025 in the field of energy.
The authors express their acknowledgement to the employees of the Research and Innovation Center "Automated Control Systems in Thermal Power Engineering and Industry" branch of scientific-research institute of Belarusian National Technical University for useful discussion of the investigation results, that form the basis of current article.

References

1. Aminov, R.Z. Vektornaya optimizatsiya rezhimov raboty elektrostantsii / R.Z. Azimov // M.: Energoatomizdat, 1994. – 304 s.
2. Voropai, N.I. Integrirovannye infrastrukturnye energeticheskie sistemy regional'nogo i mezhregional'nogo urovnya / N.I. Voropai, V.A. Stennikov, S.M. Senderov i dr. // Energeticheskaya politika, 2015. - № 3 – S. 24-32.
3. Open cycle turbines to provide backup for renewables in Belarus // Turbomachinery international, 2019. https://www.turbomachinerymag.com/open-cycle-turbines-to-provide-backup-for-renewables-in-belarus/
4. SGT-800 industrial gas turbine, 2021, https://www.siemens-energy.com/global/en/offerings/power-generation/gas-turbines/sgt-800.html
5. Lifetime energy availability factor up to 2019 - 2021. https://pris.iaea.org/PRIS/WorldStatistics - : 20.01.2021.
6. Nikitin, A.N. Pikovye i rezervnye GPES: opyt primeneniya v SShA / A.N. Nikitin, A. Vuorinen // Turbiny i dizeli. – 2007. - № 4. – S. 22-26.
7. Kraftwerke Mainz-Wiesbaden AG case study - 2018. http://wartsila.com 08.12.2019.
8. Price of imbalance power // Fingrid – 2020. https://www.fingrid.fi/en/electricity-market/electricity-market-information/imbalance-power/price-of-imbalance-power/. 28.12.2020.
9. Market data // Nord Pool – 2020. https://www.nordpoolgroup.com/Market-data1/. 28.12.2020.
10. Sednin, V.A. Optimizatsiya struktury pikovo-rezervnykh energoistochnikov / V.A. Sednin, S.A. Rumyantsev // Energeticheskaya strategiya. – 2020. – №4. – S. 19-25.
11. Teplov, B.D., Teplovye ispytaniya gazoturbinnoi ustanovki SGT5-4000F energobloka PGU-420T TETs-16 Mosenergo / B. D. Teplov, Yu. A. Radin, A. A. Filin, D. V. Rudenko // Teploenergetika. – 2016. – №8. – S. 10-17.

12. Moshkarin, A.V., Otsenka pokazatelei paroturbinnoi chasti parogazovogo bloka moshchnost'yu 400 MVt na snizhennykh nagruzkakh / A.V. Moshkarin, B.L. Shelygin, Yu.V. Mel'nikov // Vestnik IGEU. – 2008. – №2. – S. 1-10.
13. Yan, Li. Technology application of district heating system with Co-generation based on absorption heat exchange / Yan Li a, Lin Fu, Shuyan Zhang // Elsevier. – 2015. – № 90. – p. 663-670/
14. Popyrin, L.S. Matematicheskoe modelirovanie i optimizatsiya teploenergeticheskikh ustanovok./ L.S. Popyrin // M.: Energiya, 1978. — 416 s
15. Sednin, V.A. Parametricheskaya optimizatsiya parogazovoi ustanovki na biomasse / V.A. Sednin, A.I. Levshenya // Izvestiya vuzov. Energetika. — 2014. — №1. — S.58–65.