Optimization of combined heat and power plant operating mode by means of underutilized equipment mothball

Evgeniya Sukhareva¹, Alexander Fedyukhin¹, Oleg Derevianko², Mikle Egorov², Liliya Mukhametova³, Irina Akhmetova³

¹National Research University «Moscow Power Engineering Institute», Moscow, Russia, Krasnokazarmennaya 14, Moscow, 111250 Russia

²Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, Saint Petersburg, 195251 Russia

³Federal State Budgetary Educational Institution of Higher Education “Kazan State Power Engineering University”, Kazan, Krasnoselskaya street, 51
derevianko@nil-tepl.ru

Abstract. This work makes it possible to link ground rules for thermal and electrical energy markets with generation plant operating. Here we consider various procedures for optimization of combined heat and power plant operating mode by means of underutilized equipment mothball. This work results in process flow diagrams for turbine hall and relative increment charts, which can be used for plant loading in the optimal way.

Introduction

The issue of managing the power plant operating modes was thoroughly studied and has gained great scientific and practical progress [1–9]. However, in the recent years, Russian power engineering saw far-reaching reforms. The operational-dispatch management was changed, power production became concurrent. The prices at competitive market now are not regulated by the government, but are formed based on supply and demand, and its participants compete with each other. The transformations lead to a drastic change in power system and, consequently, to a change of scientific and practical methods for its management. Now the management is performed using price signals directly targeted at generators and consumers, which are formed within the market.

A lot of power plants are now heat-underutilized, as there was a great consumer outflow in the 90's, especially those who used industrial steam bleed. As a result, for this power plant the fuel consumption increases, the product cost raises, given an impact on electrical power output.

All these aspects make our research work very challenging. The aim of this investigation was to increase the combined heat and power (CHP) plant efficiency by means of appropriate choice of its operating modes.

The following tasks were defined in it:

- Study of Moscow thermal and electrical energy markets.
- Study of optimization methods for combined heat and power plant operating modes.
- Selection of appropriate optimization method for combined heat and power plant operating mode.
• Estimation of economical efficiency of the selected method.

Modern cogeneration problems

Cogeneration based on combined electrical and thermal energy production has a number of advantages. It should be noted that special aspects of CHP plant work are connected with branch industry specialization and its specification. Cogeneration power plants produce thermal and electrical energies simultaneously. This means that its operating mode depends on demands for both product types. This aspect makes the regulation process significantly complicated.

The problem of developing objective performance indicators for combined heat and power plant at combined generation of electrical and thermal energies is still unsolved in Russia, while this question is thoroughly studied worldwide [10–18].

The degree of depreciation is characterized by combined heat and power plant equipment age, its structure is presented in Fig.1.

![Figure 1. Age structure of the combined heat and power plant generation equipment [19]](image)

As the primary input of power equipment was carried out in 1960-70s, nowadays it has significant functional and moral depreciation.

The usage of the worn equipment leads to:
• reducing of generation efficiency, excessive fuel consumption and additional losses;
• enhancement of workplace accidents, increasing of repair time, growth of repair costs.
• Combined heat and power plants do not have any warranties concerning capacity loads as nuclear power plants do [20] [21,22] [23] [24]. This means that market rules do not take into account technological features of combined heat and power plant operation, though their total power production is directly proportional to the heat load. Consequently, CHP plants, operating at heating mode, have some limitations for electrical load regulating and cannot perform system power-change functions.

As there are a lot of underloaded and depreciated facilities, there arises a necessity to work out a sustainable branch development scheme. It should include both modernization of the existing generation facilities (as it is more economically-viable than new construction), and new construction, where it is impossible to renovate and reconstruct the existing facilities [25].

Over the last years the spare parts support for basic combined heat and power plant equipment has improved [26] [27]. Modern multiaxies machines allow one to fabricate various blades. There are hydraulic automatics assembly units and others.

Service life extension is essentially cheaper than replacement power construction, so it is a more preferable opportunity for a large number of old CHP plants, for which there is no need for power increasing.
During modernization, the maximum technical process automation should take place, as large staff results in high semi-fixed costs. Unlike condenser type electricity-only thermal power stations, which operate at low steam parameters, combined heat and power plants are rather competitive at thermal mode operating.

Combined heat and power plant thermal capacity decreases due to industrial production reduction, which led to closure of enterprises and steam consumption reduction. Besides this, the ratio of secondary energy resources decreases.

Russian CHP plants are characterized by an unbalance between capacity and structure of the equipment and heat and electricity market requirements. Back-pressure turbines of about 3 ml. kW total capacity stand idle [28]. This is due to absence of thermal load. Abnormal operation conditions, frequent startups and shutdowns of the equipment lead to technical depreciation and additional energy losses. And it results in additional material expenses.

Number of hours for power plant operating at installed capacity in Russia in 2014 was 4478 hours [29], in 2015 it was 4402 hours, or 50.25 % of the calendar time [30].

For industrial facilities operating hours at installed capacity (not taking into account power plants) are the following:

- for thermal power stations 4136 hours (47.21% of the calendar time);
- for nuclear power stations 7415 hours (84.65% of the calendar time);
- for hydro power stations 3354 hours (38.29% of the calendar time);
- for wind power stations 592 hours (6.75% of the calendar time);
- for sun power stations 738 hours (8.43 % of the calendar time).

Besides this, there are some regions in Russia there total power plant capacity exceeds needs of the region. This excessive electric power should be consumed somewhere. But during town and country planning every region, which imports electricity from another one, declares itself energy-deficient and develops a special program for deficit overcoming (which is actually absent) [31].

Many heating-and-power plants, despite low specific fuel consumption at cogeneration cycle, are loss-making. Typically this is due to the following reasons:

- High specific expenses for equipment exploitation and repair due to its technical depreciation and large staff of the heating-and-power plant.
- Low installed capacity utilization factor (ICUF) and mismatch between equipment composition and connected load.
- Long-term usage of combined heat and power plant equipment as a hot reserve for supplying peak electricity loads.
- Combined heat and power plant operating at condensing mode.
- Usage of understated specific fuel consumption for thermal energy production from hot-water boilers at heat tariff formation. It is accompanied by corresponding increase of specific tariffs for electricity supply (extension of cogeneration effect on combined heat and power plant segment, which is an actual fact a boiler house).
- The concurrence with hydro power plants and nuclear power plants, which compensate the major part of expenses from capacity charge at low variable expenses.
- Night marginal reduction of electricity price, so that it is less than fuel costs.
- Heat tariffs formation according to ultimate growth indices (once understated tariffs cannot be raised to the industry average level).
- Mismatch between fuel price used in heat tariffs and lack of correction during the next regulating period due to growth limitations at ultimate indices.
- Approval of understated normative values for household heat and hot water supply by local governments.
- The three latter causes have an impact only on two-production CHP plant, thus reducing it competitiveness.
- Non-payments.
Payback of overstated or unnecessary investments.

The actual reasons for loss-making of a certain combined heat and power plant might be determined by division of its economical performing results by 3 parts:

- Cogeneration mode operation;
- Electricity supply at condensing mode.
- Heat supply at boiler house mode.

Nowadays combined heat and power plant retreat from market appears to be efficient. It is surprising, but loss-making stations appear to be efficient when retreated from the market.

Electricity produced by combined heat and power plant during condensing cycle, is expensive for most of them, and is accepted by the market only during maximum consumption periods. Approximately 30 CHP plants have marginal cost of electricity (their price bid at peak consumption is used for determination of electricity delivery costs in all huge price zone). A small combined heat and power plant at peak period might level up the whole market price for 10-15% [31].

According to the Russian Federation energy strategy up to the year 2030, the following changes of installed capacity structures will take place: The portion of nuclear power plants will increase due to commissioning of new facilities, and the portion of gaz thermal power stations will decrease due to its decommissioning. In 2015, electrical energy production by UES of Russia power plants (including that at industrial enterprises power plants) has increased against the results for the year 2014 only for 0.2%, namely:

- Thermal power plants: decrease in production for 0.9 %;
- Hydro power plants: decrease in production for 4.1%;
- Nuclear power plants: increase in production for 8.2%.

In order to provide reliable power supply, as well as failure-free and cost-effective operation of the power plant equipment, it is necessary to set rational operation modes, which take into account energy demand, technical and economical characteristics. Basic, normal operation mode is that one providing capacity according to the load chart, and supplying major power at predetermined time period.

Mothball as an approach for combined heat and power plant efficiency increase

One of the most important exploitation task is economic energy loading schedule among the power plants of the energy system and its separate units and assemblies. Simultaneously, the questions about operating units number, their startups and shutdowns should be answered.

Efficient load distribution between operating units, which provides minimum heat and fuel consumption at the power plant and energy system, is performed basing on heat consumption relative increments approach [16].

Under the conditions of financial restrictions, the most preferable approaches are repair or modernization, and mothball of the excess capacity.

The question of the unused equipment removal is essentially important at excess generating power market. Removal out of service, or excess power equipment mothball, including that used at cogeneration modes but less than 1000-2000 hours annually, together with compensation of the thermal peaks by boiler houses operating at peak modes result in amortization cost reduction, and, consequently, total expenses. The underutilized equipment mothball reduces not only operating expenses, but that ones for unit start-stop. The cogeneration remains at the same level: thermal load charts for the power plant do not change. Combined heat and power plant fully supplies heat to its consumers, whereby creating artificial power deficit.

This task can be regarded as discrete, because equipment operating mode regulation has in reality a limited accuracy, and, consequently, a finite set of variants for turbine unit loading. In order to solve this task we have developed an algorithm, which implements a process of exhaustive search for various conditions. This algorithm is presented in Fig. 2.

The first step is for comparison of CHP thermal installed capacity and thermal load chart of its market. If the capacity is in excess, the operating mode of every CHP turbine unit is checked. At equipment load for more than 1000-2000 hours annually (ICUF less than 20%), the cogeneration
appears to be not efficient as compared with separate production. So, this energy unit should be conserved. Further, we calculate the energy enterprise income, which are obtained by alteration of model parameters. In such a manner we examine unit mothball possibility. The obtained variants set is tested for limitations fulfillment. If one of the limitations isn't fulfilled, the corresponding variants are rejected. After this, the maximum income alternative is selected. Fig.2 presents decision-making mechanism about mothball [32].

**Planning of the combined heat and power plant operation taking into account mothball**

This mechanism was approved by the example of combined heat and power plant CHP-21 of Mosenergo PJSC. It is located at Dmitrovskiy District, Moscow and from 2009 is combined with CHP-28. Now the power plant has 5 power units T-110 and one ST-25. Its installed capacity is 575 MW. Annual average load is 300 MW.

Basing on generation equipment characteristics, we have calculated relative increment characteristics and process flow diagram of the turbine hall (Table 1, Fig. 3).

![Process flow diagram of the CHP-21 turbine hall](image)

**Figure 3 - Process flow diagram of the CHP-21 turbine hall**

It can be seen, that plant load is well below the installed one, so the units are inefficiently loaded. 2 mothball variants are proposed: the first one is related to the absence of consumer, the second one takes into account heating load decrement. As this CHP doesn’t have any industrial load, the ST turbine maintenance appears to be inefficient. So, its mothball is proposed.
Table 1 - Characteristics of turbine hall for CHP-21

| Characteristic process flow points | Relative increment of turbine, GJ/MW·h | Turbine hall | Boiler house | Relative increment of plant, \( r_p \), toe/MW·h |
|-----------------------------------|----------------------------------------|--------------|--------------|-----------------------------------------------|
| Minimum load for boiler house    | -                                      | -            | -            | -                                             |
| Minimum load for turbine hall    | 7.34                                   | 17.5         | 355          | 5                                             | 202                            | 80                         | 1981                       | 0.0347                       | -                             |
| Minimum CHP load                 | 8.46                                   | 14.25        | 270          | 101.75                                       | 2157                          | 2221                       | 0.0347                       | 0.293                        |                               |
| 1\(^{st}\) break in turbine hall characteristic curve | 8.46/8.6                              | 85.88        | 955          | 14.25                                        | 270                           | 443.65                     | 5047                        | 5200                         | 0.0363                       | 0.307/0.312                  |
| 2\(^{nd}\) break in turbine hall characteristic curve | 8.6/9.63                              | 85.88        | 955          | 26.65                                        | 376                           | 456.05                     | 5154                        | 5309                         | 0.0364                       | 0.313/0.35                  |
| 3\(^{rd}\) break in turbine hall characteristic curve | 9.63/9.98                             | 110          | 1187         | 26.65                                        | 376                           | 576.65                     | 6315                        | 6505                         | 0.0384                       | 0.37/0.383                 |
| Maximum load for boiler house    | -                                      | -            | -            | -                                            | -                             | -                          | -                           | 7406                         | 0.04                          | -                             |
| Maximum load for turbine hall    | 9.98                                   | 110          | 1187         | 28                                           | 390                           | 578                        | 6333                       | -                            | -                             | -                             |
| Maximum CHP load                 | 9.98                                   | 110          | 1187         | 28                                           | 390                           | 578                        | 6333                       | 6523.2                       | 0.0384                       | 0.384                        |

The second variant involves one turbine T-110 mothball. Such mothball doesn't influence the supplied power, as these two turbines work less than 1000 hours annually. The two mothball variants are evaluated in the view of economical efficiency (Tables 2, 3). Cash outflows consist of equipment mothball expenses, and cash inflow consists of repair and amortization economy.

Table 2 - The calculation of discounted cash flow for the first mothball variant

| Characteristics/Step | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|----------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Mothball expenses    | -38.4 |    |    |    |    |    |    |    |    |    |    |    |    |
| Repair and amortization expenses | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 |
| Discount Coeff.      | 1  | 0.909 | 0.826 | 0.751 | 0.683 | 0.621 | 0.564 | 0.513 | 0.466 | 0.424 | 0.385 | 0.35 | 0.319 |
| Discounted cash flow | -38.4 | 5.5 | 5.0 | 4.5 | 4.1 | 3.7 | 3.4 | 3.1 | 2.8 | 2.5 | 2.3 | 2.1 | 1.99 |
| Discounted cash flow running total | -38.4 | -32.8 | -27.8 | -23.2 | -19.0 | -15.2 | -11.8 | -8.7 | -5.8 | -3.2 | -0.9 | 1.2 | 3.1 |
Table 3 - The calculation of discounted cash flow for the second mothball variant

| Characteristics/Step                      | 0     | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | 11     | 12     |
|------------------------------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Mothball expenses                        | -88.32|        |        |        |        |        |        |        |        |        |        |        |        |
| Repair and amortization expenses         | 18.4  | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   | 18.4   |
| Discount Coeff.                          | 1     | 0.909  | 0.826  | 0.751  | 0.683  | 0.621  | 0.564  | 0.513  | 0.466  | 0.424  | 0.385  | 0.35   | 0.319  |
| Discounted cash flow                     | -88.32| -71.5  | -56.3  | -42.5  | -30.0  | -18.5  | -8.2   | 1.2    | 9.8    | 17.6   | 24.7   | 31.1   | 37.0   |
| Discounted cash flow running total       |       |        |        |        |        |        |        |        |        |        |        |        |        |

It is seen from Table 4, that both mothball variants are efficient. Payback period of the second variant (ST-25-90 and T-110-130 mothballs) is less than that one for the first variant (ST-25-90 mothball) by 4 months. Discounted cash flow of the second variant is 11.75 times more than that one for the first variant. So it is preferable to choose ST-25-90 and T-110-130 mothballs.

Table 4 - Comparison of the proposed variants

| Characteristics/Variant                  | 1     | 2     |
|------------------------------------------|-------|-------|
| Discounted cash income, mln. roubles     | 3.15015| 37.0116|
| Payback period, months                   | 7     | 11    |

It is preferable to choose ST-25-90 and T-110-130 mothballs (the second variant).

Conclusions

- Thermal and electrical energy markets of Moscow were investigated. The performed analysis shows that all combined heat and power plants operate at 50-70% of its designed operating capabilities.
- It was proved, that plants operate in a rather inefficient mode, and this deteriorates their economic performance.
- We have chosen an approach for CHP operating mode optimization taking into account power equipment mothball.
- Economic effects of the proposed methods were evaluated. Both methods are efficient. Net present value is positive for both variants.

However, despite high initial expenses for two turbines mothball, its payback period is smaller. At this, the plant fully satisfies the consumer needs. So, this variant should be recommended for further implementation.

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