Evaluating the Effect from Shifting a Small-Scale Cogeneration Power Facility to Operate as a Trigeneration Plant

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Abstract. The article considers the power supply system of a really existing social facility located in the central part of Russia, which comprises an ice palace, a swimming pool, a hotel and office complex, and a business center. At present, the facility receives power according to a cogeneration arrangement: it takes electricity and heat from a power park a centralized manner. Refrigeration and air conditioning demands are met by using vapor compression heat transformers installed in the social facility rooms. A trigeneration power supply arrangement is proposed, which involves combined generation of electricity, heat, and cold with supplying them to the social facility rooms in a centralized manner. The thermodynamic advantage of the trigeneration power supply arrangement for the considered social facility is demonstrated.

1. Introduction and Problem Statement

Achieving more efficient operation of power supply systems is one of the most important challenges faced by Russia’s power industry. One possible solution of this problem lies in developing combined generation of various produced energy carriers necessary for consumers (electricity, heat, cold, compressed air, etc.) [1, 2]. Such method of achieving more efficient power supply is especially attractive in considering the problem of a non-uniform seasonal demand for heat. Thus, during the non-heating season, the demand of consumers for heat supply decreases and usually makes 20-30% of its maximum level in the central European part of Russia. As a result, the operation of installations simultaneously generating electricity and heat (combined heat and power plants, gas turbine units with recovering the heat of flue gases, etc.) becomes essentially less efficient. In such cases, the thermodynamic performance indicators of power generating equipment can be improved by utilizing the heat not demanded for heat supply purposes for producing other energy carriers, e.g., cold.

As an example of setting up a trigeneration arrangement (combined generation of electricity, heat, and cold) we consider a really existing power park containing small-capacity generating units, which supplies power and heat to a social facility (SF) located in the central part of Russia. The SF comprises an ice palace, a swimming pool, a hotel and office complex, and a business center.

With the existing cogeneration arrangement, electricity and heat are generated in the power park by means of a gas piston generation unit (GPGU) and are supplied in a centralized manner to the SF rooms, whereas cold is generated by means of vapor compression heat transformers (VCHTs) installed in each room of the SF and operating as chilling machines. The electricity generated in the power park is used as the primary energy carrier for the VCHTs.

An analysis of the SF power supply system made it possible to state the research problem: given the specified seasonal demands of the SF for electricity, heat, and cold, it is necessary to estimate the possibility of
improving the thermodynamic efficiency of its power supply system through replacing the existing cogeneration arrangement by a trigeneration one involving combined generation of all three necessary energy carriers at the power park.

For implementing the proposed technical solution, it is necessary to arrange centralized supply of cold to all SF consumers by replacing the individual generation of cold in each of the SF parts by its combined generation at the power park. With such power supply arrangement, cold, like electricity and heat, is supplied in a centralized manner to all rooms of the facility. For generating cold, the power park is fitted with additional refrigeration equipment that uses rejected heat from the GPGU as the primary energy carrier.

2. Description of the existing equipment for supplying power to the social facility

2.1. Power park equipment

Four identical GPGUs with an electrical capacity of 4300 kW each are used at the power park for electricity generation purposes. The heat rejected from the GPGUs is used for arranging the SF district heating. The thermal power output of each GPGU is constituted by the heat of flue gases (2339 kW) and by the heat removed from the engine cooling jacket (1883 kW), and makes 4222 kW. For setting up heat supply, the power park is also equipped with two standby peaking hot water boilers (PHWBs) each having a thermal capacity of 8000 kW.

Thus, the total design electrical capacity of the power park is 17200 kW, and its total thermal power capacity is 32888 kW (28.26 Gcal/h).

The GPGU operation is set up with priority given to electricity production, and the heat output produced by the power units is proportional to their electricity output. The surplus heat not demanded for heat supply purposes is discharged into the environment through the cooling towers, and the surplus electricity can be transmitted to the electric network.

The GPGU rejected heat recovering system makes it possible to adjust the generation of heat in a wide range up to autonomous operation of the GPGUs under the conditions of partial heat load and nominal electric load of the GPGUs. With such arrangement, it is possible to simultaneously fulfill the power park’s independent electrical and heat load curves.

2.2. Refrigeration equipment used in the social facility rooms

The refrigeration users in the considered social facility can conditionally be subdivided into two groups. The first group is the ice palace. The preparation of ice for the skating-rink and arrangement of comfortable conditions for visitors are the main purpose of cold supply to the ice palace. The second group encompasses the office center, the business center, and the swimming pool. The supply of cold to the second group users is intended to arrange comfortable conditions for the attendance of the personnel and visitors.

All installed refrigeration equipment fully covers the refrigeration requirements.

The installed refrigerating capacity of the VCHTs and the required refrigerant temperatures for the above-mentioned objects are given in Table 1.

| Object name           | Building area, thousand m² | Installed refrigeration capacity of cold supply units, kW | Refrigerant temperatures inlet/outlet, °C |
|-----------------------|-----------------------------|----------------------------------------------------------|------------------------------------------|
| Ice palace            | 70                          | 7579                                                     | +4 / -2                                  |
| Swimming pool         | 28.5                        | 1813                                                     | +12 / +7                                 |
| Hotel and office complex | 30                          | 3000                                                     | +12 / +7                                 |
| Business center       | 90                          | 9000                                                     | +12 / +7                                 |

The data on the consumption of electricity, heat, and cold in different times of the year with the existing cogeneration power supply arrangement are given in Table 2, which also indicates the electric and thermal power capacities necessary to cover these loads. It should be noted that the data on the required electrical, heat, and refrigeration loads of the SF given in Table 2 (lines 1, 9, and 5) were obtained experimentally, and that they are in fairly good agreement with the results of calculations carried out in accordance with the regulatory documents [3-6].
The energy balance of the SF power supply system in different times of the year in the case of using the cogeneration power supply arrangement is given in Table 3.

An analysis of the data given in Tables 2 and 3 allows the following conclusions to be drawn:

1. The electrical and heat generating capacities available in the power park (Table 1) are essentially larger than the average electrical power required for fully covering the SF electrical loads and thermal loads for space heating, ventilation, and hot water supply purposes (lines 2 and 10 in Table 2).
2. The amounts of heat supplied for space heating, ventilation and hot water consumption (line 9 in Table 2) in the winter months are significantly (maximally by more than 20 times) higher than they are in the summer months.
3. The total consumption of cold in all SF rooms and the average refrigerating power for supplying cold by the VCHTs in the summer months (lines 5 and 6 in Table 2) are 8 to 10 times larger than they are in the winter months.
4. The total amount of electric energy consumed by the SF electric loads (line 1 in Table 2) does not vary so significantly (within 10%) in comparison with the variations in the consumption of heat and cold. As regards the amount of electricity consumed for the social facility auxiliaries without taking into account its consumption for the VCHTs (lines 3 and 4 in Table 2) in the winter months is significantly larger than the consumption of electric energy and the required electric power for cold supply (lines 7 and 8 in Table 2). This is attributed to the fact that in the heating season more electric energy is consumed for lighting and for driving the pumps operating in the space heating and plenum ventilation system; on the other hand, the refrigerators consume a smaller amount of electricity. In the summer months, the amount of electric energy consumed by cold generating installations (VCHTs) is almost an order of magnitude larger than it is in the winter months (lines 7 and 8 in Table 2).
5. The rejected heat from the GPGUs (line 2 in Table 3) makes about 45% of the energy obtained during gas combustion.
6. In the period of time from November to March, the rejected heat from the GPGUs (line 2 in Table 3) is fully used for heating, ventilation, and hot water supply purposes (line 4 in Table 3). During this period of time, part of heat demand (line 9 in Table 2) is also covered by the peaking hot water boilers (line 5 in Table 3).
7. In the period of time from April to October, the rejected heat from the GPGUs (line 4 in Table 3) fully covers the space heating, ventilation, and hot water supply requirements without using the heat produced by the VCHTs. During this period of time, part of the rejected heat (line 6 in Table 3) turns to be unnecessary and is removed into the environment. The equivalent loss of power due to the non-utilized heat of the GPGUs is quite significant (line 7 in Table 3), and in the period of time from May to September, it is more than 9 MW. At the same time, the demand for cold in the period from April to October (line 5 in Table 2) in each of these months is less than the rejected heat removed into the environment during the GPGU operation. Thus, the essential energy losses connected with the impossibility of using the rejected heat from the GPGUs in the summer months should be recognized as the principal drawback of the existing cogeneration arrangement for supplying power to the social facility.

One of possible ways in which more efficient operation of the power supply system can be achieved is to change its configuration by arranging centralized cold supply to all SF rooms from the power park with employing refrigeration units that use the rejected heat from the GPGUs as the primary energy carrier. The well-known absorption heat transformers (AHTs) operating as chilling machines are used as such installations.
Table 2. Consumption of electricity, heat, and cold, and the necessary electric and thermal power capacities of the SF in different times of the year in the case of using the cogeneration power supply arrangement

| Sl. No. | Energy carrier                                                                 | January  | February | March  | April  | May    | June   | July   | August | September | October | November | December | YEAR  |
|---------|--------------------------------------------------------------------------------|----------|----------|--------|--------|--------|--------|--------|--------|-----------|---------|----------|----------|-------|
| 1       | Total consumption of electric energy for fully covering the SF requirements, thousand kW*h | 7988     | 7406     | 8014   | 7940   | 8004   | 8039   | 8024   | 7776   | 8057      | 8036    | 8738     | 95989    |       |
| 2       | Average electric power necessary for fully covering the SF requirements, MW     | 10.74    | 11.02    | 10.77  | 11.03  | 11.12  | 10.81  | 10.78  | 10.80  | 10.83     | 11.16   | 11.74    | 10.96    |       |
| 3       | Electric energy consumption for the SF auxiliaries without the VCHTs, thousand kW*h | 7815     | 7251     | 7774   | 7500   | 6759   | 6599   | 6370   | 7139   | 7762      | 7836    | 8555     | 88075    |       |
| 4       | Average electric power necessary for covering the SF auxiliaries without the VCHTs, MW | 10.50    | 10.79    | 10.45  | 10.42  | 9.08   | 9.17   | 8.56   | 9.02   | 9.92      | 10.43   | 10.88    | 11.50    | 10.05 |
| 5       | Total amount of cold consumed by all SF rooms, thousand kW*h                      | 431.52   | 386.40   | 598.92 | 1099.44| 3021.64| 4173.25| 3277.02| 1590.84| 736.56    | 500.40  | 457.56   | 19785.86 |       |
| 6       | Average refrigeration power for cold supply by the VCHTs, MW                    | 0.58     | 0.58     | 0.81   | 1.53   | 4.06   | 4.88   | 5.61   | 4.40   | 2.21      | 0.99    | 0.70     | 0.62     | 2.26  |
| 7       | Electric energy consumption required for the VCHT operation, thousand kW*h       | 172.61   | 154.56   | 239.57 | 439.78 | 1208.66| 1404.92| 1669.30| 1310.81| 636.34    | 294.62  | 200.16   | 183.02   | 7914.34|
| 8       | Average electric power necessary for the VCHT operation, MW                     | 0.23     | 0.23     | 0.32   | 0.61   | 1.62   | 1.95   | 2.24   | 1.76   | 0.88      | 0.40    | 0.28     | 0.25     | 0.90  |
| 9       | Heat consumption for space heating, ventilation, and hot water supply purposes, Gcal (thousand kW*h) | 12265    | 13451    | 10734  | 5268   | 751    | 695    | 658    | 718    | 787       | 8244    | 8294     | 13369    | 73235 |
| 10      | Average thermal power required for space heating, ventilation, and hot water supply purposes, Gcal/h (MW) | 16.49    | 20.02    | 14.43  | 7.32   | 1.01   | 0.97   | 0.88   | 0.96   | 1.09      | 8.39    | 11.52    | 17.97    | 8.36  |
### Table 3. Energy balance of the SF power supply system in different times of the year in the case of using the cogeneration power supply arrangement

| Sl. No. | Energy carrier | January | February | March | April | May | June | July | August | September | October | November | December | YEAR |
|--------|----------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|-----------|---------|------|
| 1      | Total consumption of electric energy for fully covering the SF requirements, thousand kW* | 7988 | 7406 | 8014 | 7968 | 8004 | 8039 | 8024 | 7776 | 8057 | 8036 | 8738 | 95989 |
| 2      | Rejected heat during electricity generation by the GPGUs, Gcal (thousand kW*h) | 6742 | 6251 | 6764 | 6701 | 6725 | 6756 | 6785 | 6772 | 6563 | 6800 | 6783 | 7375 | 81015 |
| 3      | Heat for space heating, ventilation, and hot water supply, Gcal/thousand kW*h | 12265 | 13451 | 10734 | 5268 | 751 | 695 | 658 | 718 | 787 | 6244 | 8294 | 13369 | 73235 |
| 4      | Utilized rejected heat, Gcal (thousand kW*) | 6742 | 6251 | 6764 | 5268 | 751 | 695 | 658 | 718 | 787 | 6244 | 6783 | 7375 | 49034 |
| 5      | Heat generated by the PHWB, Gcal (thousand kW*h) | 5524 | 7200 | 397 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1511 | 5995 | 24200 |
| 6      | Non-utilized rejected heat from the GPGUs, Gcal (thousand kW*h) | 1433 | 5973 | 6060 | 6128 | 6055 | 5776 | 556 | 0 | 0 | 0 | 1757 | 6972 | 28145 |
| 7      | Equivalent loss of power due to non-utilized heat from the GPGUs, Gcal/h (MW) | 2.0 | 8.0 | 8.4 | 8.3 | 8.2 | 8.0 | 0.8 | 0 | 0 | 0 | 0 | - |
| 8      | Natural gas consumption, thousand m³ | 3173 | 3222 | 2970 | 2412 | 2428 | 2430 | 2447 | 2443 | 2367 | 2452 | 2642 | 3443 | 32430 |
3. Shifting from the Cogeneration to Trigeneration Mode

As was already pointed out above, the main change that should be made in the power supply arrangement in shifting from the cogeneration to the trigeneration mode in implementing it in the considered SF is doing away with cold generation by means of VCHTs installed in each of the SF rooms. For generating cold, AHTs installed at the power park and supplying cold to all social facility rooms in a centralized manner should be used. For supplying cold to the second group of objects, it is necessary to use the widely known AHTs intended for producing cold only for the ventilation and air conditioning purposes. The temperature of refrigerant streams generated in such AHTs is +7°C. Lithium bromide solution is used in them as refrigerant. For supplying cold to the ice palace, it is necessary to apply, apart from lithium bromide AHTs, also quite widely used water-ammonia AHTs, which are able to produce cold at temperatures below 0°C.

With the trigeneration arrangement implemented under the conditions adopted above, the use of electricity produced by the GPGUs for the VCHT drives is no longer needed (line 3 in Table 2). The results from calculating the consumption of electricity and heat in the case of using the trigeneration power supply arrangement are summarized in Table 4.

In the performed calculations, the following data on the cold supply systems are taken:
- The specific consumption of power for the VCHTs is taken equal to 0.4 MW/MW of cold;
- The specific consumption of heat for the AHTs is taken equal to 1.075 (Gcal/h)/MW of cold;
- The specific consumption of power to the AHTs is taken equal to 0.005 MW/MW of cold.

An analysis of the data given in Table 4 and their comparison with the results given in Tables 2 and 3 shows that after shifting to the trigeneration mode, the power park power performance efficiency will be improved due to the following:
- decreasing the amount of non-utilized heat from the GPGUs in the non-heating season from 31980 to 8056 Gcal a year;
- decreasing the amount of electricity used for cold generation purposes from 7988 to 7815 thousand kW*h a year.

The improvement of the power park power performance efficiency will result in that the consumption of natural gas will be decreased by 1929 thousand m³ a year (i.e., that the initial consumption of natural gas will be decreased by 5.95%). This decrease was determined considering the fact that in the heating season the PHWB load will increase from 24200 to 28143 Gcal; in that case, the load of the boilers will increase by no more than 8% and make at the most 64.7% of their maximum possible value. This will make it possible to produce the sufficient amount of energy carriers without the need to install additional equipment for supplying heat to the AHTs.

The saving of money for gas payments will make 13.5 million rubles (at the cost of gas equal to 7000 rubles/1000 m³).

It should also be noted that in the proposed SF operation mode, in view of the conditions adopted for comparing different versions, the electric power necessary to support the operation of the SF systems should become smaller, which will lead to less efficient operation of the GPGUs because their power outputs will deviate from their nominal values. But in view of the fact that the production of electricity will decrease only by 2.2%, this change was not taken into account in the calculations.

At the same time, it should be borne in mind that there is a possibility of still further improvement in the efficiency of the SF power supply system in shifting to the trigeneration arrangement. To this end, other conditions for comparing the considered versions of power supply arrangements should be adopted: in shifting to the trigeneration power supply arrangement, the electric power generated by the GPGUs remains constant, and the surplus electric energy not consumed by the social facility is fully transmitted to the electric networks. In this case, the GPGU performance efficiency will remain unchanged because the specific consumption of fuel for electricity generation (which increases with decreasing the GPGU power output) will remain constant. In addition, the surplus electric energy produced by the GPGUs that was transmitted to the electric networks can bring an additional income.

The advisability of using the trigeneration arrangement should finally be determined based on the feasibility study with taking into account the necessary additional outlays for implementing it (procurement of the AHTs, erection of the centralized cold supply system, etc.).
| Sl. No. | Energy carrier                                                                 | January | February | March | April | May  | June | July | August | September | October | November | December | YEAR  |
|--------|---------------------------------------------------------------------------------|---------|----------|-------|-------|------|------|------|--------|-----------|---------|----------|----------|-------|
| 1      | Total amount of electric energy for supporting the SF operation, thousand kW*h  | 7815    | 7251     | 7774  | 7500  | 6759 | 6599 | 6370 | 6713   | 7139      | 7762    | 7836     | 8555     | 88075 |
| 2      | Amount of heat rejected during electricity generation by the GPGUs, Gcal        | 6598    | 6122     | 6564  | 6335  | 5717 | 5585 | 5394 | 5680   | 6032      | 6554    | 6616     | 7222     | 74419 |
| 3      | Amount of heat consumed for space heating, ventilation, and hot water supply, Gcal | 12265   | 13451    | 10734 | 5268  | 751  | 695  | 658  | 718    | 787       | 6244    | 8294     | 13369    | 73235 |
| 4      | Amount of heat consumed by the AHTs, Gcal                                        | 464     | 415      | 644   | 1182  | 3248 | 3776 | 4486 | 3523   | 1710      | 792     | 538      | 492      | 21270 |
| 5      | Amount of electric energy consumed by the AHTs, thousand kW*h                   | 2       | 2        | 3     | 5     | 15   | 18   | 21   | 16     | 8         | 4       | 3        | 2        | 99    |
| 6      | Total heat consumption, Gcal                                                    | 12729   | 13866    | 11378 | 6450  | 4000 | 4471 | 5144 | 4240   | 2497      | 7036    | 8832     | 13861    | 94505 |
| 7      | Utilized rejected heat, Gcal                                                   | 6598    | 6122     | 6564  | 6335  | 4000 | 4471 | 5144 | 4240   | 2497      | 6554    | 6616     | 7222     | 66362 |
| 8      | Heat produced by the PHWBs, Gcal                                               | 6131    | 7744     | 4814  | 115   | 0    | 0    | 0    | 0      | 0         | 752     | 2216     | 6639     | 28143 |
| 9      | Non-utilized rejected heat from the GPGUs, Gcal                                | 0       | 0        | 0     | 0     | 1718 | 1114 | 250  | 1439   | 3535      | 0       | 8056     |          |       |
| 10     | Natural gas consumption, m³                                                     | 3203    | 3249     | 3011  | 2280  | 2064 | 2009 | 1945 | 2049   | 2176      | 2364    | 2676     | 3475     | 30501 |
Conclusion

1. The use of the trigeneration arrangement instead of the existing cogeneration one will make it possible to improve the efficiency of the power supply system of the social facility considered in the study.
2. With the required electric, heat, and refrigeration loads kept fully the same, the consumption of fuel used for supporting the power supply system operation can be decreased by approximately 6%. Given the existing prices for natural gas, this will make it possible to decrease the money expenditures for power supply by 13.5 million rubles a year.

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