

# Binary Power Cycles in Russia

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The most effective and environmentally safe fossil fuel power production facilities are the combined cycle gas turbine (CCGT) ones. Electric efficiency of advanced facilities is up to 58% in Russia and up to 64% abroad. The further improvement of thermal efficiency by increase of the gas turbine inlet temperature (TIT) is limited by performance of heat resistance alloys that are used for the hot gas path components and the cooling system efficiency. An alternative method for the CCGT efficiency improvement is utilization of low potential heat of the heat recovery steam generator (HRSG) exhaust gas in an additional cycle operating on a low-boiling heat carrier.

Brayton cycle

Rankine cycle

combined cycle power plant

## 1. Decarbonizing the Power Sector

Currently, world industries experience a stable decarbonizing trend. The reduction of carbon dioxide emission by the power production industry is especially important because of its 39% contribution to emissions in 2017 <sup>[1]</sup>.

The most effective method of emission mitigation in the power production industry is the transition to low-carbon electricity production technologies. These include renewable energy sources (RES), the share of which will continuously grow in the coming decades. Their relevance has only increased in the light of escalating global environmental problems <sup>[2][3]</sup>.

It is worth mentioning that the wide introduction of RES and carbon dioxide capturing systems is limited by the high prices of “green” technology <sup>[4][5]</sup>. At the same time, today there are alternative ways to reduce anthropogenic greenhouse gas emissions associated with the development of energy-saving technologies with relatively low cost <sup>[6][7][8][9]</sup>. This approach may be applied to the large combined-cycle gas turbines (CCGT) power facilities that are now the most efficient.

## 2. Increasing Efficiency of the Binary Power Cycles

Recently, the development of heat resistant alloys, hot gas path cooling systems and thermal barrier coatings has allowed a working flow temperature increase from 800 to 1650 °C <sup>[10][11]</sup>. Foreign advanced CCGT facilities have recently reached net efficiency of 63–64% <sup>[12][13]</sup>. CCGT facilities based on the 9HA02 or M701JAC Gas Turbines (GT) have electric net efficiency above 64% <sup>[11][14][15]</sup>, which is the highest performance among the commercially available gas fuel power production technologies.

Over 100 years of binary technology development, numerous methods for efficiency improvement were proposed and some of them were introduced into practice. **Table 1** summarizes the data on CCGT-accessible efficiency improvements and their problems for introduction.

**Table 1.** Comparison of CCGT facilities efficiency improvement methods.

Improvement Method	Efficiency Increase, %	Method Shortages	Reference
100 °C initial temperature increase	0.9–1.5	Necessity to increase performance of heat-resistant alloys, thermal barrier coatings and turbine hot gas path cooling.	[16][17]
Reheat of combustion products in additional combustors	3.3–3.6	Necessity to install additional combustors, higher cooling flow losses.	[16]
Air compressor inter-cooling	0.7–1.3	Higher compressor cost and reduction of the GT maneuverability due to the higher risk of compressor stall.	[18]
Regeneration of the GT exhausts heat with a regenerator.	1.0–3.5	Necessity to install a regenerator with remarkable mass and dimensions.	[16][18]
Transition from 1P HRSG to 1P + RH	2.25–3.1	Additional HRSG surface and steam pipelines	[19][20]
Transition from 1P HRSG to 2P	1.6–1.8	Additional equipment for the second steam circuit	[19][20]
Transition from 2P HRSG to 2P + RH	0.19–0.5	Additional equipment for the third steam circuit	[19][20]
Transition from 2P HRSG to 3P	0.3–0.5	Additional equipment for the third steam circuit	[19][20][21]
Transition from 3P HRSG to 3P + RH	0.6–1.09	Additional HRSG surface and steam pipelines	[19][20][21]

Most of the known methods provide an electrical net efficiency increase of 0.6–3.6%. Their application usually requires capital investment increase, and sometimes power facility maneuverability and reliability are compromised. Therefore, the use of various methods or their combinations is not always justified from an economic point of view.

The main method for CCGT efficiency improvement is the increase of GT cycle initial temperature. A 100 °C gas turbine inlet temperature (TIT) increase leads to a power unit efficiency increase of 0.9–1.5% [16][17]. It is worth mentioning that the available nickel alloys can operate at temperatures below 900 °C, and the cooling systems efficiencies are near to their limits [22]. In this regard, further increase in the net electrical efficiency of CCGTs by increasing the initial temperature of the gas turbine is troublesome.

Reduction of the GT exhausts heat recovery losses is an alternative approach to CCGT efficiency improvement. Traditionally, the exhaust gases at the exhaust of a gas turbine are sent to a waste heat boiler (HRSG), which generates water vapor to power the steam turbine. The HRSG may be of a single-, dual-, or triple-pressure type. The larger amount of HRSG pressure improves the recovery of GT exhaust heat and thus increases useful electricity production. It is also possible to use steam reheat to improve energy efficiency. Specific features of the CCGT steam cycles are due to the properties of the heat source that is the exhaust gas flow. Efficient heat transfer combined with the maximal heat potential is reached at the minimal surface of the figure between the heating and heated flows in  $Q_t$  diagram of HRSG. Increase in pressure used and introduction of the reheat allows for reduction of heat potential losses. This limit is caused by the necessity to evaporate the heat carrier that is maintained at a constant temperature and produces maximal heat potential losses in a HRSG.

The introduction of the additional pressure in HRSG with lower parameters allows for efficient recovery of additional heat [23][24]. The maximum amount of heat recovered in this case is limited by the minimal exhaust temperature that is determined by the steam saturation condition and the low temperature corrosion of tail heating surfaces in the presence of sulfur in the fuel, and the perfection of the HRSG.

Therefore, one of the ways to increase the efficiency of steam–gas plants may be the creation of circuits with a low-boiling coolant, which will make it possible to realize the low-temperature potential of heating gases.

Galashov and Tsibulsky [25] considered the use of ammonia, butane, pentane, R236fa, and R245fa for utilizing the heat of condensate after the condensate pump and the latent heat of steam condensation after the steam turbine of a CCGT in an ORC with a regenerator. When using gas turbine NK-36ST and a single-pressure HRSG with initial parameters of 16 MPa and 440 °C, the use of ORC allows for efficiency higher than 60% at a condensing temperature in a low-potential cycle of less than 0 °C. The most effective is the use of pentane in ORC, followed by butane, R245fa, R236fa, and ammonia. The same researchers in [26] considered CCGT using 9HA.02 with low-potential cycle using pentane, butane, R365mfc, RC318, R236ea, R236fa, R123, R245ca, and R245fa. It was determined that the most promising were pentane and R365mfc. The use of low-potential cycles in CCGT with reheat with SGT5–8000H was considered in [27]. Butane was used as a low-boiling fluid.

Utilization of low-potential energy of gas turbine exhaust gases was considered by Bălănescu and Homutescu [28]. When using the gas turbine Orenda OGT1500, the gas temperature at the HRSG exhaust is 188 °C, which makes the use of ORC justified. The net electrical efficiency was 45.47% when using R134a in ORC and 45.56% when using R123, which is 1.1 and 1.19% higher than the efficiency of the prototype.

The unconventional approach was studied by Gafurov et al. [29]. The trinary cycle used NK-37 gas turbine as a heat source for two low-temperature cycles. The first one used single-pressure HRSG with benzol and the second one utilized the heat of stream from turbine and latent heat in condenser. The second cycle uses butane and has a regeneration. The use of trinary cycle allowed increase in efficiency of up to 62.6%.

Therefore, one of the methods for CCGT efficiency improvements may be creation of low-boiling heat carrier cycle that will allow utilization of the low-temperature heat of flue gases.

### 3. Binary Power Cycles in Russia

In the USSR, studies of combined thermodynamic cycles began in the 1930s of the 20th century, and practical implementation began in the 1960s. Despite this long investigation and development period, the combined cycle facilities were not widely used.

Currently in Russia, the CCGT direction is one of the power industry priorities. Transition to the carbon dioxide emission market system will result in a competition between the electric power production companies. Therefore, the main power production companies will be interested in development of highly efficient facilities.

In Russia, there are at present 68 power production companies which have 98 CCGT facilities with a total power of 25.7 GWt. The General Scheme for Power Production Facilities Locations by 2035 includes startup of 81 more facilities with 23.0 GW total power at 37 power generation companies. Therefore, the plan is to double the CCGT power in the oncoming decade. The domestic power industry is mostly equipped with CCGT facilities of 200–250 MW and 400–450 MW capacity. The most common are the single-block and double-block unit; the triple-block facilities are rare. More than 70% of Heat Recovery boilers (HRSG) are of twin-flow type [\[30\]](#).

Most of the Russian CCGT facilities have electrical net efficiency of 50–59%, which is lower than the 63–64% of the advanced foreign ones. This is mostly due to the remarkably lower level of the domestic GT technology. The CCGT facilities with about 39% of installed power are equipped with GT with TIT, which is the key parameter for the cycle efficiency below 1100 °C. High power GT with TIT above 1500 °C are absent. Large foreign power consortiums are developing GT with TIT about 1700 °C, so the prospects for domestic GT efficiency improvement are remarkable.

Reduction of this gap will require considerable time and investments. The CCGT power production efficiency and environmental safety improvement without excessive time and financial losses requires assessments of reasonable improvement directions for operational and prospective facilities.

It is possible to achieve a significant improvement in CCGT facility efficiency with low-boiling heat utilization cycle via introduction of steam turbine unit (STU) heat regeneration. This technical solution has a complex effect since its use not only leads to a significant reduction in losses in the condenser of a STU, but also allows higher heat carrier temperature in the low-temperature cycle due to the higher flue gas temperature related to the higher feed water temperature.

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