Reducing the negative environmental impact of thermal power plants by optimization of the operational modes of hydropower plants in the power grids

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Abstract. The paper analyses the current state of energy and the environment in the regions where the Russian largest HPP cascades are located – Volga region and Siberia. The effect of various limitations on HPP operations (power systems and water users restrictions, deviations from design operation characteristics) and resulting excess load at TPP are estimated. The environmental impact assessment (reducing emissions of pollutants and greenhouse gases in energy systems assuming maximum hydropower generation) is conducted. It is shown, that actions to increase HPPs usage efficiency (construction of new transmission lines, raising water reservoir level to level established by HPP design, enhancement of basic rules of water resources use) can save 3 million tce of fossil fuel annually and decrease emissions of air pollutants by 50 thousand tons and of carbon dioxide by 6 million tons annually.

1. Introduction
In 2015, Russia signed the Paris Agreement of the parties of the UN Framework Convention on Climate Change (1992), making voluntary commitments not to exceed 70-75% of 1990 amount of greenhouse gas emissions by 2030, and adopted this document in 2019. In addition to international obligations, national energy sector faces the challenge of reducing environment pollution, the state of which in many regions, especially in Siberian large cities and industrial centers, is extremely unfavorable [1]. Structural changes in the Russian economy in the 1990s led to a plunge of the fossil fuels consumption and, consequently, to a radical reduction in combustion emissions into the atmosphere [1]-[2]. At the same time, the increasing growth of urbanization and the development of some energy-intensive industries (metallurgy, etc.) lead to the formation of local hotbeds of environmental disadvantage, and the implementation of long-term programs to revive the country's industrial production should lead to an increase in national energy consumption [3], which may conflict with Russia's environmental commitments. Currently, Russia's energy base is organic fuel, accounting for almost 90% of primary energy consumption and providing about 70% of electricity generation [2]. As has been shown [3][4], only the presence of large hydropower plants and developed nuclear power, along with the predominance of natural gas as the main fuel, allow Russia to maintain acceptable (at the world average) indicators of the adverse impact of energy sector on the environment. However, with rather modest prospects for the renewable development and certain difficulties in increasing the capacity of nuclear power plants in Russia, hydropower can become an additional source of increased environmental efficiency of
domestic energy. For many countries with significant hydropower potential, construction of new hydropower plants (HPP) and the optimization of existing hydropower regimes is recognized as the main way of reducing the energy burden on the environment [[5]-[8]]. In domestic studies of Russia’s low-carbon development, hydropower is either ignored [[9]] or referred to in the context of only "small HPP"[[10]]. Nevertheless, representatives of energy companies are already developing technical modernization programs for existing HPP, which should result in significant environmental effects [[11]].

The objective of this work is to find ways to reduce emissions of pollutants and greenhouse gases from fossil fuel combustion at the thermal power plants (TPP), operating in power grids with large HPP, by optimizing the operation of the latter in the face of external and internal restrictions. The following tasks are performed:

1) analysis of the current state of energy and the environment in the regions where the largest HPP cascades are located;
2) assessment of deviations from design HPPs operation characteristics;
3) assessment of the regime restrictions of HPP by power systems and water users;
4) assessment of effect of various limitations on HPP operations and resulting excess load at TPP;
5) environmental impact assessment (reducing emissions of pollutants and greenhouse gases in energy systems assuming maximum hydropower generation)

2. The current state of energy and the environment

The main indicators of the energy sector functioning for studied regions– the European part of Russia (Europe - here Central, Volga, Ural and South federal districts) and the Siberian Federal District (Siberia) calculated according to the data of Federal State Statistics Service (Rosstat) [[2]] for 2018 are presented in Table 1.

| Region   | P, millions | $E_{cons}$, TWh | $E_{p}$, TWh | Share of self-production, % |
|----------|-------------|-----------------|--------------|-----------------------------|
|          |             | $\text{MWh per cap}$ | $\text{HPP Share in total, \%}$ | $\text{TPP Share in total, \%}$ | $\text{NPP Share in total, \%}$ | $\text{Total}$ |
| Central  | 39.3        | 227             | 5.8          | 4                            | 1.6                          | 124          | 55.8          | 95              | 42.6            | 223            | 98.1          |
| Volga    | 29.5        | 204             | 6.9          | 31                           | 16.0                        | 129          | 67.2          | 32              | 16.7            | 193            | 94.5          |
| Ural     | 12.4        | 189             | 15.3         | 0                            | 16.0                        | 186          | 67.2          | 9               | 4.5             | 195            | 103.3         |
| South    | 16.4        | 74              | 4.5          | 15                           | 18.1                        | 36           | 44.6          | 29              | 36.6            | 80             | 109.1         |
| Siberia  | 17.2        | 210             | 12.2         | 106                          | 52.3                        | 96           | 47.7          | 0               | 0.0             | 202            | 96.4          |
| Europe   | 97.6        | 693             | 7.1          | 49                           | 7.1                         | 475          | 68.8          | 165             | 23.9            | 691            | 99.6          |

Table 1 shows obvious differences in the power industry between the European and Siberian regions. Per capita electricity consumption in Siberia is almost twice as high as in the European territory of Russia, which is due to the presence of high-energy industrial production (mostly aluminum industry). The Siberian electricity generation is based on hydroelectric power, providing more than half of the electricity produced in the region. In the European part of Russia, hydro resources provide only 7% of production, whereas about 69% and 24% account for the TPPs and nuclear power plants (NPP) respectively.

The same significant differences are also observed in the fuel mixes of these regions (Table 2). Natural gas is the key energy source of European Russia, providing almost 90% of electricity and heat production. In Siberia, only a few regional power systems are gasified, and the key fuel is coal,
making up almost 80% of the fuel balance. The share of oil is insignificant in the fuel mix of both regions.

Table 2. Consumption of fossil fuels in the thermal energy sector of the studied regions in 2018 [2]

| Region     | Total  | Oil    | Gas    | Coal   | TPP    | Heat plants, total | Electricity production, total | Heat production, total |
|------------|--------|--------|--------|--------|--------|--------------------|---------------------------|------------------------|
|            | Mtce   | Mtce   | %      | Mtce   | %      | Mtce              | Mtce                      | Mtce                   |
| Central    | 54.3   | 0.1    | 0.2    | 50.3   | 93     | 1.5               | 2.7                       | 29.9                   |
| Volga      | 60.6   | 0.2    | 0.3    | 59.4   | 98     | 0.1               | 0.1                       | 31.4                   |
| Ural       | 67.2   | 1.3    | 1.9    | 54.3   | 81     | 8.6               | 12.7                      | 15.9                   |
| South      | 13.8   | 0.3    | 1.9    | 10.9   | 79     | 2.5               | 18                        | 7.6                    |
| Siberia    | 48.7   | 0.3    | 0.6    | 7.6    | 16     | 38.0              | 78                        | 28.4                   |
| Europe     | 196.0  | 1.9    | 1.0    | 175.0  | 89     | 12.6              | 6.4                       | 84.8                   |

These features of the energy sectors of the regions under study also determine the levels of their negative impact on the environment, primarily on the atmosphere (Table 3).

Table 3. Emissions of air pollutants and carbon dioxide (CO₂) from stationary sources in the studied regions in 2018 [2]

| Region     | Total CO₂ | From fuel combustion | of which TPPs |
|------------|------------|-----------------------|---------------|
|            | kg cap     | CO₂ tons cap          | Mt / GWh Mt % |
|            | Mt         |                       |               |
| Central    | 3.8        | 98                    | 155           |
| Volga      | 2.5        | 86                    | 174           |
| Ural       | 3.7        | 299                   | 210           |
| South      | 1.1        | 67                    | 43            |
| Siberia    | 5.2        | 303                   | 180           |
| Europe     | 11.2       | 114                   | 581           |

Despite nearly six-fold difference in population (17 million in the Siberia, and 98 million in four European federal districts), pollutants emissions from stationary sources (heat and electricity production, metallurgy, chemical manufacturing, etc.) in both regions differ only by half - 5 and 11 Mt/year, respectively. As a result, Siberia has almost three times more harmful emissions per capita than the European part of Russia.

A slightly different picture is with the release of carbon dioxide, the main greenhouse gas produced from fossil fuels combustion. Since the carbon content of coal and gas (referred to fuel calorific value) differs less than twice (0.7 t/tce and 0.4 t/tce, respectively), the difference in gross CO₂ emissions between the European and Siberian regions (1:3) is closer to the population ratio (1:6), and per capita difference is also not so large – 10 t per cap for Siberia and 6 t per cap for European part.

Thermal power plays a significant role in air pollution. Thus, emissions of pollutants in the production of electricity and heat in the European region account for 13%, and in Siberian - 28% of gross amount. For carbon dioxide, these figures are much higher – in European part 60-80% of the gross emission of this greenhouse gas from stationary sources falls on the TPPs and heat plants, in Siberia, due to the absence of another major source of CO₂ - the steel industry, thermal power is responsible for almost 100% of the emissions of this greenhouse gas. About half of this amount is produced by TPPs. At the same time, Siberian TPPs on average have much higher specific indicators (emissions per unit of electricity produced) of pollutants – more than 5 times higher than European ones. The difference in
carbon dioxide emissions indicators is not so significant - but, nevertheless, the figures of Siberian
TPPs are almost twice as high as the ones for European part of Russia.
As a result, according to Russian meteorological agency Roshydromet [[12]], the level of air pollution
in 26 cities where more than a half (55%) of the urban population of the Siberian Federal District lives
is characterized as high and very high. The Priority Pollution List based on the 2018 air quality
measurements includes 22 cities, 18 of them are located in the Siberian Federal District.
To address this major environmental problem, in the framework of the National Ecology Project a
federal Clean Air Project has been adopted, which aims to reduce pollutants emissions by 22% to 2024
(as compared to 2018 levels) and to improve air quality to safe levels in major industrial centers from
Priority Pollution List (10 of the 12 cities mentioned in the project are located in Siberia).
Analysis of energy and environmental statistics for Siberia (Fig. 1), where the share of HPPs in
electricity generation comprises about 50%, and TPPs mainly use coal, confirms the obvious fact that
the decline in hydropower generation in a certain period is accompanied by an equivalent increase in
TPP generation with a corresponding increase in emissions of pollutants into the atmosphere. To
exclude the influence of economic factors the linear trend was extracted from time series. Thus,
optimizing the operation modes of large HPPs cascades with an increase in their production can
become one of the solutions to the environmental problems.

![Figure 1. Changes in electricity generation ΔE at TPP and HPP and pollutants atmospheric emissions
ΔV (expressed as deviations from the linear trend)](image)

### 3. Hydro power generation
During recent decades there were substantial changes in conditions of HPP systems operations that led
to the following changes in HPP operating modes:
- development of anthropogenic activities within river basins leading to changes in operating
  conditions and creation of new, non-existing at HPP design stage requirements on water level in
  water reservoirs and on mode of water release into downstream pool;
- watercourse and banks erosion processes in upstream and downstream pools leading to changes
  of water level characteristics in downstream pool and useful volumes of water reservoirs;
new ecological and fishing industry requirements to water flow management, especially in downstreams of the lowest HPPs in HPP cascades;
- economic changes in water usage caused by switch to market based economy;
- technogenic changes caused by continuous usage of equipment and hydro-electric complexes constructions, leading to problems which could not be evaluated at HPP design stage. Example of such problems is a state of dams in high water pressure in hydro-electric complexes and equipment wear and tear leading to decrease in its efficiency;
- limitations on HPP caused by repairs and servicing of power grid leading to limitation of electricity flow and thus on the output of electricity generating units;
- decrease or elimination of power generating capacity reserve and regulating reserve at HPP.

In view of the last two points it is necessary to alter HPP power generation schedules in Unified Energy Systems (UES), this is especially important for Siberia UES where HPP share in installed power generation capacity is about 50%.

Assessment of decrease of HPP production due to limitations from water users and energy systems (power grid, etc.) was performed using “Cascade” software package [[13]] using as an example Volga-Kama HPP cascade (VKC) functioning in Central, Middle Volga, Ural and South UESs and Angara-Yenisey HPP cascade (AEC) functioning in Siberia UES, results are shown in Table 4.

Increase in TPP production was assumed to be equal to decrease in HPP production, estimation of increase of fossil fuels consumption and emissions at TPP was made using aggregate characteristics calculated according to Rosstat data [[2]] for European part of Russia (Central, Volga, Ural and South federal districts) and Siberia Federal District for 2018 shown in Tables 2 and 3.

**Table 4. Decrease in HPP production of VKC and AEC dE due to various causes, corresponding increases in fossil fuel consumption by TPPs dB, emissions of air pollutants dV and carbon dioxide dC**

| HPP cascade | Causes of HPP production decrease | dE, TWh | dB, Mtce | dV, kt | dC, Mt |
|-------------|-----------------------------------|---------|----------|--------|-------|
| VKC         | Watercourse and banks erosion [[14] - [15]] | 0.39    | 0.12     | 1      | 0.18  |
|             | Variations from design water level [[16] - [18]] | 2.70    | 0.82     | 4      | 1.24  |
|             | **total cascade**                   | **3.09**| **0.94** | **5**  | **1.42** |
| AEC         | System limitations [[19]]           | 4.20    | 1.47     | 36     | 3.43  |
|             | Outdated equipment [[111]]          | 1.50    | 0.52     | 13     | 1.23  |
|             | **total cascade**                   | **5.70**| **1.99** | **49** | **4.66** |
| **TOTAL**   |                                    | **8.79**| **2.93** | **54** | **6.08** |

Within VKC nine HPPs (Ivan’kovskaya, Uglichskaya, Rybinskaya, Nizhegorodskaya, Kamskaya, Votkinskaya, Zhigulevskaya, Saratovskaya and Volzhskaya HPPs) are in a state of permanent operation. Cheboksarskaya and Nizhnekamskaya HPPs are in a state of provisional operations because parameters of their water reservoirs (normal headwater level and dead level) do not conform to their design. Increase of water level upstream of built structures to a level envisaged in HPP design is met with objections from local authorities. Since construction of VKC is not completed yet, it is not possible to provide for cascade energy characteristics as designed as well as for through shipping with guaranteed water depth. Losses for hydro power generation as estimated by project institute Hydroproject is at 2.7 TWh in average annual production, 380 MW in guaranteed capacity, 1314 MW in available (mid-December) capacity.

Watercourse transformation is related to depositing to downstream of lighter water flow which has higher transportation capacity as well as to changes in water flow due to water flow management. Watercourse is often used as a source of sand and pebbles for construction, quantity sourced exceeds quantity deposited in a course water flow thus leading to intensive watercourse deformations.

In most cases result of watercourse transformation is lowering of river bottom which leads to lowering of water discharge characteristics \( Z_{DP}(Q_{DP}) \) and as a consequence increase is net head on HPP.
Besides positive consequences of this, namely increase in HPP production beyond the level envisaged in the design, there are negative consequences related to change in HPP cavitation characteristics. As HPP operates with fixed vertical position of turbine and dam, change in cavitation characteristics leads to nonobservance of conditions of cavitationless performance of HPP equipment, it’s increased wear and tear and decreased reliability. Lessening of guaranteed water depth during navigation period is also observed. Most intense lowering of water level is observed in downstream of Votkinskaya and Nizhegorodskaya HPPs because headwater levels of lower situated Nizhnekamskaya and Cheboksarskaya HPPs does not reach upper levels of cascade due to lack of their upstream pools fullness. Changes in flow hydraulic in downstream pools of Nizhegorodskaya and Nizhnekamskaya HPPs lead to increase of speed and washout capacity of water flow which results in lowering of water discharge-water level curve in these sections. To support guaranteed navigation water depth one has to alter operations mode of the upper level of the Rybinsk and Kama water reservoirs what leads to decrease in their energy characteristics. Loss of energy production in VKC is assessed at about 0.4 TWh annually.

For AEC HPPs in recent years practice there are occasional substantial jumps in load in electric system, during which designed schedule of power generation by a given HPS does not conform to actual conditions. Steps taken by local energy customers under such conditions can be unexpected and unpredictable, driven largely by global conjuncture in certain goods markets.

As water discharge volume is determined by requirements of water-economic complex, HPPs must maintain it by waste water discharge. One must notice that such discharge is performed when water level in upstream pool is below normal headwater level and turbine utilization is below full.

Such situation will be particularly acute in energy systems with large share of HPPs in energy production during years with water flow above average.

Long period of utilization of many HPPs leads to a substantial equipment wear and tear and thus require replacement of turbine equipment after its resource is expired. Estimated annual loss of HPPs production comprises 1.5 TWh [11].

4. Results and discussion

As it was shown above, cumulative energy loss at VKC and AEC HPP cascades due to limitations from water users and energy systems and deviation of exploiting parameters from designh ones is about 9 TWh of average annual production. Losses in guaranteed and available power generating capacity are not taken into account, however they are also substantial.

In this research we included only identified by authors or published by other researchers losses in HPP energy production, these do not cover all losses. Example of loss which is not taken into account is a loss due to water discharge performed on ecological and fishing management grounds at the Lower Volga, such a discharge is obligatory and is not subjected to revision.

To decrease HPP power production losses one must consider the following actions:

1) raising levels of water reservoirs (upstream pools of the Cheboksarskaya and Nizhnekamskaya HPPs) to levels according to these HPPs design – that would increase VKC annual electricity production by 2.7 TWh;
2) building of additional power lines to pass electricity produced by HPPs to UESs – that would cut limitation on AEC annual electricity production by 4.2 TWh;
3) changing of “Basic rules of water resources use” to reflect current requirements of energy systems and water users and current state of HPP environment with a view to increase energy production by HPPs;
4) HPPs equipment modernization – that would lead to increase in the AEC annual electricity production of 1.5 TWh.

Due to the measures described above the annual use of fossil fuel for electricity production would decrease by 1 Mtce in the European part of Russia and by 2 Mtce in Siberia, that would have substantial environmental effect, especially in the latter region, where pollution of the atmosphere would decline by 50 thousand tons a year. The climate effect of proposed measures is cutting annual carbon dioxide emissions by 6 Mt.
5. Conclusions
1) Decrease in HPPs production due to limitations from energy systems and water users leads to increase in TPPs production and corresponding increase in emission of air pollutants and greenhouse gases.
2) Main reasons for HPPs production decrease are system limitations (geographical change in energy consumers, lack of grid connections) and decrease of characteristics vs the design ones (watercourse transformation, equipment wear and tear, imperfections of water resources management rules, etc.)
3) Actions to increase HPPs usage efficiency (construction of new transmission lines, raising water reservoir level to level established by HPP design, enhancement of “Basic rules of water resources use”) can save 3 million tce annually and decrease emissions of air pollutants by 50 thousand tons and greenhouse gases by 6 million tons annually.

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Acknowledgments
This study was conducted with financial support from Russian Foundation for Basic Research (Grant No. 18-08-00026) for thermal power calculation and from the Russian Science Foundation (Grant No. 18-19-00662) for hydropower calculations.