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LIMITS TO THE GROWTH OF THE WORLD ALTERNATIVE ENERGY

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The energy and environmental security of humanity is the most discussed issue nowadays. The energy and the energy industry form the basis of any civilization. As technologies continued to develop, humanity uses more and more energy. In the 20th century, humanity increased energy consumption by ten times. The actual energy capacity of modern civilization is going to reach 20 billion kW and the average energy consumption per person on the planet is 1,900 kg of oil equivalent (OE) per year.

In 2017, the global production of coal, oil and gas reached 11,425 million tons of OE; 945 million tons of OE of energy was produced by renewable energy sources (RES). Thus, humanity is about to use 160,160x10^{12} kWh/year of energy in households, industry and transport.

During the UN Climate Change Conference in Katowice in December 2018, a non-governmental organization named Energy Watch Group (EWG) presented a forecast about the transition of the EU countries to RES, with consideration of energy stations and transport, by 2050. In this forecast, the solar energy will take 62%, wind energy – 32%, hydropower – 4%, biomass energy– 2%. In our opinion, this forecast is unfounded, as environmental limits will not allow satisfying the global demand for energy only by RES, especially by just one dominating source.

It is necessary to conduct a systematic analysis of **the limits to the growth** for the selected RES. The evaluation concerning 62% of solar energy is clearly overestimated. Its development will be restricted by natural factors, material resources, and especially by land resources.

Recently, world population growth has slowed down. Volumes of global coal production have decreased (production growth is observed only in India, Russia and Kazakhstan). World oil reserves have been depleted (since 1984, the number of developed oil reserves has been decreasing). The energy efficiency of production of one unit of GDP has also increased. The above-mentioned processes result in a decrease in the growth rate for the use of global gross energy and in an increase in carbon dioxide emissions (Table 1). The increase of CO_2 emissions falls behind the energy production growth rate due to increasing usage of carbonless green energy.

TABLE 1

GLOBAL GROSS ENERGY PRODUCTION RATE AND THE CORRESPONDENT INCREASE OF ANTHROPOGENIC CO_2 EMISSIONS IN THE PERIOD AFTER 1975 (% PER YEAR).

YEARS	ANNUAL GROWTH OF ENERGY PRODUCTION	ANNUAL INCREASE OF CO_2 EMISSIONS
1975-2000	2.0%	1.2%
2000-2010	2.8%	2.5%
2010-2017	1.2%	1.1%

Since 1973, the world has been switching to energy-saving technologies, trying to improve energy production and energy consumption simultaneously. The annual global investments in production efficiency are more than 200 billion US dollars, and as a result, the energy intensity per unit of GDP is globally reducing by 2% every year. For example, the GDP of Germany has increased by 50% since 1990, but energy consumption has increased only by 9%.

In accordance with the road map, the EU countries plan to reduce carbon dioxide emissions by 40% against the 1990 level and to increase the RES share by 27%. China plans to commission a solar plant (SP) with a capacity of 160 GW (performance is expected to be 181 TWh/year) and a wind farm (WF) with a capacity of 280 GW (performance is expected to be 432 TWh/year). Now, the worldwide installed capacity of RES is more than 1,000 GW and is going to reach the world capacity of hydroelectric power plants (HPP). Today, 25 countries provide 5% of their electrical energy from RES and 13 of them provide 10% of their electrical energy from RES.

In the 21st century, the ratio of energy resources used by humanity is going to change significantly. According to our estimations, by 2050, the share of different energy resources in the world energy industry will correspond to values, presented in Table 2. One should examine in detail the reasons for such diversification of the world energy balance.

TABLE 2

APPROXIMATE SHARE OF DIFFERENT SOURCES IN THE WORLD ENERGY BALANCE.

YEARS	COAL	OIL	GAS	BIOMASS	HYDROPOWER	WIND	SOLAR	OTHER
1900	60	3	2	33	2	-	-	-
2000	28	36	20	5	3	1	1	6
2100	5	5	16	18	6	18	16	16

Fossil fuel takes about 80% of the world energy balance. In 2017, 53.5 billion tons of greenhouse gases in CO_2 equivalent were emitted in the atmosphere. The world energy industry should continue to develop, but it should not lead to billions of tons of combusted fuel. According to Paul Ehrlich, the German Doctor and a Nobel Prize Winner, **"Perpetual growth is the creed of a cancer cell".** In pursuit of energy, the human being has narrowed fauna areas so much that all wild animals, including mice and elephants, take 3%, while people and domestic animals take 97%. Large livestock produces up to 6% of greenhouse gas methane in CO_2 equivalent.

When looking at the evolution of biosphere and society, it appears that the populations and societies who started to use new forms of energy were more competitive. The countries of the Golden Billion achieved the largest GDP values by consuming more energy (Figure 1). As it is shown in the figure, GDP growth corresponds to the growth of primary energy consumption. 20% of the Earth population consume up to 80% of the energy produced. If all people of the planet were consuming as many resources as an average European, two more planets of the same size as the planet Earth would be needed.

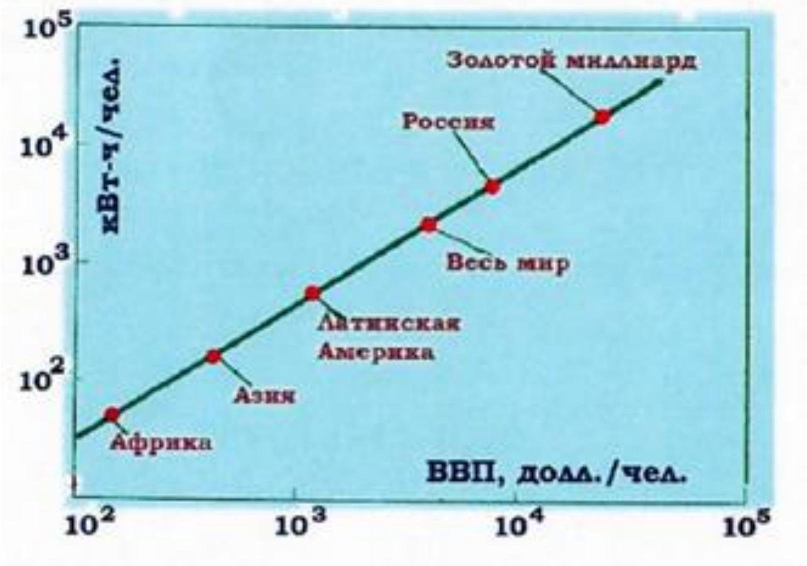
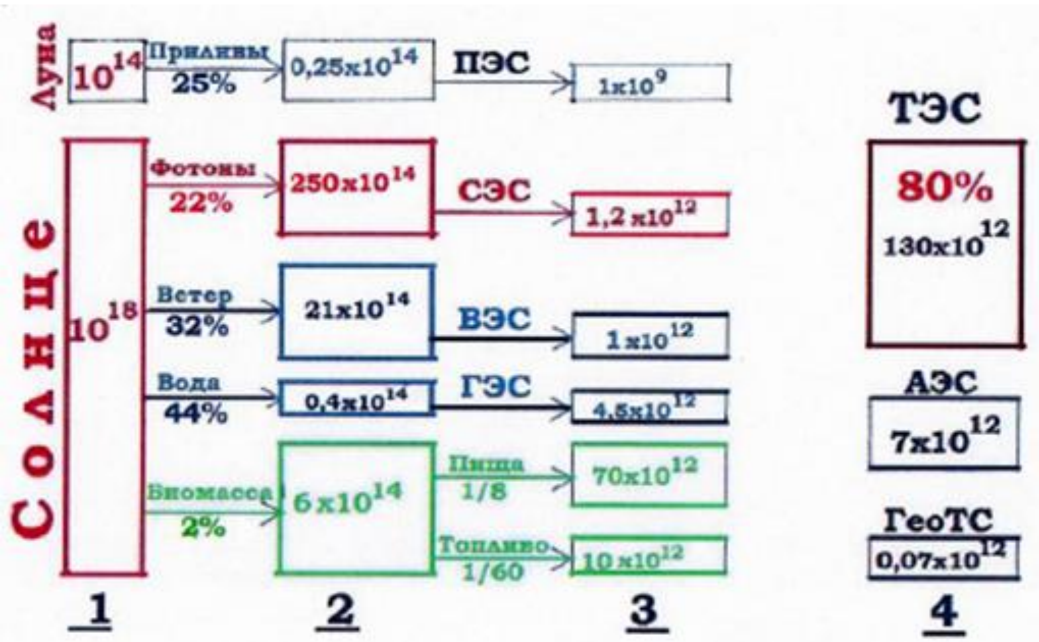


Figure 1. Correlation between GDP and energy consumption per capita.

Золотой миллиард	the Golden Billion
Россия	Russia
Весь мир	Whole world
Латинская Америка	Latin America
Азия	Asia
Африка	Africa
кВт-ч/чел.	kWh/capita
ВВП, долл./чел.	GDP, US dollars/capita

In the context of today's crisis situation, the global economy is gradually switching from fossil fuel to carbonless energy production. More particularly, China is taking active actions in its development, as a part of an "ecological civilization" policy, which is stipulated by the Constitution. According to the forecasts of the International Energy Agency, the share of fuel in the world energy balance will decrease to 55% by 2040. England and Germany are closing their minds and are actively switching their economy to the "green economy". The RES capacity in England is 41.9 GW. By 2050, Germany plans to produce up to 60% of its consumed energy from RES. In 2017, the EU countries produced 310 billion kWh (21%) of electrical energy from wind and sun; it is equivalent to the annual performance of HPP for all European countries.

Today's energy supply of human civilization is presented in Figure 2.



Луна	*Moon*
Солнце	*Sun*
Приливы	*Tides*
Фотоны	*Photons*
Ветер	*Wind*
Вода	*Water*
Биомасса	*Biomass*
СЭС	*SP*
ВЭС	*WF*
ГЭС	*HPP*
Пища	*Food*
Топливо	*Fuel*
ТЭС	*TPP*
АЭС	*NPS*
ГеоТС	*GPP*

Fig. 2. Energy of the Earth and civilization (kWh/year): 1 – radiation energy received from the Sun and tidal energy received from the Moon; 2 – transformation of the cosmic energy received by the Earth in various forms, suitable for the use by humanity: tidal energy, thermal energy of photons, wind and wave energy, energy of evaporation of water and ocean currents, energy of synthesized biomass; 3 – volume of various forms of renewable energy used by humanity; 4 – volume of non-renewable energy received by the Earth in past historic periods: the energy of fossil fuels (formed 50-100 million years ago); geothermal energy (formed 4.5 billion years ago); nuclear energy (formed more than 5 billion years ago).

The estimated potential of RES of solar origin is characterized with the following values (kWh/year) [2]: hydropower $0.39x10^{14}$; wind energy $21x10^{14}$; solar energy $1,500x10^{14}$. However, the RES are not always harmless for the biosphere, so it is not possible to use all their potential for economic and ecological reasons.

The production of any kind of energy involves the isolation of a land area, and RES require massive areas of alienated lands (Table 3).

TABLE 3

AVERAGE ECONOMICAL AND ECOLOGICAL PARAMETERS OF DIFFERENT POWER PLANTS.

TYPE OF A POWER PLANT	RELATIVE CAPITAL INVESTMENTS, DOLLARS/KW	ALIENATION OF LANDS, M^2/KW
FUEL	2,100	16
GEOTHERMAL	3,000	15
SP ON PHOTOVOLTAIC ELEMENTS	2,000	80
WF	2,000	320
HPP	3,300	40-4,000

Huge territories are needed to produce energy on an industrial scale, from sun and wind, while the area of global land resources is 130 billion km^2 (87% of all land) and is limited. Land resources are used by modern civilization as follows: 10% of land is used for ploughed fields; 25% – for hayfields and pastures; 30% – for forests; the total area of human settlements, production facilities and communication facilities is about 5%; the total area of deserts and inarable lands is 17%.

The objective of the modern energy industry is to switch from the production of $130x10^{12}$ kWh/year of fuel energy to the production of renewable energy. Different countries may have different motivation for it. For the EU countries, it is a desire for energy independence; for China, the main motivation is clean air; for India – a fight against poverty; for African countries – food supply security. It is efficient to use desert and shelf areas, as **it is forbidden to reduce the area of forests from the ecological point of view and it is forbidden to reduce agricultural lands used for the security of food supply for the civilization.**

Biomass energy. The main benefit of biomass is that the quantity of CO_2 produced during the combustion of biomass is equal to the quantity of carbon consumed during photosynthesis. Biomass has always been and remains the most important source of "energy of life" for humanity. Humanity consumes up to 20 billion tons (12%) per year of primary biological products including all food products and products for domestic animals. 2.7 billion tons of these 20 billion accounts for the worldwide grain harvest.

Every year, 10% (about 200 billion tons per year) of plant biomass is renewed through photosynthesis. It accumulates approximately $600x10^{12}$ kWh of solar energy. Using this biomass, humanity consumes up to 2 billion tons of wood for fuel every year, which is equivalent to $10x10^{12}$ kWh of solar energy, contained in wood.

The current capacity of bioenergy power plants is going to reach 100 million kW. Fuel pellets from wooden and agricultural waste are used as an energy source for this industry. Waste incineration plants are also a part of the bioenergy industry.

Humanity starts to develop different techniques for processing photosynthesis products into biofuel, such as compacting for colza oil, pyrolysis of wood for bio-oil, fermentation for bioethanol, decompounding organics for biogas, Fischer-Tropsch synthesis to produce methanol from coal and wood.

One must note that it is difficult to draw a clear line between the transport energy and industrial energy. Biofuel is going to replace oil in the transport sector. There are hundreds of filling stations in the USA and in Germany, which sell thousands of tons of biodiesel. In Brazil, more than 40% of ethanol for cars is produced from sugar cane. Hydrogenous and methanol fuel cells will be widely used in cars. By 2040, electric transport will replace almost 50% of vehicles with an internal combustion engine. Today, 30 million hectares of arable lands are sown with industrial crops. By 2050, humanity will be able to produce no more than 18% of essential primary energy ($27 \cdot 10^{12}$ kWh/year) from biomass because of the lack of land.

Solar energy. The total quantity of solar energy received by the Earth and the atmosphere during one year is $1.07 \text{x} 10^{18}$ kWh. Its consumption does not affect the global energy balance. Humanity turned to alternative energy sources when the oil price exceeded 100 US dollars per barrel. In recent years, the solar energy sector is developing rapidly, although the oil price has fallen sharply.

The capacity of SP constructed in 2017 is 98 million kW, and it has surpassed the capacity of commissioned thermal power plants. By 2017, the total capacity of all SP of the world was 402 GW (million kW), including 131 GW of SP in China, 51 GW of SP in the USA, 49 GW in Japan, 42 GW in Germany, 20 GW in Italy, 18 GW in India, 13 GW in England, 8 GW in France; in Russia total capacity of SP is only 0.4 GW.

By 2030, Japan and Saudi Arabia plan to commission a solar plant with a capacity of 200 GW. It will save 72 million tons of oil every year. India plans to start to produce 250 GW of solar energy (for reference, the total capacity of the whole energy system of Russia is 230 GW). Australia has approved a project of constructing a virtual power plant with a capacity of 250 MW. This project involves installing solar panels on roofs of 50 thousand buildings with energy storage systems for 650 MWh. In Germany, 57% of functioning solar panels are installed on the roofs of buildings. Today, the cost of a solar plant on the roof is about 1,000 euro/kW. There is an overproduction of solar energy in California (the USA), as during the day electric grids are overfull, and there are not enough storing facilities to save the produced volume of electricity. In the USA an average price of 1 kWh of electricity produced by a solar plant is 2.5 cents.

To provide 10% of humanity demands of energy by SP, it is needed to cover 160 thousand km^2 of land with solar panels. No fewer than 20 billion of one-kilowatt solar panels are required to fulfil this plan; the total mass of these panels would be about 2 billion tons. In 20-25 years, it will be necessary to replace the panels by new ones.

Taking into account the current capability of solar panel commissioning (about 100 GW/year), by 2050, the world capacity of SP could reach 6,000 GW. After this, SP number would stop growing, as the world semiconductor industry would have to replace hundreds of millions of solar panels, which would have worn out. It seems to be the capacity limit for an environmentally unfriendly solar panel industry.

An Achilles' heel of SP is the small coefficient of used capacity – it is only 12%. Moreover, solar energy production has high material consumption – it is about 15,000 t/TWh [10]. Aggressive toxic agents are used in solar panel production and it generates lots of hazardous waste. By 2050, there will be hundreds of million tons of depleted solar panels that contain 90% of glass and heavy metals such as cadmium, lead, indium, etc. The environment will not manage the further disposal of such a big quantity of hazardous waste. Now, about 80 million houses worldwide have solar water heating. Its capacity was 435 GW by 2015. By 2050 this kind of solar heating can reach 5% of total energy production.

It is necessary to provide solar and wind plants with energy storage facilities. There are several proposed technologies with unobvious prospects of the market. As of today, the best-tested solution for storage big volumes of energy is pumped storage units (PSU). To ensure a sustainable operation of RES, the share of movable energy units should be no less than 25% of the total installed capacity of power stations. It seems to be successful to produce hydrogen and methanol by water electrolysis. Hydrogen and methanol are more and more used as energy sources to fuel transport power units.

In this case, in addition to the capital costs (Table 3), the costs of hydro-accumulation will be added, and capital costs will increase 2.5 times to 5,000 dollars/kW of installed capacity.

Thus, the restriction of solar energy growth is due to high material consumption, short service life, a large number of hazardous waste and a shortage of land. It can be assumed that by 2050, the global energy production from SP and solar thermodynamic stations will not exceed 16% (25x1,012 kWh/year) of the total consumed energy. To implement this program, about 250 thousand km^2 of the earth's surface will have to be allocated for SP.

In Russia, the share of RES, including HPP, in total primary energy production is only 3.2%. 75% of the Russian territory has no centralized power supply. Therefore, SP should be built in such regions as Yakutia and Zabaykalsky Krai, where the cost of 1 kWh is more than 20 rubles (35 cents/kWh), and where there are more sunny days than in Crimea. The development of renewable generation will be even more efficient for such isolated regions if combined solar-diesel and wind-diesel power generation are used. By 2024, it is planned to build 57 SP in Russia with a total capacity of 1.5 GW.

Wind energy. Wind energy is one of the most competitive among the RES, and it is the one developing the most rapidly. Modern wind turbines usually consist of a three-blade wheel with diameter up to 100 m. The wheel is connected to the electric generator with a capacity up to 2 MW which is located at the top of the tower. The energy conversion efficiency of wind turbines is three times higher than the energy conversion efficiency of solar panels. One wind turbine can save up to 60 thousand tons of coal in 20 years.

It is more efficient to locate WF at the seaside, where the wind is very strong, as the wind turbine efficiency depends on wind speed raised to power three. It is simultaneously the benefit and the drawback of wind plants, as it affects the sustainable energy output.

In China, there is a functioning wind energy complex which includes 40 WF. The capacity of this complex will be about 20 million kW by 2020. European countries are actively commissioning wind parks at the seaside and on high seas. According to cautious estimates, wind resources of the coastal area of the EU are going to reach 600 billion kWh/year. In Denmark, wind energy provides about 40% of all energy demands, in Germany – above 10%. The average cost of the electrical energy produced by a wind farm is 1.5 cents/kWh, which is equivalent to the cost of 1 kWh of electrical energy produced by HPP.

Wind energy and hydropower are actually allied industries, as hydropower engineers can successfully use areas of water reservoirs to install WF. By 2050, the global energy production of WF can constitute 18% of the total energy production ($27 \cdot 10^{12}$ kWh/year). This will require about one million km^2 of the Earth surface.

The potential of WF in Russia is 260 billion kWh/year. Wind energy production is just starting to develop. In 2017, the installed capacity of WF was about 100 MW. It is appropriate for Russia to start constructing WF in the Far North regions, where energy demands are the highest, and the average wind speed is high.

Geothermal energy. The Earth is a kind of thermal machine with a capacity of 42 billion kW. It sends thermal energy to space. Geothermal power plants of the world produce 65 billion kWh/year. The share of the geothermal energy in the total production of some countries exceeds 15%. For example, the capacity of geothermal plants in the Philippines is going to reach 2 million kW.

Tidal and wave energy. There are about 100 coastal areas in the world which can produce 25x1,012 kWh of electrical energy per year due to tides. The biggest tidal power plant (TPP) of the world is located in South Korea; its capacity is 254 MW. The potential of tidal and wave energy in Russia is estimated at 210 billion kWh/year.

As for sea waves' potential, 1 meter of the seaside can "produce" 3,000 kWh/year. The potential of wind waves is estimated at 2.7 billion kW.

Hydropower. Hydropower is basically a consequence of solar energy. Hydropower, like solar and wind energy, is an alternative to fuel energy.

There are "atmospheric rivers" on the Earth. It is waterlogged flows of air, up to 500 km wide, which start in the tropics. There are always 11 "atmospheric rivers", flowing above the planet's surface. They discharge with precipitation, as soon as they reach a continent. The annual amount of precipitation is 577 thousand km^3. More than a third of the radiation energy received by the Earth is spent on evaporation and on the maintenance of the global water cycle. However, only a small part of the Earth's hydropower potential, about 9.5×10^{12} kWh/year, can be converted into electricity.

Today, the worldwide gross installed capacity of HPPs is 1.25 billion kW; it produces 4.2×10^{12} kWh of electrical energy per year. In 2016, HPPs with the gross capacity of about 32 million kW were commissioned. China is an absolute leader in the use of hydropower. In 2016, China produced 1,100 billion kWh of electrical energy from HPP. In 2015, China constructed about 100 high hydroelectric installations, including 55 dams above 100 m, 8 dams above 200 m, and the arched HPP dam of Jinping which is 305 m high. The next 14th five-year plan asks for an increase of HPP capacity to 40 million kW, and by 2050, it is planned to double the capacity of HPP.

The three largest HPP of Brasil are the ones of Itaipu, Belo Monte and Tucurui. They produce 169 billion kWh/year; it is equal to all HPP of Russia. They have developed from 60 to 90% of the hydropower potential of the country, where hydrocarbon resources are about to be depleted. In recent years, special attention has been paid on the development of small hydropower. More than 100 small HPPs have been constructed in Armenia and the plan is to double their number. Belarus is constructing small HPP on the Daugava, Neman, and Dnepr.

Unfortunately, Russia uses hydropower resources less than other developed countries of the world. There are 15 HPP with a capacity above 1,000 MW, 102 HPP with a capacity above 10 MW and around 300 small HPP. In total, no more than 20% of the hydropower potential of Russia is used today.

One must note that the construction of HPP should meet the criteria of sustainable use of natural resources and should be environmentally friendly. An important ecological parameter of any energy facility is the ratio of the required Earth's surface area to the installed capacity of the facility. The specific value of the earth's surface area for 1 kW of the installed capacity is different for different HPP. It can vary by two to three orders of magnitude (m^2/kW): Three Gorges HPP – 46; Sayano-Shushenskaya HPP – 92; Itaipu – 112; Guri – 420; Bratskaya – 1,218; Cheboksarskaya – 1,350; Samarskaya – 2,800; Ivankovskaya – 11,000. This value is very big for Irkutsk HPP; it is 47,900 m^2/kW, as its headrace is the whole water area of Lake Baikal. Environmental specialists are against using this unique place of the UNESCO World Natural Heritage List as a water reservoir for HPP.

In the 21st century, the Earth surface is becoming an important natural resource. Russian hydroelectric installations with a water reservoir of an area exceeding 1,000 km^2 predominate among all worldwide HPP. One may consider that hydroelectric installations with a relative indicator of an alienated area at 40-800 m^2/kW certainly meet the requirement of sustainable use of natural resources. Flat hydroelectric installations with a relative indicator of an alienated area exceeding 4,000 m^2/kW do not meet this requirement and will be demounted in the near future.

The majority of big HPP of Russia has quite high relative indicators of alienated areas; their range is from 800 to 4,000 m^2/kW. It is obvious that special arguments are needed to justify the construction of HPP in the above-mentioned range of relative indicators of alienated areas.

Hydropower industry provides a profitable and most environmentally friendly way of energy production. Hydropower industry is always commercially viable; products and services of GDP up to one US dollar are produced with one kW of electrical energy. One kW in hydropower energy costs two cents. It means that an investment of two cents in the hydropower industry will ensure GDP growth by one dollar, so the investment benefit will be 50-fold.

Today global hydropower industry faces the objective to equate electrical energy production on SP and WF. More than 460 Pumped Storage Hydropower Plants (PSHP) with the installed capacity of around 200 GW operate in the world. In 2016 the capacity of PSHP was 6 million kW. China plans to commission PSHP with a capacity of 50 million kW by 2026. In Germany, mines are being actively reconstructed for PSHP.

RusHydro PJSC should use these opportunities and prepare arguments to discuss the construction of HPP, PSHP and WF with the Government of the Russian Federation, the State Duma of the Russian Federation and the environmental community. It is necessary to define the legal status of water reservoirs, to define the scale of water reservoirs' impact on local climate, on the hydrogeological schedule and on the geodesic situation of the place, to regulate development of the tailrace, to establish a fair damage compensation for water and biological resources, to restart constructing small HPP, to start constructing WF in the Far North and to justify a broad perspective of constructing movable PSHP.

Conclusion

1. In accordance with Paris Agreement governments of developed countries are actively implementing Programs on Decreasing Coal Generation and Developing RES. Russia should more actively introduce low-carbon energy into its energy balance, as today green energy ensures a competitive advantage to companies, industries and countries, while the market of coal is going to inevitably shrink.

2. During the 21st century, it is impossible to switch fully to carbonless energy; the share of RES will not become 100%; renewable energy will go side by side with gas fuel.

3. With the development of solar and wind energy, the importance of movable and leveling hydropower will increase. To improve investment attractiveness, HPP should provide WF construction in its complex, which can be located in water reservoirs' area; energy produced by WF will be accumulated by water reservoirs.

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