

Research of the Number and Installed Capacity of the Park of Hydroelectric Units of the Georgian Hydro Power Plants

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ABSTRACT

The Georgian power system with an annual electricity consumption of about 13 billion kWh is small, but has a number of technological features. As of 01.06.2021, there are 59 hydropower plants operating in Georgia with a total installed capacity of 3398.6 MW, among them 26 are medium and 32 are small, with an installed capacity in the range of 25–250 MW and 1–25 MW, respectively. 26 medium and 32 small hydropower plants have a total installed capacity of 1828.2 MW and 274 MW, respectively, and provide electricity in Georgia in the amount of 5.5 billion kWh of electricity, which is more than 60 % of all the country's electricity needs per year. A total of 142 hydroelectric units have been installed at Georgian hydroelectric power plants, the basis of the park is 114 units with a unit installed capacity of 1 to 25 MW, their total installed capacity is 1001.63 MW. For the period up to 2027, more than 50 new medium and small hydroelectric power plants will be commissioned in Georgia. The experience of Georgian development of hydropower potential through the construction of medium and small hydropower plants, maybe interesting for the development of hydropower resources in Russia or other countries.

Keywords: *Medium and small hydropower plants of the Georgian power system, Structure of installed capacity, Structure of electricity generation, Park of hydroelectric units, Small and distributed generation.*

1. INTRODUCTION

Georgia is one of the countries of the Transcaucasia region, its territory is 69.7 thousand km², more than 3.7 million people live in Georgia. The annual gross domestic product of the Georgian economy is up to 20 USD billion, the basis of the country's economy is the mining industry, ferrous and non-ferrous metallurgy and agriculture [1, 2].

The Georgian power system is small, the volume of electricity consumption in the country is about 13 billion kWh per year. The technological operator of the Georgian power system is the Joint stock company Georgian State Electrolyte (JSC "GSE", www.gse.com). According to the annual reports JSC "GSE", based on the results of technological operation in 2020 [3], the installed capacity of all power plants of the Georgian power system amounted to 4246.7 MW, the maximum power consumption (maximum load) – 2035.0 MW, electricity generation at power plants – 11.86 billion kWh per year, electricity

consumption is 13.25 billion kWh per year. In terms of the volume of electricity consumption, the Georgian power system is comparable to one of the Russian region in the middle zone: Vologda, Lipetsk, Saratov, Primorsky regions or others.

2. FEATURES OF THE GEORGIAN POWER SYSTEM

The Georgian power system has a number of technological features that are of certain scientific interest for the Russian and world power engineering. These features are:

1. More than 75% of electricity is generated in the power system at hydroelectric power plants (HPPs). According to [3], at the end of 2020, the installed capacity of Georgian HPPs amounted to 3167 MW (75 %), and electricity generation at HPPs – 10.6 billion kWh (89 %).

2. According to [4], the hydropower potential of Georgia is estimated at 15 GW of the installed

capacity of the HPPs and 50 billion kWh of electricity generation per year. As of 01.01.2021, the potential has been developed by 20 %.

3. With regard to the Georgian power system, the Development Program for the period 2017–2027 is in force [4], according to which, by 2027, the installed capacity of the HPP should be 6419 MW, and the generation of electricity – 22.96 billion kWh. At the same time, the share of HPPs in the structure of electricity generation should grow from 79 % to 87 %.

4. Until 1991, the Georgian power system developed as part of the Unified Power System of the Soviet Union (UPS of the USSR), Soviet generating equipment was installed at the Georgian HPPs. Since 1992, specialists have been installing foreign generating equipment at Georgian HPPs, mainly of Western European production. Today, the Georgian power system is a unique platform where it becomes possible to study the technologies of power engineering of various manufacturers, and it becomes possible to study the features of the constructive performance of hydraulic units (hydraulic turbines, hydrogenerators) and their influence on the efficiency of the technological functioning of hydraulic units, including impact on the volume of electricity generation.

5. Hydroelectric units of Georgian HPPs operate in mountainous terrain, at a considerable height above sea level, which can also affect the efficiency of their technological operation.

6. Among all HPPs in Georgia, their significant generating capacities are located at HPPs, according to the Russian classification, which can be attributed to objects of small and distributed generation. Thus, the experience of Georgian development of hydropower resources through the construction of small HPPs to meet the country's electricity needs may be interesting for the development of hydropower resources in the Russian regions, on the worldwide territory of which the same significant volumes of small HPPs can be built.

In this regard, the experience of construction and technological operation of HPPs in Georgian power system is unique and definitely subject to scientific research and study.

3. POWER PLANTS OF THE GEORGIAN POWER SYSTEM

Earlier, in [5], the results of research were described, based on the results of which it was established that as of 01.06.2021, 53 power plants of three types with a total installed capacity of 4492 MW are operating within the Georgian power system, including 1 wind power (WPP) plant with an installed capacity of 20 MW, 47 HPPs with a capacity of 3282 MW and 5 thermal power plants (TPPs) with a capacity of 1190 MW.

During 2021, these data were completed and updated. It has been established that as of 01.11.2021, **59 HPPs are operating in Georgia, 142 hydroelectric units with a total installed capacity of 3398.6 MW are installed at their sites.** Also, the concentration of the number and installed capacity of Georgian HPPs and their hydroelectric units (HU) was determined by region, Figure 1, Table 1:



Figure 1 Administrative divisions of Georgia.

Table 1. Structure of number and installed capacity of Georgian HPPs by region as of 01.11.2021

No	Region of Georgia	N _{HPP} , un.	N _{HU} , un.	P _{ins} , MW	Weight, %
	HPP total in Georgia	59	142	3 398.6	100.0%
1.	Abkhazia	7	19	1 668.7	49.1%
2.	Imereti	9	27	416.0	12.2%
3.	Mtskheta-Mtianeti	9	27	354.5	10.4%
4.	Adjara	6	18	300.3	8.8%
5.	Kvemo-Kartli	6	13	269.7	7.9%
6.	Lechkhumi and Svaneti	6	12	175.3	5.2%
7.	Samtskhe-Javakheti	3	7	110.1	3.2%
8.	Kakheti	11	17	82.0	2.4%
9.	Guria	2	2	22.0	0.6%
10.	Shida Kartli	0	-	-	-
11.	Upper Svanetia	0	-	-	-
12.	South Ossetia	0	-	-	-

Thus, it was found that the largest volumes of the number of HPPs, HU and the total installed capacity of Georgian HPPs (over 300 MW) are concentrated in the regions: Abkhazia, Imereti, Mtskheta-Mtianeti and Adjara, HPPs are absent in 3 regions.

To study the structure of electricity generation by HPPs on a linear scale of the HPPs installed capacity, then it is advisable to single out the electricity generation by region and consider the structure of the installed capacity of Georgian HPPs in accordance with the Russian classification.

4. STRUCTURE OF INSTALLED CAPACITY AND ELECTRICITY GENERATION AT GEORGIAN HPPS

When studying the reporting documents on the technological functioning of the Georgian power system [1–4], and additional data sources [6–9], it was possible to establish the reporting indicators of the functioning of Georgian HPPs and then determine the volumes of installed capacities, the volume of electricity generation, and the installed capacity utilization factors (ICUF) individually for Georgian HPPs in the regions. The results are shown in Figure 2 and 3 and in Table 2:

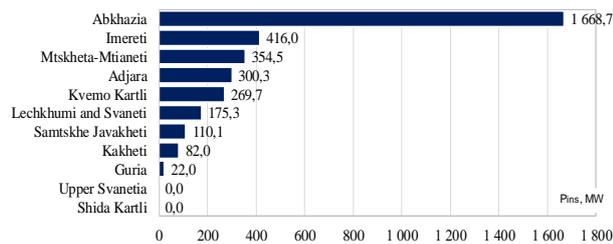


Figure 2 Installed capacity of Georgian HPPs in 2020 by region.

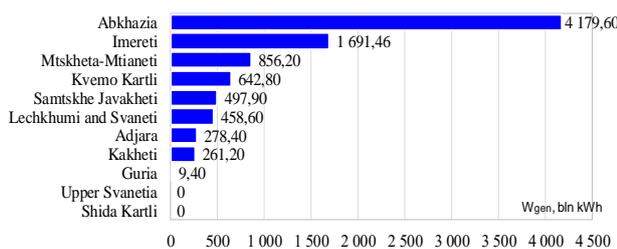


Figure 3 Electricity generation of Georgian HPPs in 2020 by region.

Table 2. Structure of number and installed capacity of Georgian HPPs by region as of 01.11.2021

№	Region of Georgia*	P _{ins} , MW	W _{gen} , mln kWh	Weight, %	ICUF
	HPP total in Georgia	3 398.6	8 819.8	100.0%	29.8%
1.	Abkhazia	1 668.7	4 179.6	47.4%	28.6%
2.	Imereti	416.0	1 691.5	19.2%	46.4%
3.	Mtskheta-Mtianeti	354.5	856.2	9.7%	27.6%
4.	Adjara	300.3	278.4	3.2%	10.6%
5.	Kvemo-Kartli	269.7	642.8	7.3%	27.2%
6.	Lechkhumi and Svaneti	175.3	402.8	4.6%	29.9%
7.	Samtskhe-Javakheti	110.1	497.9	5.6%	51.6%
8.	Kakheti	82.0	261.2	3.0%	36.4%
9.	Guria	22.0	9.4	0.1%	4.9%

*Regions are ranked in descending order of installed capacity of HPPs

The largest HPP in Georgia is the Inguri HPP with an installed capacity of 1300 MW (HU 5×260 MW). The HPP is located in Abkhazia and provides electricity generation in the amount of up to 4.5 billion kWh annually, provides up to 40% of Georgian electricity

needs. In 2020, the Inguri HPP generated 3.49 billion kWh with an ICUF of 30.65% and provided 26 % of all electricity generation in Georgia. The average ICUF for Georgian HPPs amounted to 29.81 % in the 2020th calendar year, which is lower than the ICUF for Russian HPPs at the level of ~ 40%. However, attention is drawn to the fact of a relatively high ICUF in regions with relatively small capacities of HPPs (Imereti, Kakheti) and the region with the highest ICUF HPPs – 51.62 % in the Samtskhe-Javakheti region. Further analysis of the composition of HPPs, in addition to the analysis by regions, is also advisable to perform on a linear scale of installed capacity.

5. COMPOSITION OF GEORGIAN HYDRO POWER PLANTS

In Russia, since 2012, the classification system of the installed capacity of HPPs has been in effect according to the scale introduced in STO 01.01.78-2012 of PJSC “RusHydro” [10]. At the same time, according to the Decree of the Government of Russia dated 17.10.2009, No.823 [11], when solving design and operational problems, it is necessary to take into account all power plants with an installed capacity exceeding 5 MW. In this regard, for an objective and transparent analysis of the composition of Georgian HPPs on the Russian scale, it is advisable to introduce an additional division of small HPPs along the internal border of 5 MW. The Russian scale of HPP capacity according to documents [10, 11] is shown in Table 3:

Table 3. Classification system of HPPs installed capacity

№	HPPs type	HPPs installed capacity range
1.	Micro HPPs	<0.10 MW
2.	Small HPPs from 1 to 5 MW	0.10 ÷ 4.99 MW
3.	Small HPPs from 5 to 25 MW	5.00 ÷ 24.99 MW
4.	Medium HPPs	25.00 ÷ 249.99 MW
5.	Large HPPs	≥ 250 MW

Taking into account the composition of the initial information described in Section 4, the structure of the number and the structure of the installed capacity of Georgian HPPs on the Russian scale, are shown in Table 4:

Table 4. Structure of Georgian HPPs on the Russian scale of installed capacity of HPPs

№	HPPs type	N _{HPP, un.}	P _{ins} , MW	Weight, %
	Georgian HPPs, total	59	3 398.6	100.0%
1.	Micro HPPs	–	–	–
2.	Small HPPs from 1 to 5 MW	12	28.2	0.8%
3.	Small HPPs from 5 to 25 MW	20	242.2	7.1%
4.	Medium HPPs from 25 to 250 MW	26	1 828.2	53.8%
5.	Large HPPs	1	1 300.0	38.3%

Thus, according to the Russian scale of the installed capacity of HPPs, the basis of the Georgian power system is the medium HPPs in the amount of 26 HPPs with a total installed capacity of 1828.2 MW and which have a 53.8 % share in the structure of the installed capacity, and 1 large HPP – Inguri HPP with the installed capacity 1300 MW, which has a 38.3 % share in the structure of installed capacity. In total, **there are 27 medium and large HPPs in Georgia with the total installed capacity is 3128.2 MW and the share in the structure of the installed capacity is 92.1 %.**

Small generation facilities with an installed capacity ranging from 1 to 25 MW in total in Georgia account for **32 small HPPs with a total installed capacity of 270.4 MW, their share in the structure of the installed capacity is 7.9 %.**

For Russia, the share of small HPPs in the structure of the installed capacity of power plants of the United Power Systems of Russia (UPS of Russia) is typical for Interregional power system (IPS) IPS of the North-West and IPS of the South, their share also does not exceed 10 %. In the all UPS of Russia, the installed capacity of small HPPs is 1.2 GW (0.5 %).

From the point of view of the functioning efficiency of Georgian HPPs, sorted according to the Russian scale, it is advisable to consider the volume of their electricity generation and ICUF. Such data for 2020 are shown in Figure 4, 5 and in Table 5:

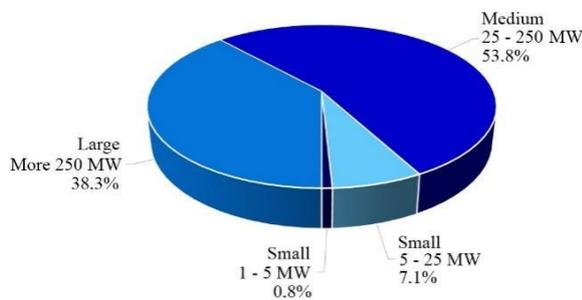


Figure 4 Share of HPPs by type in the structure of the installed capacity of Georgian HPPs on the Russian scale.

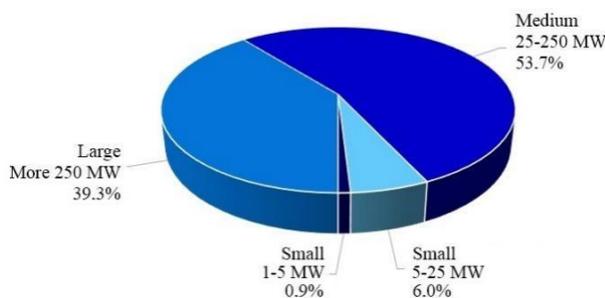


Figure 5 Shares of HPPs by type in the structure of the electricity generation of Georgian HPPs on the Russian scale.

Table 5. Performance indicators of Georgian HPPs according to the Russian scale of installed capacity of HPPs

No	HPPs type	P _{ins} , MW	W _{gen} , mln kWh	ICUF
	Georgian HPPs, total	3 398.6	8 819.8	29.81%
1.	Micro HPPs	–	–	–
2.	Small HPPs (1-5 MW)	28.2	83.5	30.65%
3.	Small HPPs (5-25 MW)	242.2	536.0	29.75%
4.	Medium HPPs (25-250 MW)	1 828.2	4 765.2	25.25%
5.	Large HPPs	1 300.0	3 490.9	30.65%

Thus, the structure of installed capacity and electricity generation of Georgian HPPs according to the Russian, scale of installed capacity are identical. Small generation facilities in Georgia account for up to 8% of the installed capacity and electricity generation.

With an insignificant share of small HPPs in Georgia, their number is significant – 32 units, and they are of great importance in the power supply of certain regions of the country. In the regions of Kvemo-Kartli and Racha-Lechkhumi, the share of small HPPs in the structure of installed capacity and electricity generation is 20 %, and in the regions of Kakheti and Guria – 70 % and 100%, respectively, Table 6:

Table 6. Performance indicators of Georgian small HPPs (1 – 25 MW) in regions

No	Regions	N _{SHPP} , un.	P _{ins} , MW	W _{gen} , mln kWh
	Georgian small HPPs, total	32	270.38	619.50
1.	Abkhazia	2	28.70	34.20
2.	Imereti*	–	–	–
3.	Mtskheta-Mtianeti	5	36.65	82.30
4.	Adjara	3	22.83	116.40
5.	Kvemo-Kartli	4	46.72	115.60
6.	Lechkhumi and Svaneti	4	34.33	32.00
7.	Samtskhe-Javakheti	2	23.10	97.70
8.	Kakheti	10	56.05	131.90
9.	Guria	2	22.00	9.40

*Only 9 medium HPPs operate in Imereti, their installed capacity is in the range of 26 ÷ 80 MW.

Taking into account the data in Tables 1–5, it can be seen that in terms of the composition of the installed capacity and electricity generation in 2 Georgian regions (Kakheti and Guria), small HPPs are the main sources of power supply, which in the case of Russia is fully consistent with the objectives of using small HPPs, which are set out in the Energy Development Strategy for the period up to 2035 [12].

In the case of Georgia, small HPPs quite successfully do the task of supplying electricity to consumers in remote and isolated territories, including in the rugged mountainous terrain of the South

Caucasus, which is a good and successful example of the use of small HPPs.

6. AGE STRUCTURE OF GEORGIAN HPPS

A total of 59 HPPs operate in Georgia, the oldest of which is the Zakhesi HPP with an installed capacity of 37 MW, which was put into operation in 1927. The newest HPPs in Georgia are Avani, Aragvi, Oro, Mestichala-1 and 2, with an installed capacity of 3.5; 8.5; 1.12; 20 and 30 MW, respectively, were commissioned in 2019.

An analysis of the time chronology and age structure of Georgian HPPs showed that in the period from 1927 to 1991, a total of 29 HPPs were commissioned with a total installed capacity of 2760.12 MW (80 % of the total capacity of HPPs). In the period from 1992 to 2003, there was no active construction of HPPs in the country, commissioning was not carried out. In the period from 2004 to 2019, active work is being carried out again on the construction and commissioning of HPPs. In total, during this period, 30 HPPs with a total installed capacity of 638.48 MW were commissioned.

It is important to note that the installed capacity of HPPs that were commissioned between 2004 and 2019 ranges from 1.12 to 178.72 MW. In total, during the same period, 6 medium and 24 small HPPs were built with a total installed capacity of 477.20 MW and 161.28 MW, respectively, an additional 10 out of 12 small HPPs with an installed capacity of 1 to 5 MW and a total installed capacity of 25.5 MW, are the newest and were introduced between 2016 and 2019.

Thus, in the period of Georgian recent history, since 2004, the country's leadership has been focused on developing the hydropower potential through the construction of mainly small HPPs. Additionally, during the research described in [5], it was found that in Georgia there are another 46 HPPs under construction with a total installed capacity of 2147 MW.

7. QUANTITY OF HYDRAULIC UNITS AT GEORGIAN HPPS

As noted in Section 3 (Table 1), 142 hydroelectric units with a total installed capacity of 3398.6 MW were installed at the technological sites of 59 Georgian HPPs. The analysis of the data [3, 4], [6–9] and [13–20] showed that the Georgian HPPs uses a scheme with an installation of 1 to 6 HU, the most common is a scheme with 2 HU. In this case, the scale of the number of all hydraulic units at the HPP sites is as follows, Table 7:

Table 7. Number and application of hydraulic units at the sites of Georgian HPPs

No	N _{HU} , un.	N _{HPP} , un.	Range P _{ins} HPP	Application
1.	1 HU	7	1.12÷2.50 MW	Small HPP only
2.	2 HU	33	2.00÷178.72 MW	Small and medium HPP
3.	3 HU	7	18.00÷220 MW	Small and medium HPP
4.	4 HU	7	19.60÷130 MW	Small and medium HPP
5.	5 HU	2	51.22÷1300 MW	Medium and large HPP
6.	6 HU	3	37.00÷47.48 MW	Medium HPP only

The least common scheme for the composition of HUs at Georgian HPPs is a scheme with the installation of 5 and 6 HU – only 2 and 3 HPPs, respectively. HPPs with 5 HUs: Kirnati (1941, 51.22 MW), Inguri (1978, 1300 MW) and HPP with 6 HUs: Zakhesi (1927, 37.00 MW) and Mtskheta (1938, 42.8 MW), are old (without taking into account the reconstruction), in the modern history of Georgia (since 1992), during the construction of a HPPs, such a scheme for installing a HU is not used. The exception is the Khelvachauri HPP (5×9.1 + 1×1.98 = 47.48 MW), which was commissioned in 2016.

The scheme with 4 HUs is conditionally outdated. All 7 HPPs, on which 4 HUs were installed, were put into operation in the period from 1933 to 1958: Sukhumi (1948, 19.6 MW), Dzevruli (1956, 80 MW), Rioni (1933, 48 MW), Gumati-1 (1958, 40 MW), Shaori (1955, 38 MW) and Khrami-1 (1947, 113 MW).

Thus, since 1992, Georgian HPPs have been used in a scheme with the installation of 1 to 3 HUs, while the unit capacity of one HU is in the range from 1.0 to 89.36 MW.

8. PARK OF HYDROELECTRIC UNITS OF GEORGIAN HPPS

In total, as of 01.11.2021, 142 hydroelectric units with a total installed capacity of 3398.6 MW operate at the sites of Georgian HPPs, their unit installed capacity ranges from 0.16 to 260 MW.

The most low-powered Georgian HUs with an installed capacity of 1.0 MW in the amount of 4 units installed at Khadori HPP-1 (Kakheti, 2004, 2×12.0 + 2×1.0 = 26.0 MW) and Nabeglavi HPP (Guria, 2017, 2×1.0 = 2.0 MW).

The largest HUs of Georgia in the amount of 5 units and with an installed capacity of 260 MW, installed at the Inguri HPP (Abkhazia, 1978, 5×260 = 1300 MW).

The all park of 142 GA of Georgian HPPs with an indication of their number and unit installed capacity is shown in Figure 6 and in Table 8:

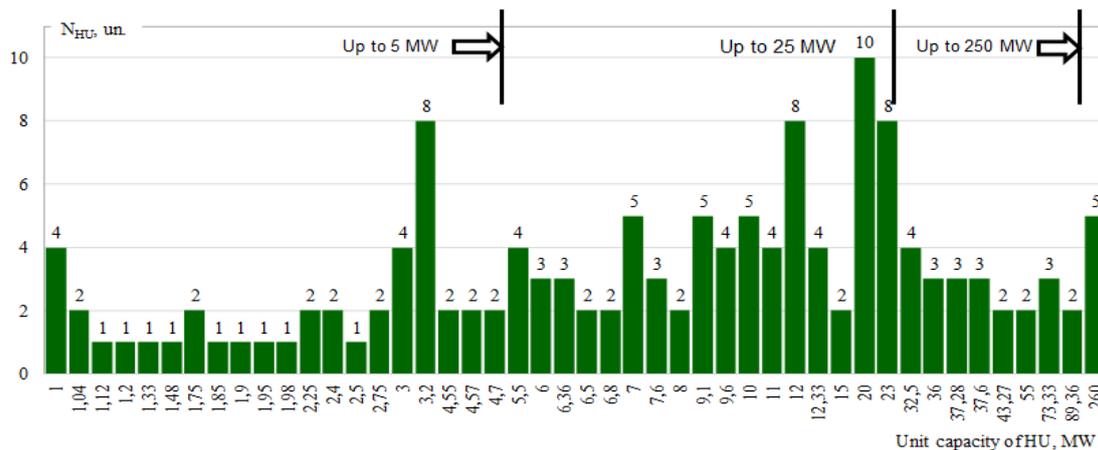


Figure 6 Park of hydroelectric units of Georgian HPPs as of 01.11.2021.

Table 8. Park of hydroelectric units of Georgian HPPs

N _o	Hydroelectric units range	N _{HU, un.}	P _{insΣ, MW}	Weight, %
	Total HU of Georgian HPPs	142	*3 398.6	100.0%
1.	HU from 1.0 to 4.99 MW	41	104.93	3.1%
2.	HU from 5.0 to 24.99 MW	74	*896.70	27.3%
3.	HU from 25.0 to 249.99 MW	22	1 057.89	31.3%
4.	HU more 250 MW	5	1 300.00	38.3%

*For the 3rd SHPPs with the 5th HUs, the installed capacity of the HU is not determined

The basis of the HU park in Georgia of number is made up of small HUs with a unit installed capacity of up to 25 MW – 115 HUs (81 %), their total installed capacity is 1001.63 MW (29.5 %). The distribution of HUs by capacity looks quite uniform – 31 % are medium power HUs (22 units) and 38.3% are large HU (key Inguri HPP with generators 5×260 = 1300 MW).

9. PROSPECTS FOR DEVELOPMENT OF GEORGIAN HPPS

According to [4], as of 01.01.2017, the installed capacity of all HPPs in Georgia was 3160 MW, the hydropower potential was developed by 20 %. Full hydropower potential of Georgia is 15555 MW. At the same time, 3421 MW of the HPPs installed capacity will be put into operation until 2027. The next 8974 MW of HPP potential will be developed in the period from 2027 to 2050.

During the research described in [5], it was found that among the additional 46 HPPs under construction with a total installed capacity of 2147 MW – 23 HPPs are medium HPPs with an installed capacity in the range of 30 ÷ 280 MW, their total installed capacity is 1851 MW. 23 HPPs are small with a capacity in the range of 2–24 MW and a total installed capacity of 296 MW. At the end of the construction of HPPs until 2027, **105 HPPs with a total installed capacity of 5545.6 MW will operate in the Georgian power system.**

10. CONCLUSION

1. One of the main technological features of the Georgian power system is large number of medium and small HPPs, which provide more than 50 % of the country's electricity generation. The experience of Georgia is interesting for the development of hydropower resources in the world power systems.

2. As of 01.06.2021, 53 power plants of three types (WPP, HPPs, TPPs) operated within the Georgian power system, their total installed capacity was 20 MW, 3282 MW and 1190 MW, respectively.

3. As of 01.11.2021, there are **59 HPPs** with a total installed capacity of **3398.6 MW** in the Georgian power system, with a total of **142 hydroelectric units** located at their platforms.

4. Out of 59 HPPs in Georgia: 1 is large (Inguri HPP), 26 HPPs are medium and have installed capacity ranging from 26 to 220 MW and 32 HPPs are small with an installed capacity ranging from 1.12 to 21 MW.

5. In the Georgian power system, 1 most powerful Inguri HPP with installed capacity of 1300 MW accounts for 38.3 % of the total installed capacity of HPPs, medium HPPs account for 1828.2 MW (53.8 %) and small HPPs – 270.4 MW (7.9 %).

6. With the electricity generation at HPPs in 2020 in the amount of ~8.8 billion kWh, one of the most powerful Inguri HPPs provided electricity generation in the amount of 3.5 billion kWh (39 %), medium HPPs produced 4.8 billion kWh (54 %) and small HPPs – 0.6 billion kWh (7 %).

7. In 2 regions of Georgia (Kakheti and Guria), 12 small HPPs with a total installed capacity of 78 MW provide the generation of 140 million kWh per year with ICF of 20 % and have a decisive importance for power supply to consumers, since provide up to 100 % of the region's electricity generation needs.

8. At the Georgian HPPs, a scheme is used with the installation of 1 to 6 hydroelectric units. Since 2004, only medium and small HPPs have been

built in Georgia, from 1 to 3 hydroelectric units with a unit installed capacity ranging from 1 to 89.36 MW are installed on their platforms.

9. The largest HPPs in Georgia – Inguri HPP (1978) with an installed capacity of 1300 MW installed the most powerful hydroelectric units in Georgia with a unit installed capacity of 260 MW in the amount of 5 units, they account for 38.3 % of the total installed capacity of hydroelectric units of Georgian HPPs.

10. As part of 142 hydroelectric units of Georgian HPPs, the most part of the park is made up of hydraulic units with a unit installed capacity of 1 to 25 MW – 115 units with a total capacity of 1001.63 MW (28.5 %). Also installed 22 hydroelectric units with a unit installed capacity of 25 to 250 MW, their total installed capacity is 1057.89 MW (31.3 %).

11. As of 01.01.2021, an additional 46 new HPPs with a total installed capacity of 2147 MW were under construction in Georgia. Among them, 23 HPPs are medium with a total installed capacity of 1851 MW. Another 23 HPPs are small, with a total installed capacity of 296 MW. For the period up to 2027, more than 50 new medium and small HPPs will be commissioning in Georgia, by 2027 the total capacity of all Georgian HPPs should be 6419 MW.

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