Possibilities for increasing energy and hydraulic efficiency in water supply systems

Aram Sahakyan[1*]

[1]National University of Architecture and Construction of Armenia, Yerevan, Armenia

Abstract. The article touches upon modern approaches to increasing the efficiency of water supply systems intended for drinking and economic needs. In particular, the problem of the possibility of converting the available hydraulic energy into electrical energy on the drinking water gravity aqueducts without disturbing the hydraulic regime of the system is observed. The presented example of the proposal introduction entailed the energy-economic indicators in the water supply systems of Yerevan, the Republic of Armenia. According to calculations, the amount of electricity produced by the proposed small hydropower plants (SHPP) on the aqueducts feeding Yerevan City can be at least 105 million kW per year, which exceeds the amount of electricity currently consumed in the water supply system for more than 3 times. In order to increase the energy and hydraulic efficiency of water supply systems, it has also been proposed to establish an appropriate performance indicator, the application of which will create an obligation for water supply organizations to make investments in the indicated area. The energy efficiency and loss reduction alternatives analyzed in the work can serve as an opportunity for decreasing the dependence of water supply systems on external energy sources and reducing operating costs.

1 Introduction

Currently, one of the most important prerequisites for the development of the world economy is the production and thrift of the required amount of electricity. Since 1971, global energy use has increased more than twice and energy carrier systems have used nearly half of all global energy. Traditional sources of primary energy resources continue to prevail, despite having limited reserves and being non-renewable. Recently, electricity generation sources have undergone significant changes. Currently, compared to 1990, the share of nuclear power in electricity production in the world has decreased by about 2 percentage points, while the share of hydropower has decreased from 18% to 16%. The share of oil has decreased significantly (from 10% to 5%), but the shares of gas (from 15% to 20%) and coal (from 37% to 41%) have increased. In developing countries, the share of nuclear power has also decreased in recent years (from 7% to 5%). It is also noteworthy that in relatively developing countries of the world, the share of nuclear power in the structure of electricity production is 3 times lower. During the last 40 years, the share of coal in the sources of electricity production in the world has increased by 4 percentage points (from 37% to 41%), but in

* Corresponding author: sahakyan.aram@nuaca.am

developing countries this amount has been 12% (from 34% to 46%), i.e. compared to the rest of the world, this indicator has grown 3 times faster in developing countries (Figure 1).

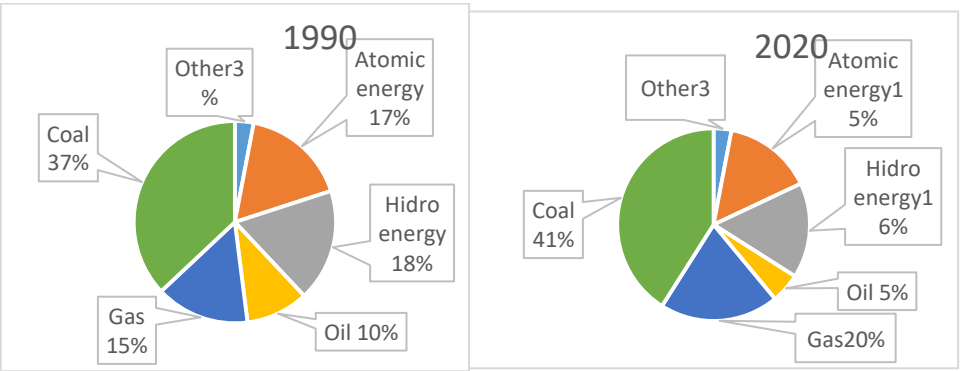

Fig. 1. Changes in power generation sources

In this regard, taking into account the growth of the population, the continuous increase in the power supply capacity of the household and industry, the further quantitative development of energy on the basis of traditional raw materials is not expedient.

Water pumping in WSSs and the other inter-relations between water and energy (i.e. hydroelectric and thermoelectric generation, fuel and biofuel production, water supply, pumping and water treatment, desalination) will intensify if predictions regarding global climate change are confirmed. In this sense, while the production and use of energy from fossil fuels is considered the main cause of global warming, the most drastic consequences of climate change, such as floods, storms, droughts, and water-borne diseases, have been attributed to water. Such states, considering the crucial links between water and energy during water planning and policy making, can lead to significant energy savings [1]. Involvement of renewable energy resources in the energy balance becomes the imperative of the time, both from the point of view of sustainable development and environment. Inturn, these savings have the potential to reduce the associated CO_2 emissions. The availability of drinking water in the near future will also require adaptations in several regions of the world in response to changes in precipitation and run off patterns, salinization and alterations in water source quality as a result of climate variability [2].

2–3% of the worldwide electricity consumption is used for pumping in water supply systems (WSSs) [3], while 80–90% of this consumption is absorbed by motor-pump sets [4]. Pumps are an important component of distribution networks and improving their operation has a major role in increasing the efficiency of the networks in terms of the defined water supply schedules, as well as the provision and reliability of electricity consumption. 30% of the energy consumed by hydraulic pumps can be avoided through the use of better designs and the selection of appropriate equipment [5]. As a source of renewable electricity, the article proposes to consider the installation of small hydropower plants (SHPP) on the sections of the water supply network and water systems intended for drinking and economic needs, where there are local hydraulic resistances, partially open valves or pressure regulating devices, as well as excess pressures. The simultaneous use of the above-mentioned systems for the purpose of electricity production and water supply is economically beneficial and serves as an example of the full use of water resources. In order to increase the energy and hydraulic efficiency of the system, it is also proposed to establish appropriate performance indicators, the application of which will create an obligation for water supply organizations and/or state institutions to make investments in the indicated area.

2 Main part

The hydropower potential of the water supply system has been known for a long time, but it has not yet been sufficiently explored worldwide. The use of small power turbines for energy production has been presented in one of our works quite substantively [6]. As a source of renewable electricity, the article proposes to consider the installation of small hydropower plants (SHPP) on the sections of the water supply network and water systems intended for drinking and economic needs, where there are local hydraulic resistances, partially open valves or pressure regulating devices. The purpose of the application of the proposal is to transform the hydraulic energy dissipated in the artificially created local resistance loop into electricity, without disturbing the hydraulic regimes of the normal operation of the aqueduct in any way. The application of the proposal is economically beneficial and serves as an example of the full use of water resources.

In addition to generating electricity, turbines have the ability to perform a pressure control function by replacing pressure reducing valves (PRV), which are important tools in water loss/leakage management [7,8]. Effective pressure management in water supply systems is almost always a crucial water loss management strategy [9]. By reducing the system pressure, it is possible to reduce the leakage volumes [10]. Studies show that pressure reducing valves (PRV) are used for both pressure control and leakage reduction purposes [11]. The optimal positioning and quantification of PRVs can be accomplished by hydraulic simulation in association with the use of optimization techniques, such as genetic algorithms [12,13]. Evaluated predictive pressure control strategies based on demand prediction, hydraulic modeling/simulation and a feedback strategy in which the system pressure is adjusted against an optimal pressure-flow curve for the control area, which is based on continuous pressure measurements. Competent performance of pressure management works can result in a 50% reduction in the volume of water entering the system [14]. The main advantages of hydropower recovery are the reduction of dependence on external energy sources and the reduction of operating costs in water supply systems [15].

In order to fully present the problem, we studied the water supply system of Yerevan, the capital of the Republic of Armenia. The water supply of Yerevan is carried out from 10 springs, including 3 - gravity (Tsaravaghbyur, Dzoraghbyur and Yerevan HPP), 2 - pumping (Araratyan 3,4 and Shor-Shor) and 5 mixed - pumping and gravity (Garni, Arzni, Aparan, Katnaghbyur, Arzakan-Gyumush) springs.

The water flow in the water system is measured at the source and at points entering the city. Measurements are also made at the demarcation points of aqueducts and village feeding networks. The change dynamics in the volumes of water reaching Yerevan City and villages over the last nine years are presented in Table 1.

Analyzing the data presented in the table, we can state that the annual loss of up to 24.5 million m^3 in aqueducts has been reduced almost 3.4 times over the course of 9 years. Losses in aqueducts were reduced mainly as a result of the following functions:

- Reduction of excess pressures;
- Decommission of aqueducts in emergency condition;
- Detection and elimination of hidden emergencies on pipelines;
- Disconnection of illegal connections;
- Dismantling of installed washer flowmeters (the installed washer flowmeters caused local resistances, excess pressures and reduction of aqueduct capacity).

Table 1. Volumes of Water Reaching Settlements (2011-2019)

Year	Production (million m^3)	Amount of Water Reaching Settlements (million m^3)	Losses in the Water System	
			(million m^3)	%
2011	367.68	347.10	20.6	5.6
2012	371.78	347.20	24.5	6.6
2013	370.11	349.75	20.3	5.5
2014	355.41	335.90	19.5	5.5
2015	334.69	317.95	16.7	5.0
2016	312.72	302.71	10.0	3.2
2017	300.50	290.88	9.6	3.2
2018	290.20	281.20	9.0	3.1
2019	275.20	268.00	7.2	2.6

As a result of the implemented measures, the loss of 24.5 million m^3/year in aqueducts was reduced by 17.3 million m^3/year.

As a result of the zoning of the water supply network, the volume of water supplied to settlements decreased by almost 82 million m^3/year, amounting to 268.0 million m^3/year (see Table 1), as a result of which the saved water volume was not only directed to the improvement of water supply, but also contributed to the reduction of water production [15].

In order to increase the efficiency of water production and the controllability of water intake, we set the objective of increasing the amount of water received from sources on high elevations as much as possible. In the Arzakan-Gyumush and Arzni springs, water from the springs below the aquifer level was pumped into the existing aqueducts through small head pumps. As a result, the amount of water supplied to the city by gravity increased with a small cost of electricity. Instead, the amount of water pumped to the city through energy-consuming pumping stations was reduced (Table 2).

Table 2. Amounts of Water Taken from Springs (million m^3/year)

№	Spring	2011		2012	2013	2014	2015	2016	2017	2018	2019
1	Araratyan 3	50.2		50.2	50.8	47.2	25.8	13.0	11.2	16.2	11.2
	Araratyan 4	47.4		42.0	43.5	34.6	30.0	9.4	8.2	4.2	3.2
2	Garni	46.5		45.2	43.8	44.4	46.5	46.7	47.2	46.3	41.6
3	Shor-Shor	11.2		14.8	13.3	12.8	12.4	5.2	3.8	1.2	0.9
4	Aparan	31.5		32.0	37.7	35.5	35.5	37.7	36.7	36.2	31.1
5	Katnaghbyur	75.4		76.8	74.2	73.4	73.9	77.4	79.4	78.1	75.6
6	Yerevan HPP	2.7		2.9	2.9	1.1	0.9	0.2.	0.2	0.2	0.2
7	Dzoraghbyur	7.6		7.6	7.6	9.3	9.3	8.5	8.8	7.3	6.3
8	Tsaravaghbyur	8.4		8.3	8.5	8.0	7.9	7.9	10.1	6.1	4.2
9	Arzni	40.3		40.7	40.7	40.9	40.7	44.8	48.9	49.3	49.6
10	Arzakan-Gyumush	46.9		50.9	50.7	48.8	51.3	62.5	55.9	55.1	51.3
Total		367.7		371.8	370.2	355.5	334.7	312.8	300.5	290.1	275.2
Gravity		million m^3	224.0	232.8	226.8	246.9	230.4	239.0	225.0	219.0	216.7
		%	60.9	62.6	61.3	69.5	68.8	76.5	75.4	75.5	78.7

Pumped	million m^3	143.8	139.2	143.4	108.6	104.4	73.7	72.7	71.2	58.5
	%	39.2	37.4	38.7	30.5	31.2	23.5	24.6	24.5	21.3

From the presented data, it can be seen that due to the mentioned measures, the volumes of water taken from the springs of Arzni (40 million m^3/year) and Arzakan-Gyumush (75 million m^3/year) increased by an average of 9 million m^3/year and 8 million m^3/year, respectively.

In order to transport the increased outputs from the springs located on high elevations, it became necessary to create a flexible system of aqueducts, which allowed the water from high-altitude springs with a relatively low prime cost to be transported to the low-lying districts of the city, which until then were fed by Soviet-production pumps from Ararat deep wells and Shor-Shor springs with a capacity of up to 2,500 kW and low energy conversion efficiency.

In order to ensure the water supply of Yerevan, in the past, during the engagement of new springs, the spring elevations were disregarded. Currently, for the purpose of energy saving, a redistribution of the feeding zones of the springs has been carried out, expanding the areas with gravity feeding.

Using the existing water system, water supply network and daily regulating reservoirs with small investments, the mentioned redistributions were carried out and as a result it was possible to reduce the outputs produced in Araratyan 3, 4 and Shor-Shor springs to a minimum and save a large amount of electricity (see Table 2).

In the reconstructed, mainly gravity-driven system, favourable conditions have been created for the installation of hydro turbines on aqueducts with a large difference in elevations.

In addition, there are also about 300 loops of artificially created local resistance in the water supply system of the city, the use of which is completely justified to obtain electricity, so favourable conditions are created here for the energy potential of water current to be used for complex purposes. In this case, it is proposed to replace the existing regulating device on the aqueduct with a hydro turbine with the same hydraulic resistance, which automatically adjusts the output of consumption released by the aqueduct through the correction device.

The present article only considers the possibilities of energy conversion on aqueducts with a large difference in elevations by installing hydro turbines.

3 Results and discussion

Table 3 below shows the characteristics of the 5 gravity aqueducts feeding the city's water supply network.

Table 3. Characteristics of the 5 gravity aqueducts feeding the city's water supply network.

Spring Name	**Spring Elevation**	**The Average Spring Elevation (m^3/s)**	**The Average Elevation of the Feeding Area**	**Elevation Difference (m)**	**Produced Electricity (1000kW/h)**
Arzakan	1432	1.6	1232	200	3.1
Aparan	1884	1.0	1200	684	6.7

Arzni	1268	1.6	1150	118	1.9
Katnaghbyur	1440	2.4	1350	90	2.1
Garni	1242	1.3	1150	92	1.2
				Total	15.0

4 Parameters of Gravity Aqueducts

From the data in the table, it can be seen that the gravity system of the city has a high power potential, the value of which is calculated through expression (1). According to the data, the calculated capacity of the SHPP will be:

$$N = \rho g Q H = 15000\ kWh: \qquad (1)$$

The energy indicators of the SHPP are calculated through expressions (4), where the following average magnitudes of energy conversion efficiency were adopted for the hydro turbine unit: $\eta_1 = 0.86$ and $\eta_2 = 0.94$. The power will be:

$$N_m = \eta_m N = 0{,}86.15000 \approx 12900\ kW, \qquad (2)$$

In the calculation, the pressure losses occurring in the aqueducts are disregarded, but according to our studies, their value is not high, because the norms of water use during the design and construction of the city's water supply network were chosen to be excessively large (sometimes up to 600 l/day per person). In addition, the city was considered an industrial centre (currently, large factories are almost non-operating), so the choice of diameters of aqueducts is made with a rather large reserve.

Based on the above-mentioned, it can be concluded that in case of increasing the energy efficiency of the water supply system of Yerevan City, it is possible to produce more than 105 million kW of electricity annually.

In the course of the present studies, the cost of water production and yard pumping stations of Yerevan City over the last three years was also studied, the values of which are presented in Figures 2 and 3.

According to the given data, in 2022, the electricity spent on water production amounts to nearly 26 million kW, and in yard pumping stations - nearly 6 million kW.

As the following calculations show, the total amount of electricity consumed by water production and yard pumping stations in the studied system is more than three times less than the amount of energy produced in the case of increasing the energy efficiency of the water supply system.

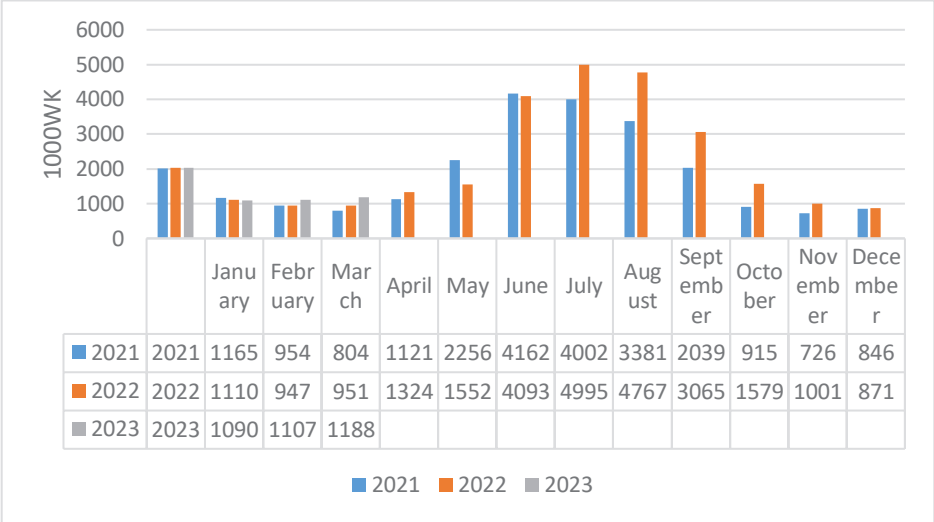

Fig. 2. Electicity Consumed by Water Production Pumping Ststions in Yerevan City

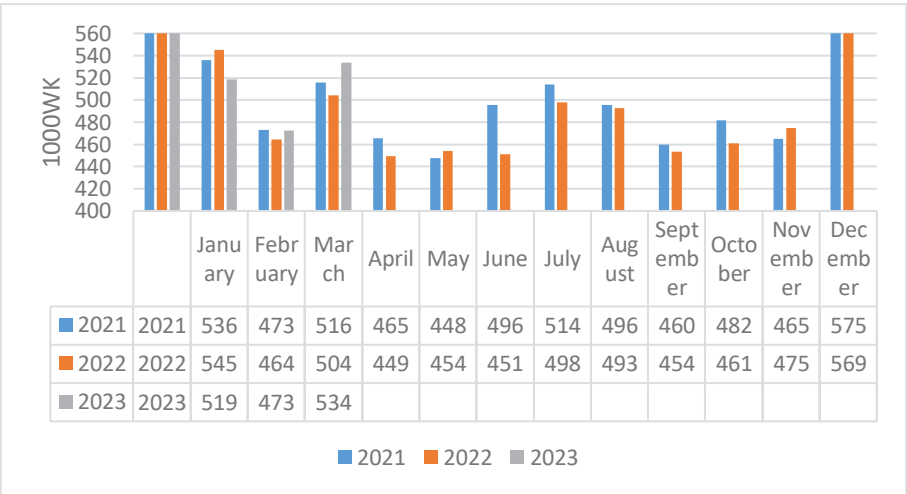

Fig. 3. Yard Pumps of Yerevan City (without Kharberd Pumping Station)

5 The Increase of Energy and Hydraulic Efficiency as a Definition of Performance Indicator

In order to evaluate the efficiency of the work of water supply organisations, performance indicators are generally defined, the provision of which is considered one of the main objectives of the organisation. The defined indicators are monitored by an independent technical auditor, an internationally recognized, reputable organisation, the duties of which entail:

- Examination of reports;
- Implementation of annual audit of technical management, operation and maintenance;
- Calculation of annual penal damages to be paid;
- Final state verification and approval.

In order to increase the energy and hydraulic efficiency of the system, it is proposed that the body controlling the functions of water supply organisations establish an appropriate performance indicator, the application of which will create an obligation to make investments in the indicated area. We recommend calculating the performance indicator through the simple expression (3) presented below:

$$P = \frac{\sum N_c}{\sum N_p} \qquad (3)$$

where

P is the coefficient characterising the efficiency indicator,

N_c is the amount of electricity consumed in the system,

N_p is the volume of alternative electricity produced in the system.

The amount of penalty is determined by the simple expression (3) below and denoted by F:

$$F = P \cdot L \cdot Revenu \qquad (4)$$

The factor L, referred to as the penalty coefficient, is determined by the regulatory body responsible for overseeing the functions of the water supply organization, typically the state authority. The values of P and L are set based on local conditions and the desired outcome target. In the formula, the variable F represents the penalty amount, which is correlated with the annual income of the establishment. The objective of the proposal is to establish a linear relationship between damages and annual income. This approach aims to mitigate the risk of contractual obligations not being fulfilled.

In case of application of the proposal, the water supply organisations will have contractual obligations to make appropriate investments aimed at increasing the energy efficiency of the system. In addition to the environmental and financial components, the proposal also has a social impact, as the volumes of electricity consumed in the system and the tariff are essential in the pricing of water supply services.

6 Conclusion

Based on the approaches presented in the article, it can be confirmed that the involvement of renewable energy resources in the energy balance becomes the imperative of the time. In this context, it is necessary to introduce an appropriate toolkit aimed at increasing the energy and hydraulic efficiency of water supply systems, which can be the actions listed below:

1. Effective management of excess pressure in water supply systems is almost always a crucial water loss management strategy.
2. Due to the relief peculiarities of the settlement, for the purpose of pressure management by the water supply organisation in the water supply network and water system intended for drinking and economic needs, local resistance creation measures are repeatedly applied using partially open valves or pressure regulating devices. Furnishing the indicated loops with a hydro turbine with automatic operation by means of a specially designed correcting device with the same hydraulic resistance will allow the mechanical energy dissipated during the artificially created local resistance to be converted into electricity production.
3. In order to increase the energy and hydraulic efficiency of water supply systems, reduce the system's dependence on external energy sources, decrease operating costs, as well as mitigate the tariff of the provided services, it is necessary to create a “fertile soil” for the development of alternative electricity production in gravity water supply systems.

References

1. E. Shrestha, S. Ahmadn, W. Johnson, J.R. Batista, Energy Policy **42**, 201–12 (2012)
2. B.C. Bates, Z.W. Kundzewicz, S. Wu, J.P. Palutikof, Climate change and water: technical paper of the Intergovernmental Panel on Climate Change. (Geneva, IPCC Secretariat, 2008)
3. Alliance to Save Energy. 2002. Water and energy: Harnessing the opportunities for unexplored water and energy efficiency in municipal water systems. (Washington, Alliance; 2002) [in Portugese].
4. M. Brandt, R. Middleton, G. Wheale, F. Schulting, Water Pract Technol **6(2)**, (2011) http://dx. doi.org/10.2166/wpt.2011.028.
5. I. Cardenes, A. Siddiqi, Mohammad Mortazavi M.N., Jim W. Hall, IWA Publishing **82(12)**, 2745-2760 (2020) https://doi.org/10.2166/wst.2020.507
6. A. Sahakyan, E. Gennady, Journal of Architectural and Engineering Research **2**, 75-82 (2022) https://doi.org/10.54338/27382656-2022.2-011
7. J.S. Ramos, H.M. Ramos, Energy Policy **37(2)**, 633–43 (2009)
8. N. Fontana, M. Giugni, D. Portolano, J Water Resour Plan Manag **138(3)**, 237–44 (2012)
9. A. Sahakyan, Journal of Architectural and Engineering Research **4**, 24-31 (2023) https://doi.org/10.54338/27382656-2023.4-002
10. M. Nicolini, C. Giacomello, K. Deb, J Water Resour Plan Manag **137(1)**, 134–42 (2011)
11. A. Sahakyan, Journal of Architectural and Engineering Research **3**, 78-84 (2022) https://doi.org/10.54338/27382656-2022.3-009
12. L.S. Araujo, H. Ramos, S.T. Coelho, Water Resour Manag **20(1)**, 133–49 (2006)
13. M. Nicolini, L. Zovatto, J Water Resour Plan Manag **135(3)**, 178–87 (2009)
14. B. Ulanicki, P.L.M. Bounds, J.P. Rance, L. Reynolds, Urban Water **2(2)**, 105–14 (2000)
15. F. Vieira, H.M. Ramos, Energy Policy **36(11)**, 4141–8 (2008)