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Small Hydropower Plant for Sustainable Electricity from RES Mix

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Abstract: In the context of the need for an increasing share of renewables in electricity mixes, the paper presents the existing RES mix, PV and wind, for partially covering the electricity consumption of a research institute, ICSTM, and proposes a solution for completion with a third form of RES, a small hydropower plant. Moreover, it is envisaged to include the proposed small hydropower plant as a new real-scale laboratory attached to ICSTM. The method includes the presentation of an existing proposal for increasing installed capacity in new PV panels and propose to install an SHPP to a weir situated a few hundred meters from the institute. The hydropower potential for two possible arrangements is assessed and some types of turbines suitable for this location are presented. The main results demonstrate that building an SHPP is a better solution for completion of PV and wind as source of electricity for ICSTM. The main conclusion of the paper is that by installing new RES capacities, ICSTM can build a real-scale laboratory for new technologies, at the same time fully covering its own electricity consumption and even supplying a green electricity mix into the national power system.

Keywords: RES; electricity independence; wind energy; PV; small hydropower; hidden hydro

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1. Introduction

There are some decades since mankind started to turn from coal and nuclear to renewable energy sources (RES), alarmed by climate change because of those technologies greenhouse gas (GHG) emissions. Starting from this, the EU elaborated the Renewable Energy Directive for the development of RES across all sectors of the EU's economy [1]. Meanwhile, all over the globe, almost all countries set up very ambitious goals related to increase the share of RES within their energy consumption mix [2,3]. At a smaller scale than a country, many authors approached isolated grids [4] or small island states [5]. In parallel, many approaches and informatic tools were imagined and realized: for assessing RES [6], for the evaluation of the optimal RES share [7], strategies for increasing the sustainability of existing objectives [8], or modern metaheuristic algorithms to determine optimal allocation of hybrid RES system [9]. Some papers underline the importance of a sustainable renewable energy mix, including wind and photovoltaic (PV) energy but also hydropower [3,10].

On the contrary, some authors raise doubts that some RES, such as PV [11], or even RES are so beneficial for human beings or for the environment [12].

The smallest scale, but also the most tangible, is that of buildings, in terms of the simulation and optimization of passive building design [13], the research and development of passive buildings [14], and the assessment of efficient energy technologies [15].

University Valahia of Târgoviște (UVT) is a state university, founded in 1992 in Târgoviște, formed by 8 faculties, granting bachelor's degree (3 or 4 years), 31 high education specializations, MSc and PhD studies, teacher pre-service, an in-service training sector, and a distance learning department [16].

The Multidisciplinary Scientific and Technologic Research Institute (ICSTM) of UVT is a professional and independent organization, legally dependent on UVT, created to attend the university personnel and the other specialized collaborators of the university in realizing experimental research with students and research projects financed by national and international programs and through contracts with other companies [17].

The priority research fields of ICSTM are the following: renewable energy sources (RES) and electric systems; the environment and physicochemical processes; nanomaterials and micromechanics; mechanical engineering and materials science; biotechnologies and biotechniques; theology; social, political, and communication sciences; and economical sciences. The Institute has the latest IT systems and software for designing and modeling in specific engineering research areas. Among the most representative experimental stands of ICSTM laboratories must be mentioned the PV and the wind power experimental platforms, the thermo-solar platform, a system for developing and prototyping PV modules, an inductively coupled plasma mass spectrometer (ICP-MS), electric vacuum deposition and dielectric layers by sputtering, a scanning electron microscope (SEM), a facility for processing micromaterials and microchannels with a focused ion beam (FIB), an atomic force microscope (AFM), laser ablation, and a nano indenter. In the ICSTM research laboratories, structural analysis, qualitative and quantitative analysis, morphological and structural determinations, atomic force microscopy (2D and 3D topography, phase contrast, adhesion forces, etc.), electrical characterizations, prototyping, and design can be realized.

Related to the first listed priority, RES systems, the ICSTM has at his disposal PV panels mounted on the roof, on the southeast side, and a fixed tracker and different types of wind turbines with vertical and horizontal axis. These are used for demonstration RES laboratories for students but also for partially cover the ICSMT's own electricity consumption.

The paper presents the existing RES mix, PV and wind, for partially cover electricity consumption of ICSTM and propose a solution for completion with a third form of RES, a small hydropower plant. There are considerations for including the proposed small hydropower plant (SHPP) as a new laboratory attached to the ICSTM related to the possibility that the ICSTM fully covers its own electricity consumption or even supplies a green electricity mix into the national power system (NPS). Thus, Section 2 briefly presents the ICSTM, underlining the short distance from a weir on Ialomița River; the present PV and wind experimental platforms; a previously proposed alternative for increasing electricity production by installing new PV panels; and the proposal to build an SHPP on the existing weir, the arrangements, and the possible turbines. Section 3 assess in a simple manner the hydropower potential for the two arrangements related to the weir and presents characteristics of some turbines that can be used. Section 4 presents some considerations related to the realization of the SHPP and in Section 5 conclusions are stated.

2. Materials and Methods

The ICSTM research institute is located on the UVT campus, at about 300 m in a straight line to the Ialomița river, 500 m to the weir axis, and 350 m to the last step of energy dissipator, there where it can be envisaged to install an SHPP, Figure 1.

ICSTM is part of UVT, the building covers an area of 2240 m^2, has a total built area of 7250 m^2, and houses 40 laboratories, 6 functional annexes, 7 administrative spaces, and 4 communication spaces, with installations and equipment used for research [18].

A detailed description of facilities related to RES real scale laboratories, namely, PV platform and wind platform, being at the same time sources of electricity for ICSTM's own consumption is presented by Nedelcu et al. [18]; here, we will just shortly review these sources of energy from RES. It is to be mentioned that these sources partially cover the ICSTM's own consumption, the difference being supplied from the National Power System (NPS), and that one PV installation supplies electricity to the NPS.

Figure 1. Proposed area for development, with a weir on river Ialomița (on the left-hand side, A, B) and ICSTM (on the top-right-hand side) (figure capture from Google Earth).

RES facilities related to electricity production consist of a PV platform covering a surface larger than 250 m^2 and an installed capacity of about 80 kWp and a wind platform with an installed capacity of about 25 kWp.

The PV experimental platform consists of the following:

- OnGrid installation, located on ICSTM's roof, three types of PV panels oriented south and an inclination of 45°; the installed capacity is 33.15 kWp, Figure 2a;
- OffGrid installation, located on ICSTM's roof, two types of PV panels oriented south and an inclination of 30°; inverters and 100 batteries; the installed capacity is 42.5 kWp, Figure 2b;
- OffGrid installation of parasolar type; the installed capacity is 250 W, Figure 3;
- OffGrid installation of curtain type; the installed capacity is 8 kWp; 7 inverters of Victron Multiplus 5 kW, 2 inverters of Victron Multiplus 3 kW, and 100 VRLA Gel Deep Cycle 220 Ah and Victron VRLA Deep Cycle 220 Ah batteries, Figure 3;
- Fixed Tracker with two axes; the 25 m^2 surface consists of 15 PV panels and 2 SMA SunnyBoy 2 kW inverters; the installed capacity is 4 kWp, Figure 3.

The wind experimental platform consists of turbines with vertical or horizontal axis, the OnGrid installation, the MagLev installation, and the SmallWind installation as follows:

- A 20 kWp OnGrid installation on the ground formed by one Aeolos HAWT wind turbine with 10 kW installed capacity, horizontal axis, and a 24 m monopole; one Aeolos VAWT wind turbine with 10 kW installed capacity and vertical axis, 260 rpm, and an 18 m monopole; two ABB Wind inverters of 15 kW;
- A 3 kWp MagLev installation, vertical axis, located on ICSTM's roof;
- A 2 kWp SmallWind installation formed by one Aeolos HAWT wind turbine, 1 kW installed capacity, horizontal axis, and one Aeolos HAWT wind turbine with 1 kW installed capacity, vertical axis.

(a) (b)

Figure 2. (**a**) OnGrid installation, located on ICSTM's roof, three types of PV panels and (**b**) OffGrid installation, located on ICSTM's roof, two types of PV panels.

Figure 3. OffGrid installation of the parasolar type, located on ICSTM's roof, three types of PV panels ("cortina" means curtain in Romanian).

For one year, the electricity generation of the PV platform was 112.4 MWh and of the wind platform 21.6 MWh, totalizing 134 MWh. For the same year, electricity consumption from NPS was 240 MWh. In this paper, we consider that this is the value, 240 MWh, for the electricity to be covered by new facilities from RES for ICSTM to become independent from the NPS or even a prosumer.

The same paper by Nedelcu et al. [18] presents a proposal to supplement the present installed capacity in facilities for producing electricity from RES to fully cover the ICSTM's own electricity consumption. Considering the further development of the institute and failure of some sources, the authors proposed a surplus of 40%, increasing the annual electricity generation from RES to about 698 MWh/year. The authors proposed as solution to install 10 systems of concentrating PV panels, tracker type, with two axes of 12 kWp each, so a total installed capacity of 120 kW. The new PV panels are to be located on same line with the existing tracker, four on the right of the alley and the other six on the left of the alley, parallel with the ICSTM building. To ensure the storage of electricity generation by the 10 trackers, the authors propose to install 4 modules of 40 batteries with a total capacity of 124.8 kW.

In this paper, we propose as an alternative to this new 120 kW PV farm an SHPP located on the weir. Among the reasons to propose an SHPP instead of the new PV panels are the following:

- PV panels to supply electricity to ICSTM need batteries for electricity storage, which decrease the sustainability of the chosen solution;
- The proposed SHPP can be dimensioned at an installed flow near the value of the mean flow, which will ensure more than 4500 h/year;
- The turbine proposed to be installed in the SHPP can be chosen to function at a satisfactory efficiency for large range of flows; this will increase the annual operating time even more;
- The SHPP will constitute a new real-scale laboratory for UVT students, where so far there are no such facilities.

There are two locations that will be considered for the proposed SHPP:

1. A turbine installed in the section of the weir, arrangement between sections A and B, with turbines such as Voith Stream Diver (Koessler), WWS PowerGate (WWS Wasserkraft), Archimedean screw (as pump and as turbine, considering the demonstration possibilities for students and stakeholders), VLH (Very Low Head), and Archimedean Screw turbine;
2. The powerhouse to be built close to the last step of the weir energy dissipator and with the evacuation of water from the turbine/s in this river section, arrangement between sections A and C, equipped with turbines such as Kaplan, Propeller, Crossflow (Banki), and Turbinator (CleanPower). In this arrangement, even the use of a pump as turbine (PAT) can be investigated.

Related to the first arrangement, a previous paper proposed solutions for empowering the "Lacul Morii" dam, on the river Dambovita, for using servitude flow and avoiding energy waste [19]. As it can be easily observed, there is a wide range of possibilities that can be considered for an SHPP to be realized close to ICSTM to fully cover its own electricity consumption and even become an electricity producer, at the same time using it as real-scale laboratory and demonstration site for students and stakeholders. The fact that the SHPP will be built on an existing hydrotechnical infrastructure (weir and its energy dissipator) prove the concept of hidden hydro very well and represents an example of how small hydropower must be further developed.

3. Results

3.1. Hydropower Potential Assessment

The proposed area for the SHPP development is presented in Figure 1, with the weir where the SHPP will be located (on the left-hand side) and the ICSTM (on the top-right-hand side).

The estimation of distances and altitudes for estimating the hydropower potential related to the proposed locations is performed using Google Earth Pro [20].

Thus, distances in a straight line from the electrical station of the ICSTM, where the electricity produced by the SHPP will be transported, are 350 m to the last step of the energy dissipator and 500 m to the weir axis.

A rough evaluation of altitudes (used for the determination of the head for different arrangements) and distances leads to the following values:

- Free surface in the pond created by the weir: 283 masl;
- Free surface downstream energy dissipator teeth: 281 masl; it corresponds to a head between the free surface of the pond and this river section of 2 m;

- The distance between the weir crest (section A) and the end of the last raw of energy dissipator’s teeth (section B): 17 m; referred to as arrangement AB;
- Free surface of water in the last step of the energy dissipator (section C): 275 masl; it corresponds to a head between the two river sections of 8 m;
- The distance between the weir crest (section A) and the last step of energy dissipator (section C): 170 m; referred to as the arrangement AC.

Therefore, a rough estimation of the gross head, H_{gr}, used for the estimation of hydropower potential leads to the following values:

$$H_{gr\,AB} = 2\ \text{m} \tag{1}$$

and for turbines installed in weir section (A):

$$H_{gr\,AC} = 8\ \text{m} \tag{2}$$

for turbines installed close to the last step of the weir energy dissipator (section A).

The mean flow, Q_m, on the Ialomița river in the weir section is considered as follows [21]:

$$Q_m = 8\ \text{m}^3/\text{s} \tag{3}$$

For the evaluation of the hydropower potential (hydraulic power at disposition of the turbine), the following well-known simplified formula will be used [22]:

$$P_h = 9.81 Q_m \cdot H_{gr},\ [\text{kW}] \tag{4}$$

For SHPPs with ponds without possibilities of regulation, usually the installed or designed flow in the SHPP turbines is considered equal to the mean flow or even lower. In this paper, we will consider the following:

$$Q_i = Q_m \tag{5}$$

The electric power generated by an SHPP can be easily considered equal to the installed capacity, and is determined with the help of the following formula:

$$P_{SHPP} = \eta_{SHPP} \cdot P_h,\ [\text{kW}] \tag{6}$$

where η_{SHPP} represents the overall efficiency related to the transformation of hydraulic energy in electricity and can be called the SHPP efficiency.

The SHPP efficiency has the following components:

- The hydraulic efficiency, η_h, related to the hydraulic route between the pond and the turbine is usually imposed in the design phase to be at least 0.9;
- The turbine efficiency, η_{tb}, usually for small applications can be considered 0.8 (especially that we want to operate in a wide range of flows);
- The generator efficiency, η_G, will be considered 0.95;
- The transformer efficiency, η_{tr}, will be considered 0.97.

Thus, the SHPP efficiency can be determined as:

$$\eta_{SHPP} = \eta_h \cdot \eta_{tb} \cdot \eta_G \cdot \eta_{tr} = 0.66 \tag{7}$$

Considering Equations (4) and (7) and rounding 9.81·0.66 = 6.47~6, Equation (6) becomes a practical formula that can be used for the evaluation of electricity generation from an SHPP:

$$P_{SHPP} = 6 \cdot Q_m \cdot H_{gr},\ [\text{kW}] \tag{8}$$

This formula is not far from practical formulas proposed by European Small Hydropower Association [6] which proposes instead of our coefficient 6 a coefficient 7 and, for being fully covered with calculations even this coefficient to equal to 5.

Applying formula (8) with data for the two arrangements, Equations (1)–(3), it results in the electrical power to be generated in the SHPP as follows:

$$P_{AB} = 96 \text{ kW}, \text{ for the arrangement AB} \tag{9}$$

$$P_{BC} = 384 \text{ kW}, \text{ for the arrangement BC} \tag{10}$$

The annual electricity generation in SHPP can be estimated with the help of the formula:

$$E_{an} = P_{SHPP} \cdot T_u [\text{kWh/year}] \tag{11}$$

where T_u represents the annual duration of use of the installed capacity in SHPP turbines (mean number of hours per year that can be considered for the SHPP to operate at the installed capacity). The Ialomița River flows are regulated by two large reservoirs in mountains and a smaller one, Pucioasa Reservoir, located just a few 10 of kilometers upstream of the weir. The modified shape of the flow duration curve due to regulated flows, the choice of installed flow equal to the mean flow, the constant head, and the choice of a turbine efficiency lower than usual (considering to be operated for a large range of flows) allow us to consider the following:

$$T_u = 5000 \text{ h/year} \tag{12}$$

obtaining for annual electricity generation for the two arrangements:

$$E_{AB} = 480 \text{ MWh/year}, \text{ for the arrangement AB} \tag{13}$$

$$E_{BC} = 1920 \text{ MWh/year}, \text{ for the arrangement BC} \tag{14}$$

3.2. SHPP Located in the Weir Section (Arrangement AB)

As a turbine installed in the section of the weir, the arrangement between sections A and B, arrangement AB (Figure 1), we will briefly present possibilities to install some turbines, such as Voith Stream Diver (Koessler), WWS PowerGate (WWS Wasserkraft), Archimedean screw (as pump and as turbine, thus reversible, considering the demonstration possibilities for students and stakeholders), and Very Low Head (VLH).

For the arrangement AB, the head and the flow presented in Equations (1) and (3), respectively, will be considered: 2 m for the head and 8 m^3/s for the flow.

3.2.1. Voith Stream Diver

StreamDiver represents a solution for low head sectors and allow construction work to be kept at a minimum, which is the requirement for an ecological and economical approach (Figure 4) [23]. The range of operation of Stream Diver is a flow of 2 to 12 m^3/s and a head of 2 to 8 m.

3.2.2. WWS PowerGate (WWS Wasserkraft)

The WWS PowerGate was specifically developed for the economical utilization of small amounts of water and low head as a compact, fully integrated in a Sluice Gate, micro-hydro turbine-generator system (Figure 5) [24]. The turbine is suitable where water flow is low or the water head is as low as 1.5 m and the efficiency is around 90%. The unit can be dropped into the slot of the existing sluice gate, so the installation costs are very low.

Figure 4. StreamDiver turbine (Voith).

Figure 5. WWS PowerGate turbine [24].

3.2.3. Archimedean Screw

The Archimedean screw is used only recently as a turbine for low head sites, allowing the use of large flows (Figure 6) [25]. For many decades, they have been used as pumps, some tens of thousands being installed worldwide, mostly in sewage treatment installations. The ranges of operation of the Archimedean screw as a turbine are a head of 1 to 8 m a diameter of 1 to 5 m, a flow of 0.25 to 14.5 m^3/s, power of 5 to 500 kW, and an efficiency of 80 to 85%. Archimedean screw turbines can have variable speed, which are far superior in operation and efficiency than a fixed-speed screw. Recent papers have underlined that comparing with other possible arrangements for low-head sites, the Archimedean screw represents a green source of electricity and is a fish friendly turbine [26]. Because the SHPP is also a real-scale laboratory for UVT students, we propose that if this solution is adopted to analyze the possibility to function also as pump even if for a very short period.

Figure 6. Archimedean screw turbine [27].

3.2.4. Very Low Head (VLH)

The basic idea of the VLH concept is to minimize the intake and outlet by increasing the size of the turbine and to integrate it into a structure that can be plunged in water or taken out (Figure 7) [28]. VLH consists of a standardized Kaplan turbine with eight adjustable blades according to the upstream level and to the flow; a self-supporting structure; a slow direct-drive variable-speed permanent-magnet generator; an electronic output frequency converter; an integrated electronic control equipment for the operation of the turbogenerator unit and the power electronics equipment; and a withdrawal device that enables taking the unit out of the water for maintenance. Other strong points of this turbine are that it does not need a gate for stopping, just fully closing the runner blades; that the distributor is used as a grill; and that the trash rack cleaner is built in. The units are built in five diameters (3.15, 3.55, 4, 4.5, and 5 m) with the following characteristics: a net head range of 1.5 to 4.5 m; a flow rate of 10 to 27 m^3/s; and power of 10 to 500 kW. There are scientific papers which underline that, based on many experimental studies conducted in laboratories and at real scale, VLH is considered a fish-friendly turbine by the French environmental authorities [29].

Figure 7. Very Low Head (VLH) turbine [28].

3.3. *SHPP Located Close to the Last Step of the Weir Energy Dissipator (Arrangement AC)*

The second arrangement for harnessing waterpower for supplementing electricity to the ICSTM is an SHPP with a water outlet in the last step of the weir energy dissipator, (arrangement AC; Figure 1).

3.3.1. Traditional Technology

There are many considerations on how to make a turbine selection for a given site: head and flow, price, efficiency, range of flows for generating electricity with a good efficiency, reliability, and possibility to be operated even in water with sediments.

Related to classical turbines that can be chosen to equip the SHPP, depending the on head and flow, the nomogram from Figure 8 can be used. As we estimated a gross head of 8 m for this arrangement and a flow of 8 m^3/s, the only traditional turbines suitable for this location are Kaplan and Banki (Crossflow).

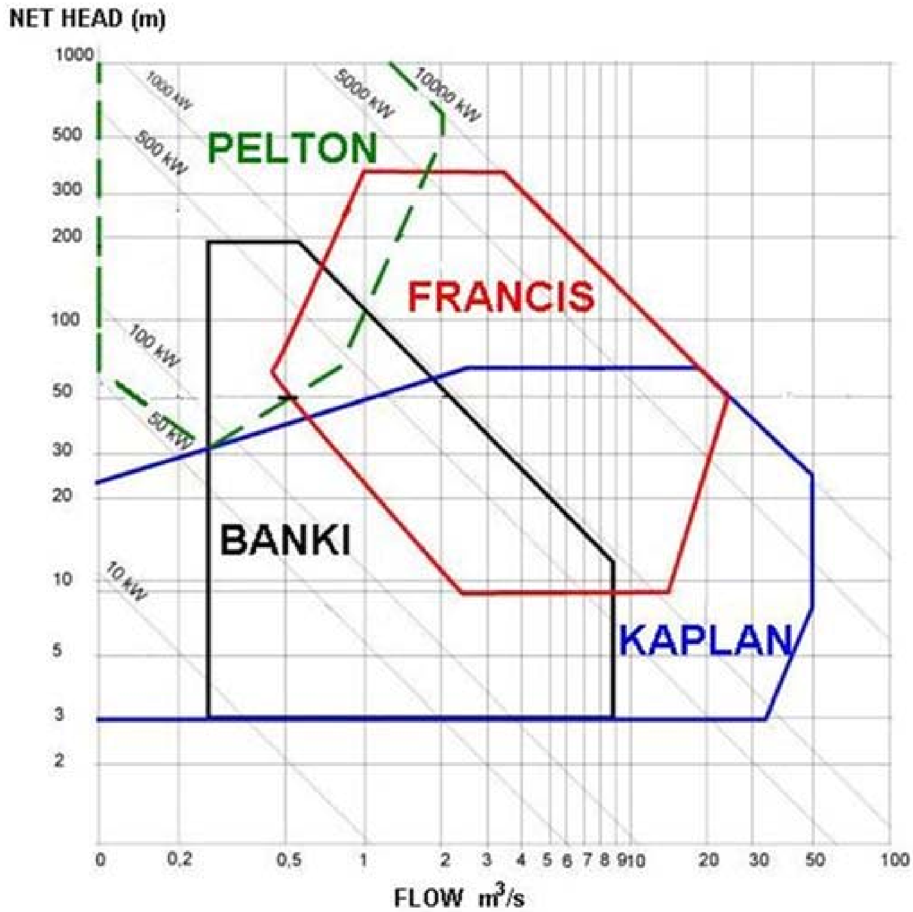

Figure 8. Turbine choice depending on net head and flow [22].

Related to efficiency, usually Kaplan has better efficiencies than Crossflow (Figure 9) and maximum efficiencies around 92% compared with around 82%.

Nevertheless, related to the range of flows for generating electricity with a good efficiency, Crossflow can work even for 10% from the maximum flow with efficiency around 75%, which, from the point of view of the security of the electricity supply, can be far more important than a 10% increase in efficiency. Having in mind that Crossflow can operate even with water with sediments, for the presented arrangement, it can be a good reason for choosing this turbine.

As a part of the classical hydropower scheme with turbines into a powerhouse, we present another possibility to use waterpower in arrangement AC, a Turbinator turbine.

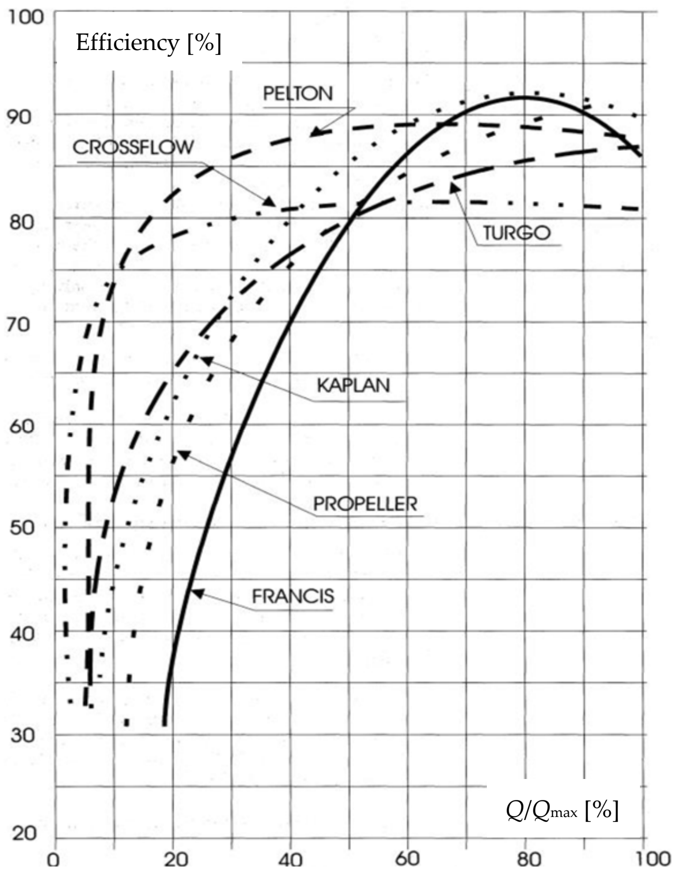

Figure 9. Turbine's efficiencies depending on percentage from designed flow [22].

3.3.2. Turbinator (CleanPower)

A Turbinator is a single regulated axial flow Kaplan turbine designed by CleanPower AS, with an integrated direct drive synchronous permanent magnetized generator (Figure 10) [30]. An adjustable guide vane is used for phase-in to grid and maximizing efficiency during operation. The ranges of operation of the Turbinator are a flow of 0.5 to 10 m^3/s a head of 5 to 55 m, and power of 100 to 3000 kW.

Figure 10. Arrangement for turbine Turbinator [30].

4. Discussion

A wide range of possibilities was considered for an SHPP to be realized close to the ICSTM to fully cover its own electricity consumption and even become an electricity producer, while at the same time using it as a real-scale laboratory and demonstration site for students and stakeholders. The fact that the SHPP will be built on an existing hydrotechnical infrastructure (weir and its energy dissipator) proves the concept of hidden hydro very well and represents an example of how small hydropower must be further developed.

If the funds will allow, even both presented arrangements can be realized. The arrangement AB, with a turbine in the weir section, can affect the possibility to spill large flows during floods, so it looks more difficult to achieve. By contrast, for the arrangement AC, with the powerhouse downstream, the powerhouse can be designed to allow turbine testing loops. A simple distributor will allow for two or even three turbines of different types (Kaplan, Propeller, Banki, PAT, etc.) to be installed in parallel for demonstration or even for testing purposes.

It is to be mentioned that UVT-ICSTM can propose a partnership with the National Administration of Romanian Waters for the realization of the SHPP.

A previous estimation for fully covering the electricity consumption of the ICSTM was made considering a surplus of 40% to the existing production, and it was 698 MWh/year [18]. This estimation was performed considering to be covered by a new PV farm, so in conditions of intermittent electricity generation. We consider that even the arrangement AB, with an estimate of 480 MWh/year, will fully cover the electricity needs of the ICSTM. Regarding the second proposed arrangement, AC, with 1920 MWh/year, its achievement will impose the ICSTM to become electricity producer, which we consider a great opportunity for the institute itself.

The realization of the previously proposed 120 kW installed capacity PV farm [18], of the 384 kW installed capacity SHPP, and of a smart grid off grid constitute good premises for UVT to become fully electricity independent. The diversification of the RES mix can be even improved if the realization of a small biomass plant will be envisaged and even planting energy crops, as the university campus is surrounded by unused vacant lots (Figure 1). This independence can be also extended for thermal energy using the biomass power plant to supplement the existing solar thermal energy [18]. Further studies related to geothermal resources can be envisaged and to extend the RES, for which demonstration can be provided for students and stakeholders.

5. Conclusions

The paper presents the existing RES mix, PV and wind power experimental platforms, of a research institute, the ICSTM, for experimental studies with students or for research-based contracts with the industry. Moreover, electricity generation partially covers the institute's own consumption. In a previous paper, a proposal was presented for supplementing the energy generation from RES by installing new PV panels [18].

In this paper, we proposed a solution for completion with a third form of RES, a small hydropower plant, by installing one or more turbines on a weir located on the Ialomița River just a few hundred meters from the ICSTM. Moreover, the proposed small hydropower plant is also a new real scale laboratory of ICSTM. The hydropower potential for two possible arrangements is assessed and some types of turbines suitable for this location are presented. The results demonstrate that the SHPP is a better solution for the completion of PV and wind as source of electricity for ICSTM due to a greater installed capacity and electricity generation. It is to be mentioned the diversification of the RES mix for sustainable electricity generation.

The main conclusion of the paper is that installing new RES capacities ICSTM can build a real-scale laboratory for new technologies, at the same time fully covering its own electricity consumption and even supplying green electricity mix into the national power system.

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