A pilot station using renewable resources to rehabilitate the inefficient small-hydro power plants

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Abstract. In Romania, based on a complex plan elaborated during 1980-1990 were built over 600 SHP-Small Hydropower Plant to assure the power supply in isolated localities. After 30 years, less than 200 are still functional, mainly due to a lack of investments or improper utilization. Nowadays a permanent campaign concerning intensive use of renewable resources is implemented. Firstly is mentioned the economically favorable solution from the selected zone to achieve the photovoltaic power plant connected to an existent SHP, which needs to be rehabilitated. The paper presents such a pilot plant realized between 2015 and 2017, built near an SHP decommissioned in 1998. Firstly was implemented a wind turbine which starts immediately producing energy. After two months, the photovoltaic power plant was interconnected. The main steps of the hydropower plant rehabilitation are presented, beginning with the selection of the necessary parameters to establish the opportunity and the pilot station efficiency. The theoretical model and the physical realization in coupling these power plants based on three different energy resources are mentioned. Some obtained results for six months are illustrated. Finally, some of the appeared problems during the execution are mentioned, considering that similar projects in the other four sites will be developed.

1. Introduction

The available capacity to generate electricity from renewable increased significantly over the last 20 years. Although the hydro remained the most significant source for electricity generation in the EU-28 in 2017, representing 36.9 % of the total produced energy, the amount of electricity generated by this resource was relatively similar to the level recorded a decade earlier. By contrast, the quantity of electricity generated in the EU countries from solar and wind power farms, was 44.4 times, respectively 3.7 times higher in 2016 as it was in 2006. As a result, the shares of power production from wind and solar resources in total generated electricity rose to 31.8 %. In the actual context, the EU has decided to reduce between 2010 and 2020 [1], the pollutant emission with 8% compared with the year 2006. Such documents concerning the principal solutions are mentioned in the Green Cart, White Cart, etc. referring at the utilization of the renewable resources from 14% in 2016 to 25% until 2020 in the EU countries.

Renewable energy has grown significantly in recent years, [2], [3] in the total amount of produced electricity. The share of power from renewable in the gross final energy consumption has almost tripled from around 8.5% in 2004 up to 17.0% in 2016 and 25% in 2020. The primary production of renewable energy within the EU in 2016 was 211 million tones of oil equivalent (toe). The quantity of renewable energy produced within the EU increased overall by 66.6 % between 2006 and 2016,
equivalent to an average increase of 5.3 % per year. In 2017, the electricity generation from renewable sources contributed more than one quarter (29.6 %) to the total gross electricity consumption.

In Romania in 2017, renewable energy has ensured about 44.29% from the entire national production of electricity. The highest share is held by the hydro, around 30%, the wind energy 11 %, 7.2% by the photovoltaic, and 1.16% by the biomass. In the present context in Romania, a consistent policy concerning the utilization of renewable resources is applied from 2009, when was adopted new legislation more favorable to entrepreneurs and international investments. Due to the Romanian high hydro-energetic potential, during '80 were built more than 600 SHP. Nowadays, many SHP are outdated or inefficient, and only half of them are still functioning. By European funding, it is possible to rehabilitate the SHP, by integrating them into a pilot station using wind, solar, or biomass, as additional resources. A new direction regarding the rehabilitation of the outdated or decommissioned small hydropower plants was implemented, followed by a constant campaign of monitoring the environmental data. The main purpose was to locate the most economically favorable zones for developing such pilot stations using the interconnections between several renewable resources. In this paper is presented such a pilot plant, built near a SHP, decommissioned in 1998.

2. Environmental data acquisition

To register the main environmental data was used a Weather Station Hawk Series 500, able to measure, store and transmit by GSM, the direction and wind intensity, air temperature and humidity, barometric pressure, solar radiation, the quantity of rainfall and the dew point. The data were stored for more than two years, starting December 2015, at each hour, with an additional option, registration of the minimum and maximum of specific parameters, considered essential.

The Weather Station was implemented at a distance of 2 km from the hydropower plant necessary to be rehabilitated, in the selected place for wind and solar power plants. In Table 1 are presented part of the registered temperatures between 2015 and 2017 and Fig. 1 illustrates the average values for temperatures and solar radiation in 2017.

Table 1. Part of the measured temperatures between 2015 and 2017.

| Month | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | 2017 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Year  | 2015| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2016| 2017 |
| 12am  | -3.1| -1.2| -0.3| 5.0 | 10.0| 15.4| 19.8| 21.7| 22.0| 20.7| 11.1| 4.3 | 2.9 | -0.38|
| 1am   | -3.2| -1.2| -0.6| 4.6 | 9.5 | 14.8| 18.9| 21.0| 21.2| 19.9| 10.6| 3.9 | 2.5 | -0.66|
| 2am   | -3.4| -1.5| -0.8| 4.2 | 9.1 | 14.2| 18.3| 20.4| 20.3| 19.1| 10.0| 3.6 | 2.4 | -1.09|
| 11pm  | -3.3| -0.7| -0.2| 6.1 | 10.9| 16.2| 20.9| 22.5| 23.3| 21.7| 11.2| 4.6 | 3.1 | -0.19|
| Avg   | -3.0| -1.5| -0.2| 5.9 | 11.5| 16.9| 21.4| 23.4| 23.5| 22.1| 11.7| 4.6 | 3.4 | -0.2 |

Figure 1. Average values for temperature and solar radiation, values measured in 2017.

In Table 2, are partially presented the average values registered for wind intensity, solar radiation, wind direction, and temperature and in Table 3 part of the extreme values recorded for the wind velocity and direction, pressure, and precipitations.

By superposing the actual positions of the SHP, around 600 Fig. 2-a, the wind, and solar radiation maps, was realized a plan of possible further implementation of such complex projects, Fig. 2-b.
Table 2. Part of the measured temperatures between 2015 and 2017.

| Wind velocity [m/s] | Solar radiation [kwh/m²] | Wind direction [°] | Temperature [°C] |
|---------------------|--------------------------|-------------------|-----------------|
| M/Y 2015 2016 2017  | Av 2015 2016 2017       | Av 2015 2016 2017 | Av 2015 2016 2017 |
| Jan 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Feb 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Mar 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Apr 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| May 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| June 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| July 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Aug 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Sep 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Oct 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |
| Nov 10.6 10.8 10.7 | 3.0 2.9 3.0           | 41.9 41.5 41.3    | 41.9 41.5 41.3    |

Table 3. Extreme values.

| P | Velocity [m/s] | Direction [°] | Pressure [mmHg] | Precipitations [mm] |
|---|----------------|--------------|-----------------|---------------------|
| Av | Min | Max | Max abs | Av | Min | Max | Max abs | Av | Min | Max | Max abs | Av | Min | Max | Max abs |
| Jan | 3.5 | 0.81 | 13.0 | 21.2 | 166 | 2 | 354 | 356 | 754 | 735 | 754 | 735 | 5 | 76 | 5 | 76 |
| Fe | 4.2 | 0.42 | 23.9 | 35 | 182 | 0 | 182 | 184 | 760 | 754 | 760 | 754 | 12 | 100 | 12 | 100 |
| No | 8.56 | 0.14 | 12.6 | 34.3 | 197 | 0 | 358 | 360 | 758 | 745 | 758 | 745 | 5 | 96 | 5 | 96 |
| De | 6.14 | 0.68 | 8.9 | 34 | 186 | 0 | 359 | 360 | 764 | 756 | 764 | 756 | 5 | 100 | 5 | 100 |
| Av | 10.2 | 0.64 | 14.6 | 52.1 | 149 | 0 | 354 | 360 | 758 | 733 | 758 | 733 | 5 | 93 | 5 | 93 |

As a first stage, based on the received finance, five places were selected, in different areas of the country. One of them actually containing two SHP not far from one of the other was chosen and built in the first phase, in the Olt county, well known with high efficiency for solar applications, Fig. 3-a.

3. Small hydropower plant

The linear theoretic potential-P, and energy-E, of SHP are based on the multi-annual river’s flow rate:

\[ P_l = 9.81 \times Q_{av} \times (z_1 - z_2) \text{ [kW]} \]  
\[ E_r = 9.81 \times Q_{av} \times (z_1 - z_2) \times 8760 \text{ [kWh/Year]} \]  
Where \( Q_{av} \) – the average flow rate on the river, \( z_1 - z_2 \) – the difference between the geodesic cotes

There is a difference between the theoretical potential and the real one, E, which is the potential possible to be transformed into electric energy:

\[ E = 9.81 \times \eta_t \times Q_{av} \times (z_1 - z_2) \]  
\[ \eta_t = \eta_h \times \eta_{g} \times \eta_{t} \]  

Here: \( \eta_t \) total efficiency, \( \eta_h \) hydraulic efficiency, \( \eta_{g} \) turbine efficiency, and \( \eta_{t} \) generator efficiency. The hydro-energetic scheme is performed for the power plant with two intakes with Coanda-type grill, noted P1 and P2, with a power of P = 4.94 MW for each one. The distance between P1-SHP1 is 3200 m, difference 98 m and between P2-SHP2 of 2700 m, difference 96 m. [4], [5].

- SHP1, P1 = 2.78 MW, H = 972 mdMN, h_t = 6.4 m (6.82%), Q_t = 2.9 m³/s
- SHP2, P2 = 2.36 MW, H = 863 mdMN, h_t = 7.6 m (7.9%), Q_t = 2.5 m³/s

The P1 water outlet is on the main course of the river, downstream the confluence between Valley Pescana and Cibin at 1066 mdMN and has a catchments surface of 18.2 km². The PS2 water outlet
is on the main course of the river Cibin, 3 km downstream, PS1 at 959 mdMN, with a basin area of 23.8 km\(^2\). Fig. 3-b presents images with the SHP before and after the rehabilitation.

Figure 3. a – SHP’s location, county Olt; b – Initial (first 3) and final (last 2) conditions for the SHP.

To rehabilitate the existing SHP in parallel with the implementation of the wind and solar components of the power plant was conducted the SHP’s modernization. As the first stage, the hydro-mechanical and hydroelectric equipment were dismantled from both SHP to be developed a new capacity of production, using modern technology, with high reliability and efficiency. The main steps:
- Modernization of assembly turbine-generator, power cabinets, control, and automation
- Realization of one additional intake for water during the winter, when the ice forms a bridge
- Achievement of a flow measurement system in SHP2
- Realization of places for the hydraulic cleaning of sediments
- Implementation of a measurement system for water levels and deposits
- Providing a system of warning for clogging; this allows improved utilization of available volumes
- Full replacement of the mechanical equipment in intakes
- Data transmission related to water and sediments levels

4. Photovoltaic power plant

The produced energy is directly dependent on the total received solar radiation. To realize the photovoltaic power plant was analyzed the actual market of producers. The first 12 producers for cells and photovoltaic modules assure more or less 80% of the entire world production. There where analyzed offers from Sunergy, Sharp, Q-Cells, Kyocera, Sanyo, Mitsubishi, Schott Solar, Hanwha, BP Solar, Suntech, Motech, Shell Solar, Isofotón and Deutsche Cell. For this project was selected the Suntech solution, with high efficiency in the domain of solar radiation registered in the selected area.

4.1. Main characteristics and the numerical modeling

In Romania, the solar radiation is between 1200-1400 h/year at maximum installed power capacity. Making a comparison between Romania and other countries with similar conditions, the solar potential is at a medium level, with an average produced energy between 2.75-4.8 kWh/m\(^2\).

Based on the registered environmental data, for the chosen area was adopted the value of 130,4 kWh/m\(^2\) with a variation of 12\%, [6]. The benefits of the solar radiation and temperature for the selected area were presented in the paragraph of the environmental measurements. Some tests result registered with the chosen panels, at different angles from the horizontal between 30°-35° for the first row of panels, 35°-40° the second one, and for 40°-45° degrees for the third are presented in Table 4.

Table 4. Main parameters registered with solar panels.

| A System in Grid-Connected Operation | Location: | Climate Data Record: | PV Output/panel: | Surface Area: | Certificate: TUV, UL, ETL, CSA, CE, ISO INMETRO | Maximum Efficiency |
|-------------------------------------|-----------|----------------------|-----------------|---------------|-----------------------------------------------|-------------------|
|                                    | Izbiceni  | Izbiceni             | 5BB Mono 156 mm/ PV | 1.95x0.99 m\(^2\)/725.5 m\(^2\) |                                | 18.7 %             |
| Number of Arrays: 6                |           |                      |                 |               |                                                |                    |
| On row: 10                         | 3 x 6 x 72 cells Mono-crystalline |                  |                 |               |                                                |                    |

Table 5 presents some aspects from the project design with solar panels - fixed position, at 40°. For this case was realized the first set of measurements and estimation of the possible produced energy, presented in this paper. A second type and a third type of measurements and calculation, but not
presented here, with panels placed at different angles for each row, but in fixed positions, and with modules oriented after the sun’s position was realized.

| Table 5. Array 3 - The main characteristics. |
|---------------------------------------------|
| **Output:** 33.76 kW | **Ground Reflection:** 20.0 % |
| **Gross/Active Solar Area:** 243.7 m² / 241.8 m² | **Output Losses:** - |
| **PV Module:** 162 x | **Deviation AM 1.5:** 2.0 % |
| **Manufacturer:** PVT Austria Technik | **Deviation from Specification:** 3.0 % |
| **Type:** PV-210AE-A | **Diodes:** 0.5 % |
| **Power Rating:** 210 W | **Due to Pollution:** 0.0 % |
| **Power Rating Deviation:** 0 % | **Inverter:** 6 x |

The numerical modeling was realized using specific software, RET and Homer. Table 6 presents one part of the obtained results by numerical modeling. Each panel has 72 cells, Power Output Range: 335-360 W, Power Output Tolerance: 0 ± 3%, Size: 1.950 x 0.990 x 0.04 m, Max. Efficiency: 18.7%.

| Table 6. Simulation results for the total system of the solar module. |
|---------------------------------------------------------------|
| **Irradiation onto Horizontal:** 979,414 kWh | **Own Use:** 161.9 kWh |
| **PV Array Irradiation:** 980,171 kWh | **Energy Produced by PV Array:** 112,551 kWh |
| **Irradiation minus Reflection:** 931,141 kWh | **System Efficiency:** 10.8 % |
| **Energy from Inverter (AC):** 105,716 kWh | **Performance Ratio:** 77.1 % |
| **Consumption Requirement:** 0 kWh | **Final Yield:** 2.9 h/d |
| **Energy from Grid:** 161 kWh | **Specific Annual Yield:** 1.042 kWh/kWp |

Considering ten modules for each row, in three rows, the photovoltaic part of the pilot station has 10.8 KW. In Table 7 are mentioned some characteristics of the operational system, allowing estimation of the economic aspects, like investments, operation costs, cash balance, time of the investment recuperation, presented in Fig. 4-b, and Fig. 4-c.

| Table 7. General economic aspects. |
|-----------------------------------|
| **System Data** |
| PV Output: 101.3kWp |
| System Operating Start: 1/2/2017 |
| Total Degradation: 10.00 % |
| **Electricity Feed-in:** |
| Grid Concept: Full Supply to Grid |
| First 20 Years: 0.2400 $/kWh |
| After: 0.2400 $/kWh |
| **Balance of Costs** |
| Investment Costs 39,680.00 $ |
| Operating Costs 396.80 $/year |
| Feed-in Payment Received in First Year 25,371.86 $/a |

4.2. Implementation of the photovoltaic power plant

For the solar power plant implementation was selected an area from zone 1 considered the best for our country. There are coupled eight PV/each panel, at a constant inclination angle of 40° (optimum for the selected area). The reference parameters registered during these tests were the quantity of electric energy produced depending on the solar radiation and the maximum delivered power, determined by the intensity-voltage characteristic. The energy transmitted to the inverter is presented in Fig. 4-a.

4.3. Experimental results

In the secure area firstly was registered the produced energy stored into batteries of 12.51 V between October 2016-November 2016-Period 1, and December 2016-December 2017 Period 2. To avoid the direct solar radiation was used a pyranometer CM 121 Kipp & Zonen, with an individual sensor, able to register even in days with rain, snow or in contrary with high level of temperatures.
After two months of testing the solar power plant was coupled at the national system delivering electric energy. In Fig. 5 is presented the cash flow, with costs and benefits. The initial investment is clearly expressed in the beginning, illustrated the maintenance costs (yellow), and the benefits.

Figure 5. Benefits and Costs breakdown.

5. Conclusions
In recent decades many of the SHP built during 1980-1990 are technologically outdated and affect the environment, in particular, the fish life (trout). As EU member Romania took some commitments considering the environmental compliance and complex utilization of renewable sources.

This paper presents a solution adopted for the rehabilitation of such SHP, by using other renewable energy resources, wind, and solar, allowing minimum investments in the SHP’s reconstruction. In the beginning, was conducted a study for suitable zones of implementation for such pilot stations.

Firstly was commissioned the wind turbine, which starts immediately to deliver energy in the national system, receiving Green Certificates on the energy market. The photovoltaic power plant was realized as the second stage. Its realization and implementation was detailed presented. By numerical modeling was estimated the produced energy and the cash balance, which allows an estimation of the benefits and the costs breakdown. In two years the pilot station was fully realized, and the SHP rehabilitated as presented in Fig. 3 last two images. After completing the rehabilitation and was established the full capacity of functioning for the pilot station, the local community starts to recover the initial investments and intend to develop a new pilot station in another location.

References
[1] Directive 2009/28/EC on the promotion of the use of energy from renewable sources, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&rid=8
[2] Energy balance sheets 2015 data, 2017 edition, http://ec.europa.eu/eurostat/en/web/products-statistical-books/-/KS-EN-17-001
[3] Carlea F P 2003 Renewable resources between reality and European Directive 77/2001
[4] Radulescu V and Nistoranu V 2004 Utilizarea complexa a resurselor de apa, (Romanian), Series Hydraulics, Publisher Bren, ISBN 973-648-255-3, Bucharest
[5] Seteanu I and Radulescu V 2005 Identification, calibration of the hydraulic parameters-linear optimization, Romanian Journal of Hydrology & Water Resources 2 1-2
[6] Kumarappan V T N 2017 Grid interconnection of renewable energy sources using multifunctional grid-interactive converters: A fuzzy logic based approach, Electric Power Systems Research 151, https://doi.org/10.1016/j.epsr.2017.06.010