energies

Article

Energetic-Environmental-Economic Feasibility and Impact Assessment of Grid-Connected Photovoltaic System in Wastewater Treatment Plant: Case Study

Horia Andrei [1,*], Cristian Andrei Badea [2], Paul Andrei [3] and Filippo Spertino [4]

[1] Department of Doctoral School of Engineering Sciences, University Valahia of Targoviste, 130004 Târgoviște, Romania
[2] Interface Engineering, 030828 Bucharest, Romania; bcristianandrei@yahoo.com
[3] Faculty of Electrical Engineering, University Politehnica of Bucharest, 060042 București, Romania; paul.andrei@upb.ro
[4] Department of Power System, Politecnico di Torino, 10129 Turin, Italy; filippo.spertino@polito.it
* Correspondence: hr_andrei@yahoo.com or horia.andrei@valahia.ro; Tel.: +40-729-104-202

Abstract: Wastewater treatment plants and power generation constitute inseparable parts of present society. So the growth of wastewater treatment plants is accompanied by an increase in the energy consumption, and a sustainable development implies the use of renewable energy sources on a large scale in the power generation. A case study of the synergy between wastewater treatment plants and photovoltaic systems, aiming to improve the energetic, environmental and economic impacts, is presented. Based on data acquisition, the energy consumption analysis of wastewater treatment plant reveals that the highest demand is during April, and the lowest is during November. The placement of photovoltaic modules is designed to maximize the use of free space on the technological area of wastewater treatment plant in order to obtain a power output as high as possible. The peak consumption of wastewater treatment plant occurs in April, however the peak production of the photovoltaic is in July, so electrochemical batteries can partly compensate for this mismatch. The impact of the photovoltaic system connectivity on power grid is assessed by means of the matching-index method and the storage battery significantly improves this parameter. Carbon credit and energy payback time are used to assess the environmental impact. The results prove that the photovoltaic system mitigates 12,118 tons of carbon and, respectively, the embedded energy is compensated by production in 8 1/2 years. The economic impact of the photovoltaic system is analyzed by the levelized cost of energy, and the results show that the price of energy from the photovoltaic source is below the current market price of energy.

Keywords: wastewater treatment plant; photovoltaic system; grid-connected; storage battery; data acquisition system; modeling and simulation; energetic; environmental and economic impact

check for updates

Citation: Andrei, H.; Badea, C.A.; Andrei, P.; Spertino, F. Energetic-Environmental-Economic Feasibility and Impact Assessment of Grid-Connected Photovoltaic System in Wastewater Treatment Plant: Case Study. *Energies* **2021**, *14*, 100. https://dx.doi.org/10.3390/en14010100

Received: 9 November 2020
Accepted: 23 December 2020
Published: 27 December 2020

1. Introduction

The "water-energy-green nexus" describes the interactions between water industry, energy production and green house gas (GHG) emissions, and is a subject to major interest from researchers and policy all three aspects have a major impact on modern life [1]. The International Energy Agency found that, in 2010, worldwide, 15% of the water withdrawals were used for energy production [2]. Other studies found that important percentages of the produced energy are used in the water industry. Generally, the water industry is the world's most intensive in terms of treated material, making it also energy intensive [3]. In a previous study Stokes and Horvath, [4], the authors stated that 19% of California's electricity is used in water facilities, and Curtis [5] states that, overall, 3% of the electricity generated in the world was used for water. From the GHG point of view, one study of the International Energy Agency, from 2012, found that approximately 42% of the global

CO_2 emissions come from power plants. These findings underline the need of better understanding the complex interactions between the nexus' elements for the purpose of sustainable development.

Several studies like Bojarsky [6], Chong [7], and Sharifzadeh [8] concentrate on the nexus at a macro level, nationwide, proposing mathematical models and optimization programs that take into consideration the economic and environmental impacts. On the other hand, when one changes focus from nationwide level to municipality level, the interactions between energy, water and GHG become even more significant. One study Venkatesh and Brattebo [9] found that, in the US, 30% to 40% of the energy consumed by municipalities for public services is linked to the water and wastewater treatment.

In general, the municipal water sector comprises water treatment stations, pumping stations, reservoirs and chlorination stations, wastewater pumping stations, and wastewater treatment plants (WWTP). Water resource deterioration, as a result of pollution produced by the accelerated urbanization and industrial parks, makes necessary innovation in the domain of water treatment, at a technological level as well as an economical level. Wastewater treatment plants are industrial installations designed to depollute the water used by a community, prior to its discharge in the natural environment, to prevent negative effects on the environment, like the eutrophization of the waters. At the same time, the technological process of, especially, small municipal WWTP, leads to negative environmental impacts on the sanitary condition of atmospheric air in the vicinity of the investigated WWTP, which consists in sources of odors and microorganisms, as presented in [10].

The industrial process of wastewater treatment in bioreactors using activated sludge has a history of more than 100 years, being pioneered by two English researchers. By aerating the wastewater in the containers, the two researchers were doing, at the same time, a complete mixing and the nitrification. The results of these experiments were the complete nitrification of the wastewater, and they observed that as they were adding new samples, the process was accelerating, the new samples being nitrificated more rapidly. Further development of the wastewater treatment process has as main subject the mitigation of nitrogen by activating the sludge process [11].

The largest energetic consumer is the WWTP plant as a consequence of the biological process and of the sludge treatment process [12]. In this context, renewable energy sources can improve the environmental impact of the water sector by reducing the GHG emissions and improving the energy and economic efficiency of the WWTP. WWTP are industrial installations designed to depollute the water used by human communities, before it is returned to the natural environment. As a consequence, the total energy consumption of the installations is dependent on the number of users connected to the water supply and sewerage infrastructure. The analysis of the energy consumption of a WWTP has been the subject of several works, concentrating mainly on the average consumption of energy per cubic meter of treated water, as in [13].

Generally, WWTP are supplied with electrical energy from the public power grid. Bibliographical study reveals that other authors have proposed the utilization of renewable sources of energy for the WWTP. Thereby, the most common renewable energy source for WWTP is obtained from the biogas produced in the bio-digesters, which is then used in cogeneration units to generate electricity and heat [14]. Another source of clean energy in WWTP is the anaerobic digestion, [15].

Another approach [16] that is common both in the literature and in practice is to install hydraulic micro-turbines. This approach is effective for very large-scale WWTP, for which the cost and operation of the micro-turbine can be compensated by the energy obtained from the water fall at the outlet of the WWTP.

Photovoltaic systems (PV) and several optimization methods of the technological process have also been proposed as a clean and sustainable energy source, and to decrease the energy consumption for the WWTP. Solar radiation is a source of power with negligible direct water consumption and GHG emissions. A discussion of different concepts and technologies that bring further development on a broad range of topics focused on efficiency improvement, smart and sustainable resource management based on the application of the smart technologies is presented in [17].

Another recent article studies the energetic and economic feasibility of a grid-connected PV system in WWTP located in the northwest of Algeria. The optimization proposed by authors is based on: energy balance, installation surface area and levelized cost of energy (LCOE). Obtained results show that the grid-connected PV system can cover 53% of WWTP electrical load and can inject 510 MWh/year into the grid, representing 65% of the load [18].

The oxidation tanks consume up to 30% of the energy of a WWTP and, for this reason, a new methodology to reduce energy consumption of aeration tanks is proposed in [19]. Based on the air temperatures, solar irradiations, biological kinetics, dissolved oxygen, and mechanical oxygenations, new analytical equations to obtain the peak power of PV installed in WWTP are proposed. Thereby, the authors maximize the auto-consumptions of aeration blowers installed in the oxidation tanks of WWTP.

Based on the data acquisition analysis of a small WWTP technological operation and on the dependence of process parameters of the connected population (equivalent population—p.e.), in a previous work [20], the authors proposed a logistic model for p.e. forecast and for energy consumption. In this respect, a procedure to increase the energy efficiency of WWTP is suggested. In another work [21], the same authors introduced four periods of WWTP' lifecycle according to p.e. connected and to the maximum capacity of the plant. For the proposed periods, the technological model of WWTP energy consumption is described and an optimal grid-connected PV system is designed to be installed in available spaces of a considered WWTP. One study is focused on describing of different operating regimes of a municipal WWTP treatment plant from an energetic point of view [22]. Optimization strategies taking into consideration technological constraints and the opportunity of using grid-connected PV system to compensate for a certain ratio of the total annual amount of WWTP consumed energy are proposed.

The present study proposes a methodology to increase the energetic efficiency of WWTP and to promote the grid-connected PV system in WWTP in order to enhance the environmental and economic performances. Compared to all the aforementioned approaches, in this work, two configurations, with and without storage battery, for grid-connected PV system are designed and studied. Furthermore, a complete impact assessment of 3-E indicators (Energetic-Environmental-Economic) has been considered in order to analyze the grid-connected PV system's integration into the WWTP and to validate the new concept "clean water through clean energy".

The two PV system configurations proposed in this paper are designed based on: (i) a detailed analysis of data acquisition system for WWTP energy consumption over a one-year period, (ii) continued with the assessment of the energy needs for the WWTP throughout the lifecycle of the plant, and (iii) with the evaluation of free spaces on the technological buildings inside the WWTP. The energetic efficiency of considered WWTP correlated with the p.e. connected to the sewerage infrastructure, which generates the final flow of water, have been treated. The requirements of electrical energy of the WWTP are presented in relation with the lifetime of the installation. The outcome of the PV system installation on the environment is analyzed using the Life Cycle Assessment (LCA) and the impact on the power distribution system is studied using the methodology "matching index".

The environmental impact of the PV system can be assessed in terms of mitigated carbon and energy payback time. Grid-impact assessment is convergent with the European Union policy towards nearly zero-energy buildings. In this context, the grid impact of the PV system has been assessed in this paper in two situations: PV system with and without storage battery. Generally, the LCOE is the method preferred in assessing the economic feasibility of renewable energy installations [23]. It provides a quantitative method to comparing the cost of two sources of energy. In this paper, the authors exemplify the use of LCOE for the assessment of different design options of PV systems for on WWTP. The use of LCOE for assessing the design options of the PV systems for WWTP is exemplified on an existing WWTP located in Central Romania. According to a report by the Romanian

Ministry of European Funding (RMEF), in the following five years, Romania will construct 360 new WWTP, making this subject of great interest for the country and, furthermore, for all similar small WWTP located in the world by changing only the climatic conditions [24].

2. Materials and Methods

Two main contributions are introduced in this research: (i) the feasibility analysis and optimal sizing of grid-connected PV system, with and without storage battery, in WWTP; (ii) the complete impact assessment of 3-E indicators of PV system integration in WWTP. Considering those two main contributions, a logical research methodology has been developed which is shown in the flowchart of Figure 1. First, three steps, 1, 2, and 3, are dedicated to data acquisition of WWTP energy consumption, and to analysis of PV system's optimal installation and to energy demand-response calculation. Next, step 4 of research methodology refers to calculating of environmental impact of WWTP along with PV system in terms of carbon released into the atmosphere and energy payback time. In order to store the energy produced by PV system in the most favorable case, a storage battery is calculated in step 5. Analysis of PV system's impact on power grid by using "matching index" and of economic impact of energy produced by PV system, with and without storage battery, by using LCOE is done in step 6, respectively 7. All these steps of the research methodology are detailed in the next sections of paper.

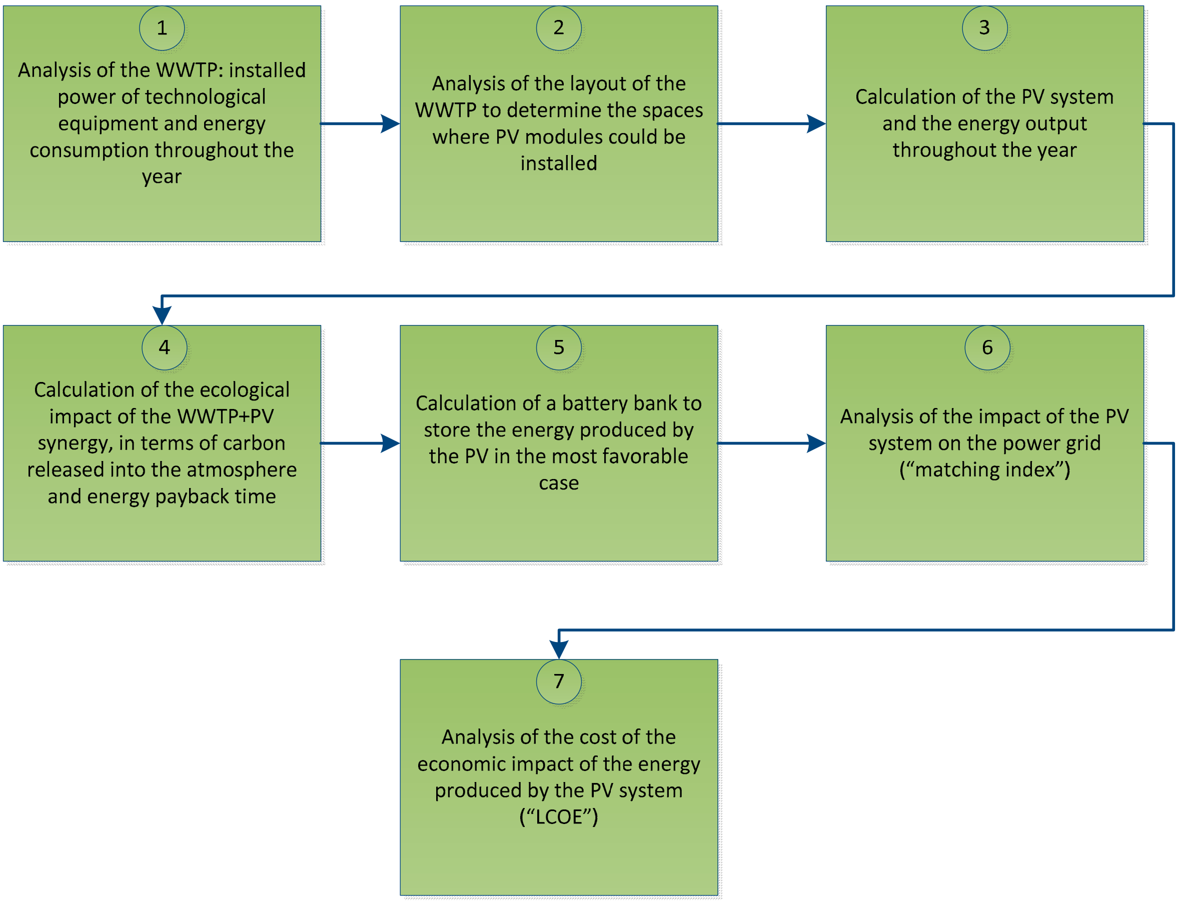

Figure 1. Flowchart of the research methodology.

2.1. Technological Process

The consumed energy of WWTP depends on water flow and pollutant charge and these technological parameters that in turn vary with p.e. connected to the WWTP. The logistic growth model for p.e. which will connect to WWTP, proposed by authors in previous work, forecast more accurately than the classical linear model the energy consumed over the lifecycle by the WWTP. In this respect, four technological functioning scenarios were proposed throughout the lifecycle, corresponding to the growth of energy demands when the p.e. increases.

In the incipient phases of the lifecycle of the WWTP, the energy generated by the PV system represents a higher percentage in the total necessary energy of the WWTP than in the last phases of the lifecycle. This combined with the fact that, in the incipient phases, there is lower population using the infrastructure, means that, for the operator, the PV system is more relevant in the incipient phases from an operational expenditure point of view. The present study is focused on two existing WWTP that are also in the incipient phases of the lifecycle. Thus, the results obtained by authors in the works mentioned above were useful for optimal sizing of the PV system installed in WWTP, as it be presented in the next section.

The WWTP analyzed in this work is a typical sequence batch reactor (SBR)—produced by Alfa Laval, Lund, Sweden—plant that is located in Central Romania (Lat: 45.815°; Long: 8.611°) and designed for 23,000 p.e., and like the one presented by Steel and McGhee in [25]. Their technological process, shown in Figure 2, was analyzed to determine the installed power of the main consumers.

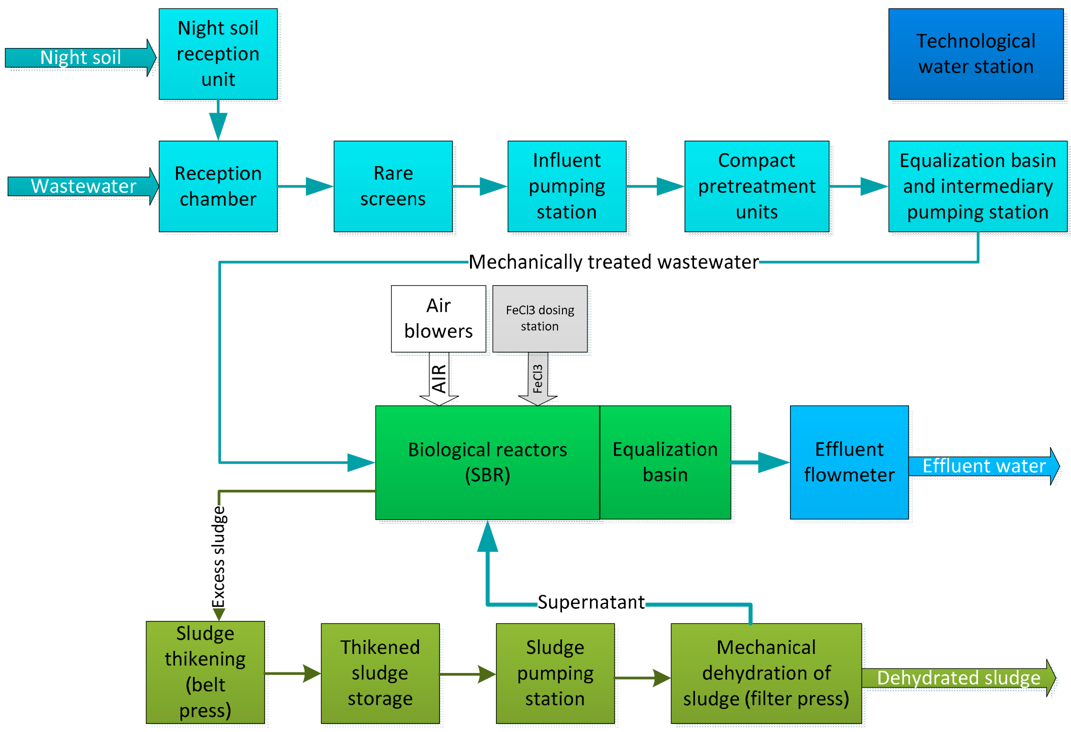

Figure 2. Process flow diagram for WWTP.

This example was chosen because, in the following years, the number of SBR-type plants in Romania will grow due to the flexibility of this technology for small and medium WWTP. Also, this type of technology provides generous spaces on the reactors to install PV panels.

In Table 1, the installed powers of different treatment stages are summarized: mechanical pretreatment (includes coarse screens and compact mechanical treatment units); influent pumping station (includes influent pumping station and night soil reception station); SBR biological reactors (includes submersible mixers, air regulating servo-valves, mobile decanter); blower station (includes the blowers for biological process); technological water pumping station; sludge thickening and dewatering (includes all processes on the sludge treatment line, according to Figure 2).

Table 1. Main consumers of the WWTP and their absorbed power.

Treatment Stage	Absorbed Power (kW)
Mechanical pre-treatment	15.69
Influent pumping station	32
SBR biological reactors	13.65
Blower station	165
Technological water pumping station	5.8
Sludge thickening and dewatering	83
Total	**315.14**

The analysis shows that the largest consumers are the blower station (165 kW) and sludge processing station (83 kW). All the values of power presented in Table 1 represent the installed power of the equipment. Measured data show that in normal operation conditions, the absorbed power is smaller than this power, due to the fact that not all equipment functions simultaneously.

The absorbed energy analysis of the WWTP was based on data measured at the WWTP, during one year, from 2 January 2016 to 2 January 2017. Throughout one year, the active absorbed power was recorded with the Supervisory Control And Data Acquisition (SCADA) Vijeo Citect system, using Programmable Logic Controller (PLC) equipment with sampling rate of 10 s. For each sensor, the system generates an *.HST* file which contains all the data recorded during the year 2016. Because the recorded data could not be processed directly, they were exported in open *.CSV* format using a Vijeo Citect tool. An example of the *.CSV* data format file is presented in Appendix A, Table A1. In order to automate the analysis of the annual data contained in the *.CSV* file, original Java software application was used, which divides the annual records into several *.CSV* files containing the data only for a single day. The same software application performs descriptive statistics of data, by days and months.

This data was used to define an average day for each month, based on which the PV system was dimensioned. The average day was calculated according to following algorithm that is illustrated in Figure 3.

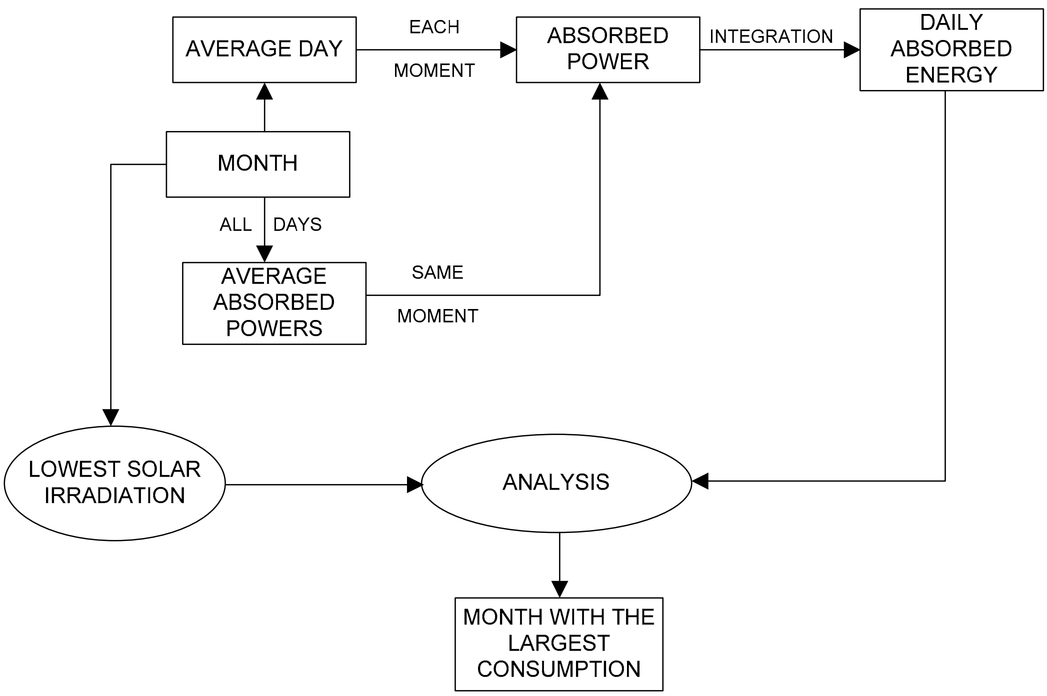

Figure 3. Flowchart of average day for consumed active power.

For each month in the year, the average day is defined as follows:

- The absorbed power is calculated at each moment of the day as the average of the absorbed powers at the same moment in all days of the month. The average day or typical day for each month was calculated by averaging the absorbed power as exemplified in Appendix A, Table A2, where the "each moment of the day" represents the "Time of Day" column. Only the values of "Average" column were represented in Figure 4.
- The power for each average day is integrated to obtain the absorbed energy for the day.
- A monthly analysis of the energy consumption is performed, to identify the month with the largest consumption in relation with the month with the lowest solar irradiation.

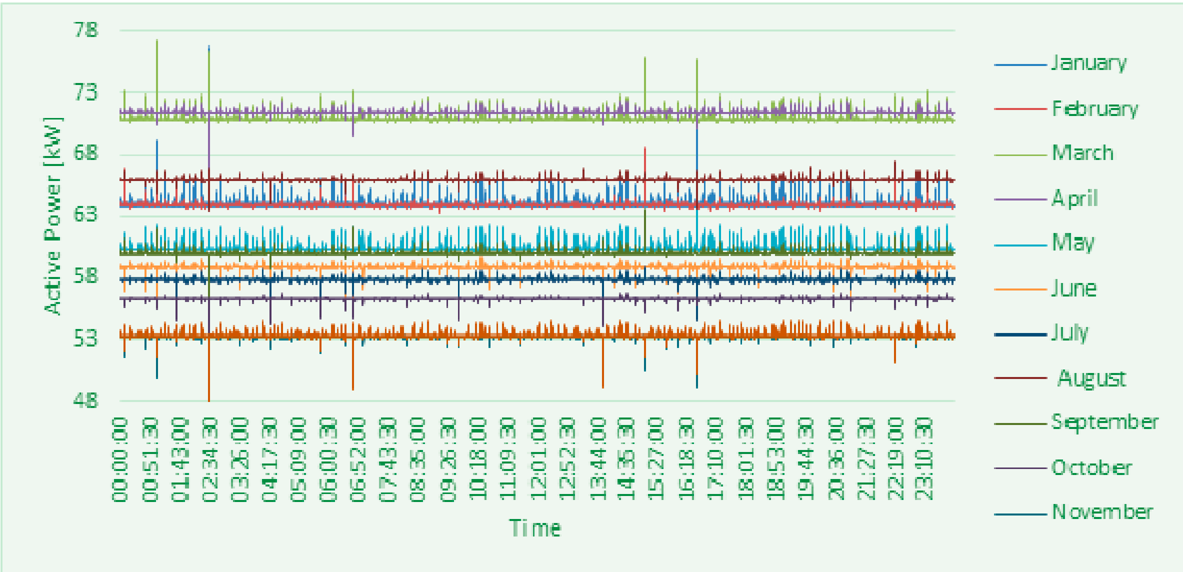

Figure 4. Average daily energy consumption for each month of 2016.

The purpose for this averaging, instead of using directly the daily energy average for PV sizing, was to identify if certain patterns of energy consumption can be identified during the day. For example, if, in a certain time interval, the energy demand would be consistently higher (or smaller) each day of a month, then the design of the PV could be optimized in what concerns the energy output at that time interval.

2.2. Modeling of PV System

The power system for the WWTP was designed as a hybrid system integrating public power grid, PV, storage battery and diesel generator, shown in Figure 5. The diesel generator is a back-up measure designed to maintain the treatment process in operation for several hours, to avoid discharging untreated wastewater to the natural effluent if grid faults would.

The PV panels were installed on the free spaces on the buildings and technological equipment of the WWTP, to maximize the use of available spaces, as explained elsewhere [21].

The PV system is verified for minimum temperature that is usual in Central Romania during winter (−15 °C) and maximum temperature on the surface of the panel during summer (80 °C), using Equations (1) and (2):

$$V_{OC}^{(-15^\circ C)} = V_{OC}^{(25^\circ C)} - \beta_{Tc}\Delta t \quad (1)$$

$$V_{MPP}^{(+80^\circ C)} = V_{MPP}^{(25^\circ C)} - \beta_{Tc}\Delta t \quad (2)$$

where V_{OC} (V) is the open circuit voltage of the PV panel, V_{MPP} (V) is the voltage of the PV panel at maximum power point, β_{Tc} (mV/°C) is the temperature coefficient of the PV panel, and Δt is the temperature difference. As it results from relation (1) and (2), the temperature of the PV cell significantly influences the open circuit voltage and the voltage at maximum power point, respectively.

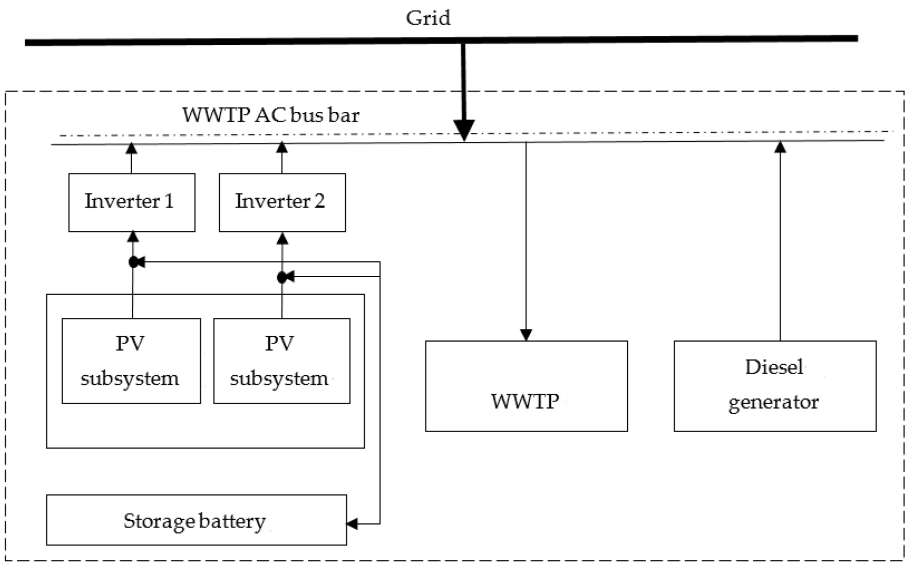

Figure 5. Schematic of a hybrid system.

A storage battery for the PV system was calculated, with the goal of storing the surplus of energy produced by the PV when the demand of energy from the WWTP is smaller than the production. To size the storage battery, a detailed analysis of the WWTP consumption and of the PV system's production has been performed, as follows:

1. The average demand of instantaneous power for an average day in each month was determined from historical data, as described in the previous section.
2. The instantaneous power produced during the average day was determined, for each month of the year, from the daily solar irradiation data. This data was obtained from the online application PV-GIS 5 developed by the European Commission—Joint Research Center. The Equation (3) is used to translate solar irradiance data to energy production:

$$P_r = G \cdot A \cdot y \cdot R_p \quad (3)$$

where P_r (W) is the instantaneous power produced, G (W/m^2) is global solar irradiance at the given moment, A (m^2) is the total area of panels, y (%) is yield of the PV panels, R_p (%) is the performance ratio of the PV system.

Consumption data determined at step 1 were subtracted from production data determined at step 2.

3. The storage battery is sized to accumulate the energy generated by the PV system but not consumed by the WWTP, during a day, in July. This methodology ensures that for every month, which has smaller production due to lesser solar irradiation, the surplus of produced energy can be stored, ensuring that all energy produced by the PV system can be used locally. The stored energy is consumed during the night or as back-up power if power shortage from the grid occurs.

The previous steps 1–3 of calculation algorithm are exemplified in Figure 6 for the month of July.

The closed area determined by the power generated by the PV and the absorbed power represents the energy that is produced but cannot be used at the same moment, so it can be stored in batteries.

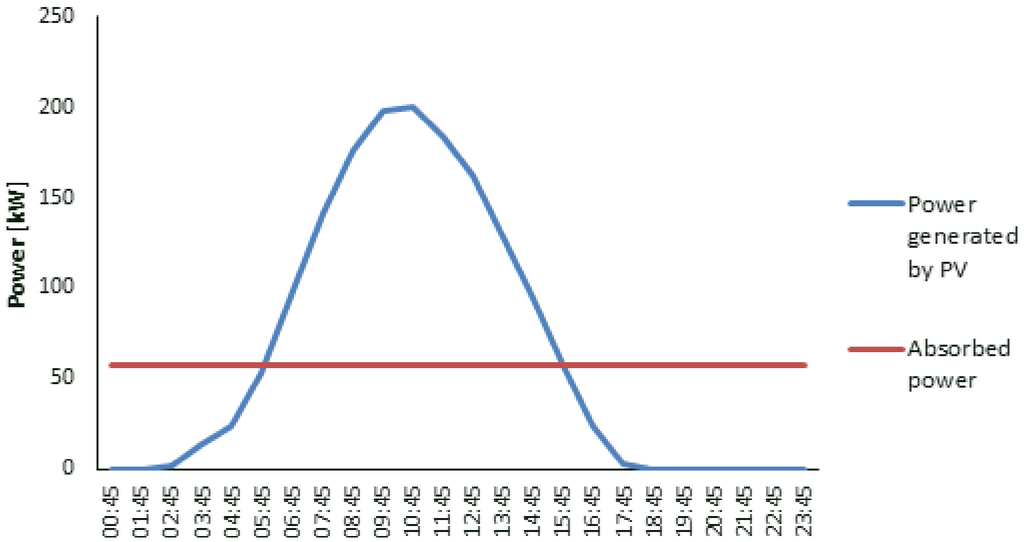

Figure 6. Hourly average power of WWTP for a typical day in July.

2.3. *The Parameters of Energetic-Environmental-Economic Impact Assessment of Grid-Connected PV System in WWTP*

In this section, the parameters that quantify the complete impact of grid-connected PV system in WWTP on each type of 3-E (Energetic-Environmental-Economic) performance indicators are defined.

The impact of the PV installation on the grid was assessed using the matching index, in both scenarios (with and without storage battery). The matching index is defined by Equation (4) [26]:

$$\varphi = \frac{M^2}{L \cdot P} \tag{4}$$

where φ is the matching index, takes values between 0 and 1, M (kWh) is production of energy by the PV system used inside the WWTP, L (kWh) is the load of the WWTP, and P (kWh) is the total annual energy supplied by the PV system.

Maximization of the matching index ensures the maximization of energy used locally and minimization of both the energy acquired by the WWTP from the grid and the grid impact. The time window chosen for calculating the matching index plays a major role in interpreting its relevance. The time window chosen for this work is one year, because in the case of the WWTP, the operator calculates the economic impacts yearly. It was shown that, ideally, the matching index has a value of unity, meaning that all the energy produced at the site is used at the site, and that all the energy needed by the site is produced at the site [26].

The environmental impact of the PV system was assessed by means of the carbon credit calculation. The potential for mitigating the atmospheric carbon is calculated using Equation (5) [23]:

$$CO_2 = (E_a \cdot T - E_{in}) \cdot \frac{1}{1 - L_a} \cdot \frac{1}{1 - L_{td}} \cdot 0.98 \tag{5}$$

where the constant 0.98 (kg/kWh) represents the quantity of carbon mitigated by one kWh of energy.

The term CO_2 (kg) is the quantity of carbon dioxide mitigated during the lifetime of the PV system, E_a (kWh/year) is the annual energy delivered by the PV system, T (yrs.) is the lifetime of the PV system, E_{in} (kWh) is the total embodied energy in the PV system, L_a (%) is the loss due to poor lighting and $L_{td.}$ (%) is the loss due to the distribution chain.

The Energy PayBack Time (EPBT) of a PV system is defined as the embedded energy of PV modules and components divided by its annual energy output [27]. EPBT shows the number of years that it takes for the energy embedded in the system to be compensated by the energy produced by the same system. The energy produced for the rest of the years until lifetime end.

Likewise, in order to compare different technologies for electricity production, the Energy Return On Energy Invested (EROEI) it introduced as

$$EROEI = \frac{E_p}{E_{in}} \tag{6}$$

where E_{in} (kWh) is the energy embedded in the PV system, E_p (kWh) is the energy produced by the system during the lifetime.

Consequently, EPBT should be as small as possible for the project to be considered feasible. EPBT is expressed according to following Equation:

$$EPBT = \frac{E_{in}}{E_{out}} \tag{7}$$

where $EPBT$ is in (yrs), E_{in} (kWh) is the energy embedded in the PV system and E_{out} (kWh/year) is the energy produced by the system.

The LCOE represents the unit cost of the energy produced by the PV system. It can be used to compare different design options for the PV system, or to compare different energy sources. LCOE was calculated integrating investment costs, operation and maintenance costs, cost of replacement of the batteries, carbon credit earned, and the cost of the matching index. All costs were calculated considering a lifetime of 30 years for the PV system [27]. In the following, the calculation of the LCOE components is detailed.

Firstly, the total cost of investment is given by the Equation below:

$$T_i = UP_{PV} \cdot Q_{PV} + UP_b \cdot Q_b \tag{8}$$

where T_i (€) is the total investment in PV system, UP_{PV} (€/kWp) is the unit price of PV system without storage battery, Q_{PV} (kWp) is the total PV capacity installed at WWTP, UP_b (€/kWh) is the unit price for the battery, and Q_b (kWh) is the total storage battery capacity installed at WWTP. The unit price of the PV system and the storage battery was determined by market enquiries. For the exemplification of this calculation, the considered costs were 1350 €/kWp for UP_{PV} and 250 €/kWh for UP_b. This cost is the "worst case scenario" determined from the market enquiries. This cost refers to the cost of the components and materials, installation and commissioning.

For this case study, the lifetime of the storage battery is seven years [23]. During the thirty-year lifetime of PV system, it has to be changed four times. Thus, the present value of the replacement cost of the storage battery is obtained according to Equation (9):

$$VR_b = (C_b + C_s)\left[\left(\frac{1+i}{1+d}\right)^7 + \left(\frac{1+i}{1+d}\right)^{14} + \left(\frac{1+i}{1+d}\right)^{21} + \left(\frac{1+i}{1+d}\right)^{28}\right] \tag{9}$$

where VR_b (€) is the present value of the storage battery replacement over the system's lifetime, C_b (€) is the cost of storage battery, C_s (€) is the salvage value of storage battery, i (%) is the inflation rate, and d (%) is the discount rate.

The salvage value of the storage battery was considered 20% of their initial cost ([23] Saini et al., 2017) for the first 3 replacements and 85% for the last replacement since, at the end of the lifecycle of the PV system, the storage battery will be only 2 years old.

In the literature, the present value of operation and maintenance for a PV system is considered to be 1% from the investment cost, per year [27]. This value is calculated over the period of 30 years and actualized to the present value, using the following Equation:

$$VO_{PV} = M \cdot \left(\frac{1+i}{1+d}\right) \cdot \left[\frac{1 - \left(\frac{1+i}{1+d}\right)^T}{1 - \left(\frac{1+i}{1+d}\right)}\right], \tag{10}$$

where VO_{PV} (€) is the present value of operation and maintenance of the PV system, M (€) is the annual operation and maintenance cost, representing a fraction from the investment cost, and T (yrs) is the lifetime of the PV system.

The salvage value of the PV system represents its expected remaining value at the end of the lifecycle. In this respect, the present salvage value of operation and maintenance is given by:

$$VS_{PV} = S \cdot \left(\frac{1+i}{1+d}\right)^{T} \tag{11}$$

where VS_{PV} (€) is the present salvage value, S (€) is the salvage value of the PV system at the end of the lifecycle, considered as a percentage from the initial investment cost.

The earned carbon credit is defined according to Equation (12):

$$E_{CO_2} = \frac{CO_2}{T} \cdot C_{CO_2} \tag{12}$$

where E_{CO_2}(€/year) is the earned carbon credit acquired in one year, CO_2 (kg) is the quantity of carbon dioxide mitigated during the lifetime, T (yrs.) is the lifetime of the PV system, and C_{CO_2} (€/kg) is the unit cost of atmospheric carbon.

The present carbon credit earned (PE_{CO_2}), is expressed in Euros, and is determined by:

$$PE_{CO_2} = EC_{CO_2} \cdot \left(\frac{1+i}{1+d}\right) \cdot \left[\frac{1-\left(\frac{1+i}{1+d}\right)^{T}}{1-\left(\frac{1+i}{1+d}\right)}\right] \tag{13}$$

where T (yrs) is the lifetime of PV system.

Life Cycle Cost (LCC) of the PV system, expressed in Euros, is calculated by using Equations (9)–(13) as:

$$LCC = T_i + VR_b + VO_{PV} - VS_{PV} - PE_{CO_2} \tag{14}$$

The Uniform Annualized Cost (UAC) of the PV system represents the LCC of the energy distributed to the number of years of lifecycle, while considering the inflation rate and the discount rate. It is calculated using Equation (15), and is expressed in Euros:

$$UAC = LCC \cdot \left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{T}}\right] \tag{15}$$

Finally, the LCOE from the PV system that represents the uniform annualized cost of the PV system divided by the total energy it produces in one year; is expressed in €/kWh, and is calculating according to:

$$LCOE = \frac{UAC}{E_a} \tag{16}$$

3. Results

3.1. Energy Demand Response

The largest consumers of the WWTP are the blower station and the sludge processing station, together representing 78% of the installed power of the WWTP. In this respect, only the main (essential) technological consumers presented in Table 1 were taken into account for this study. For the WWTP studied in this paper, on average, calculated as explained in Section 2.2, at each moment of the day, the energy demand is constant (Figure 6).

By analyzing Figure 4, it can be observed that the power demand is constant throughout the day.

For all months, the absorbed power at each moment of the average day is between 48 kW and 78 kW. Compared to the 315 kW total installed power, it means that the absorbed power represents between 15% and 24%. In the other side, the spikes shown in Figure 4 denote transient phenomena due to the starting of the blower station, which is the largest consumer in the WWTP. The explanation of this resides in the functioning details of the SBR reactors. The studied installation is a SBR type. The largest consumer of the WWTP is the blower station for the SBR reactors (see Table 1). The SBR reactors operate in cycles of 4h denitrification and 4h nitrification periods, which it reflected also in the intermittent functioning of the blower station. This aspect, in turn, results in windows of higher consumption alternating with windows of lower consumption. When averaging over 30 days of operation, then results a constant value of power absorption throughout the typical day.

The analysis in this study does not include the differentiation between week-days and week-end days for the following reasons:

1. The main focus of the study was on integration of PV system, and its production patterns throughout the year.
2. In the energy consumption data acquired from the WWTP, a significant difference between the week-days and the week-end days could not be observed. This might be due to the following reasons:
   (a) The two towns that are studied have very little industry that could change the pattern during the week, as a result of direct industrial activity or inhabitants' working patterns during the day.
   (b) At the period of data acquisition, during the year 2016, the WWTP and sewer systems were in operation for only 2 years so they did not operate yet at full capacity.

Also a more detailed analysis, taking into account the difference between week-days and week-end days, could represent the subject of future studies. According to this observation, the PV system and storage battery were designed to maximize output as a function of the irradiance [28].

Table 2 summarizes for each month the daily energy demand of the WWTP, the daily energy production of the PV system, the energy to be acquired from the public power grid (as the difference between the former and the latter), and the energy to be stored in the storage battery each day of the respective month because it can be used at the time of production by the WWTP equipment [29].

Table 2. Daily energy demand, daily energy produced, necessary to be added from the grid, and energy stored in batteries.

Month	Daily Energy Demand (kWh)	Daily Energy Production (kWh)	Necessary from the Grid (kWh)	Energy to Be Stored (kWh)
January	1534.8	366.4	1170.7	2.4
February	1534.9	628.8	1052.0	145.9
March	1699.2	1042.6	1053.8	397.1
April	1713.2	1323.3	972.4	582.5
May	1449.9	1415.8	757.0	722.9
June	1412.8	1501.5	709.8	798.4
July	1389.1	1559.5	691.6	862.0
August	1580.7	1546.3	855.6	821.2
September	1440.4	1207.8	839.1	606.5
October	1353.3	873.2	860.7	380.6
November	1277.0	304.5	976.6	4.2
December	1280.3	304.5	979.7	3.9

The daily energy demand for each month was determined by integrating the power curve of the average day in Figure 4. The daily energy production of the PV and the energy to be stored are dependent on the sizing of the PV and storage battery, and they are explained in the following paragraphs [30].

In Figure 7 and in Table 3, respectively, are presented the monthly energy demand, the monthly energy produced by the PV system, the monthly energy necessary from the grid, and the monthly energy stored in batteries, respectively, to balance the energy of the year.

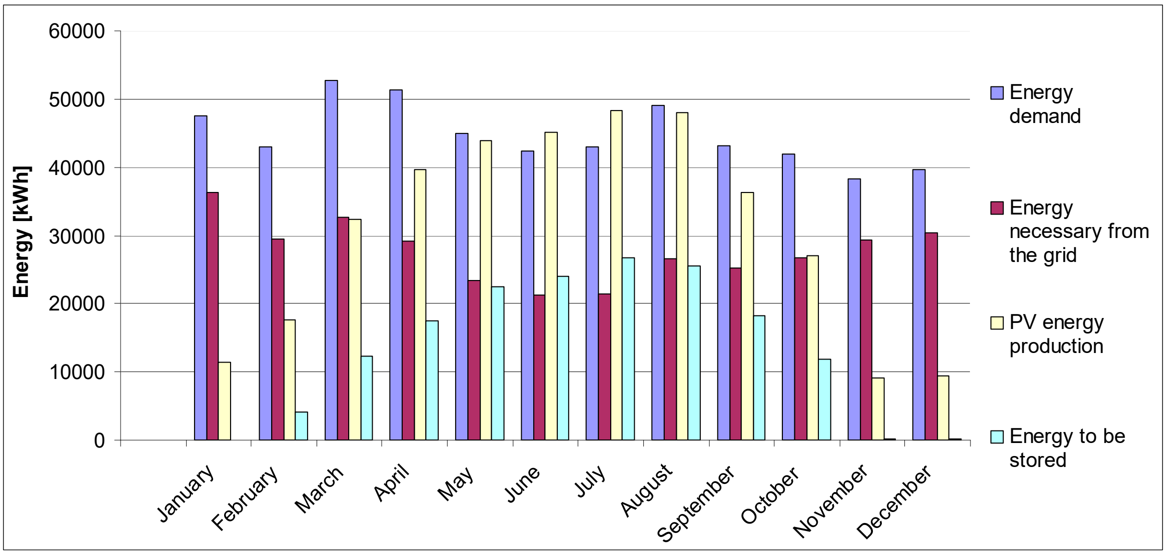

Figure 7. Monthly energy demand, energy production by PV system, energy necessary from the grid, and energy necessary to be stored in batteries.

Table 3. Year energy balance.

	Energy Demand (kWh)	Necessary from the Grid (kWh)	PV Energy Production (kWh)	Energy to Be Stored in Storage Battery (kWh)
Total by year	537,185.4	331,840.2	379,525.2	162,726.3

3.2. Simulation of Grid-Connected PV System

In total, the system is composed of 1242 panels, covering 1918 m^2, having 250 Wp, each giving a peak power of 310.5 kWp. For this system, a topology with two inverters linked to the Alternative Current (AC) bus bar of the WWTP was chosen. One inverter services 648 panels arranged in 36 strings of 18 series panels. The second inverter services 594 panels arranged in 33 strings of 18 series panels. Together, they cover the total of 1242 panels. The chosen inverters have 155 kVA each. The characteristics of the PV panels and inverters are presented in Appendix B, Table A3 and respectively in Table A4.

The month of July was chosen as input data for designing the storage battery, because it has the largest daily average surplus of energy that has to be stored in batteries; see Table 2, column 5. The data for one day of July and for the month of July is shown in Table 4.

Table 4. Calculation for energy produced, required from the power grid and required to be stored, for one day and for month of July.

Time	Irradiance (W/m^2)	Power Produced by the PV System (kW)	Instantaneous Power of the WWTP Consumers (kW)	Power from the Grid (kW)	Power to Be Stored in Batteries (kW)
00:45	0	0	57.9	57.9	0
01:45	0	0	57.9	57.9	0
02:45	8	2.1	57.9	55.8	0
03:45	52	13.5	57.9	44.4	0
04:45	92	23.8	57.9	34.1	0
05:45	205	53.1	57.9	4.8	0
06:45	380	98.4	57.9	0	40.5
07:45	547	141.7	57.9	0	83.8
08:45	680	176.1	57.9	0	118.2
09:45	764	197.9	57.9	0	140.0
10:45	772	199.9	57.9	0	142.0
11:45	709	183.6	57.9	0	125.7
12:45	627	162.4	57.9	0	104.5
13:45	497	128.7	57.9	0	70.8
14:45	364	94.3	57.9	0	36.4
15:45	221	57.2	57.9	0.6	0
16:45	91	23.6	57.9	34.3	0
17:45	13	3.4	57.9	54.5	0
18:45	0	0	57.9	57.9	0
19:45	0	0	57.9	57.9	0
20:45	0	0	57.9	57.9	0
21:45	0	0	57.9	57.9	0
22:45	0	0	57.9	57.9	0
23:45	0	0	57.9	57.9	0
Total energy/day [kWh]	**6022**	**1559.5**	**1389.1**	**691.6**	**862.0**
Total energy/July [kWh]	**186,682**	**48,345**	**43,062**	**21,452**	**26,722**

To calculate the power produced by the PV system from global irradiation data, Equation (3) was used, where the assumed area A is 1918 m^2, the PV panel efficiency is 15.7% according to the datasheet (Table 2), and the performance ratio of the system P_r is 86%, which includes the temperature dependence of power produced by PV system, and the energy losses in cables, inverters, charging regulator and storage battery [31].

The system with storage battery was simulated in PV-GIS 5 as an off-grid system, to test the charging state of the storage battery. The results are presented in Appendix C, Figure A1.

The Figure A1 shows that in 69% of the days of the year, the storage battery is charged to 40–46% from its total capacity, while it will be fully charged for 6% of the time. This means that the storage battery is oversized. The battery is oversized for the months when the production of PV energy is low, as January, February, October, November and December. During these months, the storage battery can be used to store energy from the grid overnight, when the energy tariff is lower, to be used by the WWTP in an emergency situation, when the power grid is not available. This leads to the downsizing or even elimination of the emergency diesel generator of the WWTP. This strategy of sizing the storage battery has the advantage of maximizing the matching index, but has the disadvantage of over sizing the storage battery with respect to the charging capacity of the PV system.

The amount of energy self-produced by PV generators (or batteries) and immediately consumed by the local users (WWTP) on a daily basis from a graph with hourly PV generation and hourly consumption (WWTP), as in Figure 6; this energy (equal to PV generation, if consumption is higher than PV generation, or equal to consumption, if PV generation is higher than consumption) represents the self-consumption when it is divided by the PV generation, but it represents the self-production (or self-sufficiency, corresponding to matching index) when it is divided by the consumption. In such a way, it is assumed that the compensation, between the energy injected into grid by PV generator and the energy absorbed by WWTP from the grid, is done only on an hourly basis. The energy injection into the grid may create issues on the voltage profiles (over-voltages with a reverse flow of active power from the end to the beginning) along the distribution lines of grid.

Also the PV generator can be designed in order to minimize the energy exchange with the grid; in practice, every sunlight hour, the difference between PV produced and WWTP consumption energy can be computed, then squared and summed up (summation of the squares of deviations), from January to December in order to find the PV rated power that minimizes the target value. As is well-known, the proper operation in parallel with the grid voltage is a crucial issue for the PV generators. Nevertheless, the outlined procedure to design the PV generators in this paper obtains two results: first, to increase the self-consumption and, second, to reduce the power injection into the grid. This means the values of Root Mean Square Value (RMS) current are not able to generate overload along the distribution lines up to the distribution transformer and over-voltages are within a few percent of the rated value [32]. In particular, the experimental results, from the literature, deal with the impact of PV generation on the operation of the Low-Voltage (LV) networks. The main results demonstrate that, in the presence of high PV power injection, the voltage variations also in short term (on second/minute scales) are well limited within the +/−10% of the RMS values in LV grids, while the occurrence of frequency variations is not realistic [33]. On the other hand, considering the grid impedance negligible in the majority of the applications, the voltage waveform is poorly affected by harmonic distortion [34]. Also in presence of non-negligible harmonic distortion of the waveforms of current injected into the grid (>5% of the rated current) and unbalance (some percent of the positive sequence component), in a three-phase system, the consequent harmonic distortion (2–3% of the rated value) and unbalance of the grid voltage (<1% of the positive-sequence component) is within the limits of the European Standards of power quality [35].

Examining Figure 6, it is evident that the self-consumption does not exceed 50% with respect to the PV generation: the minimization of energy exchange with the grid can give a lower PV rated power to reduce the percentage of grid injection in a day of July. From Table 4, it is important to highlight the relationship between the rated consumed power of WWTP and the rated capacity of batteries. Thus, the energy stored by batteries on a day of July is enough for the autonomous power supply of the WWTP for 14.8 h without power injected from the grid or from the PV generator.

3.3. Calculation of Grid-Connected PV System Impact Assessment on 3-E

The matching index was calculated without and with storage battery, previously calculated. The matching index for the PV without storage battery has a value of 0.21, or, in other words, 21% of the WWTP consumption is fulfilled by PV generator. The matching index for PV system with storage battery has a value of 0.68, so now, 68%, almost 2.5 times more, of the WWTP consumption is fulfilled by PV generator. These two situations are illustrated in Table 5.

Table 5. Value of the matching index for the PV system without and with storage battery.

Parameter	PV System without Storage Battery	PV System with Storage Battery
L (kWh)	537,188	537,188
P (kWh)	368,345	368,345
M (kWh)	205,476	368,345
φ	0.21	0.68

In this situation, the matching index cannot have a value of unity, because the energy produced on site cannot cover the needs of the WWTP, due to surface limitations, which is reflected in energy acquired from the power grid. This limits the matching index at a value of 0.68.

In Equation (5), the term E_a is determined by summing the energy produced by the PV system each month of the year, as it is exemplified in Table 5 for the month of July. The total found was of 368,345 kWh.

The lifetime of the PV system (term T) is 30 years [27]. For the terms L_a and $L_{td.}$ in Equation (5), a value of 20% was considered. The term E_{in} was calculated from Table 6, where the energy embodied in the battery was multiplied by five, because the storage battery is changed five times during the lifetime of the installation [23].

Table 6. Embodied energy of the PV system components.

Component	Energy Embodied (kWh/Wp)
PV cell (electrical to fuse and cool Si material)	3
PV cell (thermal)	4.68
Array support	0.22
Frame and cables	0.28
Interconnection	0.024
Inverter	0.64
Installation	0.06
Operation and maintenance	0.022
Battery	0.24
Total	**9.166**

The total energy embodied in the PV system of 310.5 kWp is 313,6050 kWh. By replacing these data in Equation (5), results that over the lifetime period, the PV system is able to/can mitigate 12,118 tons of CO_2.

Estimations made by the Institute of Scientific Research and Technological Development (ISRTD) of University Valahia of Targoviste, Romania, on a 33.15 kWp PV system installed on the roof-top (Lat: 44.912°; Long: 25.456°), show that approximately 27.7 tons of CO_2 per annum are avoided. By extrapolating this figure to a 310.5 kWp and a 30-year period, it finds 8975 tons of CO_2 avoided. This figure is comparable with the figure above, which means the calculation is satisfactory [36].

To determine the value of EROEI, the term E_{in} and E_p where calculated. E_{in} is 3,136,050 kWh and Ep is 11,050,350 kWh. It follows that EROEI has a value of 3.52, which means that this PV system produces three and a half times more energy than originally invested in its construction. This reveals the profitability of this system from an environmental point of view.

In order to determine the EPBT, the term E_{in} and E_{out} where calculated as in the previous paragraph. The resulting EPBT is eight and a half years. For the rest of twenty-one and a half years, the energy produced by the PV system represents the gain. This amounts to 7,919,418 kWh.

The input parameters for the LCOE calculation are presented in Table 7, and the results of the simulation are presented in Table 8.

The value of the LCOE is 0.154 €/kWh for the system with storage battery. On the other hand, the average price of energy on the Romanian Energy Market for 2017 was 0.036 €/kWh [37].

Under certain conditions, the water operator company may obtain subsidy from the State or from the European Commission for the initial investment cost. For example, as mentioned in the introduction section the construction of a new WWTP is funded under the POIM European Program [24]. In this case, the PV system could be included in the initial investment as part of the WWTP. The LCOE of PV energy would be thus 0.01 €/kWh, which is lower than the price of energy from the power grid.

Table 7. Input parameters for the LCOE analysis.

Parameter	Unit	Value
Unit price of PV system without battery	(€/kWp)	1350
Unit price of battery	(€/kWh)	250
Inflation rate	(%/year)	2.5
Discount rate	(%/year)	4–6
Maintenance cost	(%/year)	1
Salvage cost	(%/year)	10
Cost of battery salvage rate (first three changes)	(%/year)	20
Cost of battery salvage rate (fourth change)	(%/year)	85
Energy annually produced	(kWh/year)	368,345
Capacity of PV system	(kWp)	310.5
Capacity of storage battery	(kWh)	862
Carbon mitigation per life span	(t)	12,563
Carbon credit earned	(€/t)	12
Matching index		0.68

Table 8. Results of the LCOE analysis for the system with storage battery.

Parameter	Unit	Value
Total investment in the PV system without battery T_I	(€)	634,675
Price of battery VR_b	(€)	396,543
Price of maintenance VO_{PV}	(€)	117,988
Price of salvage VS_{PV}	(€)	23,178
Carbon credit earned EC_{CO_2}	(€)	3114
LCC	[€]	2,055,886
UAC	[€/kWh]	103,406
LCOE	[€/kWh]	0.154

4. Discussion

Firstly, this paper proposes the study of PV system integration in WWTP, and, as a novelty, in two configurations: with and without storage battery. In this respect, the first step consisted of WWTP' load profile analysis and categorization of consumers in essential and non-essential.

Data have been recorded on both electrical parameters and technological consumption: flows, levels in tanks, concentrations of chemical compounds in water (oxygen, ammonium, nitrate), and physical (concentrations of particles in water). Following data acquisition and analysis of the WWTP's equipment characteristics, it was found:

1. The main consumers of a treatment plant, regardless of consumed power, are as follows: influent pumping station, blower station for aeration of biological pools, sludge thickening and dewatering station, mechanical pre-treatment, SBR biological reactors, and technological water pumping station.
2. For this equipment, the consumed power is directly proportional to the p.e. served.
3. For the other equipment, the power differs significantly depending on the p.e. served.

Therefore, the energy output of PV system should cover consumption of equipment referred to point 1. Through an optimal use of available space, including SBR reactors and buildings inside the WWTP, the proposed methodology maximized the PV system capacity to 310.5 kWp for a studied WWTP located in Central Romania. Following a thorough analysis of energy demand, a storage battery having the capacity of 862 kWh is integrated into the PV system in order to store the energy which is not used by WWTP.

As another novelty of this study, is a complete impact assessment of the grid-connected PV system on each of the 3-E indicators are quantified. The benefit of the storage battery is that it increases the matching-index from 0.21 to 0.67, indicating a smaller impact on the power grid, because more energy produced locally is used locally. Carbon mitigation assessment shows that the PV system mitigates 12,118 t of CO_2 during the lifetime of

30 years. EPBT calculation shows that the PV system produces enough energy to compensate the embodied energy in the component in eight and a half years, compared to a lifetime of 30 years. These two values show that from an environmental point of view, the PV system has a positive impact, increasing the environmental benefit of the WWTP, when both parameters are combined. From economic aspects, the results show that the LCOE for PV energy is higher than the cost of energy from the power grid (0.154 €/kWh compared to 0.036 €/kWh). This can change if the initial investment can be financed using non-refundable financing programs, shrinking the LCOE of PV produced energy to 0.01 €/kWh. This significant reduction of the LCOE is explained by the fact that only the price of maintenance and the price of salvage are the major costs of included in the calculation. Other key aspects of economic and environmental impact optimization of the PV system are the policies of each country in what concerns the green certificates and the environmental conditions.

5. Conclusions

In this study, it was shown that the synergy of small and medium WWTP with PV is of great interest from a 3-E (Energetic-Environmental-Economic) point of view. This synergy is worth exploring and implementing on a large scale for all new WWTP.

On another side the usage of renewable energy and the adoption of "clean water through clean energy" practices in WWTP will develop the environmental sustainability, establish a better image of the country and attract foreign direct investment inflows. The obtained results are useful for the design or development of all similar small WWTP located in the world by changing only the climatic conditions and area of available spaces.

A detailed analysis, taking into account the irradiance differences between weekdays and week-end days, could represent the subject of future studies. According to this observation, the PV system and storage battery were designed to maximize output as a function of the irradiance. Also proposed control method for storage battery will be discussed in future work. Rigorously analyzing, in the prospects for development of smart cities, the integration of PV systems can be extended to all types of WWTP installed in different locations, then, in this respect, a software tool dedicated to these applications can be developed in future works.

Author Contributions: Conceptualization, H.A.; methodology, C.A.B. and H.A.; software, C.A.B. and P.A.; validation, H.A., C.A.B. and F.S.; formal analysis, P.A.; investigation, C.A.B. and P.A.; resources, C.A.B.; data curation, P.A.; writing—original draft preparation, C.A.B.; writing—review and editing, H.A. and F.S.; visualization, P.A.; supervision, H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A. Acronyms

GHG	Green House Gases
WWTP	Wastewater Treatment Plants
PV	Photovoltaic system
LCOE	Levelized Cost Of Energy
3-E	Energetic-Environmental-Economic
p.e.	equivalent population
LCA	Life Cycle Assessment
RMEF	Romanian Ministry of European Funding
SBR	Sequence Batch Reactor
SCADA	Supervisory Control And Data Acquisition
PLC	Programmable Logic Controller

EPBT	Energy PayBack Time
EROEI	Energy Return On Energy Invested
LCC	Life Cycle Cost
UAC	Uniform Annualized Cost
AC	Alternative Current
RMS	Root Mean Square Value
LV	Low Voltage
	B. Symbols/Parameters
V_{OC}	The open circuit voltage of the PV panel
V_{MPP}	The voltage of the PV panel at maximum power point
β_{Tc}	The temperature coefficient of the PV panel
Δt	The temperature difference
P_r	The instantaneous power produced
G	The global solar irradiance at the given moment
A	The total area of panels
y	The yield of the PV panels
R_p	The performance ratio of the PV system
φ	The matching index, takes values between 0 and 1
M	The production of energy by the PV system used inside The WWTP
L	The load of the WWTP
P	the total annual energy supplied by the PV system
PE_{CO_2}	Present carbon credit Earned
CO_2	The quantity of carbon dioxide mitigated during the lifetime of the PV system
E_a	The annual energy delivered by the PV system
T	The lifetime of the PV system
E_{in}	The total embodied energy in the PV system
L_a	The loss due to poor lighting
L_{td}	The loss due to the distribution chain
E_{in}	The energy embedded in the PV system
E_p	The energy produced by the system during the lifetime
E_{in}	The energy embedded in the PV system
E_{out}	The energy produced by the system
T_i	The total investment in PV system
UP_{PV}	The unit price of PV system without storage battery
Q_{PV}	The total PV capacity installed at WWTP
UP_b	The unit price for the storage battery
Q_b	The total storage battery capacity installed at WWTP
VR_b	The present value of the storage battery replacement over The system lifetime
C_b	The cost of storage battery
C_s	The salvage value of storage battery
i	The inflation rate
d	The discount rate
VO_{PV}	The present value of operation and maintenance of the PV system
M (€)	The annual operation and maintenance cost representing a fraction from the investment cost
VS_{PV}	The present salvage value
S	The salvage value of the PV system at the end of the lifecycle, considered as a percentage from the initial investment cost
E_{CO_2}	The earned carbon credit acquired in one year
C_{CO_2}	The unit cost of atmospheric carbon.

Appendix A. Data Acquisition

Table A1. Data file. Name of file: 1012017.csv (month/day/year). File content: day/month/year, hour:min:sec. hundredth, recorded value (8649 data).

1/1/2017	00:00:00.000	102
1/1/2017	00:00:10.000	100
1/1/2017	00:00:20.000	102
1/1/2017	00:00:30.000	101
1/1/2017	00:00:40.000	99
1/1/2017	00:00:50.000	99
1/1/2017	00:01:00.000	103
1/1/2017	00:01:10.000	103
1/1/2017	00:01:20.000	101
1/1/2017	00:01:30.000	102
1/1/2017	00:01:40.000	102
1/1/2017	00:01:50.000	105
1/1/2017	00:02:00.000	102
1/1/2017	00:02:10.000	100
1/1/2017	00:02:20.000	104
1/1/2017	00:02:30.000	102
1/1/2017	00:02:40.000	105
1/1/2017	00:02:50.000	104
1/1/2017	00:03:00.000	104

Table A2. Averaging procedure.

Time of Day	Day 1 (kW)	Day 2 (kW)	Day 30 (kW)	Average (kW]
00:00:00	52.03125	46.3125	42.46289	57.831
00:00:10	47.4375	46.125	38.57227	57.970
...	...	...	...	...
00:01:00	54.42188	46.03125	42.28711	57.958
...	...	...	...	...
00:01:50	59.0625	44.71875	44.6543	57.895
...	...	...	...	...
23:59:50	67.125	33.375	46.875	57.837

Appendix B. Technical Data of the PV System

Table A3. Electrical characteristics and surface of PV panels.

Parameter	Value
Rated power P (Wp)	250
Open circuit voltage V_{oc} (V)	37.1
Short circuit current I_{sc} (A)	8.92
Maximum power voltage V_{MPP} (V)	29.9
Maximum power current I_{MPP} (A)	8.35
V_{oc} temperature coefficient	−0.32%/°C
Panel efficiency (η) (%)	15.4–15.7
PV panel surface (sq.m.)	1.62

Table A4. Electrical characteristics of the solar inverters.

Parameter	Value
Recommended power (kVA)	155
Maximum input current I_{DCmax} (A)	304
MPP voltage range V_{MPPmin}–V_{MPPmax} (V)	450–820
Maximum input voltage V_{DCmax} (V)	1000

Appendix C. Charge State of the Storage Battery

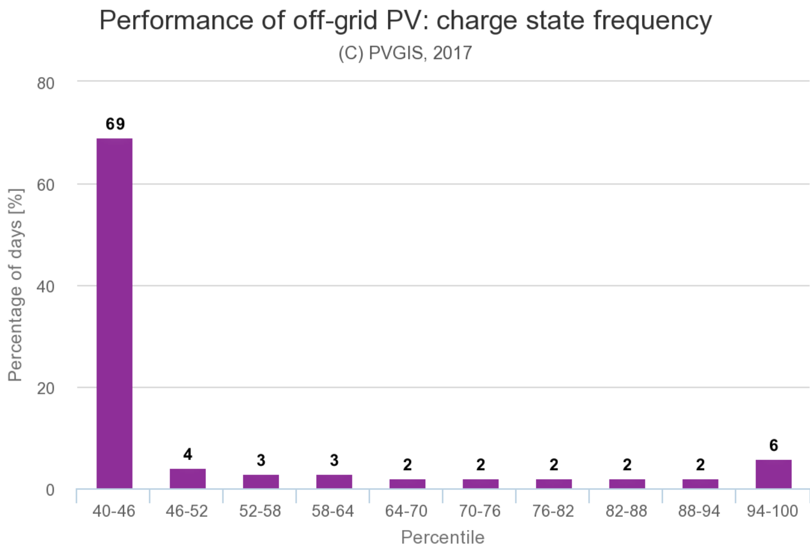

Figure A1. Charge state of the storage battery.

References

1. Gu, A.; Teng, F.; Wany, Y. China Energy-Water Nexus: Assesing the Water-Saving Synergy Effects of Energy-Saving Policies during the Eleventh Five-Year Plan. *Energy Convers. Manag.* **2014**, *85*, 630–637. [CrossRef]
2. GWEC (Global Wind Energy Council). *Global Wind Energy Outlook 2014*; Glob Wind Energy Council: Brussels, Belgium, 2014; pp. 1–60. [CrossRef]
3. Puzowski, P.; Puzowski, P.; Szatyłowicz, E. Experience from the Implementation and Operation of the Biological Membrane Reactor (MBR) at the Modernized Wastewater Treatment Plant in Wydminy. *Water* **2020**, *12*, 3410. [CrossRef]
4. Stokes, J.R.; Horvath, A. Supply-Chain Environmental Effects of Wastewater Utilities. *Environ. Res. Lett.* **2010**, *5*, 140–152. [CrossRef]
5. Curtis, T.P. *Low-Energy Wastewater Treatment: Strategies and Technologies*; John Wiley & Sons: Hoboken, NJ, USA, 2010; pp. 301–318.
6. Bojarski, A.D.; Laínez, J.M.; Espuña, A.; Puigjaner, L. Incorporating Environmental Impacts and Regulations in a Holistic Supply Chains Modeling: An LCA Approach. *Comput. Chem. Eng.* **2009**, *33*, 1747–1759. [CrossRef]
7. Chong, F.K.; Lawrence, K.K.; Lim, P.P.; Poon, M.C.Y.; Foo, D.C.Y.; Lam, H.L.; Tan, R.R. Planning of Carbon Capture Storage Deployment Using Process Graph Approach. *Energy* **2014**, *76*, 641–651. [CrossRef]
8. Sharifzadeh, M.; Lubiano-Walochik, H.; Shah, N. Integrated Renewable Electricity Generation Considering Uncertainties: The UK Roadmap to 50% Power Generation from Wind and Solar Energies. *Renew. Sustain. Energy Rev.* **2017**, *72*, 385–398. [CrossRef]
9. Venkatesh, G.; Brattebø, H. Energy Consumption, Costs and Environmental Impacts for Urban Water Cycle Services: Case Study of Oslo (Norway). *Energy* **2011**, *36*, 792–800. [CrossRef]
10. Jadczyk, P.; Sówka, I.; Pawnuk, M.; Wroniszewska, A. Impact of a Small Wastewater Treatment Plant on the San-Itary State of Atmospheric Air. *Middle Pomeranian Sci. Soc. Environ. Prot.* **2020**, *22*, 927–939.
11. Najy, M.; Talbi, F.Z.; Ech-Chafay, H.; Lachhab, M.; El Qreyfi, M.; Belghyti, D. Exploitation of the Domestic Wastewater Treatment Plant by Activated Sludge in the Airport Area of the City Ben Slimane (Morocco). *ISPRS Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2020**, *4*, 303–308. [CrossRef]
12. Yapıcıoğlu, P.S.; Yeşilnacar, M.I. Energy Cost Assessment of Sludge Dewatering Process. In Proceedings of the EurAsia Waste Management Symposium, Istanbul, Turkey, 26–28 October 2020.
13. Di Fraia, S.; Massarotti, N.; Vanoli, L. A Novel Energy Assessment of Urban Wastewater Treatment Plants. *Energy Convers. Manag.* **2018**, *163*, 304–313. [CrossRef]
14. Masłoń, A.; Czarnota, J.; Szaja, A.; Szulżyk-Cieplak, J.; Łagód, G. The Enhancement of Energy Efficiency in a Wastewater Treatment Plant through Sustainable Biogas Use: Case Study from Poland. *Energies* **2020**, *13*, 6056. [CrossRef]
15. Silvestre, G.; Fernández, B.; Bonmatí, A. Significance of Anaerobic Digestion as a Source of Clean Energy in Wastewater Treatment Plants. *Energy Convers. Manag.* **2015**, *101*, 255–262. [CrossRef]
16. Helal, A.; Ghoneim, W.; Halaby, A. Feasibility Study for Self-Sustained Wastewater Treatment Plants—Using Biogas CHP Fuel Cell, Micro-Turbine, PV and Wind Turbine Systems. *Smart Grid Renew. Energy* **2013**, *4*, 227–235. [CrossRef]
17. Nižetić, S.; Djilali, N.; Papadopoulos, A.; Rodrigues, J.J. Smart Technologies for Promotion of Energy Efficiency, Utilization of Sustainable Resources and Waste Management. *J. Clean. Prod.* **2019**, *231*, 565–591. [CrossRef]
18. Bey, M.; Hamidat, A.; Nacer, T. Eco-energetic Feasibility Study of Using Grid-Connected Photovoltaic System in Wastewater Treatment Plant. *Energy* **2020**. [CrossRef]

19. Colacicco, A.; Zacchei, E. Optimization of Energy Consumptions of Oxidation Tanks in Urban Wastewater Treatment Plants with Solar Photovoltaic Systems. *J. Environ. Manag.* **2020**, *276*, 111353. [CrossRef]
20. Badea, C.A.; Andrei, H.; Gonciariuc, A.; Rus, E. Predictive Methods to Increase Energy Efficieny in Processes of Wastewater Treatment. In Proceedings of the 8th International Conference on Electronics, Computers and Artificial Intelligence (ECAI); Institute of Electrical and Electronics Engineers (IEEE), Ploiesti, Romania, 30 June–2 July 2016; pp. 1–6.
21. Badea, A.; Andrei, H.; Rus, E. Power Analysis of PV System Used in Wastewater Treatment Plant based on Technological. *Sci. Bull. Electr. Eng. Fac.* **2016**, *16*, 34–39. [CrossRef]
22. Badea, C.A.; Andrei, H. Optimization of Energy Consumption of a Wastewater Treatment Plant by Using Technological Forecasts and Green Energy. In Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC); Institute of Electrical and Electronics Engineers (IEEE), Florence, Italy, 7–10 June 2016; pp. 1–5.
23. Saini, V.; Tiwari, S.; Tiwari, G. Environ Economic Analysis of Various Types of Photovoltaic Technologies Integrated with Greenhouse Solar Drying System. *J. Clean. Prod.* **2017**, *156*, 30–40. [CrossRef]
24. RMEF. Romanian Ministry of European Funding, Operational Programme Under the Investment for Growth and Jobs' Goal. Available online: www.fonduri-ue.ro/images/files/programe/infrastructura/2018/18.04.2018/poim_march_2018.pdf (accessed on 2 April 2018).
25. Steel, E.W.; McGhee, T.J. *Water Supply and Sewerage*; McGrew Hill, Inc.: New York, NY, USA, 1979.
26. Cao, S.; Hasan, A.; Sirén, K. On-Site Energy Matching Indices for Buildings with Energy Conversion, Storage and Hybrid Grid Connections. *Energy Build.* **2013**, *64*, 423–438. [CrossRef]
27. Peng, J.; Lu, L.; Yang, H. Review on Life Cycle Assessment of Energy Payback and Greenhouse Gas Emission of Solar Photovoltaic Systems. *Renew. Sustain. Energy Rev.* **2013**, *19*, 255–274. [CrossRef]
28. Wang, J.; Yang, Y.; Mao, T.; Yang, A.; Jin, H. Life Cycle Assessment (LCA) Optimization of Solar-Assisted Hybrid CCHP System. *Appl. Energy* **2015**, *146*, 38–52. [CrossRef]
29. Hestnes, A.G. Building Integration of Solar Energy Systems. *Sol. Energy* **1999**, *67*, 181–187. [CrossRef]
30. Hartner, M.; Ortner, A.; Hiesl, A.; Haas, R. East to West—The Optimal Tilt Angle and Orientation of Photovoltaic Panels from an Electricity System Perspective. *Appl. Energy* **2015**, *160*, 94–107. [CrossRef]
31. Hong, T.; Lee, M.; Koo, C.; Jeong, K.; Kim, J. Development of a Method for Estimating the Rooftop Solar Photovoltaic (PV) Potential by Analyzing the Available Rooftop Area Using Hillshade Analysis. *Appl. Energy* **2017**, *194*, 320–332. [CrossRef]
32. Andrei, H.; Dogaru-Ulieru, V.; Chicco, G.; Cepisca, C.; Spertino, F. Photovoltaic Applications. *J. Mater. Process. Technol.* **2007**, *181*, 267–273. [CrossRef]
33. Spertino, F.; Graditi, G. Power Conditioning Units in Grid-Connected Photovoltaic Systems: A Comparison with Different Technologies and Wide Range of Power Ratings. *Sol. Energy* **2014**, *108*, 219–229. [CrossRef]
34. Spertino, F.; Di Leo, P.; Corona, F.; Papandrea, F. Inverters for Grid Connection of Photovoltaic Systems and Power Quality: Case Studies. In Proceedings of the 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG); Institute of Electrical and Electronics Engineers (IEEE), Aalborg, Denmark, 25–28 June 2012; pp. 564–569.
35. Chicco, G.; Corona, F.; Porumb, R.; Spertino, F. Experimental Indicators of Current Unbalance in Building-Integrated Photovoltaic Systems. *IEEE J. Photovoltaics* **2014**, *4*, 924–934. [CrossRef]
36. ISRTD. Available online: 916.icstm.ro/content/rezultate-obtinute/ (accessed on 26 July 2018).
37. OPCOM. Available online: www.opcom.ro (accessed on 2 April 2018).