|  |  |
| --- | --- |
| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS*** ***VOL. 96, 2022*** | A publication ofaidiclogo_grande |
| The Italian Associationof Chemical EngineeringOnline at www.cetjournal.it |
| Guest Editors: David Bogle, Flavio Manenti, Piero SalatinoCopyright © 2022, AIDIC Servizi S.r.l.**ISBN** 978-88-95608-95-2; **ISSN** 2283-9216 |

Economic analysis of the self-generations of photovoltaic energy for the treatment of wastewater in Colombia

Velandia Camilo, Epalza Jesús, Galvis Angel.

Universidad de Santander (UDES), Environmental Engineering, Bucaramanga, Colombia.

je.epalza@mail.udes.edu.co - manuelepalza@gmail.com

Wastewater treatment is a necessary process, with which healthier ecosystems, better quality of life and health, as well as other positive effects, can be guaranteed. The treatment is carried out through different phases in which physicochemical and microbiological processes are involved in order to remove contaminants such as organic matter, suspended solids, nitrogen, phosphorus, infectious agents and others; On the other hand, wastewater treatment systems need energy supply to carry out some processes, such as oxygen supply in biological treatments, pumps for the transport of wastewater or sludge, temperature regulation for anaerobic processes, and other operations. Due to various effects that have occurred in recent years due to climate change, concern has increased and is leading to the search for alternatives to help mitigate it. From the concept of wastewater treatment, it is sought to direct these systems towards sustainability, by increasing the capacity for energy self-sufficiency. Regarding the energy consumption of a wastewater treatment system, this implies between 25% and 40% of the operating costs (OPEX) of the entire treatment system; It is estimated that to treat one m3 of wastewater, between 0.3 Kw/h and 2.1 Kw/h are consumed (Gikas, 2017; Panepinto, Fiore, Zappone, Genon, & Meucci, 2016)

In Colombia, according to the Superintendency of Domiciliary Public Services, of the 1,122 municipalities only 541 have wastewater treatment systems, that is, 51.8% of the country's municipalities do not have these systems, in the same way there is similarity between The most remote areas of the country, in the sense that they do not have appropriate wastewater treatment systems, do not have a solid energy matrix or even do not have access to it, due to this, the need to implement projects that incorporate alternatives increases. for the generation of energy to wastewater treatment systems, thus increasing the coverage of said systems in areas not interconnected to the national electricity grid (NIZ) or improving the coverage of the service in places that have it.

This study performs an economic analysis for the supply of photovoltaic energy to wastewater treatment system (WWTS), that are not yet projected or are in the design phase, a random sample of fifteen (15) different flows was selected which can be applied, either to areas of the country that has good quality electrical interconnection or to isolated regions of the country with difficulties in access to energy. Additionally, the energy consumption of simulated treatment systems was estimated, studying technological alternatives for aerobic treatment systems. Therefore, 15 simulated treatment systems were analysed for methodological purposes with flow rates between 0.5 l/s and 480 l/s. The expected result is a response surface to a mathematical model, which indicates whether it is economically viable to have a partial supply of photovoltaic energy, depending on the flow of wastewater to be treated and the type of aerobic technology used for wastewater treatment, seeking to encourage the analysis of self-generation with photovoltaic energy in the design processes of future (WWTS) to be built in the country.

* 1. Introduction

This research stems from concern about the negative environmental impact, caused by three different but related factors: the low rate of wastewater treatment in Colombia, with negative effects on ecosystems, the use of conventional energy for the operation of wastewater treatment plants, in municipalities of the country that have systems or that are in the formulation and design phase of the same, and finally the isolated areas that are not interconnected to the national electricity grid (NEG) due to it’s geographical location, which has an impact on climate change.

Due to this, the task of seeking an alternative energy supply was undertaken, for the wastewater treatment process, through the self-generation of photovoltaic solar energy, with the purpose of proposing a favourable proposal from the environmental and economic point of view, that can encourage the different stakeholders in the subject, to consider this possibility as a viable solution to the problem raised, especially in those municipalities of the country located in non-interconnected areas (NIZ).

The method used to develop the research is based on the design of mathematical models, capable of determining the energy consumption of wastewater treatment plants, making simulations for different levels of flow to be treated, as well as to establish the number of panels solar energy required for energy supply based on different percentages of self-generation of photovoltaic energy, to finally establish the values ​​(determined by the response variable Net Present Value NPV) in which this alternative is viable.

To develop this research, it begins with the conceptual and theoretical synthesis about the subject to be treated, which served as the basis for the design of the mathematical models mentioned above.

This work ventures into a new field of research, for which the existing literature on the specific topic is scarce, on the other hand, in its development, multiple questions appeared that, when resolved, sometimes led to new questions to be resolved.

* 1. Materials and methods
		1. Type and focus of research

This research was carried out through an applied type of study, which consisted of creating new knowledge from bases acquired through research, the information obtained can be applied anywhere, because it offers opportunities of great importance for its dissemination.

The focus of this research was quantitative, since it aimed to carry out a mathematical design that would allow different numerical variables to be related, which, when analyzed, allowed us to infer different conclusions.

* + 1. Techniques and instruments

The techniques used were based on the reading and content analysis of various authors, which allowed having a wide margin of selection of mathematical models to follow, in the same way, with this analysis the subject was deepened until it was possible to determine the base line of each one of the authors, to make the selection of the method that was considered most successful.

To achieve the stated objectives, it began with the review of existing mathematical models, which have been used over time to model processes in wastewater treatment systems, the process selected to be modelled was the biological reactor, because this is the process that represents the highest energy consumption compared to other processes, it was modelled considering two types of reactors, continuous stirred tank (CSTR) and plug flow (PFR).

The selected mathematical model made calculations for 30 biological reactors, simulated water treatment plants with flows ranging from 0.5 to 480 L/s, the modelling was carried out considering fifteen (15) flows for the CSTR reactor. And fifteen (15) flow rates for the PFR reactor. It was decided to model the biological reactor process considering that this is the process with the highest energy consumption due to the compressors that are required to send air and guarantee an adequate biological process.

The number of flows that it was decided to use for this investigation was fifteen (15), considering that it offered a sufficiently wide and representative range of flow selection to obtain the required data, which were analysed and compared to achieve the solution of the problem. hypothesis raised, it was also determined that the research obtained a wide range of research that in the future can be analysed and contrasted in another research that may arise from it.

The range of flows selected to obtain the energy demands ranges between 0.5 and 480 L/s since the main treatment plants of the intermediate cities of Colombia are in this range, due to the fact that they are common flows in the country and can be simulated with other plants in the design phase or that have already been designed, the flows that fall outside this range can serve as a basis for future studies and designs, based on the model developed as a result of this research or other models that can be based on this study.

The process of elaboration of the research project began with defining, from the consulted literature, the existing mathematical models to be considered, in order to select the most robust and most used model for its recognitions, in the same way, it was carried out investigation of the typical characteristics of domestic wastewater in Colombia, in terms of the following parameters: COD, BOD5, and total suspended solids, in order to develop the model with typical parameters and thus generate sufficiently reliable results.

Next, the identification of the main equipment that is part of the WWTS and that involves energy consumption for aerobic treatment using activated sludge technology was carried out, to develop the mathematical model around said equipment; As a result, the equipment selected for modelling was biological reactors due to their energy consumption by compressors for air supply.

Standardized design parameters were defined for a wastewater treatment system so that they comply in terms of design with the characteristics of standard 0631 of 2015, for BOD5. Subsequently, the mathematical model was designed and executed in the Excel tool, which allowed the formulation of said models; the continuous flow reactor (CSTR) was developed under parameters used by Romero Rojas in his book "Treatment of wastewater" in the same way, the mathematical model of the plug flow reactor (PFR) was developed taking as a guide the approaches of Álvaro Orozco described in his book "Wastewater Bioengineering" and "Wastewater Engineering Treatment and Reuse" by Metcalf & Eddy

The elaborated model raised different assumptions that allowed the objective to be achieved, which were applied to all the simulated flows. The assumptions that were considered for the elaboration of said model are listed below:

**Continuous Flow Reactor (CSTR) Model**

1) Standard temperature for all flow rates. 2) Width-depth relationship. 3) Cell retention time. 4) Volatile Suspended Solids in the Mixing Liquor. 5) Relationship food - microorganisms. 6) Concentration of total solids of the settled sludge. 7) Suspended solids in the effluent.

**Plug flow reactor (PFR) model**

1) Standard temperature for all flow rates. 2) Width-depth relationship. 3) Cell retention time. 4) Sludge concentration in the reactor. 5) Concentration of total solids of the settled sludge. 6) Suspended solids in the effluent. 7) Sludge Volume Index (SVI)

The developed model allows the assumptions to be presented as modifiable data, to be able to simulate different environments and thus be able to compare the locally results, with known data from other plants that have been built or are in the process design; the elaborated mathematical model gives different results because it also provides design data of the reactors. For each simulated reactor, a certain required power was obtained, necessary to continue with the photovoltaic calculations.

Subsequently, a table of loads was elaborated, based on the estimation of the energy consumption required by the 15 simulated treatment systems, using aerobic technologies, these energy loads were necessary for the calculation of the number of solar panels and other equipment necessary for the photovoltaic systems.

After obtaining the load table of the estimated energy of each of the plants, the compilation of said information was carried out, as well as the cost data of the different photovoltaic energy production systems: panels, inverters, regulator, wiring, installation, structure, for different installed capacities and that are commercially offered.

The reason why the CSTR reactor has lower energy consumption compared to the PFR reactor is because the oxygen required throughout the reactor is higher due to its length and also because the behaviours of the mixed liquor is not totally mixed like the of the CSTR, if not that it behaves like a piston, it can be compared to hermetic packages that run through a pipe without mixing with each other, thus, more oxygen is required to achieve the necessary biological activity in each of these packages.

To obtain the average solar radiation of the location where the fifteen (15) wastewater treatment plants could be, IDEAM databases were consulted where said information was found, which was contrasted with the NASA database where it was also found information on solar radiation during peak hours, so that the chosen solar radiation was the average.

Based on the energy demands of the plants, a micro-network model was made, which allowed determining the number of panels and inverters necessary to cover the energy demand fully or partially. In this model, the evaluation of ten (10) different consumptions between 0% and 100% of the energy demand of each of the previously modelled plants, the evaluation of the consumptions had the purpose of determining the optimal value in which it is feasible from the economic point of view, supply the plant with self-generation of photovoltaic energy.

On the other hand, an inflation value was also calculated for the cost of energy over time, making the projection for a period between 2020 and 2040, this estimate was made using a linear model which worked adequately, equally The inflation value for the cost of labour required in the maintenance of the photovoltaic system was projected for the same period of time based on the linear model used for the cost of energy, the estimate was made based on the historical data of the CPI , which allowed us to infer the behaviour of the same, the data was obtained from the Bancolombia group, the estimated values ​​served to have costs more approximate to reality, in the periods of time mentioned and thus determine the feasibility of the project in development.

Once the inflation values ​​were estimated, the formulation of the net present value (NPV) was carried out, this being a useful tool for the evaluation of projects, which allowed us to carry out a sensitivity analysis of the opportunity cost, for the different powers to self-generate in (kWh); The best net present value (NPV) data was found for each modelled network using the previously estimated inflation values.

Finally, the NPV of the self-generation systems was related, according to the treatment flow of the simulated plants, each of the results obtained was modelled by means of response surfaces, this methodology being the appropriate one to present said results, In the same way, the costs of self-generated kWh were compared with the commercial costs of conventional energy in a timeline between 2020 and 2040.

* 1. Results and discussion
		1. Results of the CSTR reactor model.

The results found in this research project were presented graphically because it allows presenting and interpreting the data obtained in a simple way, the following graphs show the behaviour of the net present value (NPV) evaluating different percentages of self-generation of photovoltaic energy for sewage treatment plants.

Graph 1. Percentage of self-generation Vs Net present value minimum flow CSTR

Graph 2. Percentage of self-generation Vs Net present value maximum flow CSTR

The graphs in which the percentage of self-generation are greater than 100%, that is, the total energy required, is due to the fact that the present study analysed the feasibility of the implementation of solar panels for the total supply of energy, therefore which the installed capacity is oversized to avoid a bias when making the comparison with the other results, in the same way, the energy that is generated and is necessary due to oversizing, is taken into account as energy that is sold to the net.

The NPV at an opportunity rate of 12% for the different percentages of self-generation gave negative results except for a couple of cases (flow of 2 l/s with 50% energy supply and 3 l/s with a 60% of energy supply) where profitability was evidenced, although with very low values compared to its investment.

For an opportunity rate of 20%, no profitability was found for any flow rate or percentage of self-generation.

Like the reactor model (CSTR), three different percentages of opportunity rates were taken to be able to evaluate the best opportunity rate for self-generation of photovoltaic energy for wastewater treatment plants. The graphs show that profitability can be obtained at an opportunity rate of 10%, for self-generation supply percentages greater than 50% of the total demand, for any level of flow. On the other hand, it is observed that the highest profitability is obtained for all flows, in percentage of supply by self-generation between 70% and 90%.

To make an investment in a construction project of a wastewater treatment system with partial energy supply by self-generation of photovoltaic solar energy, access to any form of financing by those interested in carrying out the project must be equal to or less than 10% effective annual.

The profitability obtained varies depending on the flow rate and the type of reactor used, the average profitability for the CSTR reactor is 12.7% of the value invested while for the PFR reactor it is 6.5% of the value invested in a horizon of 20 years, in this way, the reactor model that offers a more optimistic scenario -from the financial point of view- at the moment of self-generating photovoltaic energy is the CSTR, this due to the fact that the power required is less, which translates a lower CAPEX than that of a PFR reactor.



Graph 3. Percentage of self-generation Vs Net present value minimum flow PFR



Graph 4. Percentage of self-generation Vs Net present value maximum flow PFR

According to the sources consulted in the world context, the energy used to treat wastewater is in the range of 0.5 and 2 kWh/m3, through the project carried out it was determined that in the research context the energy consumption for each meter cubic of water is in the range of 0.3 and 0.5 kWh, this consumption was obtained depending on the type of activated sludge reactor selected, according to this, the results obtained are within a very close magnitude range. According to the research "The feasibility and challenges of energy self-sufficient wastewater treatment plants" in which they studied the energy consumption of WWTPs together with the factors that influence their energy use, including treatment techniques, treatment and regional differences, results were obtained such as those found in graphs 1 and 2 of this study, where the flow rate is plotted vs. the kWh/m3 used, the comparison of the results with those obtained in this study is found in the same orders of magnitude which generates a higher reliability margin of the study carried out.

* 1. Conclusions

The most optimal reactor to treat wastewater supplied by photovoltaic solar energy is the continuous flow stirred reactor (CSTR), this can be evidenced by the mathematical model developed in which the capital costs necessary for a plug flow reactor are higher in all the flows studied. Partial energy supply to wastewater treatment plants is possible through the self-generation of photovoltaic solar energy, obtaining economic profitability.For this type of project to be economically viable, the profitability generated by the project must be at least equal to that obtained in the development of the simulations using the model developed in which the NPV produced results given in positive numbers.These types of projects have a social impact, which are aimed at improving the quality of life of the communities. For this reason, it is possible to propose measures such as urging the national government to generate incentives aimed at improving the Colombian energy matrix, this is an issue that has been booming in different places. The incentive should focus on reducing costs related to CAPEX, that is, reducing taxes and tariffs generated for panels, inverters, cables, batteries, and other elements that make up a photovoltaic system to achieve a decrease in the investment that is needed to access these systems. If it is possible to increase the incentives or improve the sale price of energy to the network, the opportunity costs will increase; Colombia is one of the countries that bet on renewable energies.

The economic study is implemented with action plans framed to improve and expand the current energy matrix, hand in hand with municipalities and communities willing to develop self-generation photovoltaic energy projects for wastewater treatment plants.

Acknowledgments

We thank the University of Santander for supporting our research.

References

POWER Data Access Viewer. (s. f.). Recuperado 26 de septiembre de 2019, de https://power.larc.nasa.gov/data-access-viewer/

DUNCAN, Mara, Domestic Wastewater Treatment in Developing Countries. London ; Sterling, VA: Earthscan Publications, (2004).

Adaptado de: Abogada Juanita Hernandez Vidal, juanita@estudiolegalhernandez.com, Directora Derecho Energético, Minero y Servicios Públicos, Estudio Legal Hernández Abogados Asociados.

Bachmann, N. (2015). Sustainable biogas production in municipal wastewater treatment plants. IEA Bioenergy.

Barroso Soares, R. (2017). Comparative Analysis of the Energy Consumption of Different Wastewater Treatment Plants. International Journal of Architecture, Arts and Applications. https://doi.org/10.11648/j.ijaaa.20170306.11

Batstone, D. J., Hülsen, T., Mehta, C. M., & Keller, J. (2015). Platforms for energy and nutrient recovery from domestic wastewater: A review. Chemosphere, 140, 2-11. https://doi.org/10.1016/j.chemosphere.2014.10.021

Bernal-Agustín, J. L., & Dufo-López, R. (2006a). Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renewable Energy, 31(8), 1107-1128. https://doi.org/10.1016/j.renene.2005.06.004

Bernal-Agustín, J. L., & Dufo-López, R. (2006b). Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renewable Energy, 31(8), 1107-1128. https://doi.org/10.1016/j.renene.2005.06.004

Cantillo Guerrero, E., & Conde Daníes, F. (2011). Diagnóstico técnico y comercial del sector solar fotovoltaico en la región Caribe colombiana. Prospectiva, 9(2), 81-88.

Chae, K. J., & Kang, J. (2013). Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. Energy Conversion and Management. https://doi.org/10.1016/j.enconman.2013.08.028

Gabarrón, S., Dalmau, M., Porro, J., Rodriguez-Roda, I., & Comas, J. (2015). Optimization of full-scale membrane bioreactors for wastewater treatment through a model-based approach. Chemical Engineering Journal, 267(2015), 34-42. https://doi.org/10.1016/j.cej.2014.12.097

Gikas, P. (2017). Towards energy positive wastewater treatment plants. Journal of Environmental Management, 203, 621-629. https://doi.org/10.1016/j.jenvman.2016.05.061

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Wang, X., … Li, F. (2017). Energy Self-sufficient Wastewater Treatment Plants: Feasibilities and Challenges. Energy Procedia. https://doi.org/10.1016/j.egypro.2017.03.868

Gude, V. G. (2015). Energy and water autarky of wastewater treatment and power generation systems. Renewable and Sustainable Energy Reviews, Vol. 45, pp. 52-68. https://doi.org/10.1016/j.rser.2015.01.055

Helal, A., Ghoneim, W., & Halaby, A. (2013). Feasibility Study for Self-Sustained Wastewater Treatment Plants—Using Biogas CHP Fuel Cell, Micro-Turbine, PV and Wind Turbine Systems. Smart Grid and Renewable Energy. https://doi.org/10.4236/sgre.2013.42028

Hoppmann, J., Volland, J., Schmidt, T. S., & Hoffmann, V. H. (2014). The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. Renewable and Sustainable Energy Reviews, 39, 1101-1118. https://doi.org/10.1016/j.rser.2014.07.068

Jaramillo Orozco, A. (2005). Bioingeniería de aguas residuales (teoría y Diseño). En Acodal.

Li, J., & Danzer, M. A. (2014). Optimal charge control strategies for stationary photovoltaic battery systems. Journal of Power Sources, 258, 365-373. https://doi.org/10.1016/j.jpowsour.2014.02.066

Luo, Y., Guo, W., Ngo, H. H., Nghiem, L. D., Hai, F. I., Zhang, J., … Wang, X. C. (2014). A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Science of the Total Environment, 473-474, 619-641. https://doi.org/10.1016/j.scitotenv.2013.12.06