Urban wastewater treatment with combinations of electrooxidation – photocatalysis and electrocoagulation – photocatalysis

Demetrios Marmanis [1], *Kalliopi* Ladomenou[1], *Jacob G.* Fantidis[2*], *Kyriaki* Marmani[3], *Vassiliki* Mesazou[4] and *Demetrios* Zisiadis[4]

[1]Hephaestus Laboratory School of Chemistry, Democritus University of Thrace, 65404 Kavala, Greece
[2]School of Physics, Democritus University of Thrace, 65404 Kavala, Greece
[3]Delft University of technology- MS, Sustainable Energy Technology, 2600 AA Delft, Netherlands
[4]School of Chemistry, Democritus University of Thrace, 65404 Kavala, Greece

Abstract. Water quality of is an issue of vital importance in every aspect of everyday life. The improvement of the quality of wastewater aligns with this direction. Electrocoagulation and electrooxidation were the two methods which used in the presented work. In the case of electrooxidation, experiments were carried out with a current of 600 mA and a voltage of 10 volts with BDD and Ti/Pt electrodes for two cases: with and without the use of UV photocatalysis. The electrocoagulation experiments included six different cases: Al/Al electrodes with a current of 400 mA and 600 mA, Fe/Fe electrodes with a current of 400 mA and 600 mA, Al/Al electrodes with a current of 400 mA and 600 mA, combination of electrocoagulation with Al/Al electrodes at a current of 400 mA and visible-light photocatalysis and a combination of electrocoagulation with Al/Al electrodes at a current of 400 mA and UV photocatalysis. A small village named Hortokopi, near Kavala was used as a case study. All required energy was supplied by an autonomous photovoltaic power plant, designed using the RETScreen Clean Energy Management Software.

1 Introduction

Without a doubt, water quality is a vital issue in every aspect of everyday life. However, the modern way of life very often compromises the water quality and not only owing to the industrial procedures. Wastewater from residences and hotels includes various hazardous impurities etc. It is obvious that all these substances are threatening both to the environment and to the population which lives in this area. The European Union (EU) officially addressed this problem and since 2006 any area with more than 2000 citizens must treat its wastewater via biological action. Based on this legislation every village with a smaller population does not have the obligation to manage its wastewater. This is a challenging reality in Greece because there are many small villages with smaller population during the winter months but

* Corresponding author: ifantidi@physics.duth.gr

with a large number of visitors in the summer months because they are typical summer touristic destinations.

Electrochemical procedures such as electrooxidation and electrocoagulation can help in order to improve the quality of the wastewater with the intention to use these quantities in other ways [1-2]. The idea to cover the energy needs from renewable energy sources such as the photovoltaic panels is gaining more and more ground in Greece. Of course, this is not strange because Greece is a sunny country and electricity demand peaks follow patterns similar to the energy produced using photovoltaic panels. In this work an extensive set of experiments was carried out to discover the most feasible procedure. A small village in Northern Greece, Hortokopi was used as a case study. The main novelty of this work is that all the necessary electricity was supplied by photovoltaic panels, the size of which can be calculated using specialized software. In this article all the energy simulations have been realized using the RETScreen Expert software [3].

2 Material and methods

One of the most common methods for removing contaminants from wastewater is electrocoagulation. Electrocoagulation needs electricity which flows through electrodes constructed from conductive materials such as aluminium and iron. Another well-known method for this purpose (eliminating impurities from wastewater) is electro-oxidation. Like electrocoagulation, electrooxidation requires direct current (DC) through metal electrodes. It should be noted that the integration of Ultraviolet (UV) radiation into both electrocoagulation and electrooxidation can enhance the treatment efficacy of the wastewater facilities [4]. In this work all experimental procedures were based on experiments which were carried out at the Democritus University of Thrace and more specifically in the laboratories of the School of Chemistry.

The facility includes all the necessary equipment such as direct current (DC) power supply, a 300 ml electrochemical cell, a multimeter, a conductivity meter, a pH meter (WTW), chemical oxygen demand (COD) meter with a reactor (TR 420, Merk), a photometer (Spectroquant Pharo 100, Merk), a magnetic stirrer, electrodes: BDD (DiaCCon GmbH, Germany) for the anode and Ti/Pt for the cathode a UV lamp (50 W, 385 nm). The distance between the UV lamp and the sample was 15 cm. The specific values for both current and voltage based on the best results from previous work [5]. The presented article includes 8 separate measurement sets and more specifically:

1. Electrooxidation with BDD and Ti/Pt electrodes with a current of 600 mA and a voltage of 10 V,
2. A similar set up but adding and a UV lamp,
3. Electrocoagulation with Al/Al electrodes which are supplied with a current of 400 mA and a voltage of 4 V,
4. The same as case 3, but with a current of 600 mA and a voltage of 5 V,
5. Electrocoagulation with Fe/Fe electrodes which are supplied with a current of 400 mA and a voltage of 4 V,
6. Similar to case 5, but with a current of 600 mA and a voltage of 5 V,
7. A hybrid facility which combines the case 3 (electrocoagulation with Al/Al electrodes, a current of 400 mA, and a voltage equal to 4 V) and visible-light photocatalysis and
8. A similar hybrid facility to case 7 but using a UV photocatalysis with a UV lamp (50 W, 385 nm).

The duration of the experiments was not fixed; they lasted until the COD values were nearly below the detection limit (COD<50 mg/L). In each experiment the wastewater had a COD value of 516 mg/L and a pH of 8.3 while the volume was 300 mL. In small villages like Chortokopi without industries the wastewater originates mainly from households, and for this reason, it is relatively clear.

In order to minimize the ecological impact of the treatment procedures all the required energy can be provided by a photovoltaic park, which, owing to the need for direct current from the facility does not require the use of an inverter. The RETScreen Clean Energy Project Analysis Software has been chosen to determine the necessary size of the photovoltaic system. Hortokopi (Figure 1) is a small village in the Municipality of Pangaio, within the Regional Unit of Kavala, in the Region of Eastern Macedonia and Thrace. According to the 2021 census, it has 355 residents. It is located at an elevation of 90 meters, at the foot of Mount Pangaio, and is a tourist destination because it is approximately 8–10 kilometers from the nearest coastline, about a 10-minute drive. Based on data from previous works the water needs are approximately 200 L/day per person [6].

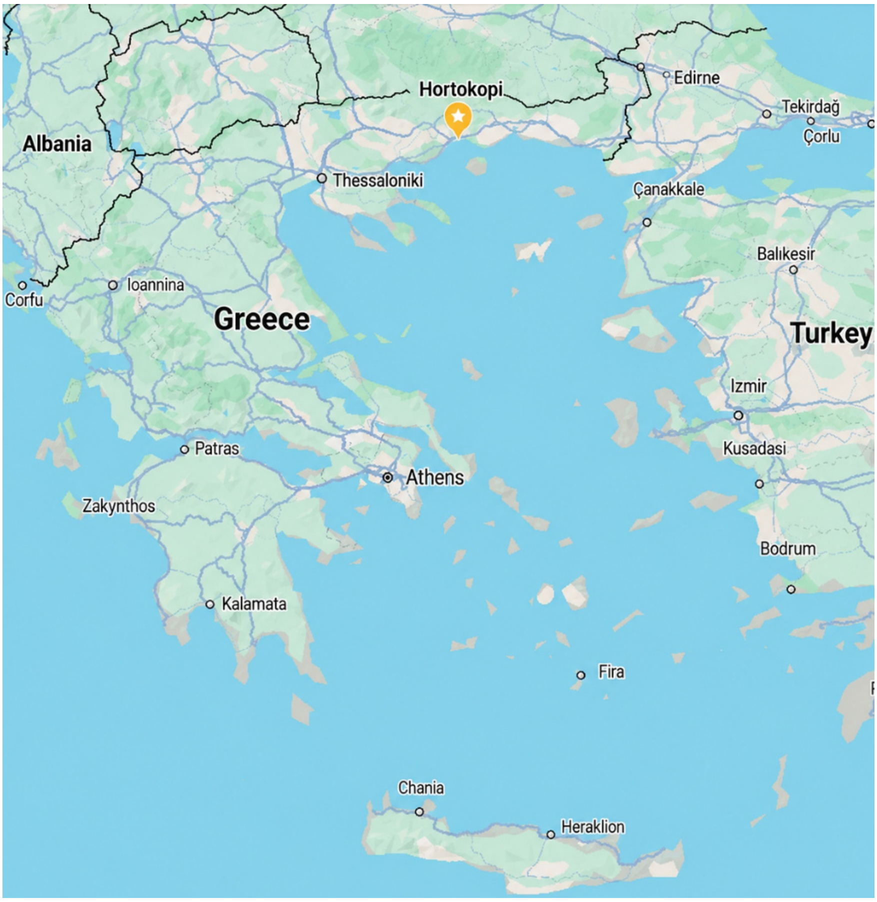

Fig. 1. Map of the Hortokopi location.

The necessary long-term (2005 up to 2023) data for solar radiation were derived from the European Union Photovoltaic Geographical Information System (PVGIS) and are illustrated in Table 1 for the optimum angle [6-7]. The average daily solar radiation has a large fluctuation from 2.49 kWh/m^2 in December up to 7.15 kWh/m^2 during July. As expected, solar radiation is significantly higher during the summer months, which is highly desirable since the energy demand is much higher in the summer due to the doubling of the population during that period.

Table 1. Daily average global irradiation per month for optimum angle for Hortokopi [kWh m^{-2}]

Month	**Global irradiation, optimal angle**
Jan	2.92
Feb	3.75
Mar	4.63
Apr	5.52
May	6.34
Jun	6.95
Jul	7.15
Aug	6.72
Sep	5.72
Oct	4.35
Nov	3.13
Dec	2.49

3 Results and discussion

It is important to note that all presented results are average values obtained from three repeated experiments in each case. The uncertainties are very low, with variations in the measured values of less than 3%. Table 2 shows the results from the first experiment (electrooxidation with BDD and Ti/Pt electrodes with a current of 600 mA and a voltage 10 V voltage). After 2 h, the COD values decreased to 516 mg/L to less than 50 mg/L which is the lowest value that can be measured by our equipment. The relevant electricity consumption was 40 Wh per liter. In the second case when apart from the BDD and Ti/Pt electrodes the presence of a UV lamp enhanced the treatment procedures the required time was shorter (Table 3). However, it is wrong just add the 2 energy values because the UV lamp can operate and for a larger quantity, than that of the presented experiments (0.3 l in each experiment).

Table 2. Electrooxidation experiments using BDD and Ti/Pt electrodes with a current of 600 mA and a voltage of 10 V.

Time (h)	**pH**	**COD (mg/L)**	**Electricity Consumption (Wh) per l**
0	8.3	516	
1 h	8.37	229	20
2 h	9.7	<50	40

Table 3. Electrooxidation experiments using BDD and Ti/Pt electrodes with a current of 600 mA and a voltage of 10 V using and UV lamp.

Time (h)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	8.3	516	
0.5 h	7.15	94	10+50
1 h	6.9	<50	20+50

Apart from electrooxidation, another extended set of experiments was realized based on electrocoagulation. Hence Al/Al electrodes were supplied initially with a current of 400 mA and a voltage of 4 V and afterward with a current of 600 mA and a voltage of 5 V. Tables 4 and 5 illustrate the results of the experiments. According to these results the lower values for current and voltage ensure lower consumption and a similar required time, while the COD values after 2 hours of treatment time are nearly the same. Moreover, the comparison of these experiments with the previous ones which are shown in Tables 2 and 3 reveals that the electrocoagulation experiments using a current of 400 mA and a voltage of 4 V are the optimum solution.

Table 4. Electrocoagulation experiments with Al/Al electrodes using a current of 400 mA and a voltage of 4 V.

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	18	7.78	516	
1 h	19	8.26	243	5.33
2 h	20	8.82	67	10.67

Table 5. Electrocoagulation experiments with Al/Al electrodes using a current of 600 mA and a voltage of 5 V.

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	19	7.73	516	
1 h	21	8.26	198	10
2 h	22	8.82	62	20

The next set of experiments also examined the supplied voltage and current but used Fe/Fe electrodes (Tables 6 and 7). However, the results indicated poor performance in the treatment procedure in both cases. Hence the use of Fe/Fe electrodes does not appear to be an effective method for minimizing the COD values. The electricity consumption was similar to the previous cases, and the lower cost of the iron electrodes offers no advantage due to the high final COD values.

Table 6. Electrocoagulation experiments with Fe/Fe electrodes using a current of 400 mA and a voltage of 4 V.

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	18	7.91	516	
1 h	19	8.68	463	5.33
2 h	21	8.91	322	10.67

Table 7. Electrocoagulation experiments with Fe/Fe electrodes using a current of 600 mA and a voltage of 5 V.

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	18	7.82	516	
0.5 h	20	8.44	432	5
1 h	21	9.12	297	10

The best results from the third set (electrocoagulation with Al/Al electrodes, a current of 400 mA, and a voltage equal to 4 V) were further enhanced with the help of photocatalysis. First, the necessary UV radiation was provided by sunlight. The results in Table 8 show that the COD values reached minimum levels in each case, while the electricity consumption remained the same. This means that, especially in the summer months, the use of a transparent tank can further improve the treatment method. As expected, the use of a UV lamp resulted in lower COD values. However, we cannot compare the electricity consumption results with the previous cases because the UV lamp could handle larger quantities of wastewater. It should be noted that, apart from clearer water, the use of a UV lamp offers a considerably shorter treatment time (Table 9).

Table 8. Electrocoagulation experiments with Al/Al electrodes using a current of 400 mA and a voltage of 4 V with the help of visible-light photocatalysis.

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	15	7.96	516	
0.5 h	17	8.54	233	2.67
1 h	19	9.04	146	5.33
1.5 h	20	9.23	106	8
2 h	21	9.49	<50	10.67

The necessary energy can be generated with the help of photovoltaic panels. Based on an energy consumption of 10.67 Wh per litre and a required quantity of 200 litres per person per day, we can calculate the rated power of the installed photovoltaics. The energy demand was determined for 400 citizens during the winter months and for 800 residents during the summer months.

Table 9. Electrocoagulation experiments with Al/Al electrodes using a current of 400 mA and a voltage of 4 V but using a UV photocatalysis with a UV lamp (50 W, 385 nm).

Time (h)	Temperature (°C)	pH	COD (mg/L)	Electricity Consumption (Wh) per l
0	16	7.88	516	
0.5 h	18	8.56	98	2.67+50
1 h	20	8.76	67	5.33+50
1.5 h	21	8.91	<50	8+50
2 h	22	9.03	<50	10.67+50

All the simulations were performed with the help of RETScreen software, with an inverter efficiency of 92% and general losses equal to 10%. Figure 2 presents the results: a small photovoltaic power plant with a rated installed power of 13 kW can cover all the electricity demands. The installed power was determined so that, in each month, the produced energy exceeded the required energy. The minimum excess energy occurs in November, while the maximum occurs in July. The results are similar to those of previous work, but the energy cost when using photovoltaic panels is lower [8, 9]. It should be noted that the excess energy can be sold to the grid, resulting in even greater economic benefits [10].

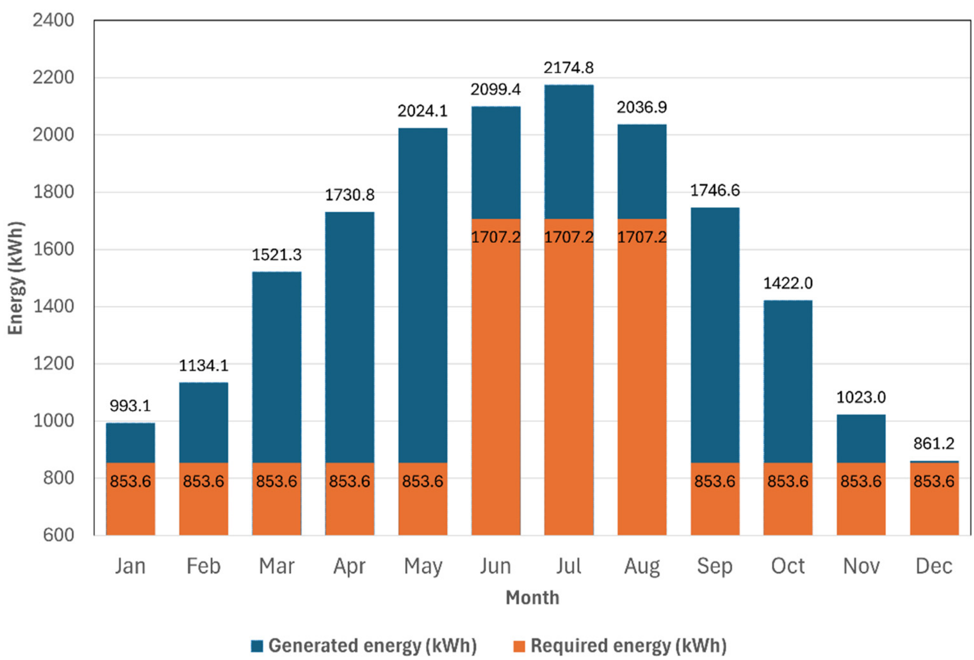

Fig. 2. Generated and required energy in Hortokopi village.

4 Conclusion

To determine the optimum solution for wastewater treatment 8 different sets of experiments, utilizing electrocoagulation and electrooxidation methods, with and without photocatalytic assistance, were conducted at the School of Chemistry at Democritus University of Thrace. Electrocoagulation with Al/Al electrodes with a current of 400 mA and a voltage of 4 V provides the best balance between treatment efficiency to clean the local wastewater. The use of photocatalysis based on UV radiation not only based on a UV lamp but also using radiation from the sun can further improve the COD values without additional energy cost. Energy consumption is low, and the required energy can be produced via a small power plant using photovoltaic panels. In this work a small tourist village in Northern Greece, named Hortokopi was used as a case study. Hortokopi with a permanent population of less than 400 citizens which doubles during the summer months requires a photovoltaic system with 13 kW of installed capacity.

References

1. M. Y. A. Mollah, R. Schennach, J. R. Parga, D. L. Cocke, Electrocoagulation (EC)-science and applications. Journal of hazardous materials, **84**(1), 29-41 (2001)
2. I. Linares-Hernández, C. Barrera-Díaz, B. Bilyeu, P. Juárez-GarcíaRojas, E. Campos-Medina, A combined electrocoagulation–electrooxidation treatment for industrial wastewater. Journal of hazardous materials, **175**(1-3), 688-694 (2010)
3. C. S. Psomopoulos, G. C. Ioannidis, S. D. Kaminaris, K. D. Mardikis, N. G. Katsikas, A comparative evaluation of photovoltaic electricity production assessment software (PVGIS, PVWatts and RETScreen). Environmental Processes, **2**, 175-189 (2015)
4. Q. Zhuo, J. Lu, J. Niu, J. C. Crittenden, G. Yu, S. Wang, Z. Chen, Electrocatalytic oxidation processes for treatment of halogenated organic pollutants in aqueous solution: A critical review. Acs Es&T Engineering, **2**(10), 1756-1775 (2022)
5. D. Marmanis, C. Emmanouil, J. G. Fantidis, A. Thysiadou, K. Marmani, Description of a Fe/Al electrocoagulation method powered by a photovoltaic system, for the (pre-) treatment of municipal wastewater of a small community in northern Greece. Sustainability, **14**(7), 4323 (2022)
6. M. Suri, T. Huld, T. Cebecauer, E. D. Dunlop, Geographic aspects of photovoltaics in Europe: contribution of the PVGIS website. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, **1**(1), 34-41 (2008)
7. Photovoltaic Geographical Information System, 2026. Available at: https://re.jrc.ec.europa.eu/pvg_tools/en/,(accessed on 14.03.2026)
8. N. Hassan, J. Lezy, D. Parmentier, S. W. H. Van Hulle, Electrocoagulation flotation as a municipal wastewater (pre-) treatment technology: Effect of weather conditions and current density. Journal of Environmental Management, **345**, 118906 (2023)
9. B. Y. Karabulut, F. D. Alay, F. Z. Adalar, Integrated enviro-economic optimization of solar-powered electrocoagulation for sustainable nitrate removal from groundwater. Journal of Contaminant Hydrology, **276**, 104745 (2025)
10. S. B. Karmankar, A. Sharma, R. C. Ahirwar, S. Mehra, D. Pal, A. K. Prajapati, Cost cutting approach of distillery effluent treatment using solar photovoltaic cell driven electrocoagulation: Comparison with conventional electrocoagulation. Journal of Water Process Engineering, **54**, 103982 (2023)