Koc. J. Sci. Eng., 7(1): (2024) 89-95 https://doi.org/10.34088/kojose.1349807

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

The Effect of Energy Saving in Wastewater Treatment Plant on the Environmental Sustainability of the Plant

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Article Info

Research paper

Received *: August 25, 2023*
Accepted *: February 15, 2024*

Keywords

Energy saving
Life cycle assessment
Sustainability
Wastewater treatment plant

Abstract

Wastewater treatment plants (WWTPs) have significant function for the urban water management. However, they can consume large amount of energy for reducing the pollutant concentration in aquatic environments. In this work, the effect of energy saving in the selected wastewater treatment plant (before and after the energy saving revisions) on the environmental sustainability of the plant was investigated by life cycle assessment (LCA). Two situations were assessed comparatively: WWTP-1 (before energy saving) and WWTP-2 (after energy saving). Life cycle impacts were evaluated in terms of both mid-point and end-point impact categories by ReCiPe 2016 methodology. The results showed that contribution of electricity consumption in WWTP-2 significantly decreased in almost all mid-point impact categories compared with WWTP-1. Considering damage assessment, overall environmental burden of WWTP-2 was determined to be 36% lower than WWTP-1. It was also noted that in addition to electricity saving, the method chosen for sludge disposal was decisive in the environmental performance of the wastewater treatment plant.

1. Introduction

Water-energy nexus is one of the crucial elements for sustainable development and wastewater treatment plants (WWTPs) are central to water-energy interactions [1]. Although WWTPs play an important role to improve the water quality, they consume large amount of energy during their life cycle to remove pollutants from aquatic environment [2].

According to the literature, electricity demand for wastewater treatment constitutes about 1% total consumption of a country [3]. In the United States, wastewater treatment consumes approximately 4% of all electrical power produced in the country [4].

Electricity consumption varies approximately 0.3 – 2.1 kwh/m^3 of treated wastewater in a conventional WWTP, and about 25-40% of operating costs is mainly related to electricity consumption [5]. It has been estimated that energy consumption in the WWTPs will continue to rise by 20% in the next 15 years [6]. Therefore, sustainable wastewater treatment processes must be developed in order to decrease electricity consumption and the carbon footprint of WWTPs [4].

There are numerous approaches to investigate the environmental sustainability aspects of production and consumption [7]. Life cycle assessment (LCA) methodology is one of them and is often used to evaluate environmental impacts of products and services throughout their life cycle [8,9]. It has been continuously developing over the past 30 years, with notable improvements at the modelling level both in the inventory and impact assessment [10]. Recently, many LCA studies have been conducted in the field of wastewater treatment [11-13].

In this study, environmental sustainability of the selected wastewater treatment plant before (called as WWTP-1) and after the energy efficiency revisions (called as WWTP-2) was assessed comparatively by life cycle approach. In addition to the mid-point impacts, end-point impacts were also evaluated in order to compare the environmental performance of the two situations. Additionally, the most dominant processes (electricity, chemical usage, transport, etc.) that contribute to impact categories were identified with process contribution analysis.

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2. Materials and Methods

2.1. Description of the WWTP

In this study, environmental sustainability of the selected WWTP was assesssed before and after the energy saving revisions in order to reveal the effect of electricity consumption on environmental performance of the plant. For this purpose, two situations were investigated by LCA: conventional wastewater treatment without energy saving (called as WWTP-1) and advanced biological wastewater treatment with energy saving after revision (called as WWTP-2). WWTP-2 is the improved version of the WWTP-1. In 2021, WWTP-1 was revised to progress the advanced treatment and energy saving. The treatment configuration of WWTP-1, which is a conventional activated sludge (CAS), was transformed to anaerobic-anoxic-aerobic (A^2O) treatment configuration after revision. A diffuser-blower system has been introduced in aeration tank. In addition, a submersible mixer was installed in the tanks. As a result of this revision, significant savings were achieved in electrical energy consumption. In addition to electricity consumption and treatment configuration, there are some other differences (sludge treatment method, transport distances, etc.) between operational stage of the WWTP-1 and WWTP-2. The main characteristics of the two WWTP systems were comparatively summarized in Table 1.

Table 1. Main characteristics of the WWTP-1 and WWTP-2.

Inflow	**WWTP-1**	**WWTP-2**
Flow rate (m^3/d)	25782	35040
Treatment configuration	CAS	A^2O
Sludge treatment	Sent to cement plant with heat recovery (100%)	Sanitary landfill (95%) Incineration (5%)
Pollutant concentrations (mg/L)		
Inflluent		
BOD	352	200
COD	778	753
TN	22.6	34.8
TP	2.54	5.02
SS	420	403
Effluent		
BOD	12.5	15.6
COD	33.5	22.4
TN	7.81	8.36
TP	0.93	0.75
SS	13.3	7.12

2.2. Life Cycle Assessment

Life cycle assessment was conducted by four steps according to the ISO 14040: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 14040).

The goal of this LCA study is to determine the effect of energy saving in wastewater treatment plant on its environmental sustainability. Two situations (called as WWTP-1 and WWTP-2) were compared to achieve this goal. The scope of this LCA can be defined as “expanded gate-to-gate” that includes operational stage of wastewater treatment plant. System boundary constitutes transportation of chemicals to the WWTP, electricity and chemical consumption for WWTP operations, transportation of sewage sludge to disposal site, and treatment of sewage sludge. The functional unit (FU) was chosen as 1 m^3 of wastewater.

For inventory analysis, foreground and background data were used. Foreground data was obtained from operating reports of the selected WWTP and it includes the amount of chemical substances, suppliers of chemicals, electricity consumption, effluent concentration, air emissions, and waste declarations (the amount of wastes generated in plant and disposal methods). Background data (production of chemicals used in the WWTP, electricity grid mix, etc.) was obtained from Ecoinvent 3.7.1 database embedded in SimaPro (v.9.2). All input and output data for WWTP-1 and WWTP-2 were summarized in Table 2.

Table 2. Input and output data for LCA (FU: 1 m^3 of treated wastewater)

Parameter	**WWTP-1**	**WWTP-2**
Input:		
Land (m^2)	4.93E-03	4.08E-04
Chemical (kg):		
Polyelectrolyte	9.94E-04	5.71E-04
Iron (III) chloride		1.32E-02
Electricity consumption (kWh)	6.89E-01	5.47E-02
Transport (tkm):	2.49E-02	4.99E-01
Output:		
Air emissions (g):		
CH_4	3.72E+00	1.33E+00
N_2O	2.72E+00	2.09E+00
Water emissions (g):		
BOD	1.25E+01	1.56E+01
COD	3.35E+01	2.24E+01
TN	7.81E+00	8.36E+00
TP	9.30E-01	7.50E-01
SS	1.33E+01	7.12E+00
Wastes:		
Sewage sludge to treatment (kg)	3.64E-01	1.41E+00
Other wastes (kg)	7.50E-04	3.18E-02

Life cycle impact assessment is the third step of LCA process and constitutes compulsory (category definition, classification, characterization) and optional (normalization, grouping, and weighting) stages (ISO 14040). In this study, characterization (mid-point analysis) and damage (end-point analysis) assessment were conducted to evaluate the environmental performance of the selected WWTP. For this purpose, eighteen mid-point impact categories were evaluated using ReCiPe 2016 (v.1.03) Mid-point method, Hierarchist version; and three end-point impact categories were determined using ReCiPe 2016 (v.1.03) End-point method, Hierarchist version. The End-point method is used to aggregate results into three higher aggregation levels: environmental impact to human health, damage to ecosystems, and damage to resource availability (Life cycle assessment of mechanical recycling of post-consumer polyethylene flexible films based on a real case in Spain). Additionally, normalization and weigthting were performed to reveal most dominant end-point impact categories related to the wastewater treatment.

In the interpretation step, which is the final step of LCA, the effect of energy saving in the wastewater treatment was investigated and process contribution analysis was conducted to determine the significant processes that contribute to mid-point and end-point impact categories. Additionally, uncertainty analysis was conducted to reveal the difference between two situations (WWTP-1 and WWTP-2). Interpretation of comparisons was performed by Monte Carlo Simulation using SimaPro software (v.9.2). 1000-run were used for both situations.

3. Results and Discussion

3.1. Characterization Results

Life cycle impact assessment results of WWTP-1 and WWTP-2 were given in Table 3, comparatively. According to the Table 3, the impact categories of stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, human carcinogenic toxicity, and fossil resource scarcity in WWTP-2 were lower than WWTP-1. Especially human carcinogenic toxicity is quite low in WWTP-2 compared to WWTP-1. On the contrary, the other mid-point impact categories were determined higher in WWTP-2 compared to WWTP-1. The impact category of marine eutrophication was by far larger in WWTP-2, followed by mineral resource scarcity, ionizing radiation, and marine ecotoxicity. It is thought that the main reasons for this increase are the differences in the operational processes of WWTP-2 and WWTP-1 (sludge treatment method, transportation distances of sludge and chemicals, amount of chemicals, etc.). Apart from electrical energy savings, the most important difference between the operational stages of the two situation is the preferred method for the disposal of treatment sludge. While in WWTP-1, sewage sludge was sent to cement plant for incineration with heat recovery, in WWTP-2 sewage sludge was sent to sanitary landfill for final disposal.

Table 3. Characterization results.

Impact category	Unit	WWTP-1	WWTP-2
Global warming	kg CO_2 eq	1.33E+00	2.56E+00
Stratospheric ozone depletion	kg CFC11 eq	3.00E-05	2.41E-05
Ionizing radiation	kBq Co-60 eq	1.27E-04	1.87E-03
Ozone formation, Human health	kg NOx eq	8.83E-04	1.03E-03
Fine particulate matter formation	kg $PM_{2.5}$ eq	5.39E-03	8.01E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.55E-04	1.05E-03
Terrestrial acidification	kg SO_2 eq	2.11E-03	1.12E-03
Freshwater eutrophication	kg P eq	9.95E-04	9.53E-04
Marine eutrophication	kg N eq	4.92E-06	8.25E-03
Terrestrial ecotoxicity	kg 1,4-DCB	-4.24E-02	1.71E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.83E-04	5.50E-04
Marine ecotoxicity	kg 1,4-DCB	2.17E-04	1.68E-03
Human carcinogenic toxicity	kg 1,4-DCB	2.38E-03	-7.90E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	6.15E-02	8.82E-02
Land use	m^2a crop eq	-2.55E-02	1.23E-02
Mineral resource scarcity	kg Cu eq	6.91E-05	1.17E-03
Fossil resource scarcity	kg oil eq	1.03E-01	6.67E-02
Water consumption	m^3	2.48E-03	8.96E-04

For more detailed analysis, process contribution analysis was performed and the results were given in Figure 1. When Figure 1 was examined, it was clearly seen that contribution of electricity consumption on mid-point impact categories significantly decreased by electrical energy saving in WWTP-2 compared to WWTP-1. On the contrary, electricity consumption has significant contribution (above 90%) on almost all mid-point impacts (resource scarcity, freshwater ecotoxicity, ozone formation, toxicity, water consumption, fine particulate matter formation, and terrestrial acidification) in WWTP-1. The lowest contributions of electricity consumption was determined for stratospheric ozone depletion (0.40%), land use (5.05%), and freshwater eutrophication (6.54%). It was also observed that chemical consumption (polyelectrolyte) has high contribution (83%) on marine eutrophication for WWTP-1. Compared with WWTP-2, it is possible to say that the most important environmental friendly process was sludge treatment. In WWTP-1, dewatered sewage sludge (22% SS) is sent to cement plant, where sludge is dried by using waste heat and used as an alternative fuel in clinker manufacturing process. Treatment of sewage sludge by incineration for energy recovery ensures environmental gains on almost all mid-point impact in WWTP-1 as can be seen from Figure 1. The highest environmental gains of this process were determined on land use and terrestrial ecotoxicity (approximately 100%).

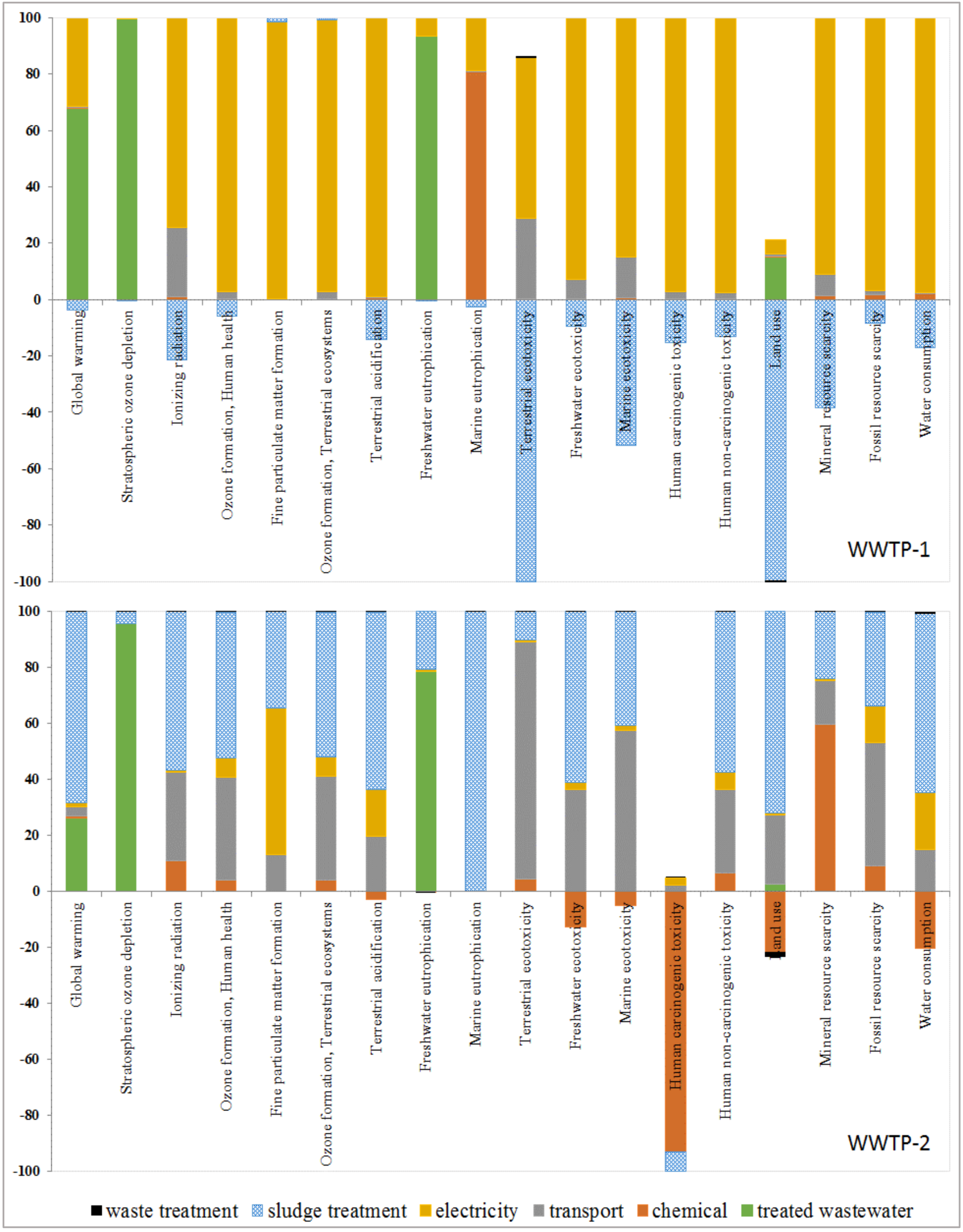


Figure 1. Process contributions to characterization results for WWTP-1 and WWTP-2.

Comparing with WWTP-1, the significant increase of marine eutrophication in WWTP-2 is mainly related to the treatment method of sewage sludge as can be seen from Figure 1. In WWTP-2, sewage sludge is sent to sanitary landfill for final disposal. It was observed that almost all the marine eutrophication impact category (99.9%) was associated with the landfill process according to the process contribution analysis (Figure 1). While energy saving in WWTP-2 ensures significant environmental advantages on almost all mid-point impacts, disposal of sewage sludge by sanitary landfill has adversely affected some of the mid-point impact categories. Treatment of sludge by sanitary landfill has significant contribution on land use (71.8%), global warming (68.4%), water consumption (68.4%), terrestrial acidification (63.3%), and freshwater ecotoxicity (60.9%). On the contrary, treatment of sludge by sanitary landfill ensures 7% environmental saving on human carcinogenic toxicity impact category. Additionally, it is noteworthy that consumption of iron (III) chloride provides 93% environmental gain on human carcinogenic toxicity. In alignment with this result, Selvarajan (2020) has also determined that preffering the iron (III) chloride as a coagulant decreased the human health impacts [14].

3.2. Damage Assessment Results

Three end-point impact categories were evaluated within the scope of damage assessment that was modelled by ReCiPe 2016 End-point (H) methodology: Resources (resource consumption), ecosystems (damage to ecosystems), and human health (damage to human health). After normalization and weigthing step, the results in milipoints (mPt) obtained from ReCiPe 2016 End-point (H) method were presented in Figure 2. As can be seen from Figure 2, overall environmental burden of WWTP-1 was 55% higher than WWTP-2 regarding environmental sustainability. Damage to human health constitues 97.6% and 93.5% of overall environmental burden for WWTP-1 and WWTP-2; respectively. Considering the mid-point impacts that contribute to human health impact category, it was identified that the main responsible mid-point impact category was fine particulate matter that is mainly related to electricity consumption for WWTP-1. For WWTP-2, the main dominant mid-point impact category that damages human health was determined as global warming that is mainly related to sludge treatment.

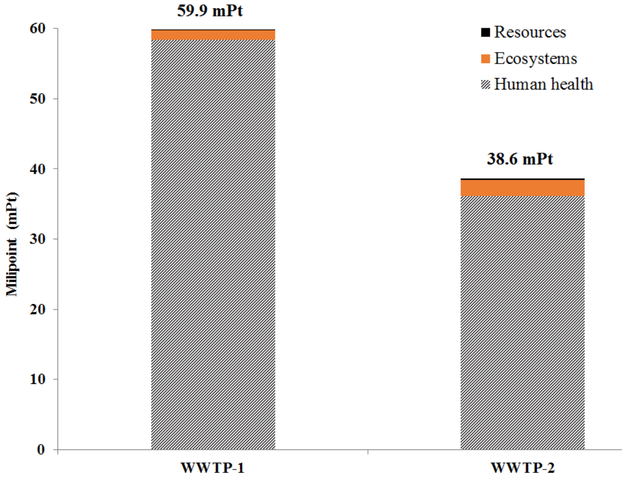
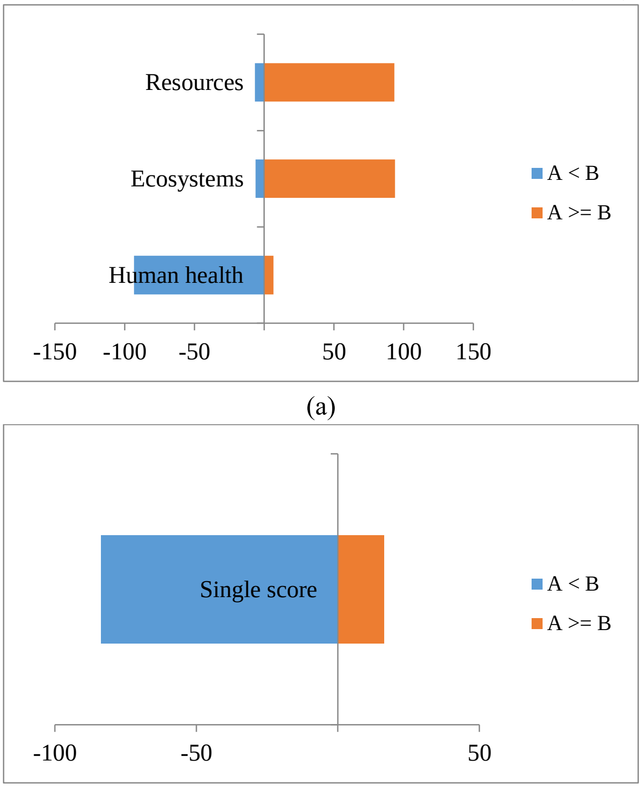


Figure 2. Damage assessment results of WWTP-1 and WWTP-2.

3.3. Uncertainty Analysis

Monte Carlo simulation results of damage assessment and single score for comparing WWTP-1 and WWTP-2 were given in Figure 3(a) and Figure 3(b), respectively. It showed that WWTP-2 preceded WWTP-1 with respect to human health impact category (93%). On the other hand, WWTP-1 was better in 93% and 94% of the iterations for resources and ecosystems. Considering the uncertainty analysis results of single score, WWTP-2 preceded WWTP-1 in terms of overall environmental burden (84%).



(a)

(b)

Figure 3. The results of uncertainty analysis of damage assessment (a) and single score (b). (A: WWTP-2, B: WWTP-1).

4. Conclusions

In this study, the effect of electrical energy saving on the selected WWTP to its environmental sustainability was investigated by life cycle assesment. Both mid-point and end-point impact analysis was conducted within the scope of this LCA study. The results have shown that adverse effects of electricity consumption decreased in almost all mid-point impact categories. However, treatment method of sewage sludge has significant effects on the mid-point impact categories. By energy saving, overall environmental burden of WWTP-2, which is the revised version of WWTP-1, have decreased 36% compared to WWTP-1. Considering with a life-cycle approach, the results indicated that damage to human health was the most significant category related to the wastewater treatment, and efficiency in electrical energy consumption plays a significant role in order to ensure the environmental sustainability in WWTPs. The results of this study can be beneficial in terms of demonstrating that ensuring energy efficiency in wastewater treatment plants has a significant contribution to environmental sustainability.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by Kocaeli University Scientific Research Projects Coordination Unit. Project Number: FKA-2020-2087.

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