Special issue of the 3rd International Conference on Computational and Experimental Science and Engineering (ICCESEN 2016)

# Thermoeconomic Analysis and Assessment of Gaziantep Municipal Solid Waste Power Plant

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This paper presents a thermoeconomic analysis and assessment of a municipal solid waste power plant system in Gaziantep. The operation of an existing municipal solid waste power plant is described in detail and a thermoeconomical methodology based on exergoeconomic relations and specific exergy costing (SPECO) method is provided to allocate cost flows through subcomponents of the plant. SPECO method is based on a step by step procedure which begins from identification of energy and exergy values of all states defined in the present system through fuel ($F$) and product ($P$) approach and ends at the point of establishing related exergy based cost balance equations together with auxiliary equations. The actual exergy efficiency of the solid waste power plant is determined to be 47.84% which shows that 52.16% of the total exergy input to the plant is destroyed. The net electrical power output of the Gaziantep municipal solid waste power plant is 5.655 MW. The total cost rate of the power plant is evaluated as 18.44\$/h as a result of thermoeconomic analyses.

DOI: 10.12693/APhysPolA.132.513
PACS/topics: thermoeconomy, solid waste, waste-to-energy

## 1. Introduction

There are many vital parameters to improve system efficiencies in solid waste power plants. The efficiency improvement is a big problem for the companies which are not only related with technical reasons, it is fundamentally related with economic reasons, because maintenance cost and consumed fuel directly affect to the solution of this problem. There are many studies in this field in the literature which are outlined as follows. Kwak et al. [1] analyzed 500 MW combined cycle plant in terms of exergetic and thermoeconomic analyses by means of an exergy-costing method, MOPSA to estimate the unit costs of electricity produced from gas and steam turbines. The unit cost of products can be estimated with accurate information of the initial investments, salvage values and maintenance costs for each component using a novel program. Abuşoğlu and Kanoğlu [2] performed an energy, exergy, and exergoeconomic analyses for a diesel engine powered cogeneration (DEPC) plant using actual operating data. Specific exergy costing (SPECO) method was used to achieve thermoeconomic analysis of the power plant [2, 3]. Abuşoğlu and Kanoğlu [4] carried out a review study which includes a brief historical overview on the exergoeconomic analysis and optimization for combined heat and power production (CHPP).

Available thermoeconomic methodologies in literature were represented and their advantages and disadvantages were compared and discussed through a well-known problem, namely CGAM. Thermoeconomic analysis and optimization of combined heat and power production were listed based on the methodology used and the type of system was considered. An exergoeconomic analysis of a pilot scale gas engine driven heat pump (GEHP) drying system was investigated based on the experimental values using exergy, cost, energy, and mass (EXCEM) analysis method by Gungor et al. [5]. It resulted that the dead state temperature affected the performance parameters, particularly the drying process parameters. Increase of the dead state temperature led to an increase in the exergy efficiencies of the drying process and a decrease in the ratio of the thermodynamic loss rate to the capital cost values in a polynomial form. Abuşoğlu et al. [6] presented the thermoeconomic analysis and assessment of a municipal wastewater treatment system using specific exergy costing (SPECO) method.

Actual operational plant data were used to perform thermoeconomic analysis for Gaziantep waste water treatment plant. It was concluded that better exergy performance and cost effectiveness can be achieved by reducing exergy destruction through better operation conditions as well as by reducing operational and exergy destruction costs through all WWTP subcomponents. Erbay and Hepbaşlı [7] carried out the conventional and advanced exergoeconomic analyses for a heat pump food dryer using different drying air temperatures and analyzed the components separately for the drying system and investigated the effects of the operating temperature on the system components. It was stated that the increase in inlet drying temperature caused lower costs and higher improvement potentials. Also it was suggested that optimization studies related with cost efficiencies and product quality should be considered.

Khaljani et al. [8] performed a thermodynamic, exergoeconomic and environmental assessment of a cogeneration of heat and power cycle (CHP), considering three objective functions of first and second law efficiencies and the total cost rates of the system. It resulted that the

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maximal exergy destruction rate took place in the combustion chamber, and after that in heat recovery steam generator and gas turbine, respectively. Also it was evaluated that the exergoeconomic factor for the whole cycle as 10.59% which indicated that the exergy destruction cost rate was more than capital investment cost rate. A parametric study was carried out in order to determine the effects of design parameters on the objective functions. It was claimed that the increase in the pressure ratio and the isentropic efficiency of the air compressor and the gas turbine efficiency played a favorable role for the thermodynamic performance of the system. There are also many recent studies on municipal solid waste (MSW) management and thermoeconomic developments which has become a very critical issue for all countries [9–16].

In this paper, a thermoeconomic analysis and assessment of a municipal solid waste power plant system in Gaziantep were performed utilizing the existing MSW power plant by means of SPECO method considering cost flows through subcomponents of the plant. The actual exergy efficiency of the plant, the total exergy input to the plant, the net electrical power output of the plant, the exergy cost rate and the specific unit exergy cost of the power produced by the plant were evaluated as a result of the thermoeconomic analyses. This paper gives an original contribution to the open literature due to the extensive thermoeconomic analysis of a MSW power plant using the actual operating data to emphasize such future studies which are becoming vital phenomena in view of energy, economic, and environmental aspects.

## 2. System description and thermoeconomic analyses

In Gaziantep municipal solid waste power plant (GMSWPP), landfill gas (LFG) is created during the anaerobic decomposition of organic substances in MSW, industrial and medical wastes. The total MSW carried to GMSWPP is 1,500 tons which produces 20,203 $m^3$ landfill gas daily [17]. All wastes which are collected in GMSWPP are subjected to mechanical segregation of plastic, metal and glass, and then rest of MSW is sent to sanitary landfilling area. On the other hand, medical waste is sterilized first as a pre-treatment and then sent into landfilling area. MSWs which are buried underground in landfilling area are led to produce LFG for months. The produced LFG from the storage area is collected, then transferred to 6 manifold stations. If the temperature of the LFG is higher than 40–45 °C, it is cooled through the chiller unit by means of chilled water. The LFG whose temperature is under 40–45 °C or which is cooled with chilled water (nearly to 15 °C) is sucked into 5 identical V-type 16 cylinder Jenbacher 416 GS type gas engines coupled with a generator. Schematic layout of GMSWPP is shown in Fig. 1.

The electricity production process is summarized as follows: the produced LFG is transported to the five gas engines with mass flow rate of 0.76 kg/s using six blowers. LFG and air combined in an air fuel tank are then delivered to the compressor coupled with turbine which are components of the turbocharger unit. The mixture of LFG and air is conducted to the power unit after its temperature is decreased to the 40 °C by using intercooler. In power unit, there are one combustor, four heat exchangers and one power generator in order to produce electricity from the gas engine. The exhaust gas which has a temperature of roughly 560–570 °C is discharged from the gas engine to the atmosphere after the turbocharger turbine. The schematic representation of the engine room is given in Fig. 2.

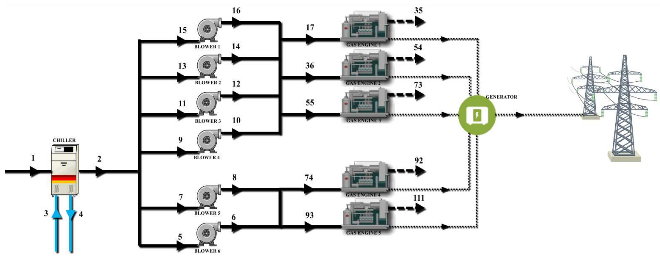


Fig. 1. Schematic layout of Gaziantep municipal solid waste power plant.

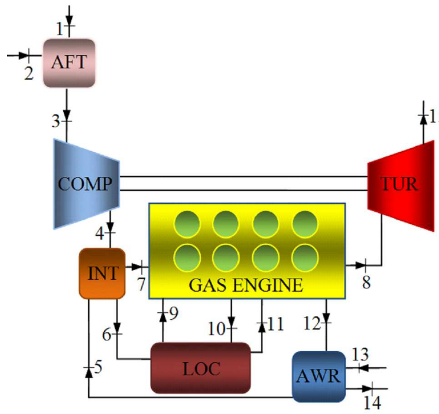



Fig. 2. Schematic layout of the gas engine in Gaziantep municipal solid waste power plant.

This model is designed in ASPEN Plus Engineering and analyzed in Engineering Equation Solver (EES) software programs. Air and the exhaust gases are assumed as ideal gases at given state temperatures and pressures. Heat transfer rates, work, exergy destructions and exergy efficiencies are calculated by means of the governing equations given below. The specific flow exergy is given by

$$\psi = (h - h_0) - T_0(s - s_0), \quad (1)$$

$$\dot{E}x = \dot{m}\psi, \quad (2)$$

where the subscript 0 stands for the restricted dead state, $h$ and $s$ are enthalpy and entropy values, respectively. Isentropic efficiencies of turbine and compressor can be defined as:

$$\eta_t = \frac{w_a}{w_s} = \frac{h_i - h_e}{h_i - h_{es}}, \tag{3}$$

$$\eta_{comp} = \frac{w_s}{w_a} = \frac{h_{es} - h_i}{h_e - h_i}, \tag{4}$$

where $w_a$ is the actual specific work, $w_s$ is the isentropic specific work, the subscript $es$ is isentropic condition at exit state. The thermal efficiency of a power plant can be evaluated by means of the following equation:

$$\eta_{th} = \dot{W}_b / \dot{m}_f \dot{Q}_{HV}, \tag{5}$$

where $\dot{W}_b$ is break power, $\dot{m}_f$ is mass flow rate of fuel and $\dot{Q}_{LHV}$ is lower heating value of fuel. The exergy (second law) efficiencies of turbine and compressor are given as follows:

$$\varepsilon_t = \frac{w_a}{w_{rev}} = \frac{h_i - h_e}{h_i - h_e - T_0(s_i - s_e)}, \tag{6}$$

$$\varepsilon_{comp} = \frac{w_{rev}}{w_a} = \frac{h_e - h_i - T_0(s_e - s_i)}{h_e - h_i}, \tag{7}$$

where $w_{rev}$, reversible specific work is equal to the sum of specific exergy destruction $e_D$ and actual work. The exergy efficiency of a heat exchanger in a power plant is evaluated by taking the ratio of the increase in the exergy of the cold stream and the decrease in the exergy of the hot stream

$$\varepsilon_{he} = \frac{(\dot{E}x_e - \dot{E}x_i)_{cold}}{(\dot{E}x_i - \dot{E}x_e)_{hot}} = \frac{\dot{m}_{cold}\left(h_e - h_i - T_0(s_e - s_i)\right)_{cold}}{\dot{m}_{hot}\left(h_i - h_e - T_0(s_i - s_e)\right)_{hot}}, \tag{8}$$

where $\dot{m}_{cold}$ and $\dot{m}_{hot}$ are the mass flow rates of the cold and hot streams, respectively.

The energy and exergy analyses of all subcomponents are given in Table I. The highest and lowest exergy efficiencies are found for the gas engine and intercooler, respectively. Heat exchangers have lower exergy efficiency when compared to other sub-components in the power plant due to their high exergy destructions. The energy and exergy efficiencies of the Gaziantep municipal solid waste power plant are found to be 38.87% and 47.84%, respectively.

TABLE I

Energy and exergy analyses of the sub-components.

| Component | $\dot{Q}$ [kW] | $\dot{W}$ [kW] | $\dot{E}_f$ [kW] | $\dot{E}_P$ [kW] | $\dot{E}_D$ [kW] | $\varepsilon$ [%] |
|---|---|---|---|---|---|---|
| COMP | – | 271.7 | 271.7 | 197.5 | 74.23 | 72.68 |
| INT | 313.7 | – | 93.02 | 13.68 | 79.35 | 14.70 |
| LOC | 1309 | – | 228.3 | 146 | 82.25 | 63.97 |
| GE | – | 1131 | 1164 | 1131 | 32.81 | 97.18 |
| AWR | 1486 | – | 192.6 | 120.4 | 72.26 | 62.49 |
| TUR | – | 385.7 | 475.2 | 385.7 | 89.51 | 81.16 |
| energy efficiency of the plant | | | | | | 38.87 |
| exergy efficiency of the plant | | | | | | 47.84 |

Thermoeconomics can be defined as the combination of exergy analysis and economic principles, which is very helpful for system designers or operators in order to understand the capability of systems in terms of available useful energy, that cannot be well-understood by means of conventional energy and economical analyses solely [2]. In this study, specific exergy costing (SPECO) method is used for the thermoeconomic analysis of the power plant system. In SPECO method, firstly, all energy and exergy flows in all states of system are determined. Then, all sub-components of the system are designated with respect to fuel and product approach. All exergy additions and removals to a sub-component are considered as the fuel ($F$) and product ($P$), respectively. As a result, the cost balance and auxiliary equations for each part are written as [8]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k, \tag{9}$$

$$\dot{C}_j = c_j \dot{E}_j, \tag{10}$$

where $\dot{C}$represents the cost rate [$/h] and $e$ and $i$ indicate entering and exiting flows rate of the any sub-component $k$. $\dot{Z}_k$ shows the entire cost rate related to capital investment (CI) and operation and maintenance costs (OM) of the sub-component $k$.

The performance of a sub-component can be defined by using SPECO method and in order to consider this aim, the cost flow rates through any sub-components related with the exergy loss are evaluated by means of the cost history of the power plant. This is supplied by using the exergoeconomic factor $f_k$, and it is defined for a sub-component $k$ as [2]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k}\dot{E}_{D,k}}, \tag{11}$$

where $c_{f,k}$ is the unit exergy cost of the fuel of any sub-component $k$ and $\dot{E}_{D,k}$ is the corresponding exergy destruction of the same component. Relative cost difference, $r_k$ is another important parameter in thermoeconomic evaluations. It is the relative increase in the average cost per exergy unit between fuel and product of the component. For a sub-component $k$, it is defined as:

$$r_k = \frac{c_{p,k} - c_{f,k}}{c_{f,k}}, \tag{12}$$

where $c_{p,k}$ is the unit exergy cost of the product of any sub-component $k$. The relative cost difference is very significant parameter for considering and optimizing system components. The cost rate of exergy destruction, $\dot{D}_{D,k}$, is defined as:

$$\dot{D}_{D,k} = c_{f,k}\dot{E}_{D,k}. \tag{13}$$

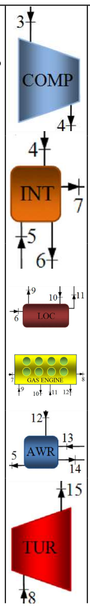
## 3. Results and discussion

In this study, the operating and economic data of LFG and all sub-components of the plant are taken from Gaziantep municipal solid waste power plant and then thermoeconomic analysis is performed. Exergy cost rate balance and corresponding auxiliary equations are tabulated for each sub-component of gas engine and given in Table II. Auxiliary equations are carried out using fuel and product principles for sub-components of the plant.

Table III shows the actual investment costs and other equipment costs which are taken from the CEV Energy Group who is the contractor company of Gaziantep municipal solid waste power plant until 2046. The operating cost of each sub-component is also taken as 20% of the

TABLE II

Exergy cost rate balance and corresponding auxiliary equations for all sub-components of gas engine.




| Component | Exergy cost rate balance | Auxiliary equations |
|---|---|---|
| COMP | $c_e\dot{W}_{COMP} + \dot{Z}_{COMP} = c_4\dot{E}x_4 - c_3\dot{E}x_3$ | $c_3 = c_4$ |
| INT | $c_4\dot{E}x_4 + c_5\dot{E}x_5 + \dot{Z}_{INT} = c_7\dot{E}x_7 + c_6\dot{E}x_6$ | $c_5 = c_6$ |
| LOC | $c_6\dot{E}x_6 + c_{10}\dot{E}x_{10} + \dot{Z}_{LOC} = c_{11}\dot{E}x_{11} + c_9\dot{E}x_9$ | $c_6 = c_{11}$<br>$c_9 = c_{10}$ |
| GE | $c_7\dot{E}x_7 + c_9\dot{E}x_9 + c_{11}\dot{E}x_{11} + \dot{Z}_{GE} = c_8\dot{E}x_8 + c_{10}\dot{E}x_{10} + c_{12}\dot{E}x_{12}$ | $c_7 = c_8$ |
| AWR | $c_{12}\dot{E}x_{12} + c_{13}\dot{E}x_{13} + \dot{Z}_{AWR} = c_5\dot{E}x_5 + c_{14}\dot{E}x_{14}$ | $c_{13} = 0$ |
| TUR | $c_8\dot{E}x_8 + \dot{Z}_{TUR} = c_e\dot{W}_{TUR} + c_{15}\dot{E}x_{15}$ | $c_8 = c_{15}$ |

capital investment cost according to the contractor company.

It is predicted by the company that the process with full load will be carried out at approximately 8040 h per year for 10 years. The total PEC of all sub-components in the plant are presented in Table IV evaluating the link between first capital investment (CI) cost and operating and maintenance (OM) costs using operation time. The exergy flow rate $\dot{E}_x$, cost flow rate $\dot{C}$ and the unit exergy cost $c$ of each stream in the plant (Fig. 1) are evaluated by means of the exergy cost rate balance and corresponding auxiliary equations (Table II) and the results are given in Table V.

The unit exergy cost of fuels and products, the relative exergy cost difference, the exergoeconomic factor, the cost rate of exergy destruction and the total investment cost rate of the sub-components in the plant are tabulated in Table VI considering fuel ($F$) and product ($P$) costs of each sub-component and also CI and OM costs which are given in Tables IV and V.

SPECO method is applied for one gas engine then the results are evaluated for 5 identical engines. The capital investment cost rate, the operating and maintenance costs rate, and the total cost rate of the Jenbacher 416 GS gas engine are found to be 3.497 \$/h, 0.699 \$/h, and 4.197 \$/h, respectively. The total cost rate of power plant is found to be 18.44 \$/h.

## 4. Conclusion

In this study, the thermodynamic and thermoeconomic analyses of Gaziantep municipal solid waste power plant is carried out using actual operating data. The engine room is designed in ASPEN Plus Engineering environment and thermodynamic analyses are performed in EES software program. Thermoeconomical method, SPECO, is identified and exergoeconomic relations are used to allocate cost flows through sub-components of the power plant. Results are summarized according to the thermodynamic and thermoeconomic analyses as follows:

- The thermodynamic analyses of all subcomponents are evaluated and the exergy efficiency of the power plant is found to be 47.84%. Beside this, the thermal efficiency of the gas engine is evaluated

TABLE III

Capital investment [k\$] of the GMSWPP.

| | |
|---|---|
| **A1. Direct costs onsite** | |
| chiller | 113.89 |
| blower | 1.18 |
| $DeSO_x$ | 97.62 |
| compressor | 54.67 |
| intercooler | 20.83 |
| lubrication oil cooler | 52.06 |
| gas engine | 283.15 |
| air water radiator | 52.06 |
| turbine | 54.67 |
| other equipment (radiator, booster and flare) | 351.43 |
| **Purchased equipment costs (PEC)** | **1079.56** |
| purchased equipment installation | 520.63 |
| piping | 488.1 |
| instrumentation and controls | 569.44 |
| electrical equipment and materials | 488.1 |
| **Total onsite costs** | **2066.27** |
| **A2. Offsite costs** | |
| civil, structural, and architectural work | 162.7 |
| service facilities | 455.56 |
| **Total offsite costs** | **618.26** |
| **Total direct costs** | **3764.09** |
| **B. Indirect costs** | |
| engineering and supervision | 146.43 |
| construction costs | 244.05 |
| **Total indirect costs** | **390.48** |
| **Fixed capital investment** | **4154.57** |
| **C. Other outlays** | **146.43** |
| **Total capital investment** | **4301** |

TABLE IV

Cost rate of first CI and OM cost for the sub-components of the plant.

| Component | PEC [k\$] | $\dot{Z}_k^{CI}$ [\$/h] | $\dot{Z}_k^{OM}$ [\$/h] | $\dot{Z}_k^t$ [\$/h] |
|---|---|---|---|---|
| chiller | 113.89 | 1.417 | 0.283 | 1.700 |
| blower | 1.18 | 0.015 | 0.003 | 0.018 |
| $DeSO_x$ | 97.62 | 1.214 | 0.243 | 1.457 |
| compressor | 54.67 | 0.680 | 0.136 | 0.816 |
| intercooler | 20.83 | 0.259 | 0.052 | 0.311 |
| lubrication oil cooler | 52.06 | 0.648 | 0.130 | 0.778 |
| gas engine | 283.15 | 3.497 | 0.700 | 4.197 |
| air water radiator | 26.03 | 0.648 | 0.130 | 0.778 |
| turbine | 54.67 | 0.680 | 0.136 | 0.816 |
| other plant equipment | 351.43 | 4.371 | 0.874 | 5.245 |
| **Total PEC** | **1079.56** | **13.427** | **2.685** | **16.113** |

TABLE V

The exergy flow rates, cost flow rates and the unit exergy costs of each stream in the plant

| State | Fluid | $\dot{E}x$ [kW] | $\dot{C}$[\$/h] | $c$ [\$/GJ] |
|---|---|---|---|---|
| 1 | air | 19.75 | 0 | 0 |
| 2 | lfg | 3992 | 2.491 | 35.8 |
| 3 | lfg+air | 187.2 | 53.14 | 35.82 |
| 4 | lfg+air | 384.7 | 53.14 | 73.6 |
| 5 | water | 20.27 | 1247 | 90.96 |
| 6 | water | 33.94 | 1247 | 152.3 |
| 7 | lfg+air | 291.7 | 12.02 | 12.62 |
| 8 | exhaust | 1456 | 12.02 | 62.97 |
| 9 | luboil | 1638 | 796.9 | 4701 |
| 10 | luboil | 1867 | 796.9 | 5356 |
| 11 | water | 180 | 1247 | 807.7 |
| 12 | water | 212.9 | 139 | 106.6 |
| 13 | air | 0 | 0 | 0 |
| 14 | air | 120.4 | 36.92 | 16 |
| 15 | exhaust | 980.3 | 3.21 | 11.33 |

TABLE VI

Unit exergy costs of fuels and products, relative exergy cost difference, exergoeconomic factor, cost rate of exergy destruction and total investment cost rate of the subcomponents in the plant.

| | $c_{f,k}$ [\$/GJ] | $c_{p,k}$ [\$/GJ] | $f$ [%] | $r$ [%] | $\dot{D}_D$ [\$/h] | $\dot{Z}^T$ [\$/h] |
|---|---|---|---|---|---|---|
| COMP | 37.79 | 53.14 | 7.476 | 40.62 | 10.1 | 0.816 |
| INT | 53.14 | 12.02 | 2.008 | 77.38 | 15.18 | 0.311 |
| LOC | 795.4 | 1245 | 0.3292 | 56.51 | 235.5 | 0.778 |
| GE | 12.02 | 64.45 | 74.72 | 81.35 | 1.42 | 4.197 |
| AWR | 139.3 | 38.5 | 2.102 | 72.36 | 36.23 | 0.778 |
| TUR | 12.02 | 37.79 | 17.4 | 68.19 | 3.873 | 0.816 |

as 38.87%, which is compatible with the technical specifications of the Jenbacher 416 type.

- The exergy efficiencies of the compressor and the turbine of the turbocharger are 72.68% and 81.16%, respectively. This represents that a remarkable exergy losses are shown from the turbocharger.
- The exergy efficiencies of the INT, LOC and AWR are evaluated as 14.7%, 63.97% and 62.49%, respectively. It is clearly shown that heat exchangers have lower exergy efficiencies when compared to other components.
- The capital investment cost rate, the operating and maintenance cost rate, and the total cost rate of the Jenbacher gas engine are found to be 3.497 \$/h, 0.699 \$/h, and 4.197 \$/h, respectively.
- The net electrical output of one engine is 1131 kW. The total cost rate of the power plant is found to be 18.44 \$/h.
- Marketing price of 1 kWh electricity is set to 13.3 cents throughout 10 years regarding to agreement between the government and CEV Energy Group. The price of 1 kWh electricity production in GMSWPP is found to be 1.631 cents which is less than marketing price.
- There are 5 identical gas engines in GMSWPP which have electricity production capacity of 5655 kWh. As a result of thermoeconomic analyses, the total investment cost and annual gain of GMSWPP are found to be \$21,505,000 and \$5,305,450, respectively.
- The payback period of Gaziantep municipal solid waste power plant is found to be 4.05 year in consequence of thermoeconomic analyses, which is rational for energy production power plants.


## Acknowledgments

This study is supported by TUBİTAK (The Scientific and Technological Research Council of Turkey) with the project under the grant number of 114M142. The authors would like to thank TUBİTAK and CEV (Clean Energy & Vehicles) energy.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