Article

Integration of Methane Reforming and Chemical Looping Technologies for Power Generation from Waste Plastic: Technical and Economic Assessment

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Abstract: An imperative environmental concern is escalating due to the widespread disposal of plastic waste in oceans and landfills, adversely impacting ecosystems and marine life. In this context, sustainable methods for plastic waste utilisation were evaluated, particularly for power generation. Two case studies were developed to assess the potential utilisation of waste plastic, specifically polyethylene and polypropylene, by integrating gasification with steam methane reforming (SMR) alongside two oxygen-supplying techniques for combustion including cryogenic air separation (ASU) and chemical looping combustion (CLC) for case 1 and case 2, respectively. For this, thorough process simulations of both case studies were performed to obtain detailed material and energy balances. The techno-economic analysis was performed to assess the economic performance of the processes by estimating levelized cost of electricity (LCOE). The results indicated that case 2 is more efficient (5.4%) due to the lower utility requirement of the CLC process as compared to ASU. Consequently, case 2 generated a LCOE of USD 137/MW. It was also seen from the results that the power output is directly proportional to the methane input while the increase in gasifier temperature enhances the H_2 and CO content in syngas.

Keywords: waste utilisation; feasibility assessment; reforming; gasification; circular economy

1. Introduction

Polymers and plastics are widely used around the world due to their versatility and cost-effective manufacturing processes. They offer practical qualities such as lower density, chemical resistance, durability, and affordability compared to traditional materials such as wood, metals, and ceramics. Since 1950, plastic production has expanded, and as of the beginning of the twenty-first century, it reached a global total of 200 million tonnes. Due to industrial activity and societal lifestyle preferences, the yearly production of plastic surpassed 400 million tonnes by the end of 2019 [1].

According to a study, the United States currently produces 2 billion tons of municipal solid waste (MSW), and by 2050, it is predicted that the country will produce 3.4 billion tons of plastic garbage annually [2]. Given that the majority of solid and plastic trash is either disposed of in landfills or discharged into the ocean, this has become a global concern. As a result, the environment and marine life have been impacted. Polyethylene and polypropylene make up 29.6% and 18.9%, respectively, of the most commonly used plastic wastes, while the remaining polymers account for 51.5% [2]. Plastic trash incineration has been a popular alternative to landfilling; however, it is extremely damaging to the environment as it releases CO_2 and other hazardous gases. Most of these gases are greenhouse gases, which can alter the climate on a global scale.

Unchecked accumulation of non-recycled plastic waste poses significant environmental hazards, and this issue carries substantial implications for the Kingdom of Saudi Arabia

(KSA). By 2035, the KSA expects to earn USD 32 billion dollars a year through recycling waste plastic [3]. KSA is putting a strong emphasis on the country's sustainable development by enacting reuse, recycling, and reconstituting policies regarding waste plastic. To promote sustainable development, the SIRC and SABIC have partnered with the Saudi Arabian government.

To avoid polluting the ecosystem and to provide clean energy for a sustainable future in line with the sustainable development goals provided by United Nations, mitigation of the unchecked disposal of plastic waste is desirable. One key approach in this regard is the circular economy, which includes the recycling and reutilising of waste material. Many recycling methods have been studied and proposed for the recycling of waste plastic. Pyrolysis, for instance, converts plastic waste into valuable fuel, potentially contributing significantly to sustainable growth [4,5]. Quaternary techniques offer a short-term solution for reducing the lifespan of plastic materials. Given that Europe accounts for 19% of the global plastic waste production, which totalled 299 million tonnes in 2013 [3], tertiary recycling is strongly advised. Whilst 26% of the plastic waste in Europe can be recycled through primary or secondary processes, waste plastic can be turned into fuel or syngas for sustainable development, and tertiary recycling may be quite advantageous in this case [6]. In this regard, the thermochemical recycling of waste plastics is the method that is most practical for not only minimizing solid waste disposal but also for producing several significant fuels and chemicals [7,8]. More specifically, gasification processes at a commercial scale can convert waste plastic into syngas which can be thus utilised in chemicals production, biofuels production such as for bioethanol, hydrogen production after RWGS, and electricity production [9–11]. Additionally, gasification is a mature technology with lower environmental emissions as compared to combustion [8]. Thus, due to its wide range of application and environmental benefits, gasification was selected as the conversion process in this study.

Recent studies on the subject have mostly been limited to the syngas production, whereas for power generation, additional processing of the syngas is required [12,13]. A combined-cycle power plant (CCPP) plays a crucial role in this scenario, producing energy and electricity through a combination of steam and gas turbines [14]. The combustion of fuel, such as syngas, powers the gas turbine, generating electricity and producing steam that drives the steam turbine, further contributing to electricity production. This system incorporates the Brayton and Rankine cycles to enhance energy recovery, minimize heat losses, and optimize electricity generation [15]. The heat recovery steam generation section (HRSG) is a pivotal component, seamlessly integrating both the steam and gas turbines into a heat recovery system.

To achieve greater efficiency and carbon dioxide removal, CCPPs with chemically looping combustion (CLC) systems show significant promise. In the CLC process, fuel undergoes combustion in the presence of an intermediate agent, often a metal oxide [16,17]. This oxidized fuel and intermediate are cycled between two fluidized bed reactors, with the metal oxide undergoing reduction in a dedicated reactor. Subsequently, the fuel undergoes exothermic oxidation in the designated reactor [18]. The system's advantage lies in the production of by-products that do not contain diluents, differentiating it from conventional combustion processes.

The primary objective of this study was to develop a feasible model for power generation through waste plastic. For this, two hybrid models were conceptualized including (1) gasification + SMR with air separation unit (ASU) and (2) gasification + SMR with CLC model for power generation as an effort to enhance economic feasibility. To evaluate the proposed models, detailed process simulations were performed on Aspen Plus V11 to obtain the material and energy balance for these processes. When these balances were obtained, a techno-economic analysis was performed to identify the most feasible process. A discounted cash flow model was developed to generate the cash flows of the project and estimate the key economic parameters such as levelized cost of electricity (LCOE) and net present value (NPV). Key technical parameters were identified through these analysis,

which were then employed in sensitivity analysis to determine the impact of their variation on power output.

2. Process Simulation and Model Development

2.1. Development of Case Studies

Two different case studies were conceptualized to comprehensively investigate the power generation using waste plastic utilising various oxygen-supplying techniques. The developed case studies included (1) gasification + SMR with ASU and (2) gasification + SMR with CLC. A brief description and the process flow diagrams of each case are detailed below.

2.1.1. Case 1 (Base Case)

Case 1 consisted of a feed preparation unit, entrained flow gasifier, steam methane reformer, air separation unit, combined cycle, and a carbon purification unit as shown in Figure 1. Before being sent to the gasifier, the feed preparation machine dehumidifies and shreds the plastic feed. The steam gasification unit, operating at 1300 °C and 25 bar, is charged with the prepared plastic feed and gasified by means of steam [19]. The gasifier converts the solid plastic into gaseous components generating syngas and solid residue. The outlet stream at 1300 °C is used to preheat the feed for the SMR to minimize the heating load of the unit. The same amount of waste plastic (1000 kg/h) and natural gas (300 kg/h) were fed into the gasifier and reformers, respectively, to provide equal grounds for comparison. Furthermore, steam-to-plastic (1.25:1) and steam-to-methane (1.83:1) ratios were also kept constant in both cases for the two processes [12].
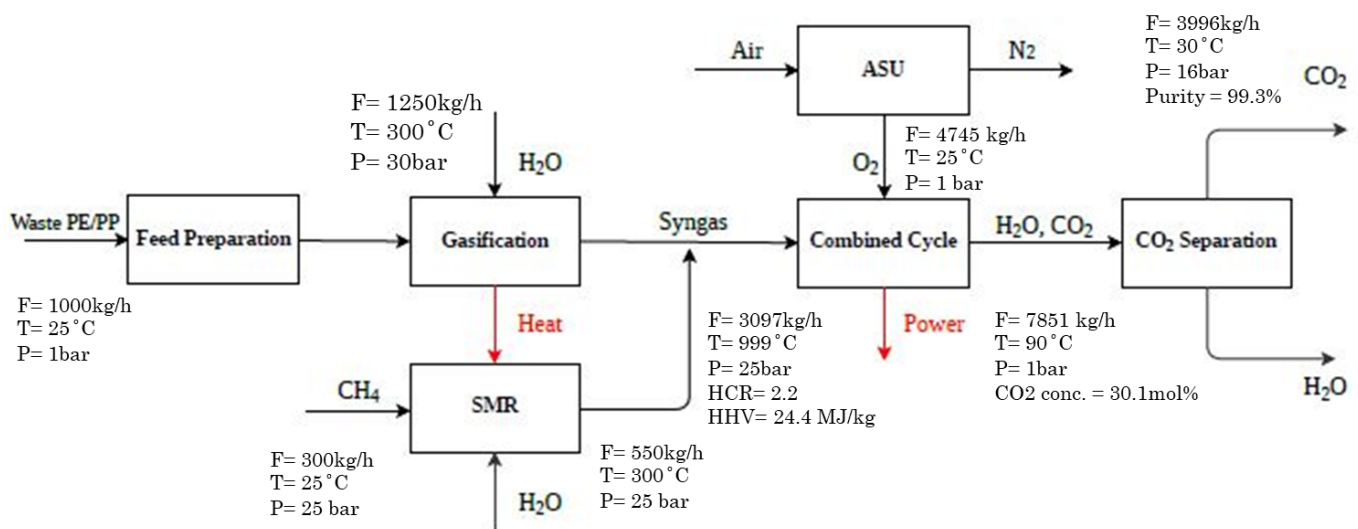

Figure 1. Block flow diagram of power generation from waste plastic utilising steam methane reforming (SMR) and air separation unit (ASU).

Once syngas is produced, the combined cycle unit burns syngas using pure oxygen to drive the gas turbine (GT) in order to generate electricity. Pure oxygen is provided to avoid the addition of the carbon capture unit downstream of the power generation process and its energy penalty. For this, ASU is used to separate the oxygen using cryogenic temperatures of -196 °C [20,21]. The outlet flue gases of the GT are still at high temperatures, which are passed through an HRSG to produce superheated steam at 300 °C and 30 bar [22]. The steam generated in the HRSG powers the steam turbine, producing additional power as a result. Carbon dioxide, a byproduct of the process, is eliminated using a straightforward cooling and knock-out drum and subsequently compressed and dehydrated to achieve the selling grade purity of 99.5%.

2.1.2. Case 2 (Alternative Case)

In this case, the source of oxygen for the combustion in the gas turbine was changed from ASU to CLC, with the rest of the process kept as it is as shown in Figure 2. CLC is a unique concept which allows the process to be operated with impurities while still providing easy separation and purification of the final product [15,23]. It is based on the inherent reactivity of metal oxides to facilitate the separation of hydrogen from water while avoiding the direct contact of hydrogen with air [24]. This unique process neither requires the upstream nor the downstream CO_2 removal, providing economic and environmental savings [24].
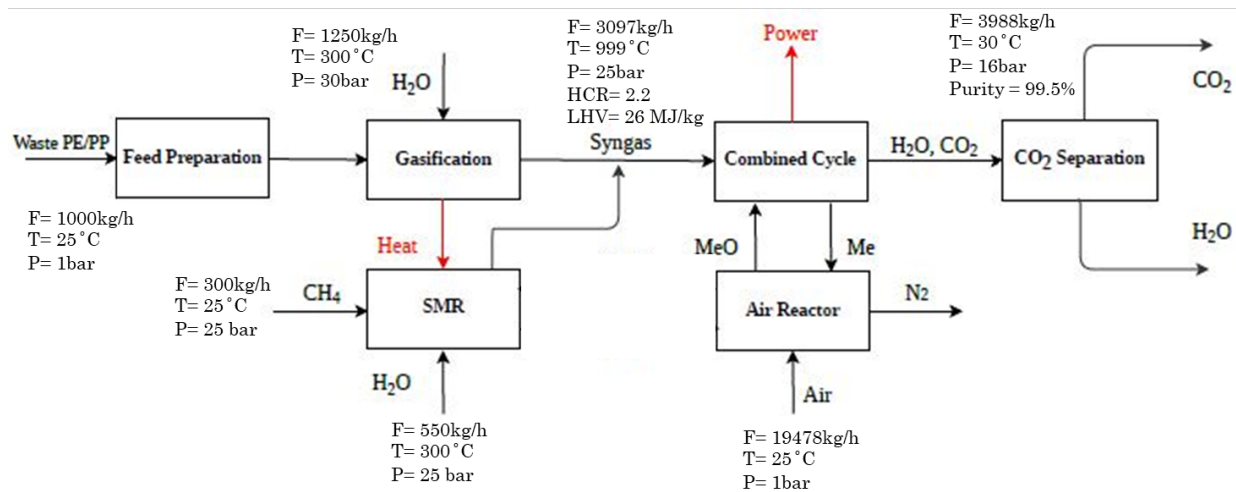

Figure 2. Block flow diagram of power generation from waste plastic utilising steam methane reforming (SMR) and chemical looping (CLC).

In CLC, fuel is burned in the presence of an intermediate agent, typically a metal oxide, which undergoes reduction and oxidation in two fluidized bed reactors [25,26]:

$$Fe_2O_3 + H_2 \rightarrow FeO + H_2O \tag{1}$$

$$Fe_2O_3 + CO \rightarrow FeO + CO_2 \tag{2}$$

The resulting CO_2 is separated from oxygen-rich metal oxide using a cyclone, and the metal oxide is recycled. This process offers advantages over traditional combustion, as byproducts do not contain diluents.

2.2. Development of Simulation Model

To materialize the suggested models, they were simulated using Aspen Plus V11. PP and PE were introduced as the non-conventional components through a definition of their ultimate and proximate analysis, as presented in Table 1 [12]. The Peng–Robinson equation of state model was used to estimate the properties of the involved components and phase equilibrium calculations. RYield was used to simulate the gasification process generating the simple components from the waste plastics. RGibbs was used to model the SMR calculating the products based on the minimization of the Gibbs free energy. To visualize the gas turbine HRSG, a combination of Rstoic, turbine, and HeatX were used for accurate representation.

Based on the material and energy balance obtained from the process simulation, various technical parameters were estimated to yield a comprehensive comparison between the two cases. First the syngas production and its HCR were computed using the following formula:

$$HCR = \frac{Mole\ flow\ rate\ of\ hydrogen\ in\ syngas}{Mole\ flow\ rate\ of\ carbon\ monoxide\ in\ syngas} \tag{3}$$

Table 1. Ultimate and proximate analysis of polyethylene and polypropylene used in the study [12].

Components	Polyethylene	Polypropylene
Ultimate analysis (wt%)		
Moisture content	0.02	0
Ash content	0.15	0.70
Volatile matter	99.83	99.30
Proximate analysis (wt%)		
Carbon content	85.81	86.23
Hydrogen content	13.86	12.28
Nitrogen content	0.12	0.62
Sulphur content	0.06	0.17
Ash content	0.15	0.70
LHV (Lower heating value) MJ/kg	38.04	44.70

Secondly, a more important parameter providing a wholistic view of the two process was calculated, i.e., process efficiency, through the following formula:

$$\eta = \frac{Electricity\ produced}{LHV_{PP} + LHV_{PE} + LHV_{NG} + Utilities\ consumed} \times 100 \tag{4}$$

where *PP* is polypropylene, *PE* is polyethylene, and *NG* is natural gas.

2.3. Techno-Economic Analysis

An economic analysis of the two cases was performed to analyse their feasibility in the current market. The economic analysis consisted of capital and manufacturing costs. The assumptions used in the analysis are summarised in Table 2.

Table 2. Assumed parameters for the economic analysis.

Assumed Parameters	Value
Costing year	2023
Plant operational life	20 years
Construction period	2 years
Operating hours/year	8000
Depreciation of general plant	7 years
Discount rate	8% per year
Tax rate	15% per year

Installed costs of general equipment were calculated through Aspen plus cost analyser, whereas the specialised equipment, such as reactors, was scaled with the help of previous studies [27,28] using the following formula [29,30]:

$$Installed\ Cost = \left(\frac{New\ Capacity}{Reference\ Capacity} \right)^n \times Reference\ installed\ Cost \times \left(\frac{CEPCI_{2023}}{CEPCI_{Ref}} \right) \tag{5}$$

where *n* is the scaling factor. These installed costs were then used to calculate the total CAPEX using multiple factors as summarised in Table 3.

The OPEX was computed based on the raw material (C_{RM}), utility (C_{UT}), wastewater treatment (C_{WT}), labour (C_{OL}), and other direct operating expenses including maintenance (2% of *FCI*) and laboratories charges (10% of C_{OL}). The formula for *OPEX* is as follows:

$$OPEX = 0.28FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \tag{6}$$

Table 3. Factors used for calculation of total capital investment. ISBL—inside battery limit.

Economic Factors	Values
Total direct cost (TDC)	
Warehouse	4% of ISBL
Site development	9% of ISBL
Additional piping	4.5% of ISBL
Total indirect cost (TIDC)	
Field expenses	10% of TDC
Prorateable costs	10% of TDC
Project contingency	10% of TDC
Home office and construction	10% of TDC
Other costs	10% of TDC
Capital expenditures (CAPEX)	
Working capital (WC)	5% of FCI
Fixed capital investment (FCI)	TDC + TIDC
Land	6% of (Installed costs)

The net present value (*NPV*) and the rate of return on investment were estimated as follows [29]:

$$NPV = \sum_{n=0}^{20} \frac{(Cash\ Flow)_n}{(1+r)^n} \tag{7}$$

where *r* is the discount rate, and *n* is the project life. The calculation of MSP involves an iterative process where the electricity price is adjusted until the project's NPV reaches equilibrium at zero. Finally, the calculation of LCOE was performed to compare the proposed process with the conventional power generation process. The equation used for *LCOE* is as follows:

$$LCOE = \frac{NPV\ of\ total\ cost\ over\ life\ time}{NPV\ of\ electrical\ energy\ produced\ over\ life\ time} \tag{8}$$

3. Results

3.1. Technical Analysis with Stream Compositions

Detailed material and energy balances of both cases were obtained from the simulations performed on Aspen Plus, as shown in Table 4. With the same input flows as described in Section 2.1.1, the gasifier generated a constant 2250 kg/h of syngas, with an HCR of 1.86. Both cases implementing the same reforming technique produced the same amount of syngas, i.e., 850 kg/h, with an HCR of 3.5.

Table 4. Operating parameters and stream compositions at the exit of each unit.

	Plastic Feed	Steam to Gasifier	Gasifier Outlet	Methane to SMR	Reformer Outlet		GT Outlet (Flue Gas)		ST Outlet (Steam)		CO$_2$ Purification	
	Case 1/2	Case 1/2	Case 1/2	Case 1/2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
T (°C)	25	300	1300	25	900	900	756	728	49	49	30	30
P (bar)	1	30	25	25	30	30	1	1	0.1	0.1	16	16
Mass flow (kg/hr)	1000	1250	2250	300	850	850	7633	7633	3070	2870	3996	3996
Mole (%)												
PE	50	-	-	-	-	-	-	-	-	-	-	-
PP	50	-	-	-	-	-	-	-	-	-	-	-
H$_2$	-	-	63.3	-	67.2	67.2	-	-	-	-	-	-
CO	-	-	34.1	-	19.1	19.1	-	-	-	-	-	-
CO$_2$	-	-	0.11	-	2.4	2.4	29.4	30.1	-	-	99.5	99.5
H$_2$O	-	100	0.57	-	11.2	11.2	68.2	69.8	100	100	0.3	0.3
O$_2$	-	-	-	-	-	-	2.3	-	-	-	0.2	0.2
CH$_4$	-	-	1.84	100	-	-	-	-	-	-	-	-

When combined with the syngas produced from the gasifier, the HCR for both cases were reduced to 2.2 due to the lower HCR of the gasifier outlet stream. The combined syngas was burnt in the presence of 5 mol% excess oxygen in the combustion chamber of gas turbine to achieve complete combustion. The combustion produced 7633 kg/h of flue gas at 1500 °C and 1454 °C, respectively. The difference in the temperature of the flue gas resulted in slightly different power outputs for the two cases, as shown in Table 5. Finally, the cooled flue gas from the HRSG was separated in the knockout drum to generate 3996 kg/h of CO_2 with a purity of 99.5 mol%.

Table 5. Key process parameters obtained from process simulation and technical analysis.

Process Parameters	Case 1	Case 2
Syngas production (kg/h)	3097	3097
Syngas HCR	2.2	2.2
Syngas HHV (MJ/kg)	25.9	25.9
Syngas temperature (°C)	1500	1454
Minimum utility required (MW)	7.8	6.0
Power production (MW)	3.78	3.65
Process efficiency (%)	16.7	17.6
CO_2 captured (kg/h)	3996	3996

3.2. Process Performance Analysis

Key performance parameters were estimated through process simulation and technical analysis, as presented in Table 5. As the cases utilised same syngas production techniques and input flows, the syngas and its HCR were equal in both cases. The divergence lay in the combustion process, as although both cases utilised a 5 mol% of excess oxygen for combustion, the flue gases produced emerged at different temperatures. In case 1, which utilised oxygen through ASU, an outlet stream of 1500 °C was generated, whereas in case 2, the temperature was slightly lower at 1454 °C. The probable reason for this difference lies in the inclusion of metal in the CLC which absorbs some heat of combustion during the process.

Additionally, the utility requirement of the two processes varied due to the difference in the way oxygen was supplied for the combustion. ASU, being the energy intensive process, resulted in higher utility requirement of 7.8 MW. On the other hand, case 2, utilising CLC, required 23.1% less utility for its operation, as shown in Figure 3. As a result of the combination of these factors, although case 1 generated 3.4% more electricity, case 2 exhibited a 5.4% higher efficiency.
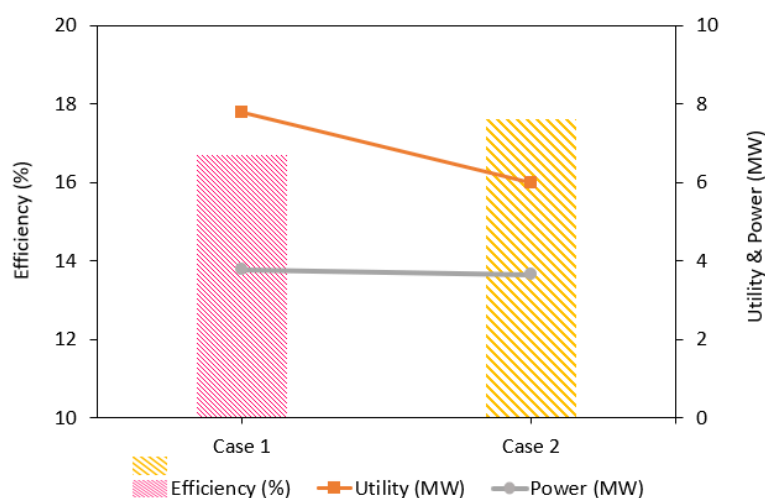

Figure 3. Correlation of the utility requirement and power generation of process efficiency for the developed scenarios.

3.3. Impact of Operational Conditions on Process Performance

Initially, a sensitivity analysis of the power output against the methane input was performed. Figure 4 shows a linear increase in power production with the increase in the CH_4 input in SMR for both scenarios. The linear trend gives us the indication that the process efficiency and economic would remain same with the increase in capacity. However, the graph shows that case 2 has a steeper trend. It starts with a lower power generation output but matches the capacity of the case 1 at 500 kg/h methane input. This indicates that the efficiency difference between the two scenarios will keep on increasing with the increase in the methane input.

Figure 4. Sensitivity analysis of (**A**) power generation and (**B**) captured and uncaptured CO_2 against methane input, (**C**) power generation, and (**D**) captured and uncaptured CO_2 against gasification temperature.

Secondly, the effect of the gasifier temperature on the syngas composition was evaluated. The graph shows an exponential increase in H_2 and CO (desired) components in the syngas exiting from gasifier until approximately 1300 °C and vice versa for the CH_4 and CO_2. After 1300 °C, the trend becomes steady, which emphasize that the further increase in the gasifier temperature does not help in increasing the desired components.

After that, impact on power generation can be observed with the variation in gasifier operating temperature. The graph shows no variation in the overall power production with the increase in the gasifier's temperature. This is due to the fact that although the increase in temperature converts the CH_4 produced during the gasification into H_2 and CO, the overall combustible components remain the same, and in turn, the power produced due to the combustion remains the same. However, it is important to note that the form of combustibles (either H_2 or CH_4) does not affect the material and energy balance, but it is important for the designing phase where the pipelines, equipment, burners, etc., are specifically designed for a certain component. Inclusion of a component for which the equipment is not designed will result in operational problems and hazards.

3.4. Economic Analysis

The economic analysis of the studied cases was performed to assess the economic viability of the power generation processes in the current market. First, the CAPEX and OPEX for both cases were calculated, as shown in Table 6. Notably, the calculation shows a significant difference between the CAPEX of the developed cases. However, the OPEXs of

both the cases were quite consistent with each other. The observed difference in the CAPEX is primarily due to the higher capital investment required for the ASU, whereas the CLC is relatively cheaper in construction. On the other hand, although case 2 requires fewer overall utilities as compared to case 1, the cost of utilities is slightly higher for the same case. This is due to the fact that the case 2 has a higher contribution of heating utility, which typically incurs higher expenses than does the cooling utility. As a result, the overall cost for case 2 slightly exceeds that of case 1.

Table 6. Summary of capital and operating expenditures of the two case studies.

	Case 1	Case 2
CAPEX calculation (M$)		
Equipment and installation cost	23.70	10.51
Direct cost	4.15	1.84
Indirect cost	13.92	6.17
Working and land cost	3.51	1.56
Total CAPEX	**45.28**	**20.08**
OPEX calculation (M$/yr)		
Labor Cost	0.59	0.59
Raw material cost	0.01	0.01
Utility cost	1.07	1.09
Total OPEX	1.68	1.70
LCOE ($/MW)	**227**	**137**

A cost breakdown of CAPEX and OPEX of the developed cases is shown in Figure 5. Figure 5A shows the constituents of the CAPEX contributing to the total value, with equipment installation costs emerging as the primary contributor at 52.3% for both cases. On the other hand, the utilisation of waste plastic as a raw material minimises the raw material cost as compared to other constituents of the OPEX. Therefore, it makes the utility costs as the main economic driver in the OPEX, followed by the labour cost.

Figure 5. Breakdown of (**A**) capital expenditures (CAPEX) and (**B**) operating expenditures (OPEX).

Base on the economic cashflows, LCOE was calculated for the two scenarios, providing a good parameter for direct comparison with the current electricity prices as shown in Figure 6. Due to a significant difference in the CAPEX of the cases, LCOE for the case 1 was significantly higher than rest of the cases, yielding an absolute value of USD 227/MW, whereas the case 4 (USD 131/MW) proved to be most economical among the competitors.

To rate and compare various wastes and their respective recycling processes for specifically power generation purposes, the literature was consulted. The LCOE for various cases is summarized in Table 7. At the first glance, it can be concluded that the recycling of waste is not a cheap process, specifically for power generation. Only one out of five processes

yielded a LCOE below USD 100/MW. Process 1 resulted in exceptionally high cost because it employed fuel cell from gasified waste instead of CCPP. Apart from waste type and recycling process, waste utilisation also depends upon the supply chain and handling of the waste, which can improve the economics if done properly. As seen from the data, two MSW processing studies employing anaerobic digestion resulted in significantly different results. Furthermore, anaerobic digestion using landfill gas has a limited life span with varying landfill gas production which effects its performance. Lastly, the comparison shows that the LCOE of the present study employing gasification had the second lowest value, which indicates that it warrants further exploration and that it is feasible for power generation.

Figure 6. Levelized cost of electricity (LCOE) for the developed cases.

Table 7. Validation and comparison of the levelized cost of electricity from various wastes. MSW—municipal solid waste; LFGTE—landfill gas to energy.

T	Waste Type	LCOE ($/MW)	Recycling Process	Reference
1	Waste toilet paper	203	Gasification	[31]
2	MSW	170	Anaerobic digestion	[32]
3	MSW	93	Anaerobic digestion	[33]
4	MSW	160	LFGTE	[34]
5	Waste plastic	137	Gasification	

4. Conclusions

The study conducted a comprehensive evaluation of the power generation potential derived from waste plastic, employing gasification and methane reforming techniques. This research sheds light on the efficacy of waste plastic utilisation for power generation, providing valuable insights into key process parameters, LCOE and CO_2 savings. The two developed case studies differed in their oxygen-supplying techniques due to which the power output and the process efficiency varied. Techno-economic analysis showed that the case 1, utilising ASU, required 23.1% more utilities, thereby resulting in 5.4% lower efficiency despite its higher power output. Consequently, case 2 generated a lower LCOE of USD 137/MW, whereas both cases effectively mitigated CO_2 emissions by avoiding almost 3996 kg/h of CO_2. Additionally, sensitivity analysis highlighted a direct relationship between power output and methane input, while an increase in gasifier temperature enhanced the H_2 and CO content in syngas. Interestingly, gasifier temperature exhibited a flat response on power output due to the same level of combustibles, indicating no significance for the power generation process. Lastly, the comparison of LCOE with the previous studies showed that the current process is more compatible and shows the potential of sustainable power generation. However, it is essential to conduct more research to further improve the

design to optimize the LCOE. Furthermore, government and industrial support is required for performing scale-up studies and practical demonstration.

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