Techno-economic Analysis of Small Scale Electricity Generation from the Lignocellulosic Biomass

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Abstract

In this study, the techno-economic analysis of lignocellulosic biomass conversion to electricity in a small scale power plant was conducted. The proposed process is based on the thermal pathway of electricity production from a carbon content feed. Woods, forest and agricultural residues were considered as the biomass feed, which are available extensively in Iran. Besides, the process benefits not only from the maturity of the method and non-selectivity toward feed but also carbon neutrality and CO2 emission credit income. In order to estimate the minimum selling price (MSP) of the product by this process, the bare module cost model was used. Various equipment sizes were determined by mass and energy balances, whereas the studied power plant capacities were considered 0.5, 1, 5 and 10 MW. The model estimated that the product MSP were 5.83, 4.16, 1.99 and 1.58 ¢/kWh for 0.5, 1, 5 and 10 MW capacities, respectively. Furthermore, a sensitivity analysis was performed to investigate the relative significance of economic parameters on the MSP. The feed, transport, purchased equipment costs and CO2 emission credit income were considered as the sensitivity analysis parameters. Results have proved that the MSP was mainly impacted by the CO2 emission credit income.

Keywords

Electricity;
Lignocellulosic Biomass;
Power Plant;
Sensitivity Analysis;
Techno-economic

1. Introduction

Energy is the backbone in the civilization structure. Among various energy types, the electrical energy role in the society is vital. Increasing demand for electrical energy has resulted from different factors including population growth and industrial development. The major energy source for this massive worldwide energy consumption is dominated by fossil fuel (i.e., coal, natural gas, and crude oil) [1]. However, fossil fuel as the main energy supply has critical drawbacks such as emission of pollutants to the environment (i.e., carbon dioxide) that negatively affects the climate change and increases the water level in the oceans [2-4]. In order to overcome these issues and mitigate the emission of pollu-

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tants, other sources of energy should be exploited.

Biomass as a renewable and sustainable energy source is a viable option for addressing concerns of electrical energy production [5]. Because there is an ample supply of biomass and more importantly its price does not depend on the scale of consumption [6]. In addition, as a promising energy resource, biomass benefits from the local availability. Consequently, a power plant can be constructed near the biomass sources; hence, undesired transportation impacts on the environment would be limited or reduced. On the other hand, it could positively impact on the socio-economic growth of less developed regions [7]. Besides, biomass utilization as an energy source in the decentralized region can provide electricity not only to residents but also to electrical grids [8]. Biomass conversion to the electrical energy is carbon neutral. Hence, compared to other renewable and sustainable sources such as wind and solar, biomass conversion is not climate or weather dependent [9]. Further, biomass conversion to electricity is reliable and continuous; thus, the storage facility is not required [10]. Heat can also be produced as a valuable side product in the conversion of biomass to electrical energy.

There are three routes for biomass conversion to value-added products namely biological, chemical and thermochemical. Among them, the thermochemical pathway is the most suitable for electricity generation from dry biomass [11, 12]. In this method, the energy stored in the chemical bonds of feedstock is released by direct combustion or gasification. The process implies heat and pressure steps to produce electricity. Various efforts have been reported in this regard including a 100 kW gasification plant in India [13] or biomass conversion to electricity in Brazil [14]. Power plants in the range of 500 kW to less than 100 MW have been studied in Scandinavian countries that used wood residue, wood chips, sawdust, peat or bark as the fuel to produce electricity [15]. Rice husk or straw as an appealing feedstock in East Asian countries (i.e., Thailand, China, Vietnam, etc.) have been used in the 200 kW to 10 MW power plants [16-18]. Direct combustion processes are benefitted from mature technology experiences [19] and biomasses are used as the feedstock non-selectively that result in the consumption of various biomass as the fuel [20, 21]. Among these processes, implementing the steam turbine is the most preferred method for large-scale plants (over 1000 kW) [5, 10]. Besides, different configurations for the burner, including fluidized bed and stoker grates were studied [22, 23].

The aim of this study was to conduct a techno-economic analysis of the lignocellulosic biomass conversion to electricity by a direct combustion method in Iran. To do so, a thermal process based on the Rankine cycle was introduced. In this process, biomass is burned in a reactor and high-pressure steam is produced. Then, the steam is transferred to a steam turbine to provide the required energy. The studied power plant capacity was in the range of 100 kW to 10 MW. The paper proceeds by detailing economic analysis and estimating the minimum selling price (MSP) of electricity. Moreover, a sensitivity analysis was performed to investigate different parameters that affected the minimum selling price of the product.

2. Process Description

The process flow diagram is illustrated in Fig. 1. The process is based on a Rankine cycle using water as the working fluid. The main components of the plant are a boiler, steam turbine, pump, condenser, and cooling tower. The lignocellulosic biomass was used as feed for electricity generation and was crushed and screened before entering to the boiler. Besides, the humidity content of the feed was reduced to less than 15 wt% by stacking gas outlet stream. The high moisture content in the biomass negatively impacts the efficiency of the process [24]. The crushed, screened and dried biomass is burned in a bubbling fluidized bed boiler. The energy released during combustion of biomass increases the temperature of a working fluid in the internal boiler tubes and generates high-pressure steam (HPS). The produced steam flow rates for different capacities are presented in Table 1, which temperature and pressure of superheated steam are 410 ºC and 50 atm, respectively. After the boiler, the HPS is led into a steam turbine running a generator. After the turbine, a heat exchanger is applied to condense low-pressure steam (LPS) using of the cooling water (CW) stream. The cold water with an inlet temperature of 25 °C was used to condense exhaust LPS from the turbine at 46 °C. The condensed LPS is recycled into the boiler by a pump at 51 bar. In order to reuse the CW for the next cycle, a counter flow induced draft cooling tower was used to reduce the CW temperature. In counter flow induced draft cooling tower, the water which is being cooled moves from the top through the tower, while air is pulled in the counter direction from the bottom.

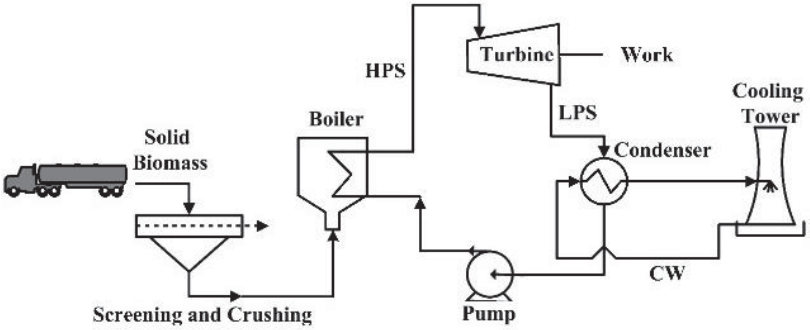

Figure 1. Power generation flow diagram

Table 1. Simulated feed water flow rates at different capacities

Generated Electricity (MW)	Feed Water (kg/h)
0.5	2603
1	5224
5	26125
10	52236

3. Economic Model

The economic model of the process is schematically presented in Fig. 2. The capital investment of the process was estimated based on the bare module cost [25]. The bare module cost is a detailed estimation method, which contemplates the construction materials, the operating pressure and size of the equipment in the estimation of capital investment. The method for estimating the capital investment requires determination of the delivered-equipment cost and all other costs, which are related back to the purchased cost of equipment. The equipment cost and installation factors were obtained from the public databases [26, 27] and were indexed to US$2015 values. The cost of the manufactured product included raw materials, utility and transportation costs. The revenue of the process was achieved from the sale of electricity and carbon credit.

A carbon credit is a permit or certificate allowing the holder to emit carbon dioxide or other greenhouse gases. A credit means, the owner has the right to emit one ton of carbon dioxide equivalent per year (1 credit = 1 tCO_2e). Table 2 presents the estimation of total capital investment (TCI) for four different power plant capacities based on the purchased equipment cost.

The plant was assumed to operate in a continuous mode for 345 days per year. The plant life was assumed to be 25 years and 10 percent investment profit per year was considered in the estimation of the total capital investment. Moreover, the discount cash flow analysis was performed to obtain the minimum selling price (MSP) of electricity. MSP is a product price in which the net present value of the plant (including a 10 percent internal rate of return) is equal to zero. In other words, at a minimum selling price, the plant is at the breakeven point and the revenue of the plant still covers the costs.

As mentioned, the manufactured cost includes raw material, utility, and transportation cost. The biomass encompasses a large variety of materials, including wood from various sources, agricultural and forestry residues, municipal solid and animal wastes. In this work, agriculture residue was used. Currently, agriculture residues have no significant industrial applications in Iran and they are normally burnt. The cost of raw material was considered to be 0.021 $/kg (21 $/tons) [28]. The utility costs for different power capacities were estimated based on the bare module cost as presented in Table 2. Truck transport is well developed and usually the cheapest mode of transportation for low travel distances, which has been considered as transport method in this study. The truck transport depends on travel distance and it increases as travel distance increases. Sokhansanj et al. [29] compared the cost of transporting biomass for four different modes of transportation. In their model, the transportation cost was changed linearly with distance and the truck transport was the least expensive option for distances less than 160 km. The truck transportation cost for 160 km distance is 27 $/ton. Since the biomass may be collected from locations lower than 160 km away from the plant, 20 $/ton was considered as the transportation cost.

4. Results and Discussion

Installed equipment costs for the biomass power plant at four different capacities are shown in Table 2. Total equipment costs for 0.5, 1, 5 and 10 MW capacities are $ 0.87, $ 1.18, $ 2.24 and $ 3.2 million, respectively. The most expensive equipment for lower capacities is the steam turbine.

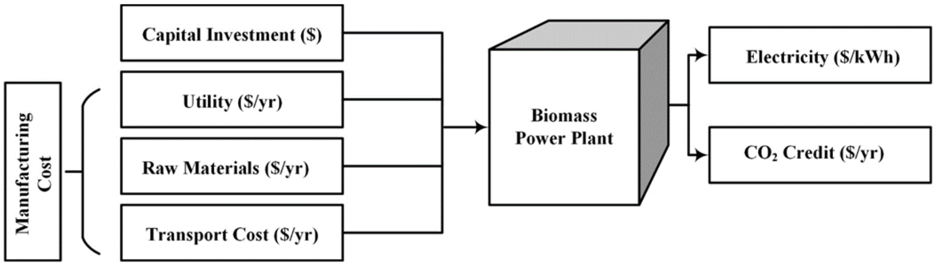

Figure 2. The model considered for the economic analysis

Table 2. Capital costs of power generation process for four different power capacities

Cost Category ($)	Capacity (MW) 0.5	1	5	10
Boiler	80,500	153,700	434,600	731,400
Turbine	126,900	176,300	324,300	423,000
Pump	55,300	56,400	62,300	71,500
Condenser	40,300	71,300	276,000	521,200
Cooling Tower	85,000	106,000	282,000	352,000
Total purchased equipment cost (PEC)	388,000	563,700	1,379,200	2,099,100
Total installed cost (TIC)	876,880	1,189,407	2,248,096	3,211,623
Total indirect plant costs (TIPC)	488,880	710,262	1,737,792	2,644,866
Fixed capital investment (FCI)	1,365,760	1,899,669	3,985,888	5,856,489
Startup cost (SC)	38,800	56,370	137,920	209,910
Total capital investment (TCI)	1,404,560	1,956,039	4,123,808	6,066,399
Total Profit for 25 Years (10%)	3,511,400	4,890,097	10,309,520	15,165,997
Total capital investment with profit ($/yr)	196,638	273,845	577,333	849,295

As the capacity increases, the boiler price has a higher contribution in the total installed equipment costs. Moreover, the total indirect plant costs and startup costs for different capacities are also presented in Table 2. The total capital investment in the power plant are obtained as $1.40 million, $1.95 million, $4.12 million and $6.06 million for 0.5, 1, 5 and 10 MW capacities, respectively.

The simulated biomass consumption rates, biomass costs for different power capacities, and the transportation costs for different power plant capacities are presented in Table 3. As can be seen, the biomass and transportation costs increase with an increase in power plant capacity due to higher biomass consumption at higher capacities. The utility costs for different capacities are shown in Table 4. It should be noted that the electricity price of the plant was excluded from the utility cost since the electricity can be obtained from the produced power of the project.

Table 3. Production costs of biomass electricity generation

	Capacity (MW)			
	0.5	**1**	**5**	**10**
Biomass consumption (tons/yr)	2335	4690	23,465	46,915
Biomass costs ($/yr)	49,034	98,503	492,776	985,204
Transportation costs ($/yr)	46,699	93,812	469,310	938,290

Table 4. Utility costs of biomass electricity generation

	Capacity (MW)			
	0.5	**1**	**5**	**10**
Utility cost ($/yr)	24,000	28,800	36,000	43,200

As pointed out before, in the economic analysis of biomass power plant, the main source of income is the emission credits earned through the reduction in fossil fuel usage. Replacing fossil fuels with biomasses will reduce the net flow of CO_2 to the atmosphere [5]. The price of CO_2 offset was obtained from the public databases [30] and then the credit income can be calculated by estimation of CO_2 emission reduction. The yearly reduction in CO_2 emission and emission credit income are presented in Table 5.

In order to investigate the economic feasibility study of the biomass power plant, the MSP of the produced electricity is obtained and presented in Table 6 and Fig. 3. The MSPs of electricity are 5.83, 4.16, 1.99 and 1.58 ¢/kWh for 0.5, 1, 5 and 10 MW capacities, respectively. It is obvious that the MSP of the generated electricity for higher capacities is sufficiently low to replace fossil fuels by biomass for a thermal electricity production.

As pointed out, cost analysis showed that the MSP of the electricity generated from biomass for the 10 MW power plant capacity is comparable to the 2015 coal electricity generation price (1.43 ¢/kWh). However, the electricity price for smaller scales is still high when compared to the 2015 prices. The total capital investment in the power plant with 0.5, 1, 5 and 10 MW capacities are estimated to be $393, $273, $115 and $85 per annual kW, respectively. The major contributors to the MSP of electricity are presented in Fig. 4. As can be seen, the total capital investment per year contributes to the major portion of electricity cost for 0.5, 1 and 5 MW capacities. The contribution of TCI reduces as the project capacity increases. The TCI contributes to 30 percent of electricity price for 1 MW capacity, while a significant expense is also incurred in the biomass feed and transportation cost. The utility cost constitutes only 2 percent of the electricity MSP.

Table 5. Yearly CO_2 emission credit income [30]

	Capacity (MW)			
	0.5	**1**	**5**	**10**
Reduction in CO_2 emission (tons/yr)	2137	4293	21,476	42,938
Credit income ($/yr)	74,796	150,256	751,677	1,502,823

Table 6. Minimum selling price of electricity

	Capacity (MW)			
	0.5	**1**	**5**	**10**
MSP of electricity (¢/kWh)	5.83	4.16	1.99	1.58

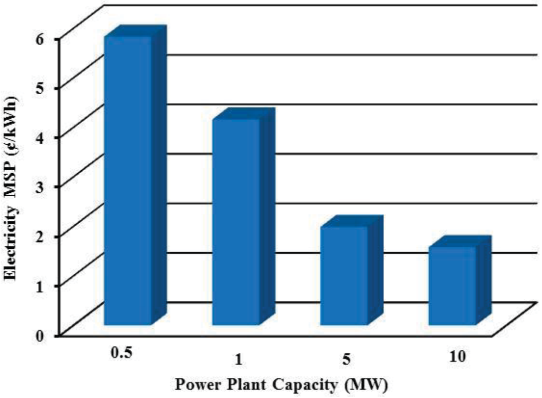

Figure 3. Minimum selling price of produced electricity at different power plant capacities

The sensitivity analysis also has been conducted to study the relative significance of economic parameters on the MSP of electricity. In order to do that, the sensitivity of MSP was measured for a ±20 percent in the values of total purchased equipment cost, biomass price, transportation cost, and CO_2 emission credit income. The sensitivity analysis results on the MSP of electricity are shown in Fig. 5. It is evident that the credit income is the most significant parameter affecting the MSP of electricity. Thus, a 20 percent increase in the price of CO_2 offset results in a 22.8 percent decrease in MSP to ¢1.22 per kWh. Moreover, the results show that the equipment cost, biomass price, and transportation cost have also the same impact on the MSP of electricity. A 20 percent increase in these economic parameters resulted in a 14 percent increase in the MSP of electricity.

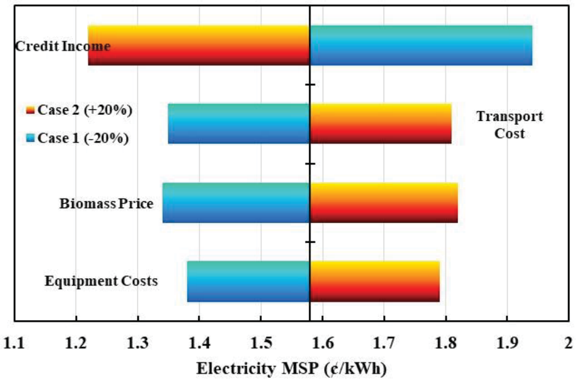

Figure 5. Sensitivity analysis on MSP of electricity

5. Conclusions

In summary, the techno-economic analysis of the lignocellulosic biomass conversion to electricity was conducted in this study. The proposed process was established based on the direct combustion method, which took advantage of the mature technology experiences. Besides, this pathway of electricity generation was not dependent on the feed. The bare module cost model was used to estimate the MSP of the product. Equipment sizes were determined by mass and energy balances and the range of studied power plant was from 0.5 to 10 MW. Consequently, the electricity MSPs were 5.83 and 1.58 ¢/kWh for 0.5 and 10 MW, respectively. The results indicated that by increasing the production capacity the MSP significantly decreased. The results also illustrated a correlation between plant size and major contributors to electricity price. While the TCI by 62 percent has the highest share at a 0.5 MW plant product price, its contribution in costs falls to 55, 36.8, and 30 percent for 1 MW, 5 MW and 10 MW plants. On the other hand, the portions of biomass feed and transportation costs in the price increase significantly from 15 percent in a 0.5 MW plant to 35 and 30 percent, respectively in price contribution of a 10 MW plant. In order to investigate the relative significance of economic parameters on the MSP, the sensitivity analysis was conducted. Parameters were included the feed price, transportation cost, purchased equipment cost and CO_2 emission credit income. Results illustrated the fact that the CO_2 emission credit income has a major impact on MSP of electricity.

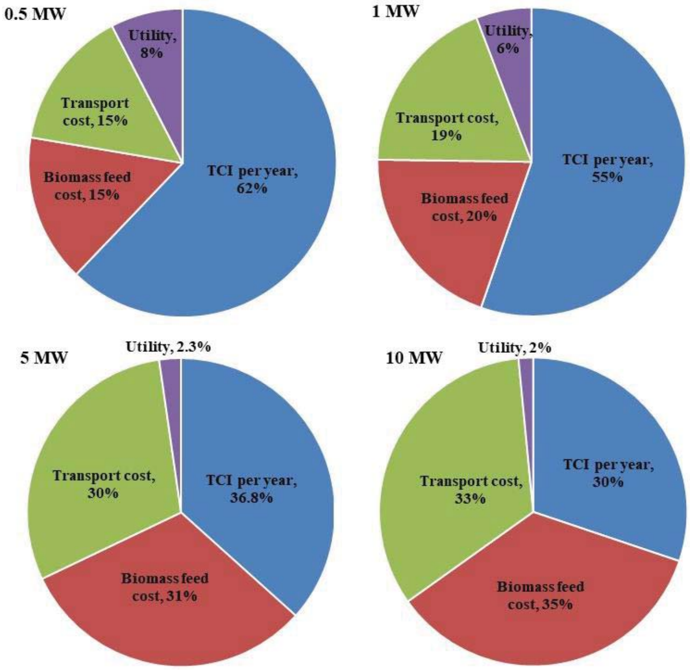

Figure 4. Major contributors to electricity price at different project capacities

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