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Energy Modeling and Techno-Economic Analysis of a Biomass Gasification-CHAT-ST Power Cycle for Sustainable Approaches in Modern Electricity Grids

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ABSTRACT

In this study, an advanced combined power generation cycle was evaluated to obtain sustainable energy with high power and efficiency. This combined cycle includes biomass gasification, the Cascaded Humidified Advanced Turbine (CHAT), and the steam turbine. The fuel consumed by the system is derived from the gas produced in the biomass gasification process. The biomass consumed in this study is wood because of its reasonable supply and availability. The economic analysis conducted in the present research has produced significant gains. The proposed cycle with current prices intended to sell electricity in Iran has a positive Net Present Value (NPV). Therefore, the presented cycle in terms of energy supply has good economic value. Due to the significantly higher purchase/sale price of electricity from renewable power plants in developed countries in Europe or the United States, the power generation cycle proposed in this study may be more economically feasible in other regions than Iran. Of course, with a slight price increase in electricity sales in Iran (3 USȻ kWh^{-1}), the proposed system will have acceptable NPV. Because of the complicated equipment used in high-pressure and low-pressure turbines and compressors sets, the equipment used in this cycle requires a higher initial investment cost than conventional power generation systems. The results showed that the investment cost per unit of energy was approximately 909 USD kW^{-1}.

1. INTRODUCTION

According to the report of international energy outlook [1], CO_2 emissions, which are related to energy production, will increase to 43.2 b tons in 2035. One of the major contributors to climate change is greenhouse gas emissions through consuming fossil fuels to generate power, therefore making a big change and shift from conventional to renewable energy sources, particularly solar, wind, biomass, and hydropower is necessary [2].

Since biomass resources are distributed almost everywhere and also are usually abundantly available, they are significantly used as one of the renewable energies.

It is a fact that biomass energy is the most important energy source after fossil energy sources (oil, natural gas, and coal) which approximately provides 10 % of the world's energy consumption. Besides, municipal and industrial wastes along with agricultural biomass wastes can supply almost ¼ of the primary energy in 2050 [3-6]. The output power efficiency of a gas turbine can be increased by humidifying the working fluid. Many different cycles have been suggested with a water or steam injection system. Although only a smaller number of the proposed cycles in the previous researches have been commercialized and used in the power plants yet. The humidification of the gas turbines leads to special benefits such as achieving high electrical efficiency and specific energy efficiency, reducing specific investment costs, reducing the formation of nitrogen oxides (NO_x) in the combustion process, and reducing the degradation of energy output due to high ambient temperatures or low ambient pressure. Improved system performance under part-load conditions compared to the combined cycle is another characteristic of humidified gas turbines. One of the most efficient humidified gas turbine cycles is Cascaded Humidified Advanced Turbine (CHAT) which is considered in this research using biomass gasification as the fuel supply system.

Studies that have been reported in this paper demonstrate energy and economic analysis and also important aspects of a novel integrated biomass gasification as a power system. Since such important issues concerning cost estimation are associated with the capital investment in the humidified turbine-based system, the electricity and heat generation costs in the mentioned combined cycle power plants must be taken into account. The investment cost in the advanced turbine-based cycle according to the Brayton-Rankine system usually consumes approximately 40 % of the overall expenditure in a conventional power system. However, only the gas turbine needs about 30 % of the total investment cost. Additionally, the implementation and installment activities constitute 30 % of the remaining investment cost, which consists of remarkably about two-third of the physical functions that need to be allocated in the works involving the combined power systems. As a result, the specific investment cost that means unit cost per electrical power in simple gas turbine systems is approximately two times smaller than the combined cycle cost that includes steam or district heating bottoming systems [7-9]. Thus, attempts have been made to find alternative ways to

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reduce the electricity cost and heat generation related to the turbine-based cycles installed in the integrated and combined heat and power plants.

Jitka Hrbek [10] compared different thermal gasification projects that operate as a power generator. The main objective of this study is to explain the principals of the mentioned systems and describe relevant actual projects. The economic feasibility of gasification-based power technology plants has been described in this research. He found that the most important factors influencing the price of the biomass gasification outlets included the cost of renewable power, biomass cost, size of gasification unit, and number of operating hours per year. Also, the author showed that in a power to gas project, the total cost is between 5.7 and 7.1 €ct kWh^{-1}, which is 2-3 times higher than the price of a project that uses fossil fuels.

In a review study by Bocci et al. [11], some aspects of power plants using biomass gasifier due to energy and economic analysis have been considered. They expressed that biomass gasification power plants based on downdraft gasifier and internal combustion engines were considered, and the results showed that the electrical and cogeneration efficiencies were about 20 % and 80 % with a global capital cost of about 500-1000 € kW^{-1}. The application of fluidized bed technologies causes a significant increase in the total capital cost of the power plant. They indicated that a micro gas turbine-fuel cell-based power generator attached to a fluidized bed biomass gasifier would require about 10000-15000 € kW^{-1} capital investment.

In research presented by Omar et al. [12], a detailed thermodynamic and economic analysis of a combined power cycle was conducted, which integrated a topping cycle with the M-cycle heat exchanger. The proposed cycle experienced a 6 % improvement in the overall thermal efficiency compared to the conventional combined cycle, and the corresponding electricity cost reduction was 3.8 USD MWh^{-1}.

A novel combined cycle using biogas to supply the required fuel of the system was proposed by Ghavami et al. [13]. They performed a 4E optimization method, while the mentioned system operated as a multi-generation power cycle. The results demonstrated that cooling capacity, heating capacity, and net power were 123.59 MW, 0.73 MW, and 280.35 MW, respectively. Also, the results of economic analysis demonstrated 6.79 USD GJ^{-1} as unit product cost.

Dibyendu et al. [14] presented a techno-economic assessment and environmental investigation of a power plant that includes biomass gasification which is integrated with a solid oxide fuel cell, a gas turbine based on external fired combustion system, and an organic Rankine cycle. Their economic analysis results predicted that, in this plant, the minimum power generation cost could be 0.086 USD kWh^{-1}.

A humidified advanced turbine (HAT) cycle combined with a micro gas turbine and a solar collector system was proposed by Li et al. [15]. Also, an organic Rankin cycle was proposed to increase power generation capacity by recovering heat losses of the cycle. Thermodynamic and economic analysis of this power system was performed. The presented plant generates approximately 254 kW power, of which almost half of the produced electricity is related to gas turbine and the rest of that is produced due to heat recovery of exhaust gasses by the bottoming cycle. Economic studies in this research showed that the specific plant cost in the main scenario was 0.2 USD kWh^{-1}.

According to previous studies, the economic aspects of advanced humidified power cycles coupled with biomass gasification units have not been received much deliberation. It appears that due to the complexity of these systems and the integration issues, concerted efforts have been directed at efficiency and power outputs. Furthermore, alternative renewable energy sources have not received much attraction compared with conventional power generators consuming fossil fuels because of lower calorific values, lower delivered power, and thus lower financial incomes. Hence, not only should the enrichment of energy capacity approaches in the biomass-based power plants be determined, but also the economic advantages must be considered to make a competitive observation for the investors.

This paper discusses the economic field related to the biomass gasification application in a power plant that uses a cascaded humidified advanced turbine (CHAT) as a top cycle and a steam turbine (ST) as a bottoming cycle, which offers a new aspect in the current research. For this purpose, the entire cost of purchased equipment in each part of the comprehensive cycle has been calculated based on the empirical formulations. In return, total capital investment is obtained by considering other direct and indirect costs to implement a power plant. Establishing a relationship with fixed capital functions is one of the main tasks of this study. Another important matter is that the total variable cost could be estimated when some parameters have been defined such as labor, fuel, utilities, maintenance, etc. Therefore, all principal variable cost factors have been selected in this study to increase the accuracy rank of the prediction. One of the important matters here is to develop a mathematical model to explain the economic profitable conditions of this advanced cycle. For this purpose, some popular financial indicators have been calculated by running the computational model. Net present value, internal rate of return, payback period time, and specific unit cost are common indicators whose values are presented in this research. Moreover, some parametric studies have been carried out to illustrate how the proposed cycle could compete with conventional power plants.

2. TECHNOLOGY DEVELOPMENT

According to the scientific documents, gasification technology was proposed to produce electricity from solid fuels in 1792 for the first time. Moreover, the next step was the installation of a gasifier plant, performed by Siemens in 1861. Meanwhile, the first fluidized bed gasifier unit was implemented in 1926, and the first installation of coal gasification was done in 1999. Accordingly, the fluctuation of fossil fuel prices, specifically oil, at the end of the previous century and climate change concerns are the reasons why biomass gasification has been introduced as an interesting approach to generating heat and power in the current era [16].

Generally, biomass gasification is explained as thermochemical oxidation that is executed partially and biomass is converted into synthesis gas (which usually called syngas). This process happens in the presence of gasifying agents, e.g., pure oxygen, air, steam, carbon dioxide, and maybe a mixture of the mentioned agents [17]. The syngas obtained in this process is a mixture of combustible components (especially hydrogen, carbon monoxide, carbon dioxide, and methane, along with ethane and propane as hydrocarbons). This process also produces char and tars that should be left from the gasifier reactor. Biomass feed material highly affects produced gas quality. Moreover, there are other important factors like gasification agents, characteristics of the reactor design, catalyst quality (is used), and operational conditions [18]. Previous experience shows that as a function of biomass feed, operational conditions, and the type of gasifier, the syngas lower heating value could be achieved between 4 and 13 MJ Nm^{-3} [16].

As mentioned before, char is the main byproduct of the gasification process that consists of unconverted biomass fractions and ash. Moreover, the lower heating value of the produced char was measured between 25 and 30 MJ kg^{-1}. This calorific value is directly related to the volume of unconverted fractions [19].

Increasing the energy efficiency of the biomass gasification technology should be continued to create optimized reactors. The amount of the produced tar and biomass moisture content are the principal obstacles in this field that must be considered. In recent activities, some novel approaches have been demonstrated as effective solutions to generate power from toxic and wet biomass.

There are some steps in a biomass gasifier that includes drying, pyrolysis, combustion, and reduction. To obtain syngas from waste valorization, various gasification methods have been identified among which fixed bed, fluidized bed, and plasma are the main categories. Furthermore, to achieve higher produced gas quality and better purification levels based on economical ways, combined and integrated systems have been developed. Higher efficiency of the conversion process is the most important purpose of this new equipment. Hence, the gas cleaning technologies are attached to the gasification units to supply convenient fuel for consuming in the power plants [20, 21].

Fluidized bed biomass gasifiers are notably different from fixed bed gasifiers in terms of thermodynamic properties such as operational temperature, which is between 800 and 1000 °C. This temperature range is compulsory due to the reduction of ash composition. Another attribute of a fluidized bed biomass gasifier is related to the bed form, which consists of inert materials to transfer heat and also make a mixture of be and fuel components. However, fluidization phenomena are caused by the gasification agent in the reactor. Generally, particles of the biomass fuel receive heat from the bed based on the hotbed, and contact and drying of fuel particles and pyrolysis processes occur in this condition. The most popular method of fluidized bed gasification is bubbling and circulating. However, various types of gasifiers have been demonstrated, among which an advanced model of these two methods is selected.

A bubbling fluidized bed enjoys some advantages such as uniform temperature distribution and the quality of bed and fuel mixing rate. On the other hand, the diffusion rate of oxygen from the bubbles to the emulsion phase occurs slowly, which is one of the negative points of this method. Incomplete char conversion and lower gasification efficiency are two other disadvantages of the bubbling fluidization [16].

Circulating fluidized bed gasifier is performed in two segments. The first one is combustion that takes place in a bubbling fluidized bed and generates the required heat of the gasification process. The second one includes pyrolysis and gasification that take place by the force of blowing gas agents. In the cyclone, the bed materials are separated from the produced gas and, then, are circulated into the first gasifier zone.

Since fluidized bed biomass gasification is the most promising technology to convert biomass fuel resources to high-quality combustible gas, one of the recently developed techniques has been considered in this study to respond to the advanced gas turbine fuel demand [22-24].

The chemical efficiency of the biomass gasifier, also known as cold gas efficiency, pertains to biomass characteristics. It also depends on the composition of produced gas and, therefore, the following equation indicates this relationship:

$$h_{chemical} = \frac{\dot{m}_g \, LHV_g}{\dot{m}_f \, LHV_f} \quad (1)$$

Brayton cycle is one of the most popular ways to produce electricity in the world, which introduces a gas turbine as a thermal to mechanical energy convertor. Despite all gas turbine benefits, its main drawback is the low efficiency. Hereupon, several efforts have been made by the academic and industrial sectors in recent decades. Humidification of the working fluid in a gas turbine could remarkably improve the energy efficiency of the system.

In a Cascaded Humidified Advanced Turbine (CHAT), two combustors are in series, while an intercooler and recuperated reheat gas turbine are the heart of the system. In Figure 1, a basic schematic of this cycle is displayed; however, the possible heat recovery from intercoolers has been ignored. In the CHAT cycle, a three-section compressor makes an adequate compression rate in a train along with two intercoolers that are located between compressor sections. The Intermediate Pressure and High Pressure (IP & HP) compressors stand on a distinct shaft, which includes the Low Pressure (LP) shaft. The major proportion of the power capacity is produced in the low-pressure section of this cycle [25, 26].

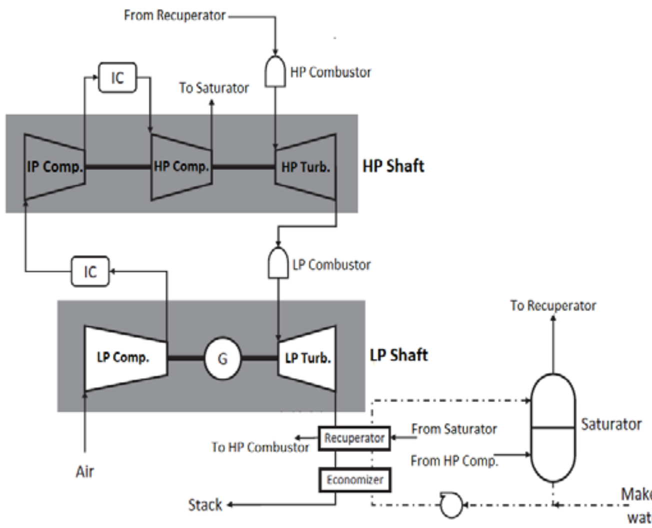

Figure 1. CHAT cycle schematic and its main elements.

Four intercoolers are applied to save power in the compression process in this cycle. Although it causes an increase in energy saving in the compression unit, it is not useful for the energy efficiency of the system due to the low outlet temperature just before the combustion chamber. In the humidification unit, heat transfer occurs based on simple observable phenomena and also humidification of the compressed air by increasing the air-water mass mixture. This heated air which comprises water particles is entered into the combustion chamber of the HP turbine. The T-S diagram of the CHAT cycle is shown in Figure 2. The NO_x proportion in the CHAT cycle exhaust gas is significantly lower than the GT simple cycle since water vapor acts as a heat sink in the combustion air [27-31].

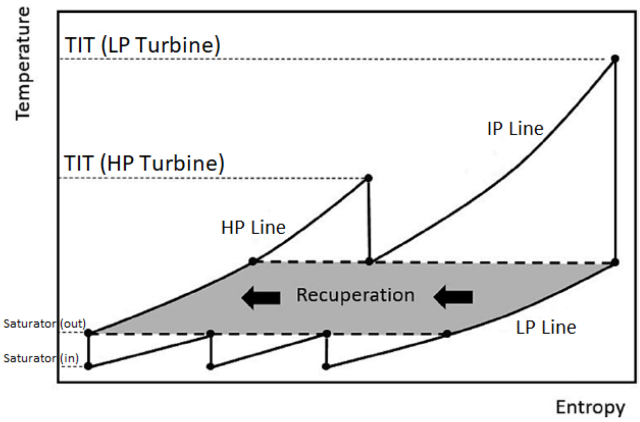

Figure 2. T-S diagram of the CHAT cycle.

The electrical efficiency of the whole cycle can be presented as follows:

$$\eta_{el}=\frac{P_{out}-P_{aux}}{\text{Biomass LHV}}=\frac{P_{net}}{\text{Biomass LHV}} \quad (2)$$

In addition, the total efficiency of the proposed cycle is defined by Equation (3) below:

$$\eta_{total}=\frac{P_{out}-P_{aux}+Q_{useful}}{\text{Biomass LHV}} \quad (3)$$

where Q_{useful} is the amount of useful heat that is consumed in the combined cycle to increase power generation. The conceptual diagram of the proposed cycle in this study is displayed in Figure 3.

3. ECONOMIC ANALYSIS APPROACH

In the present study, the economic analysis of a proposed cogeneration system based on the advanced CHAT gas turbine cycle, with the specified power generation capacity, along with the required fuel by the biomass gasification mechanism, which is presented in earlier parts of the paper, has been comprehensively carried out. Then, based on international fuel and electricity prices, economic indices such as internal rate of return (IRR) and net present value (NPV) of the power plant are calculated, and the level of competitiveness of the system with conventional power generation systems is investigated.

In general, the objectives of the economic model for the comprehensive cycle can be stated as follows:

1. Due to the necessity to develop an economic model in the field of investment cost analysis, the formulation of the purchase cost of system components is calculated.
2. From a systematic perspective, the costs studied including both direct and indirect costs have been examined and calculated. Typically, working capital expenses, startup costs, production costs, and general costs have been included in economic analysis. In previous studies, these parameters are often not considered for gasification-based combined systems, while they are generally presented in other studies. Therefore, the reliability of the obtained results has also been investigated by comparing the unit cost of the power generation.
3. Given the general use of this cycle as a power generation system and its impact on the geographical area in terms of energy carrier prices, this approach has been taken into account when the cycle operation is evaluated based on the current conditions of electricity and fuel prices in European and American countries. The analysis of these results provides a good understanding of the current utility of the system and its economic future.

The economic feasibility of the comprehensively presented cycle is estimated by considering criteria such as NPV, IRR, and total unit cost for the minimum fuel calorific value. The amount of initial investment required to pay back the equipment cost used in the proposed cycle is also economically analyzed in this model, and the results are shown in a comparative diagram [32, 33].

3.1. Total investment cost

Before the power plant can be used, there are different costs involved in purchasing and installing different machinery and equipment. The sum of fixed investment costs and working capital is known as total investment costs. The fixed costs of power plant setup and operation can be divided into two parts. Some of the costs are directly related to the type of equipment and how the cycle operates; for example, the costs of tools, founding, and site preparation are just a few instances of the costs required to prepare power plant units. These costs, which are usually spent to purchase and install equipment, are called direct costs. The other part of fixed investment costs can be costs that are not directly related to the power plant's performance; however, should be added to the fixed costs of the industrial units overhead. Such costs can be called indirect costs [34-36].

3.1.1. Gas turbine cost functions

The main parts of the GT system are the gas turbine and compressor, where cost relations are shown in Equations 4 and 5. Based on these relationships, the turbine and compressor shaft work are the parameters that influence the cost of the GT system [37].

$$C_{GT}=\left[(-98.328\,\text{Ln}(W_{GT})+1318.5)\,W_{GT}\right] \quad (4)$$

$$C_{comp}=91562\left[\frac{W_{comp}}{445}\right]^{0.67} \quad (5)$$

3.1.2. Steam turbine cost functions

The main components of the ST system are the turbine and the condenser, which are cost formulated in a system using 6 to 7 relationships. Based on these relationships, the shaft work of the turbine based on horsepower is the parameter that affects the cost of the ST system [38].

$$C_{ST}=20000\ (P)^{0.41} \quad (6)$$

$$C_{CO}=3000\ (Q_{CO}/10)^{0.6} \quad (7)$$

$$Q_{CO}=\dot{m}\,(h_{in}-h_{out}) \quad (8)$$

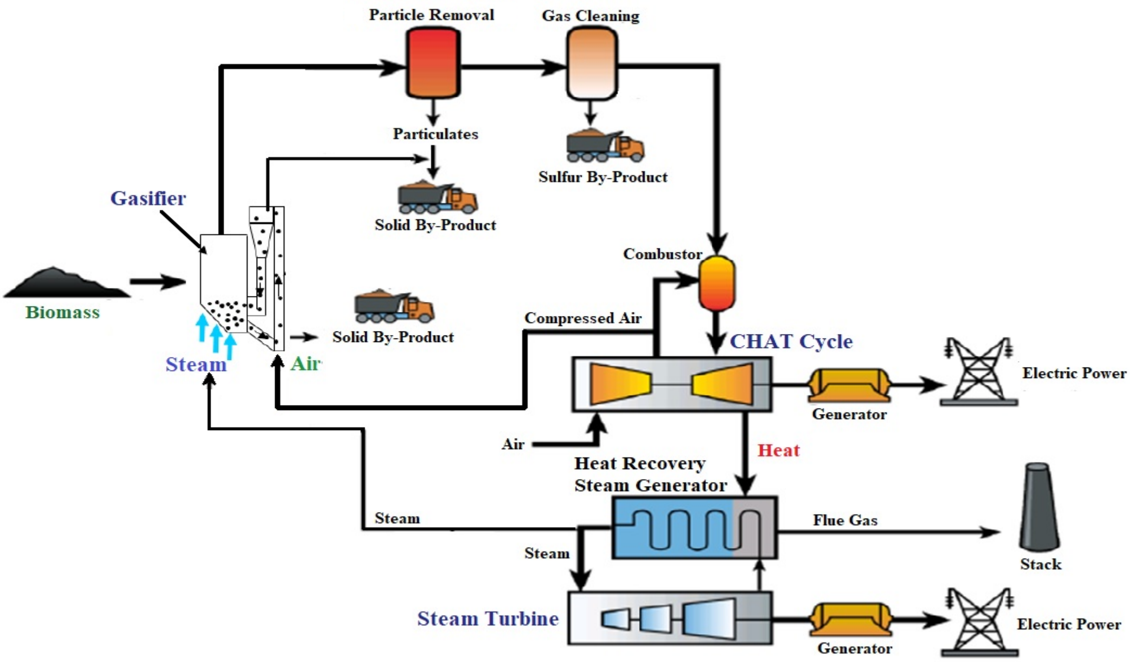

Figure 3. Conceptual view of the proposed combined cycle.

3.1.3. Fluidized bed gasifier cost function

Fluidized bed gasification systems including biomass gasifier and ash output cyclone based on Equations 9 and 10 have been studied in the cost calculations of equipment supply. Moreover, the scale coefficient was calculated 0.67 based on the mentioned references [39].

$$C_g = 1600\ (m_g)^{0.67} \tag{9}$$

$$C_{cyclone} = \exp\left\{ \begin{array}{l} 8.9845\text{-}0.7892[\mathrm{Ln}(S)] \\ +0.08487[\mathrm{Ln}(S)]^2 \end{array} \right\} \tag{10}$$

In Equation 10, the size factor is equal to the volume of discharged gas in $ft^3\ min^{-1}$.

3.1.4. Gas cleaning cost functions

Equations 11 and 12 are used to calculate the cost of the gas treatment system. Cyclic separator with ceramic border plus filter was used for desulphurization and particle separation from bio syn-gas.

$$C_{sep} = 35\,A_{mem} \tag{11}$$

$$C_{filter} = 3800\,A_{filter}^{0.52} \tag{12}$$

The cost of other major equipment used in the cycle in the proposed power generation system is estimated using the relationships 13 to 26 present in Table 1 [36].

3.2. Total variable costs

Estimating the investment cost is only a part of the process of completing the cost analysis. Another important part is to calculate costs associated with power plant operation and electricity sales. These costs are known in a general classification as total variable costs, which are divided into two categories: production costs and general costs. Production costs are also known as performance costs. The variable cost in this study has been considered annually [34].

Table 1. Cost functions of the economic study for the present combined cycle.

Cost function	Parameter	No.
HRSG parameters		
$3650\sum_i (f_{Pi}\ f_{Ti,steam}\ f_{Ti,gas}\ K^{0.8})_i$	$C_{HE(HRSG)}$	(13)
$0.0971(P_i/30)+0.9029$	f_{Pi}	(14)
$1+\exp(T_{out,steam}-830/500)$	$f_{Ti,steam}$	(15)
$1+\exp(T_{out,gas}-990/500)$	$f_{Ti,gas}$	(16)
$(Q_i / DT_{Lm,i})$	K_i	(17)
$11820\sum_j (f_{Pj,steam})$	C_{piping}	(18)
$0.0971(P_j/30)+0.9029$	f_{Pj}	(19)
$685\,m_{gas}^{1.2}$	C_{gas}	(20)
$C_{HE(HRSG)}+C_{piping}+C_{gas}$	C_{HRSG}	(21)
Other equipment's cost		
$130\left(A_{HE}/0.093\right)^{0.78}$	C_{HE}	(22)
$442(\dot{W}_{pump})^{0.71}\ 1.41 f_h$	C_{pump}	(23)
$\exp\left\{ \begin{array}{l} 10.158+0.1003[\mathrm{Ln}(A)] \\ +0.04303[\mathrm{Ln}(A)]^2 \end{array} \right\}$	C_{dryer}	(24)
$760\,V^{0.22}$	C_{shs}	(25)
$0.04\,\text{HRSG Cost}$	$C_{HRSG\,stack}$	(26)

3.3. Assumptions

Technical and operation assumptions of the proposed cycle have been presented in reference [26]. In this study, to solve the presented economic model, the following assumptions are applied:

- The lifespan of the cycle is assumed to be 25 years.
- In this study, the discount rate is set at 8 %.
- According to the available information on the guaranteed purchase price of renewable energy sources in industrial units in Iran, the value of USD kWh^{-1} is considered to be 0.037. Because of the considerable difference between the price of electricity sales in most European countries and that in the United States, electricity prices are also calculated based on both European and American criteria. The average selling price of electricity to industries in Europe is 0.1 USD kWh^{-1} and in the US is 0.07 USD kWh^{-1}.
- The biomass fuel used in the calculations of the proposed power generation system is wood chips, and information about its constituents and characteristics is accessible in reference [40]. The biomass fuel price is set at 20 USD ton^{-1}.

3.4. NPV and IRR calculation

Net cash flows are calculated based on the plant's annual revenue and expenses. Annual costs of the system include fuel costs and total variable costs annually. To compare different options, it is necessary to convert all cash flows to a specific factor. This is because the liquidity available today may be more valuable than its value in the future. To calculate the Net Cash Flow (NCF) value per year, Relation (27) is used [36].

$$NCF = (\text{Electricity Gross Payments} - TVC - \text{Fuel Cost}) \quad (27)$$

According to the values obtained for NCF, the NPV value for the performance cycle is obtained through Relation (28).

$$NPV = \sum_{n=1}^{m} \frac{CF_n}{(1+R)^n} - TCI \quad (28)$$

In this study, the value of m is equal to 25 in Equation 28.

The IRR criterion is the rate of interest that gives the system performance at the expected current cash flow value, compared to the current cash flow. The IRR is equal to the interest rate that results in zero NPV.

4. RESULTS AND DISCUSSION

The overall results of simulation are presented in Table 2. According to the simulated results, the overall vapor rate in the gasifier is about 1.275 kg s^{-1}, whereas the biomass flow rate and air mass flow rate in the gasifier are about 7.63 kg s^{-1} and 4 kg s^{-1}, respectively. Inlet mass flow of fuel is about 4 kg s^{-1}. The overall process efficiency is over 56 % and cycles of electrical efficiency are 56.64 %. The electrical efficiency of the proposed model is about 2.2 times that of the simple IBG-GT cycle, which is quite impressive.

Parametric analysis was performed to calculate NPV and IRR changes based on electricity price variations in the considered geographical areas. The price range of electricity from 0.03 USD kWh^{-1} to 0.1 USD kWh^{-1}, which is its selling price in Iran and its average price in the EU and the US respectively, is considered in the model. As shown in Figure 4, the variation of the NPV value calculated for the duration of the cycle operation is shown. It should be noted that negative NPV values indicate that the cycle is uneconomical under these conditions and, therefore, is not considered as acceptable outputs of the model.

Also, the IRR is obtained at the point where the NPV is zero based on the considered interest rate. These results are presented in Figure 5. As can be seen, the current cycle with the current prices intended for electricity sales in Europe and the United States has the best positive NPV and the acceptable positive value in Iran.

Table 2. The main results of the integrated biomass gasification-cascaded humidified advanced turbine-steam turbine simulation [26].

Parameter (unit)	Value
HP generator electricity generation (kW)	12,497.13
LP generator electricity generation (kW)	15,721.31
Steam turbine electricity generation (kW)	5411.80
HP turbine outlet temperature (K)	1088.28
LP turbine outlet temperature (K)	957.92
FICFB syngas outlet temperature (K)	1094.55
FICFB syngas outlet flow rate (kg s^{-1})	4.15
Inlet air flow rate (kg s^{-1})	39.15
Gasifier cold gas efficiency (%)	80.71
Gasifier hot gas efficiency (%)	89.22
Gasifier thermal efficiency (%)	79.62
Hydrogen production potential (%)	83.79
Electrical energy efficiency (%)	56.54
Net energy efficiency (%)	50.33
Heat energy efficiency (%)	6.12
Total energy efficiency (%)	56.45

As noted above, the results presented in Figures 4 and 5 show a better economic status in Europe and the United States than in Iran. This is due to the higher selling price of electricity from renewable power plants in these countries.

Additionally, Table 3 shows the payback period time of the system capital for different values of electricity price for the sample cycle performance case studies mentioned earlier. According to Table 3, the Break-Even Point (B.E.P.) return of capital for the cycle operation in Iran has been estimated at the current electricity price of approximately 5 years.

Table 3. The Break-Even Point value of the payback period for the sample case studies.

Electricity price (USD kW^{-1})	B.E.P. (year)
0.03	7.5
0.037 (Guaranteed electricity purchase price in Iran)	5.0
0.07	1.9
0.1	1.3

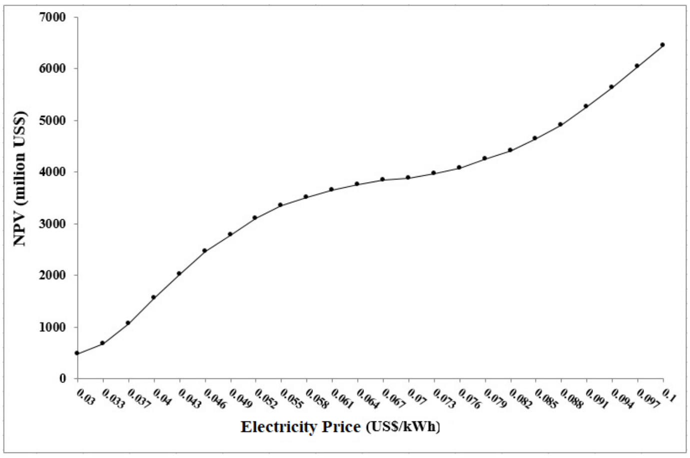

Figure 4. NPV changes for sample case studies based on different electricity sales prices.

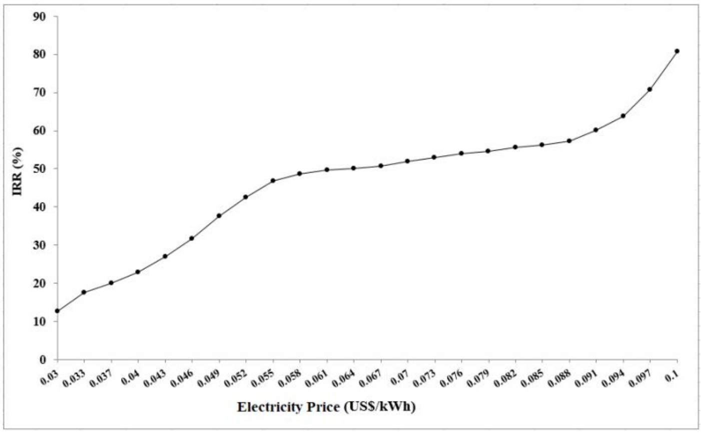

Figure 5. IRR changes for sample case studies based on different electricity sales prices.

Table 4 shows the values of the EPC estimated for the different units of the cogeneration system, as discussed in the previous sections. The purchased cost of the CHAT system for generating electricity, as shown in Table 4 and Figure 6, is substantially higher than the cost of other parts of the plant.

Table 4. The equipment purchase cost for the proposed combined heat and power system.

Equipment	Cost (USD)
Gas turbines and compressors	10,982,973.3
Steam turbine and condenser	839,761.11
Heat recovery steam generators	607,986,7
Gasifier	1,526,758.25
Heat exchangers	12,421.16
Other equipment	145,295.41
Total equipment purchased cost	14,115,195.9

The values of the required parts following TCI estimation are presented in Table 5. A significant increase in the proportion of direct costs versus indirect costs to calculate fixed investment costs indicates the importance of cost parameters in this section. Among the parameters affecting the estimation of direct costs, as can be predicted through the relations presented in Table 5, the EPC has the highest amount.

The results of estimating variable costs and startup costs are also shown in Table 5. Based on the results of the present study, the production cost per unit of energy is approximately 909 USD kW^{-1}.

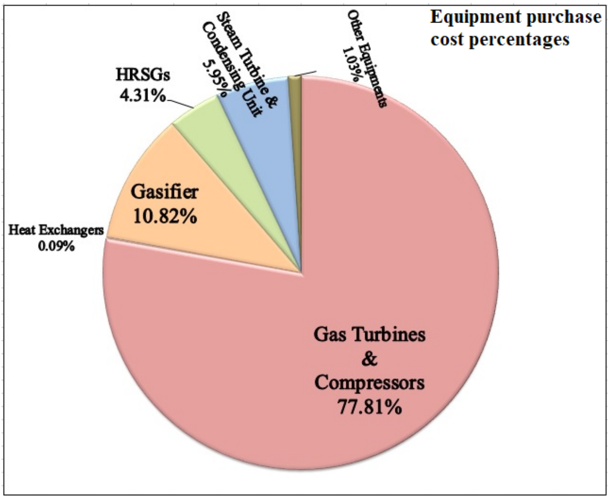

Figure 6. The proportion of equipment purchase cost of the proposed power generation system.

Table 5. TCI & TVC results for the proposed combined cycle.

Cost factor	Cost (USD)
Fixed capital investment	24,755,230
Direct costs	22,302,009
Equipment purchase costs	14,115,195
Installation cost for equipments	3,528,798
Total instrumentation and control cost	846,911
Piping cost	1,411,519
Electrical installation	141,151
Building including services	141,151
Yard improvements	141,151
Service facilities	1,411,519
Land	564,607
Indirect costs	2,453,221
Engineering and supervision	1,115,100
Construction expenses	892,080
Contractor's fee	446,040
Contingency	245,322
Working capital	2,475,523
Total capital investment	27,230,753
Manufacturing cost	1,263,837
Direct variable costs	840,383
Raw materials	-
Operating labor	84,691
Direct supervisory and clerical labor	8469

Utilities	169,382
Maintenance and repairs	495,104
Operating supplies	74,265
Laboratory charges	8469
Fixed charges	338,764
Depreciation	141,151
Local taxes	141,151
Insurance	56,460
General expenses	152,444
Administrative costs	33,876
Distribution and selling costs	33,876
Research and development costs	84,691
Financing	-
Total variable cost	2,426,012
Startup cost	30,000

The Levelized Cost of Electricity (LCOE) calculates by first taking the net present value of the total cost of building and operating the power generating asset. According to Equation 29, this value is divided by the total electricity generation over its lifetime [34].

$$\text{LCOE} = \frac{\text{NPV of Total Cost Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}} \qquad (29)$$

Based on the above relation, the amount of LCOE is 0.66 USD kWh^{-1}.

$$\text{NCF} = (\text{Electricity Gross Payments} - \text{TVC} - \text{Fuel Cost}) \qquad (30)$$

The notable points about the presented results are as follows:

1. Power plant operation is considered to take 365 days and 24 hours; therefore, no shutdown costs are incurred during repairs.
2. Costs such as patents, franchise costs, and depreciation costs for buildings have also been excluded from the calculation of total variable costs because of their insignificance values.

5. CONCLUSIONS

From the economic analysis carried out in the present study, the following conclusion can be considered as the most important achievements of this evaluation:

1. As can be observed from the results, the presented cycle at current prices intended for electricity sales in Europe and the United States has the best positive NPV and in Iran the acceptable positive value. Here are two things to consider: first, the price of electricity in several countries around the world is now above 0.1 USD kWh^{-1} and, secondly, inevitable increase in energy consumption and consequently the price of electricity in the coming years is expected. Therefore, the presented cycle in terms of energy supply has favorable economic benefits, and hence its justification for industries with the amount of electricity consumed by the proposed cogeneration system is reasonable.
2. Based on the results presented in this study, at present, the proposed power-generation cycle may be more favorable in economic terms in other areas studied than in Iran. One of the important reasons could be a substantial increase in the purchase/sale price of electricity from renewable power plants in such countries, along with the stability of financial markets. Also, due to the low fuel price in Iran, if the guaranteed purchase price of renewable electricity or the sale of electricity with full implementation of the subsidy targeting law increases, the NPV and IRR values are higher than those in the other two case studies. On the other hand, with an increase in electricity sales price in Iran to only about 3 US₵ kWh^{-1}, the proposed system will reach NPV with high positive values. However, the Break-Even Point value based on the current guaranteed electricity purchase price in Iran is approximately 5 years.
3. The main reason for the higher cost of purchasing equipment in the proposed cycle than conventional power generation systems is the use of complicated equipment used in high-pressure and low-pressure turbines and compressors sets. The results indicated that investment cost to generate electricity per unit of energy was approximately 909 USD kW^{-1} in the proposed power plant. Also, levelized cost of electricity was obtained 0.66 USD kWh^{-1}. However, in recent years, numerous efforts were made by manufacturers to reduce the cost of biomass gasifier implementation and set targets for reduction below half of the current value. Similarly, a list of estimated prices for other cycle equipment, steam turbine, and condenser assembly and the steam recovery generator are in the next category of expensive equipment, respectively, due to the presence of removable components or high heat-resistant components.

Based on the aforementioned results and sustainable energy targets, the integration of advanced power generation systems into highly efficient biomass gasifiers will be comparative in the future world energy market.

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