Energy Proceedings
Vol 42, 2024

ISSN 2004-2965

Profitability Analysis of Integrating Fast Pyrolysis into Existing Combined Heat and Power Plants for Biofuel Production

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ABSTRACT

Existing combined heat and power plants are seeking additional heat sinks to address challenges arising from the declining district heating demand and the increasing share of renewable energy in primary energy use in the coming decades. In the meantime, the world's demand for sustainable fuel production keeps increasing due to the need to reduce carbon emissions and mitigate the effects of climate change. Fast pyrolysis, as a thermochemical conversion process based on widely available feedstocks such as lignocellulosic biomass, is promising to provide a long-term supply of sustainable fuels, and could be integrated into existing combined heat and power plants due to the scalability and maturity of this method. This work focuses on techno-economic analysis of integrating fast pyrolysis into existing combined heat and power plants for biofuel production. A process model of fast pyrolysis and bio-oil upgrading is established in Aspen Plus to simulate the integration process. In this work, particular attention is given to the profitability analysis based on different final fuel products(crude pyrolysis oil and upgraded bio-oil). Different hydrogen generation solutions (electrolysis, and gasification) for onsite bio-oil upgrading are also examined. This study also performs an analysis of several economic indicators, such as payback period, net present value, and internal rate of return to provide insights for the future business model development for such systems. Sensitivity analysis is also carried out to further reveal the impacts of key variables in the economic evaluation process on the system's profitability.

Keywords: fast pyrolysis, combined heat and power, biofuel production, profitability analysis, uncertainty quantification

NONMENCLATURE

Abbreviations	
AEM	Anion exchange membrane
BOP	Balance of plant
BtL	Biomass-to-liquid
CEPCI	Chemical Engineering Plant Cost Index
CFB	Circulating Fluid Bed
CHP	Combined Heat and Power
IRR	Internal Rate of Return
LHV	Lower Heating Value
NPV	Net Present Value
FCI	Fixed Capital Investment
O&M	Operating and Maintenance
PBP	Payback Period
PSA	Pressure Swing Adsorption
RDF	Refuse-derived Fuels
TCI	Total Capital Investment
TDC	Total Direct Cost
WGS	Water Gas Shift

1. INTRODUCTION

Biomass-to-liquid (BtL) thermochemical routes are the leading green alternatives for producing sustainable hydrocarbon fuels in the near future [1]. As a thermochemical pathway for biomass conversion, fast pyrolysis will likely provide a long-term supply of sustainable drop-in fuels, mainly due to the widely available feedstocks and the scalability and maturity of this method [2].

Many studies show that integrating fast pyrolysis into existing CHP plants could increase the system efficiency as compared to the standalone pyrolysis plant ,and could increase the operational hours of the CHP plants during the low heating demand seasons [3,4]. To

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This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

facilitate the uptake of this technology, the profitability of the integrated system needs to be further investigated. This work focuses on the detailed economic analysis of integrating fast pyrolysis into existing combined heat and power plants for biofuel production. A thermodynamic CHP plant model established in Ebsilon® Professional, along with a thermochemical fast pyrolysis and biooil upgrading model in Aspen Plus, is employed to conduct the techno-economic analysis. The results of this work will provide insights for the future business model development of such systems.

2. SYSTEM DESCRIPTION

The goal of this work is to investigate the economic feasibility of integrating fast pyrolysis into an existing combined heat and power plant in Västerås, Sweden for biofuel production. The idea is to use part of the heat released from refuse-derived fuels (RDF) incineration to support the fast pyrolysis in the G-valve for biofuel production. The configuration described in Fig. 1 summarizes the real configuration of one of the boilers of Mälarenergi, which is the city-owned electric power and district heating provider based in Västerås, Sweden.

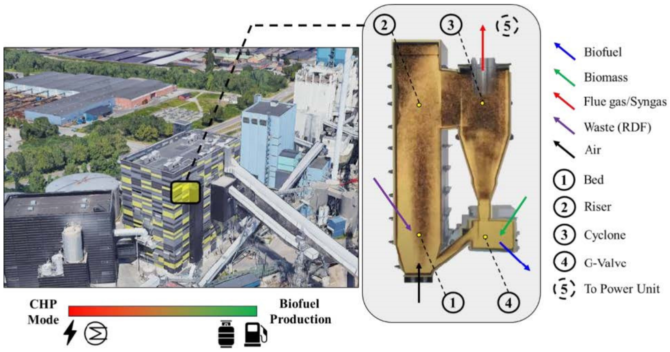

Fig. 1. Circulating fluidized bed boiler (CFB). Image taken from Google Earth of one of the boilers of Mälarenergi, Västerås, Sweden [5,6].

Three cases based on crude pyrolysis oil production and upgraded pyrolysis oil production are considered in this work:

Case 1 - crude biooil production: in this case, the final product of fast pyrolysis is crude pyrolysis oil without an oil upgrading process. Fig. 2 shows the process diagram in case 1. Biomass is fed into the G-valve during the operation of this polygeneration system. The pyrolysis vapor generated in the G-valve is then sent to the quench loop to condensate the vapor to bio-oil, which is the final product in this case. The byproducts from the fast pyrolysis process, primarily biochar and pyrolysis vapor left from the quench loop, are recycled back to the CFB boiler to enhance heat and power production.

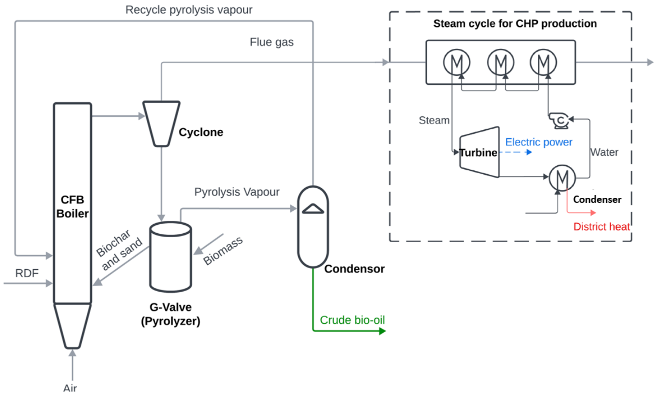

Fig. 2. Process diagram of the polygeneration system in Case 1.

Case 2 - upgraded biooil production with H_2 from Electrolyser: in this case, the crude biooil produced by fast pyrolysis is sent to the hydrotreating (hydrodeoxygenation) reactor for upgrading, followed by a distillation process for final fuel production. The biochar produced in the G-valve is recycled back to the CFB boiler and provides additional energy from its combustion. However, the pyrolysis vapor left from quench loop passes through a reformer and a two-stage water-gas shift reactor to produce hydrogen required in the bio-oil hydrotreating process. It is also worth noting that additional hydrogen supply comes from the anion exchange membrane (AEM) electrolyser system driven by electricity produced in the CHP plant.

Case 3 - upgraded biooil production with H2 from gasifier: similar to case 2, the final product of fast pyrolysis in case 2 is the upgraded biooil. However, in case 3, additional hydrogen supply is provided by a small-scale CFB gasifier driven by the heat produced in the CHP plant, noting that additional fuel is also required for the gasification process in case 3.

3. METHODOLOGY

3.1 Thermodynamic modeling of the CHP plant

A thermodynamic model simulating the CHP plant performance is established in Ebsilon® Professional, which allows for conducting design and off-design analysis of the CHP plant after process integration with fast pyrolysis. In this work, a boiler of a CHP plant located in Västerås, Sweden is selected to be the reference case. The nominal parameters of the CHP plant are summarized in Table 1 [7].

Table 1

Nominal operating parameters of the CHP plant.

Boiler steam generation, kg/s	56
Boiler capacity (heat output), MW LHV biomass	170
Steam turbine inlet steam pressure/temperature, bar/℃	70/472
Boiler efficiency, %	90
Maximum heat generation, MW	102
Maximum power generation, MW	48
Power-to-heat ratio	0.44
Electrical efficiency, %	30
The electric consumption of the CHP, MW	3.3

3.2 Process modeling of fast pyrolysis and biooil upgrading

Aspen Plus is a process modeling software widely used in design and simulation of chemical processes. In this work, a process model is developed in Aspen Plus to simulate the fast pyrolysis, pyrolysis vapor condensation, biochar/pyrolysis vapor combustion, biooil upgrading, and hydrogen production processes.

3.2.1 Fast pyrolysis

The capacity of the fast pyrolysis reactor is set to be one-third of the capacity of the CHP boiler, which gives a capacity of 57 MW LHV biomass for the pyrolysis reactor. A RYield reactor is used to simulate the pyrolysis process in the G-Valve. The normalized feedstock ultimate analysis and the mass yield fraction of the pyrolysis product were taken from Lisa et al. [8] with pyrolysis temperature fixed at 480 ℃. After the fast pyrolysis process in the G-valve (Pyrolyzer), the generated pyrolysis vapor is then directed to a quench loop to produce liquid biooil.

3.2.2 Crude biooil upgrading

In Case 2 and Case 3, a hydrotreatment process is employed after the quench loop to upgrade the crude biooil. A RStoic block in Aspen Plus is employed to simulate the hydrotreating process. The hydrotreatment reactions and operating parameters employed in the Hydrotreatment Reactor block are taken from Dutta et al. [9]. The product resulting from the hydrotreatment process is directed to the distillation column, where biofuel (the final product in Case 2 and Case 3) is separated and produced.

3.2.3 Hydrogen generation system

The pyrolysis vapor left from the quench loop is used to produce hydrogen for the hydrotreating process in Case 2 and Case 3. A reformer and a two-stage water-gas shift reactor are implemented to enhance hydrogen production in this work. A RStoic reactor is employed to simulate the steam reformer, and the water-gas shift reactor is simulated by the REquil reactor in Aspen Plus. In case 2, an anion exchange membrane (AEM) electrolyser system is introduced to produce additional hydrogen by using the electricity produced from the CHP plant. While in Case 3, a standalone gasifier is employed to enhance hydrogen production by consuming

Table 2

Base capital costs for main equipment in the pyrolysis system for biofuel production.

Equipment	Base capacity	Base cost (Million €)	Base year	Capacity scaling factor	BOP Cost factor	Installation cost factor	Indirect cost (% of TDC)	Ref
Biomass preparation	198.1 ton/h (biomass)	3.5	2007	0.62	0.16	included	32	[10]
Biomass dryer	204,131 lb/h (biomass)	0.1	2011	0.8	included	1.0	60	[9]
Fast pyrolysis reactor	2000 ton(biomass)/day	6.9	2011	0.5	3.6	2.1	60	[9]
Condensation and Separation	310,342 lb/h (pyrolysis vapor)	1.1	2013	0.6	4.8	0.92	60	[9]
Hydrotreating	56,010 lb/h (crude biooil)	4.8	2013	1.0	1.0	0.67	60	[9]
Oil fractionation	46,446 lb/h (upgraded oil)	0.5	2013	0.7	2.8	1.5	60	[9]
Steam reformer	31,000 kmol/hr (syngas at exit)	93.7	2007	0.9	included	included	included	[10]
WGS reactor (two stages)	815 MW (dried biomass LHV)	8.4	2007	0.67	0.16	included	included	[10]
PSA	5218 Lb/hr	0.98	2013	0.6	included	1.8	60	[9]
H2 Compressor	10 MW	6.3	2007	0.67	included	included	32	[11]
Gasifier (CFB)	483 MW biomass LHV	173	2007	0.5	included	included	included	[10]
Electrolyser	1 MW	1.0	2018	1.0	included	included	included	[12]

additional biomass feedstocks, the steam required in the standalone gasifier is taken from the CHP plant.

3.3 *Economic analysis*

By following the evaluation procedures illustrated in Ref. [9], a detailed economic analysis has been carried out to examine the profitability of the proposed polygeneration system. The base year selected to conduct economic analysis is 2022. The total direct cost (TDC) is first evaluated by calculating the equipment cost, balance of plant (BOP) cost, and installation cost. A capacity scaling factor and the base cost shown in Table 2 are introduced to estimate the equipment cost for each equipment in the proposed system [13]. The Chemical Engineering Plant Cost Index (CEPCI) is implemented to estimate the cost at a specific year to take inflation into account [13]. The Installation cost and BOP cost for each main piece of equipment is estimated by applying installation factors and BOP factors to each piece of equipment. The sum of equipment cost of main components, BOP cost, and installation/construction costs is defined as the total direct cost (TDC).

In this study, indirect cost is estimated as a fraction of the TDC. The sum of direct and indirect costs is defined as the fixed capital investment (FCI). Working capital, retrofitting cost, and Operation and maintenance (O&M) cost are estimated based on FCI. The total capital investment (TCI) is then calculated based on all the costs mentioned above. The prices of crude biooil and upgraded biooil are calculated by adjusting the price on the same energy content basis as the crude oil/gasoline. The assumptions and some critical inputs employed in the economic analysis are summarized in Table 3.

Table 3
Assumptions and key inputs in the economic analysis.

Parameters	Value	Ref
Project economic life, years	30	assumed
Construction period, years	3	[14]
Equity, % of FCI	40	assumed
Loan interest, %	8	[9]
Loan term, years	10	[9]
Discount rate, %	10	[9]
Retrofitting cost, % of FCI	20	assumed
Working capital, % of FCI	15	[15]
O&M cost, % of FCI	4	[14]
Operating hours, hr/year	7884	[9]
Prices		
Biomass price, €/MWh	20	[16]
Electricity, €/MWh	82	[17]
District heat, €/MWh	90	[18]
Crude oil price, €/barrel(Fossil-based)	95	[19]
Gasoline price, €/litre(exclude tax)	1.37	[20]

3.4 *Integrated simulation*

The system analysis of the proposed polygeneration system is carried out by the co-simulation of a thermodynamic CHP plant model in Ebsilon® Professional and a thermochemical fast pyrolysis and biooil upgrading model in Aspen Plus. The process diagram of integrated simulation is illustrated in Fig. 3.

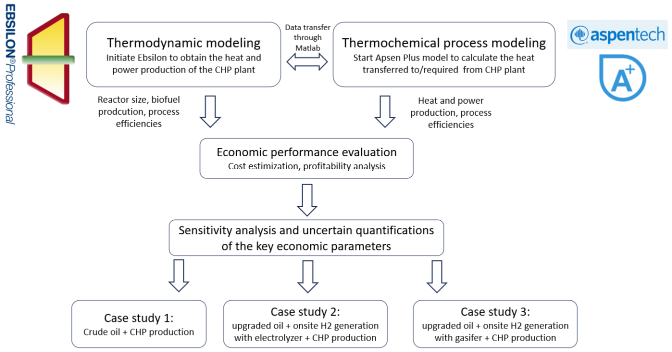

Fig. 3. Process diagram of integrated simulation and economic evaluation.

4. RESULTS AND DISCUSSION

4.1 *System efficiency*

The system efficiencies of the polygeneration system are calculated based on Equation (1), where district heat, electric power, and biofuel are considered as the products of the polygeneration plant in MW. The input of the polygeneration system is the sum of biomass fed into the CHP boiler and the fast pyrolysis system in MW. The system efficiencies examined in the standalone CHP system and the three cases for polygeneration are summarized in Table 4.

$$Efficiency = \frac{(Heat + Power + \mathrm{Biofuels})}{\mathrm{Biomass}} \tag{1}$$

Table 4
Energy consumption and production in the polygeneration system.

	CHP	Case 1	Case2	Case3
Biomass input in Boiler, MW	185	185	185	185
Biomass input in Pyrolysis system, MW	/	56.7	56.7	61.5
Additional heat from pyrolysis byproducts to CHP Boiler, MW	/	10.2	4.8	4.8
Heat (from steam extraction) sent to pyrolysis system, MW	/	0	5.6	8.0
Heat released from the pyrolysis system, MW	/	0.8	5.8	6.7
Electricity consumption in Pyrolysis system, MW	/	0.5	9.4	1.6
Total heat production, MW	102	107.5	107.0	106.5

Total power production, MW	48	50.7	38.3	47.0
Biofuel production, MW	/	37.8	38.0	38.0
Overall efficiency, %	81.1	81.3	75.8	78.5

In general, the results reveal that fast pyrolysis integrated into the CHP plant will not significantly affect the heat and power production, and could maintain the overall efficiency of the polygeneration system at a higher level.

4.2 Economic performance

Three economic performance indicators (net present value (NPV), payback period (PBP), and Internal Rate of Return (IRR) are investigated as well in this study.

The NPV, PBP, and IRR for the studied cases are summarized in Table 5. The PBP of case 1 with crude oil production is around 10 years with an IRR of 16.5%. While for the upgraded oil production cases (Case 2 and Case 3), Case 2 gives the highest PBP of 15 years, which is primarily caused by the high investment cost of the electrolyser system and the higher electric power consumed to produce hydrogen. Table 5 also shows that upgraded oil production with onsite hydrogen generation from a standalone gasifier (Case 3) has a better economic performance among the studied cases, resulting in a PBP of about 6 years and an IRR around 23%.

Table 5

Economic performance indicators for the polygeneration system.

	NPV (million Euros)	PBP (year)	IRR (%)
Case 1	22.4	10	16.5
Case 2	30.9	15	13.3
Case 3	80.4	6	23.0

4.3 Sensitivity analysis

To understand how those cost data and assumptions will impact the economic performance of the polygeneration system, a sensitivity analysis is carried out for the three studied cases. A set of key input variables including biooil selling cost, biomass cost, loan interest rate, TCI, and operating hours for the plant are selected in the sensitivity analysis with values changed by a factor of ±25%. The results of sensitivity analysis on the effect of important parameters on net present value are illustrated in Fig. 4.

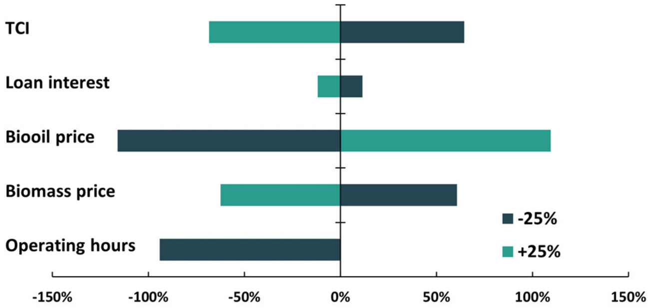

Fig. 4a. Effect of important parameters on net present value for Case 1.

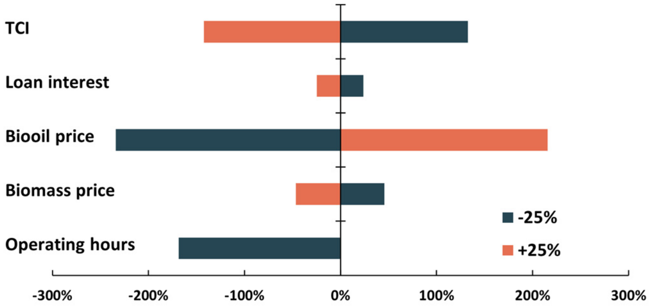

Fig. 4b. Effect of important parameters on net present value for Case 2.

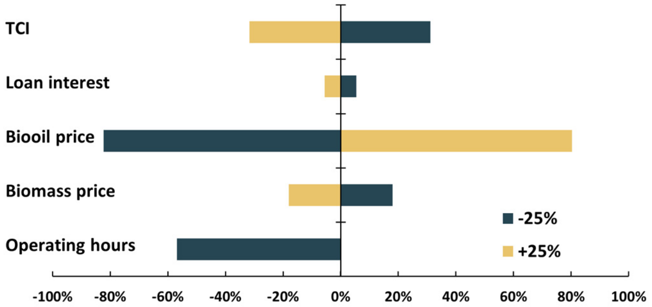

Fig. 4c. Effect of important parameters on net present value for Case 3.

The sensitivity analysis shows that the profitability of the polygeneration system in all studied cases is highly sensitive to the biooil (crude biooil in Case 1, upgraded biooil in Cases 2 and 3) selling price. In case study 1, biomass price also shows a high impact on the net present value of the polygeneration system. In Case 2 and Case 3, the net present value of the system is less sensitive to the biomass price as compared to Case 1. Note that the operating time is another critical factor that affects the profitability of the polygeneration system. CHP plants normally operate on part load during low heating demand seasons which will reduce the operating time of the system. Nonetheless, by burning a small part of biomass in the reactor, the fast pyrolysis process system can sustain its operations, mitigating the impact of insufficient heat supply from the part load operating the CHP plant. It is noteworthy that the economic analysis in this work relies primarily on data sourced from the literature. Conducting optimization under uncertainties (using sampling method) [21, 22] could provide deeper insights into the effects of cost fluctuations on the profitability of such systems.

5. CONCLUSION

Profitability analysis of integrating fast pyrolysis into an existing CHP plant is carried out in this study. The results show that the polygeneration system could maintain a relatively high efficiency after the integration, above 75%. Economic evaluation results also indicate that biooil selling price shows a significant impact on the profitability of the biofuel production subsystem in all the studied cases. While in the cases of upgraded biooil production, the profitability of the biofuel production system is less sensitive to the biomass (feedstock) price as compared to the crude biooil production system. Among the two studied upgraded biooil production cases, onsite biooil upgrading with hydrogen supply from a standalone gasifier gives a better economic performance with a payback period of about 6 years and an internal rate of return of 23%.

ACKNOWLEDGEMENT

This work was carried out in IFAISTOS project (Intelligent electroFuel production for An Integrated STOrage System), which is funded under the framework of the joint programming initiative ERA-Net Smart Energy Systems. The initiative has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements no. 646039 and no. 755970.

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