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Digitalization of Biomass Gasification Plant in Capturing and Translating the Technical and Economic Uncertainties – A Review

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Drastic demand on the global renewable energy (RE) transition delineated in the 2030 Agenda for Sustainable Development and Circular Economy Action Plan have turned to a massive deployment and exploitation of biomass-based RE. Though, there are numbers of commercial RE plants available on the ground, progression of academic research with regards to the biomass technology is actively growing and evolving. This is due to the urge of technical and economic (TE) intervention to ensure sustainability, feasibility, and viability of large-scale biomass-energy technology such as for gasification plant. Digitalization via high-fidelity simulation and integrated optimization and machine learning is able to capture those TE uncertainties via Process System Engineering (PSE). PSE tools have evident to offer significant contribution to a body of knowledge especially on deciphering the technology/system, predicting, and capturing the TE uncertainties and solving the challenges face by the industries and investors before the technology can be commercialized. At present, no noticeable review articles have been conducted related to the deployment of PSE tools in the biomass technology research area. Thus, the objective of this study is to provide recent progress and highlight contribution and trend of PSE tools in capturing and translating the TE uncertainties subsequently to provide insight on the TE values of biomass-based RE technology. This comprehensive review encompasses of different types of computational tools such as Aspen Plus and Matlab. Concurrently, to evaluate how the tools plays a part towards experimental output and practical result targeting the TE key parameters for instance, net present value (NPV), payback period (PBP) and rate of return. Ultimately, we suggest that applying PSE techniques is critical for TE evaluation to access more compelling systems with maximum efficiency while improving a profound knowledge on TE sensitivity.

1. Introduction

Rapid urbanization leads to massive surge in energy consumption. It is expected that the demand will exceed 20,000×10^6 t of oil equivalent by 2050 (Energy Information Administration, 2019). To provides for the future supply, massive deployment and exploitation of biomass based renewable energy (RE) is needed. This adaptation is in line with the Sustainable Development Agenda 2030 and the Circular Economy Action Plan, which aim to increase RE sharing in Malaysia by 40 % by year 2035 (SEDA Malaysia, 2021). Malaysia has a high potential to be renowned as a green energy hub, considering the significant contribution to massive waste generation from biomass, especially in agriculture sector. However, it is unfortunate to learn that Malaysia green energy technology for biomass is still at the developing stage. Table 1 shows some list of identified and successful biomass commercialized plant project in Malaysia and the project progression by 2022. Based on the data, most of these power producing facilities only working on a small capacity (10-14 MW). Aside from that, there are no historical and contemporary database setup to provide a synchronised information on economic status on these projects. Inadequate economic data also makes it difficult for potential investor to estimate the project feasibility. This has been identified to be among the main challenges for biomass based commercialized RE project to be established in Malaysia. Thus, a review on the existing technical and economic analysis (TE) study is required to highlight the recent progress on the existing projects and facilities.

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Table1: Biomass plant commercial facility in Malaysia

Project name/ developer	Current Status (2022)	Biomass fuel	Technology	Capacity (MW)	Project cost/ Economic info	Reference
BELL Eco Power's Biomass Power Generation Plant/ Bell Eco Power Sdn. Bhd*	In operation, generate 1,436 MW and sold 1,195 MW*	Palm Oil Mill Effluent, PKS, EFB	Gas Turbine	10	Total cost: RM 54.576 $\times 10^6$; Sale Price: RM 0.21 – IRR: 6.69 % for 20 y; 2.14 % for 10 y	(Climate Bonds Initiative, 2020)
TSH Resources Berhad Biomass Power Generation Plant/TSH Resources Berhad*	In operation, generate 79,246MW and sold 65,440 MW*	Palm waste	Steam turbine	14	RM 150$\times 10^6$ (US\$37$\times 10^6$), Private funding from THS Resources Berhad	(Climate Bonds Initiative, 2020)
Recycle Energy Sdn. Bhd.	In operation, generate 67,570MW and sold 56,481a	RDF	Steam turbine	5-6	-	(Afrouzi & Wimalaratna, 2021)
Teluk Intan Biomass Power Plant/TNB	Under erection	Empty fruit bunch	Greenfield power plant	12.5	RM 202.46$\times 10^6$ (US\$ 44.62 $\times 10^6$)	(Carmen, 2022)

*Under the Renewable Energy Power Purchase Agreements (REPPA) agreement with TNB to supply energy to national grid

Process System Engineering (PSE) tools have clearly demonstrated a significant contribution to a body of knowledge, particularly in deciphering the technology/system, predicting the TE uncertainties, and resolving the challenges faced by industries and investors before the technology can be commercialized. There have been numerous studies on the application of PSE in renewable energy studies which cover the aspect of technical sensitivity, optimization studies, and energy analysis (Kikuchi, 2022). However, currently, there is no noticeable review articles have been conducted related to the TE perspective using PSE tools in the biomass technology research area. Thus, this study aims to provide recent progress and highlight the effort to digitalizing and translating TE uncertainties of biomass technology through PSE tools. Whereas digitalization in this context reflects by the high-fidelity simulations and process optimization (ABB, 2018). This review highlights some of the main PSE tools and how they contribute to provides a reliable experimental output and practical results based on key parameters which includes: net present value (NPV), payback period (PP) and rate of return (ROR).

2. PSE tools in techno-economic analysis

Biomass for energy production involves many chemical processes. Thus, system efficiency and syngas output are affected by many parameters such as the gasifier operating condition and biomass feedstock properties. Due to many sensitive factors involves in the process, a large price variance is observed when using a specific type of gasifier and biomass feedstock. For instance, high-moisture biomass is inefficient for energy production since it takes extra heat for drying, thus may reduce system efficiency and electricity output (Rezaei et al., 2019). This small variance may affect the economic performance of the system, including the basic economic performance such as initial cost and revenue that can be harvested from power generation. To ensure the right decision is made for optimal plant design, it is crucial to develop an economic sensitivity of the biomass power plant project. Several studies have successfully conducted a techno-economic analysis through simulation and numerical software such as Aspen Plus and Matlab.

2.1 Aspen Plus software

Jana and De (2015) conducted a techno-economic study of polygeneration systems using rice straw by using Aspen Plus software. Multiple techno-economic parameters have been tested in this study. It is found that as biomass feed rate increases, NPV is increasing, annual net profit increases and the payback period (PBP) is decreased. However, return of investment (ROI) increment falls slowly when this setting is applied. For biomass distribution density, it is found that as the distribution density is increasing, the economic scenario has become positive since ROI is increasing and transportation costs (TC) are decreased. However, as a feedstock price increase, the economic scenario becomes negative due to increasing in PBP and decreasing in ROI. From the sensitivity analysis, as product price and electricity price increased, the economic value becomes positive since annual profit and ROI is increased and PBP decreased.

Salisu and Quan (2021) developed and conducted a simulation model using Aspen Plus software. Biomass used in their study are plastic and rice husk. The techno-economic analysis has been conducted by studying the downdraft gasifier system and assuming electricity from syngas generation as the main product. From the analysis, for a 15-y lifetime, the PBP of the project is in 6 y and is expected to have a total investment of 7773/kW. While,US$ 1.68×10^6 of NPV, Internal Rate of Return (IRR) of 24 % and the system's Levelized Cost of Electricity (LCOE) of around US$ 0.07 to 0.11/kWh is estimated simultaneously. Their study also tested a sensitivity for plant lifetime and feedstock price. It is noted that as the plant availability increased, IRR is increased. However, the PBP becomes longer, and it also lowers the LCOE. The effect of feedstock price is also studied. The positive implications from raising the feedstock price are it can increase the LCOE and decrease the PBP. But, at the same time, IRR also will decrease. This study also suggested that in order to make a profitable investment, the plant needs be run for more than 5,500 h each y.

Since different biomass carries different properties, a few studies conduct a comparative analysis by comparing the economic feasibility of different biomass feedstocks. For example, AlNouss et al. (2020) compares the economic potential of coconut coir pith and coconut coir pith char using Aspen Plus software. In their study, char, bio-oil, and syngas has been treated as a target product. For a project that has a 20-y lifetime, total capital cost, total operating cost, total installation cost, and total revenue is for coconut coir pith is US$ 4,740,790, US$ 1,672,140/y, US$ 1,126,700, and US$ 2,108,584; while for coconut choir pith char is US$ 4,647,490, US$ 1,654,640/y, US$ 1,075,100, and US$ 2,357,968. The comparative study indicated that the coir pith char gasification generated 27 % more syngas output and 25 % more H_2 + CO composition than the coir pith gasification. The TE indicated that the coir pith char steam gasification can generate 1.12 times more revenue than coir pith steam gasification. Since the total revenue of coconut choir pith char is higher, it is considered more economically feasible as compared to coconut choir pith biomass alone.

Similar studies conducted by Zhang et al. (2021). In their study, a model simulating bio-methanol production through the gasification of different woody bioresources (pine biomass, biochar, and pyrolysis oil) has been developed in Aspen Plus. The process includes gasification, syngas post-treatment, methanol synthesis with recycling, and purification. The model outputs were utilized as inputs for the TE analysis. Economic assessment is carried out utilizing three indicators, the NPV, IRR, and discounted payback time (DPBP). The sensitivity analysis was performed to assess the economic viability of various plant sizes while modifying factors such as bio-methanol price, biomass price, total capital investment (TCI), and plant lifetime. The early economic assessment findings suggested that bio-methanol production from charcoal might be an appealing alternative. When compared to pine biomass, the IRR produced with biochar is higher. At a minimum plant size of 1,000 t per day (TPD) and a bio-methanol price of US$ 1300, biochar may achieve an IRR of 5.3 %, which is greater than biomass at the same plant scales, even though raw biochar price is more expensive. The IRR reached in the pyrolysis oil scenario is just 5 % unless the price anticipated for bio-methanol is as high as US$ 2500/t at a plant capacity of 2000 TPD. Their research suggested that biochar is the most economically viable, followed by biomass and pyrolysis oil. It is noted that PSE tools such as Aspen Plus software also capable to estimates and compares revenue that can be obtained from various by-products of the same biomass.

2.2 Matlab software

Some studies have developed a techno-economic analysis and using Simulink approach across different PSE tools such as Matlab. Násner et al. (2017) developed a model for gasification process of Refused Derived Fuel (RFD) in Aspen Plus and later the model is developed further in Matlab software. Results for the TE analysis reveals that such pilot plant that expected to operate 6,500 h/y can generate 279,500 kWh/y, thus annual saving for this project might reached up to only USD 13,845/y. NPV estimated for this project was USD230,728, which implies project is not feasible for such power capacity. NPV becomes positive at 120 kW_{el} installed capacity. Similarly, at this point the IRR reaches a value above the assumed 12 % discount rate.

Thus, it is concluded that with an installed capacity above 120 kW_{el}, the construction of the plant proved to be economically viable. García et al. (2017) conduct gasification of the coffee cut stem in a downdraft gasifier. The initial model was developed using Aspen Plus, while further mathematical modeling of the concentration profiles using kinetic models was performed in Matlab. In their study, three possible scenario is considered based on products outputs that can be generated from the system The first scenario solely examined hydrogen as a product, the second considered hydrogen and electricity, and the third included hydrogen, electricity, and ethanol. The product flow of the first, second, and third scenarios is 2.1 ton H_2/day, 0.72 tonH_2/day + 2.94 MW, and 0.68 H_2/day+10,244.1 L ethanol/day +1.2 MW. It has been noted that when plant capacity grows, the hydrogen production cost (HPC) is reduced. At the same time, NPV and energy efficiency noted a significant increase. The third scenario has the greatest NPV, followed by the first and second scenario. As a result, it is stated that by considering hydrogen, electricity, and ethanol as a product is more economically viable rather than focusing on single products.

2.3 Monte-Carlo simulation

Some other researchers preferred to use Monte-Carlo as it has been considered as the great PSE tools for TE assessment. Voets et al. (2011) have been able to identify the key variables that influence the NPV in their study by performing Monte Carlo simulations. The study compared the economic performance of two plant capacity (5 and 10 MW). For lower scale (5 MW), NPV projected that the plant to applied combined-heat power (CHP), since the sole production of electricity is not profitable at this low scale. At higher scale (10 MW), electricity production becomes more profitable, but gasification for electricity production is still not viable. However, even if merely 25 % of the generated heat is sold, the additional expenditures necessary for combined heat and electricity generation are already compensated. You et al. (2016) proposed two decentralized gasification-based schemes for sewage sludge and food wastes disposal in Singapore. Monte Carlo simulation-based cost-benefit analysis was conducted to compare the proposed schemes with the existing incineration-based scheme. It was found that the gasification-based schemes are financially superior to the incineration-based scheme based on the net present value (NPV), benefit-cost ratio (BCR), and IRR. In another study, Colantoni et al. (2021) evaluates the overall uncertainty in the NPV of investment in cogeneration systems consisting of a biomass-fed gasifier and a bottoming Internal Combustion Engine fed by the gasification product gas. From the study, Monte Carlo simulation has capable to estimate the positive NPV for three different capacities of a co-generation facility. The positive NPV varies from 66 to 90 %, with bigger plants having a better possibility. It is also suggested that biomass price and biomass cost, electricity price, and gasification product gas amount can dominantly influence the economic scenarios.

2.4 HOMER Pro software

HOMER Pro is a sophisticated software that emphasizes on the technical, environmental, and economic aspects of energy systems. Bagherian et al. (2021) explains the effects of various conversion processes on the TE performance of bioenergy systems for residential energy supply. The study compares TE performance of Organic Rankine Cycle (ORC) and Dual Fluidized-Bed (DFB). Results shows that the feedstock price has greater effect on the economic performance in ORC compared to DFB. Furthermore, ORC may be a preferable alternative for wood chips below US$ 55/t owing to cheaper capital and maintenance expenditures. In contrast, DFB may withstand feedstock price fluctuations better, giving 8 % reduced energy costs at US$ 65/t wood chips. Another study by Chambon et al.(2020) was also conducted using HOMER Pro. The case-study focusing on biomass gasification TE feasibility in off-grid and grid-connected mini-grids for community-scale energy applications in India. Off-grid hybrid PV-biomass is found to be the most reliable at the lowest cost. While single-source PV was cheaper than biomass gasification, biomass gasification-based mini-grids are not cost-competitive with PV unless the two power sources are merged in a hybrid system. Table 2 summarizes the main advantage and disadvantage of these PSE tools for TE assessment.

Table 2: Advantages and disadvantages of the different PSE tools

PSE tools	Advantages	Disadvantages
Aspen Plus software	• Direct and hands on to project. • Industry/product oriented. Need to model only necessary part.	• Proper modelling methods needed to be explored independently.
Matlab software	• Easy to use, platform independent.	• Interpreted language, may execute more slowly than compiled language.
Monte-Carlo simulation	• Strong way of estimating uncertainty. • Simple & intuitive, this approach is quite easy to understand.	• Computationally inefficient - requires a lot of time and a lot of computations to approximate a solution when dealing with large variables.
HOMER Pro software	• Contains an optimizing function, allowing cost minimization and optimization of scenarios based on various factors.	• Detailed input data is needed • Could be time consuming.

3. Conclusions

Low RE commercialization in Malaysia enhances the importance to study the TE aspect. it can be concluded that the electricity generation from biomass is indeed complex since small changes will produce variance product output and give a massive impact on economic performance of the system. In brief, implementing the PSE tools is crucial for TE assessment to access more feasible system with optimal efficiency, while improved a comprehensive understanding on TE sensitivity. From the review, it is also revealed that the TE study of biomass based commercialized RE systems in Malaysia is still limited. Therefore, PSE tools offers a significant contribution to discover the commercialization potential of the future RE biomass-based projects while aiming to achieve the RE target in Malaysia by 2035. Though fully digitalization of biomass technology might seem to be an ambiguous at this moment, PSE tools implementation may assist in achieving the goals quicker. In conclusion, Aspen Plus and Matlab offers simple interface for model development and economic analysis, thus is suitable for quick economic assessment for small-scale biomass gasification projects. On the other hand, while HOMER Pro and Monte-Carlo simulation is particularly for more complex, medium to large scale projects, Monte-Carlo seems to be the best for TE assessment since it can provide multiple economic uncertainty analysis at once. 3. Challenge and way forward

4. Challenges and way forward

Biomass-based gasification process involves multifaceted process with complex interaction. To ensure the viability of biomass technology, application of PSE approach and evolution in digitalization is able to overcome the challenges in biomass gasification technology, especially in term of TE uncertainties. Implementing digitalization may boost operational efficiency, saving an average of $91,261 per company employee globally (Countryman & Frandina, 2018). Moving towards digitalization, DIGIBIO (Digitalization of biomass energy revalorization processes with high added value) is centralized as a pioneer project for the digitalization in RE industry, which focusing on biomass based RE technology (Sopo, 2021). Through such approach, PSE tools offers a viable contribution as it is potentially proven to mimic the plant system, enabling real-time visibility of the biomass plant's procurement process, eliminate manual reporting process, significantly simplify administrative operations, and increasing time optimization. Much of these comes with the additional economic benefit, as it possible to cut waste and stock by 10–20%, which contribute to cost savings (Kurniawan et al., 2022). Digitalization's commercial case in the RE sector has been established and will likely grow. AI-driven analytics, augmented reality, and process optimization are already accessible. As corporations pursue economies of scale, expended, super-efficient sites and more non-proprietary open designs of PSE tools would likely to be introduced. The methodical application of future business strategies is made accessible using PSE tools, lowering economic data transparency. By expanding data accessibility, prospective investors would be able to make more informed decisions, increasing the probability of more commercialized RE setup in Malaysia.

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