A sustainable conceptual model for pyrolysis to power project using lignocellulosic waste

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Abstract (12 font)

A base case process design for the pyrolysis of pinedust and *Acacia tortilis* residues was rated unsustainable due to the use of a fossil-based, high-cost energy source; the absence of energy integration and low yields of the targeted dry oil. Incremental improvements were made using a logical matrix based on demonstrated best practices from literature, including the use of a fast pyrolysis regime to increase bio-oil quality and yield. More sustainable sources of energy such as the use of char by-products in a self-energizing system or the use of concentrated solar were proposed. Integrating such improvements will improve the techno-economic outlook of the project by lowering the production cost of the pyrolysis oil while reducing the ecological impact of the process. We assumed the technical feasibility of utilizing the bio-oil as a substitute for fuel oils in slow engines, which has been theoretically proven and partially demonstrated. The logical matrix led to sustainable conceptual models for a pyrolysis system that can supply bio-oil for use in a heavy fuel oil power generator. Bio-oil would be a cost-effective solution for substituting fuel oil, which is facing stiffer regulatory restrictions due to its high sulphur and black carbon emissions.

Keywords (12 font)

Biomass, bioenergy, conceptual model, pyrolysis, sustainability

1. Introduction

1.1 General introduction

Current global policies and trends emphasize sustainability- the ability to balance technical, socio-economic, ecological and cultural polarities surrounding a project in the long term. Sustainability highlights the ability to meet present-day needs without compromising the needs of the future generation, which justifies project continuity (Yawson et al., 2009). There has been a global shift in researches and implementations of bioenergy projects to reflect this concept. Sustainability studies can take any form: feasibility assessments, optimizations to ascertain viability, case-focused impact studies or life cycle assessments, among other options. Charis et al., (2018) buttress on the need for a holistic approach when ascertaining the viability of bioenergy projects to include socio-economic, techno-economic and ecological factors.

Indeed the factors affecting bioenergy projects are a mix of techno-economic issues on the plant and its operations; socio-economic forces around the market, logistics and attitudes; and ecological boundaries (Charis et al., 2018). The government and civic laws or policies are mostly categorized as socio-economic aspects since they are made to improve the lives of governed subjects. The environmental issues- namely the negative or positive impact that the particular project would have on climate change, surrounding ecosystems and on human health are covered by policy restrictions. They frequently intersect with the socio-economic factors since they emanate from anthropogenic activities.

The bioenergy economy is centred on biomass, which has become the third most utilized fuel for the generation of electricity and other thermal applications (Uddin et al., 2018). The diversity and abundance of sources make it a promising sustainable and renewable energy source, which is also ubiquitous, therefore available for use even in remote locations. Recent technological advancements have given birth to conversion and utilization pathways that facilitate cleaner exploitation of this renewable energy source, with low levels of emissions and environmental impacts. Pyrolysis is one such thermochemical method requiring investment technology that is less technically complex and could be a short to medium-term answer to the energy poverty of developing regions like Southern Africa (Charis et al., 2019b). The pertinent question has been around the high-value application of bio-oil in such developing regions without intensive investment requirements. The application of bio-oil as a direct furnace fuel is already a proven concept; therefore, this research will look into potential stationary engine applications for power production.

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1.1 Objectives, approach and methodology
The objective of this research is to build a conceptual case for a sustainable project for the pyrolysis of pine residues from Zimbabwe and encroacher bushes from Botswana. The base case used is the experimental results obtained by Charis et al., (2020) and the current state around the waste management as described for the case studies in Zimbabwe (Charis et al., 2019b) and Botswana (Charis et al., 2019c). The sustainability matrix then builds on this base case by benchmarking against demonstrated sustainable approaches from literature under the socio-economic, technical and ecological or environmental banners. Technical aspects are discussed first, since they can be an immediate bottleneck to the overall project feasibility, before considering other factors.

2. Considerations for a sustainable model

2.1 Technical aspects
In many cases, the optimization of technical aspects of a chemical process is meant to make the project economically sustainable. Therefore, this section can also be described as 'techno-economic' although the plant economics are not discussed in detail.

2.1.1 Yields and quality of bio-oil
Charis et al., (2020) carried out pyrolysis experiments to give basic information about the feedstocks in question and the properties of pyrolysis product oils and chars, using a simple bench-scale fixed bed pyrolysis system designed to operate in the intermediate pyrolysis regime. This was the only available system at the time, and the tests were conducted to assess the base level potential of these feedstocks. However, the fast pyrolysis mode would be more efficient as it produces more oils (~75 wt%) of better fuel quality, especially in terms of calorific value (Charis, Danha, Muzenda, et al., 2019a). Still, the typical value of bio-oil obtained using *conventional* condensation systems is 17 MJ/kg as given by Bridgwater, (2011), or in the range 15.8-21.9 MJ/kg (Papari & Hawboldt, 2018), which is about half the heating value of eavy fuel oil (HFO) (40 MJ/kg). The use of *fractional* condensation has been proven to increase the quality of oil giving dry/heavy oil fractions of calorific values in the range 22-31 MJ/kg (Papari & Hawboldt, 2018). The best values of the oil mentioned in literature for a dry oil from fast pyrolysis with fractional condensation were obtained by Gooty, (2012) in the fast pyrolysis of birch bark and Kraft lignin using a modified bubbling fluidized bed. They obtained a 35 wt% yield of bio-oil from the first condenser and electrostatic

precipitator (ESP) which had a water content less than 1 wt% and high heating value (HHV) of 31 MJ/kg, just above that of ethanol. In their review, Papari & Hawboldt, (2018) mention three cases of pine sawdust/wood fast pyrolysis with fractional condensation systems where the best fuel value of oil obtained was 24 MJ/kg. This particular case had an exceptionally high yield of dry oil (55 wt %) whose water composition was 2.5 wt%. The first inference from these results is the possibility of getting high yields of the heavy/dry oil fractions in the range of 35-55 wt% using fast pyrolysis set up. Secondly, we observe an inherent limitation of pine in producing bio-oil of competitive calorific value. The maximum HHV of pine dust bio-oil obtained in this research (15.78 MJ/kg) also confirms this. The best consideration, therefore, when using pine bio-oil in fuel oil engines would be blending using higher ratios of the fuel oil.

This research applied the intermediate pyrolysis regime given limited supplies of inert gas (N_2) and the absence of a flow meter. In both cases, however, pyrolysis would have to be conducted in the fast mode using controlled flow rates of the inert gas in the fixed bed reactor or an alternative fast pyrolysis reactor.

2.1.2 Energy supply

Another techno-economic consideration, besides increasing the dry oil fraction yield, would be to use a process design that is self-sufficient in terms of energy. Dutta et al., (2015) discussed fast pyrolysis and upgrading of products using in-situ and ex-situ catalysis. They modelled the processes using Aspen plus in such a way that there is the utilization of the heating values of solids (char and coke) and off-gases and export of ~1% of the lower heating value (LHV) of biomass. Crombie and Masek, (2014) considered several variables to evaluate their effect on the HHV of the pyrolysis fuel gas, intending to use it to supply all the heating requirements of the pyrolysis system. They observed that most proposed values of heating requirements of pyrolysis systems in the literature they reviewed fell within a 6-15% of biomass HHV range. On manipulating several variables, they concluded that most conditions produced gas at a lower limit of 6%, which is not enough for self-sustaining pyrolysis. Bridgwater, (2018) asserted that the char from the pyrolysis system contains ~25% of HHV of biomass and can meet the heating requirements of the pyrolysis (~15% of feed HHV); while the gas contains ~5% of feedstock energy. A properly energy integrated system, therefore, has the potential, not only to be self-sustaining in terms of energy but also to export energy. The drawback with such a self-sustaining model is that it still incurs some emissions, which should be fewer in the case of the char compared to combusting un-carbonized biomass. Figure 1 exemplifies a self-sustaining pyrolysis system where the energy is recovered from the gas and char using a separate combustion chamber.

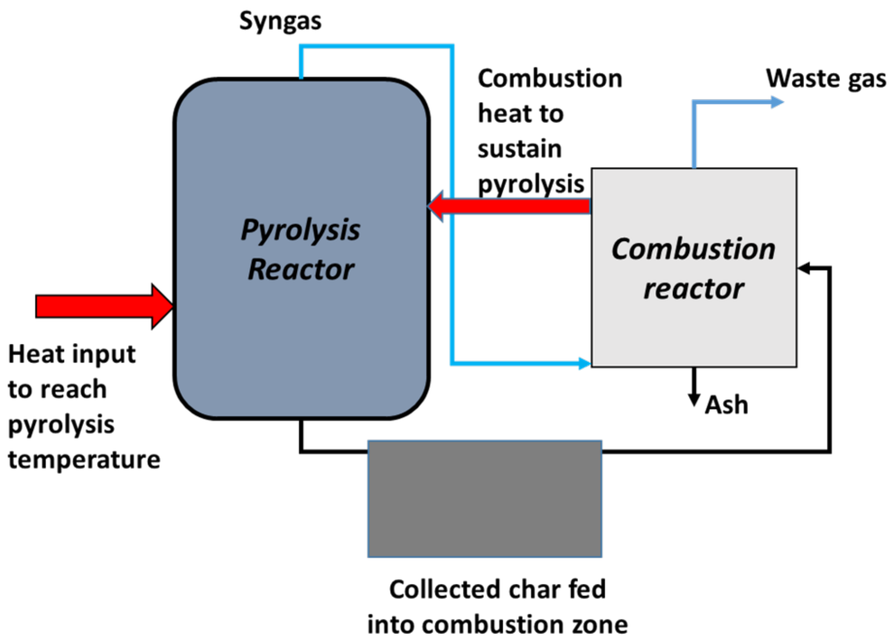

Figure 1. A self-energized pyrolysis system

Figure 2 also shows how the energy from all by-products can be recovered for onward power generation in the concentrated solar pyrolysis system. The gaseous product is used to generate steam for the gasification of the char-gas mixture in a CFB bed reactor. The fuel gas from this reactor is then used to generate power using a gas internal combustion engine, a fraction which can be used to provide energy to the pyrolysis system in conditions of low solar radiation (Bashir et al., 2017).

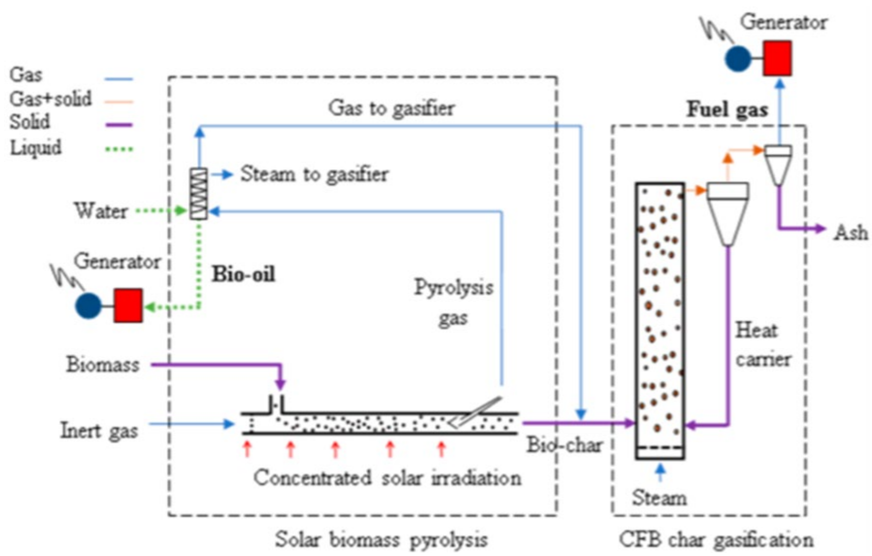

Figure 2. Sustainable pyrolysis using concentrated solar as an energy source (Bashir et al., 2017)

2.1.2 Techno-economic feasibility, including the industrial application of the product

The findings from the lab-scale plant were not adequate to give a conclusive remark on the techno-economic feasibility of the pyrolysis operation. There would be a need for up-scaling and demonstration at a pilot or industrial scale plant that incorporates the optimal operation levels and energy models suggested above. This should also include the final application of the bio-oil, such as on HFO marine or power generation engines.

The technical feasibility of using bio-oil to power marine engines is currently being assessed by organizations such as the U.S Department of Energy (DOE). Their work has mostly focused on evaluating bio-oil's compatibility with the engine or in blends with HFO; effects on efficiency and emissions reduction (Kass, 2019a). The driving hypothesis has been that bio-oils could offer an economically competitive alternative to HFOs while reducing sulphur, particulate and CO_2 emissions (Kass et al., 2018). This is at the backdrop of the technical and ecological complexities surrounding the use of HFO, as detailed in Figure 3. Since such marine and power generation engines are designed to burn low-grade residual fuels with high moisture content (MC) and solids like HFO, they should be compatible with bio-oils.

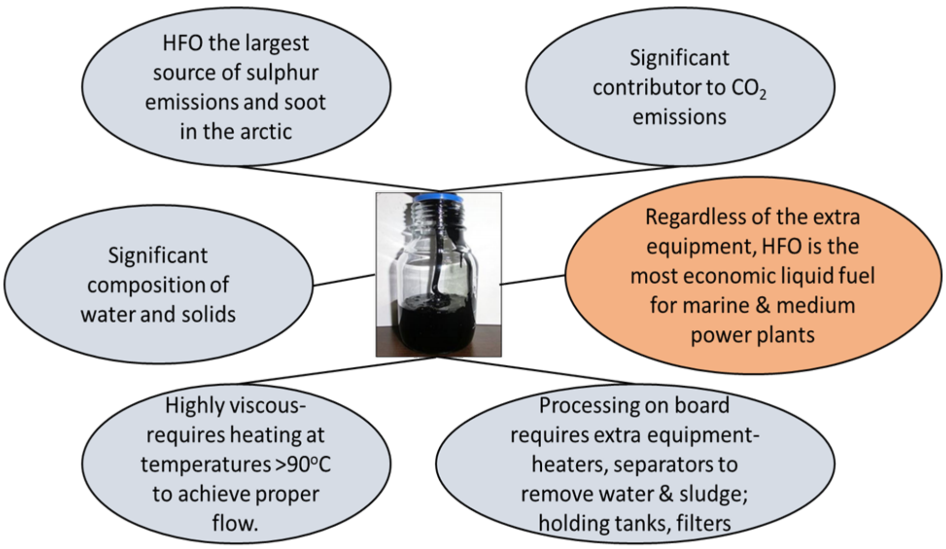

Figure 3. Techno-economic and environmental facts on the use of HFO

Power generation using HFO is a commercialized technology, promoted by companies like MAN Diesel & Turbo (Germany)[1]. However, both marine and power plant HFO projects face a stiffer future from regulatory authorities who are tightening standards around emissions from HFOs, causing higher compliance costs. For instance, the International Maritime Organization has set aggressive fuel quality standards by revising the marine fuel sulphur limit from the current 3.5%, down to 0.5% (Kass et al., 2018). Regulations on CO_x and NO_x are underway. Bio-oils may, therefore, offer an economic alternative for the HFO since upgrading them to be compatible with distillate transport fuels requires high investment costs. Moreover, bio-oil has been characterized and found to be generally miscible with HFO, improving overall efficiency, and reducing energy requirements for heating and pumping HFO in a flowable state (Kass, 2019a). The key findings to date on the compatibility of bio-oil as reported by the U.S DOE Bioenergy Technologies Office (BETO) are summarized in Table 1:

Table 1. Key findings on the compatibility of bio-oil with HFO (Kass, 2019b)

Milestones and findings	Implications
• Bio-oil has been confirmed as miscible with HFO with excellent blend uniformity	• A critical finding implying there is no extra cost when bringing in bio-oil to HFO infrastructure. • Bio-oil is a drop-in fuel in that case.
• A viscosity study was completed for blends of up to 25% pine bio-oil in HFO at 25°C, 50°C, 90°C and 120°C. • Even small blend compositions of 5-10% dramatically reduced the HFO viscosity at low temperatures (25°C and 50°C).	• There are no extra energy costs in handling HFO/bio-oil blends. • Instead, there is reduced energy requirements for heating and pumping HFO in a flowable, low viscosity state.
• At higher temperatures, below 120°C, the bio-oil blends of up to 25% still exhibit	• Bio-oils are compatible with HFO at a wide temperature range (within HFO operating range) and blending ratios of up to 25%.

[1] https://www.powerengineeringint.com/2016/06/14/man-diesel-delivers-heavy-fuel-oil-engines-to-comoros/

similar viscosity behaviour as HFO and rates of shear above 10 s^{-1}.	
Pending tests (as from March 2019) - Rheology studies to determine if levels of polymerization or water separation in bio-oil would be a concern at blending ratios of up to 25%. - Evaluation of blends behaviour at higher blending ratios. - Assess the effect of bio-oil use in HFO existing infrastructure (storage, engines, and separators etc.) and any necessary upgrades.	

Similar case facts and findings for marine HFO engines can be protracted to medium scale power generation systems that use this fuel. HFO is the most economical fuel to use in such plants instead of the costly diesel. Although natural gas is cheaper than HFO, it is not available in many nations. Substituting the HFO with bio-oil through blending would, therefore, increase the economic and ecological sustainability of producing power using such power plants.

A concise techno-economic analysis of the pyrolysis plant is outside the scope of this research. Shemfe et al., (2015) reported that techno-economic analyses on the production of bio-oil have mostly covered the production cost of bio-oil, coming up with a final price of bio-oil in comparison with HFO and other potential marine or power plant generation fuels. The prices of fast pyrolysis (FP) oil obtained in these researches, which depend on the technology, are in the range US$0.60-1.40/gallon for raw FP bio-oil compared to $1.72/gallon for HFO. Other techno-economic studies such as Badger et al., (2011), Dutta et al., (2015) and Carrasco et al., (2017) have gone beyond determining the price of the raw bio-oil to evaluate the economics around upgrading through processes such as hydro-treating. However, this is mostly for transportation fuels, which are not the focus of this study. Within our scope, only the raw and moderately upgraded bio-oils are compared to their competitors in the marine and power generation industry (Table 2). These prices show that bio-oil from FP would still be way cheaper than diesel, HFO and its distillates or its blends.

It must also be noted that prices of bio-oil vary with the price of feedstocks and the distance where they are collected. In our case, the feedstocks are free, and the collection radius is less than 30km for both biomass for a centralized pyrolysis unit. However, the biomass would have to be ground first to increase the transportable bulk density. When there is a need to collect outside this radius, the mobile fast pyrolysis model can be employed so that the energy-dense bio-oil is transported in place of biomass, which has low energy density. These techno-economic aspects are considered, along with socio-economic and ecological issues, in the sustainability matrices modelled for both the acacia and pine dust in Tables 3 and 4.

Table 2. Comparison of fuels that can be used for the marine and power generation industry using 2019 prices (Kass, 2019b, 2019a).

Fuel	**Availability**	**Price ($/gallon)**	**Blending potential**
Bio-diesel (fatty acid methyl esters)	Commercial	\$3–\$3.5	With Marine Gas oil (MGO). Approved at 7%.
Fischer tropsch (FT) diesel	Commercial, but currently not from biomass	\$1.20 when using 100% natural gas \$3.10 using 100% biomass at \$60/dry ton.	Miscible with MGO with excellent combustion properties.
Raw FP bio-oil	Commercial	~\$0.60-\$1.40	Miscible with HFO (<25%) but with poor combustion properties.
Moderately upgraded bio-oil (through fractional Condensation)	Not yet commercial; does not need much equipment modification to commercialize	~\$0.94-\$1.40	Miscible with HFO (<25%) with improved combustion properties.

Upgraded bio-oil	Not yet commercial	~$3.70	Miscible with MGO with a good heating value
Bio-crude from hydrothermal liquefaction	Not yet commercial	~$2–$2.4	Miscible with HFO with good heating value compared with FP bio-oil
MGO- high sulphur distillate fuel	Commercial; ~10 Mt consumed/year	$2.62	
Heavy Fuel Oil (HFO)	Commercial; ~250 Mt consumed/year	$1.72	
Marine Diesel oil (MDO)- a blend of MGO and MGO	Commercial; ~70 Mt consumed/year	~$2.62	

2.2 Socio-economic aspects

Charis et al., (2018) showed the necessity of conducting other surveys besides the technical feasibility studies, to assess if the projects thrive well in a particular socio-economic context. In both the Zimbabwean and Botswana cases, a feasibility assessment was made using the information obtained from a field study and literature review to show the context of the potential bioenergy projects. In the case of Zimbabwe, it was established that sawdust is the most common, unutilized fraction (pending the construction of power plants), which is already marring the aesthetic appeal and posing a fire hazard (Charis, Danha, & Muzenda, 2019b). For Botswana, the encroacher *Acacia Tortilis* was found to be an equally unwelcome waste that has to be de-bushed at least monthly in various areas within a 30km radius in cities, towns and villages. De-bushing is even more necessary in rangelands to restore grazing land and increase livestock productivity (Charis, Danha, & Muzenda, 2019c). For both cases, a GIS integrated study was recommended to evaluate the temporal and spatial dynamics of the wastes and ascertain the supply viability of the feedstocks at the given scale of operation. The GIS could be embedded with an economic and GHG calculator to show the effect of obtaining feedstocks at increased radii from the conversion plant. For radii more than 30km a mobile fast pyrolysis system can move around and conduct pyrolysis at the biomass sites. This presents an alternative of transporting the more energy-dense bio-oil product rather than the low energy density biomass, thereby reducing logistic and storage costs. Charis, Danha, & Muzenda, (2019a) reviewed how similar GIS studies have been carried out for biomass and MSW ecosystems to help in conversion facility location for reduced transport/logistic costs and also to identify the best supply routes. This is especially important when big plants would be installed, to ensure that operations are not constrained due to erratic supplies of biomass. Even in the case of a mobile fast pyrolysis system, a similar study would tell the quantities of the de-bushed encroacher or pine residues that can be found at scattered supply points, enabling the proprietor to plan on the points that could be exploited successively over time and when to come back to them, depending on the temporal accumulation dynamics.

The uptake and valorization of the forestry waste would have a positive socio-economic impact by relieving the environment of the waste burden and GHG emissions, which is a service that would be typically paid through carbon tax credits or exemptions (IRENA, 2016). However, in the absence of such incentives, the pyrolysis project itself should be economically sustainable. The use of residues is considered sustainable when they are used within a certain radius, in such a way that transport costs and emissions do not exceed limits. Moreover, the fact that they do not lead to land-use change (LUC), directly or indirectly, means they offer no threat in that regard to socio-economic dynamics (Pradhan & Mbohwa, 2014).

The biochar by-product has alternative uses besides being burned as a fuel for the process, which could be of socio-economic value to the community. The first option is to briquette the char into a solid, smokeless fuel that can be used in households to substitute raw firewood, which has more threats to health (Safana et al., 2018). The char can also be used as a soil conditioner to increase agricultural productivity and reduce the incidence of foliar and soil-borne diseases. Bio-char has an excellent nutrient and water retention index due to the porous surfaces that facilitate ion exchange and offer shelter to good soil microbes. Given the recalcitrance of the char to decomposition, the char can carry out these functions for a long time and help improve the soil structural integrity, ultimately improving yields significantly, especially in sandy and acidic soils (Rakshit et al., 2012). This is an essential consideration for Botswana, which has a desert climate and sandy soils.

2.3 Ecological considerations

One of the advantages of using forestry residues such as de-bushed acacia and sawmill wastes is that they do not involve LUC, which has associated ecological effects like deforestation, biodiversity loss and increased GHG emissions (Pradhan & Mbohwa, 2014). Notably, for forestry residues, there is little concern for sustainable harvesting rates since the sawmill wastes take up space that could, otherwise, have accommodated some vegetation. Similarly, the encroachers have to be removed to encourage undergrowth, especially in the form of grass (Charis, Danha, Muzenda, et al., 2019b). Therefore, harvesting these wastes does not pose ecological threats, but benefits. However, the residues have to be harvested within a defined threshold radius to maintain carbon neutrality; otherwise, the system becomes ecologically unsustainable. Ultimately, lifecycle assessment (LCA) studies that consider the whole system can be conducted to ascertain the potential ecological impact of such a project.

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A preliminary evaluation of the environmental impacts of process streams can alternatively be made using a method for early process development such as given by (Biwer & Heinzle, 2004) if the mass balance of the process is established. For instance, pyrolysis vapours are known to have polycyclic aromatic hydrocarbons (PAHs) which can have chronic carcinogenic effects to health, therefore a vapour proof system should be operated along with a good extraction system and proper safety clothing. The quantities can be very small, however, exposure times and their effect have to be investigated.

At this point, the general notion that bioenergy processes are generally more environmentally friendly is adopted- due to the use of green feedstocks and a more energy-efficient process with less waste production. Moreover, the use of waste as a resource has many positive effects in reducing solid waste menace and improving the carbon economy.

3. The conceptual models

Given the points discussed, it is possible to come up with a conceptual evaluation of the sustainability of the pyrolysis project in the context of power generation. Table 3 shows the sustainability matrix for the utilization of acacia bio-oil for power generation using HFO engines. Most improvements are made on the technical aspects which impact on the overall economics of the system and its environmental impacts through increased efficiency and reduced waste. Also, from the socio-economic and ecological views, the system already has more credits, therefore it is natural to emphasize on techno-economic improvements.
From both tables, it is clear that the most sustainable method across the pillars is the concentrated solar process where solar thermal energy is transformed into chemical energy in the form of energy-dense products. Detailed process design for this or the self-sustaining method would then have to be done using Chemcad or Aspen. Subsequently, a techno-economic feasibility study can be made to evaluate the capital (direct and indirect) and operating (fixed and variable) costs to come up with a discounted cash flow analysis and the potential selling price of the bio-oil. Given the higher HHV, lower moisture content and compatible viscosity of the acacia bio-oil, blending ratios above the tested 25% should be feasible. They should give higher cost savings when the acacia bio-oil substitutes HFO compared to pine bio-oil, whose blending ratios have to be kept low. This is, of course, when we assume that supply logistics costs for the two biomasses are not very different. Table 4 shows the sustainability matrix for the utilization of pine bio-oil for power generation using HFO engines.
Although the price of bio-oil is lower than the HFO at the most sustainable level, it would be necessary to compare the actual cost of producing electricity for the case of pure HFO to various levels of HFO/bio-fuel blends. Such a comparative model should take into consideration the possible reduction in efficiency when using blends, especially in the case where the bio-oil has a low HHV. It should regard the modifications of engines that may need to be done, or the extra maintenance costs that could be incurred by the use of blends. There are no policy restrictions in both countries for the use of the waste forestry residues, therefore the only binding issues on sustainability were the supply chain issues. The supply chain capacity should also take into consideration sustainable harvest rates, in this case, only encroached land should be harvested from to avoid deforestation. When this is done, the ecological sustainability account is positively credited, implying that we are counting benefits instead of constraints. The same logic implies to the socio-economic impacts, which are mostly benefits due to the clean energy supply, improved aesthetics and environment, along with employment creation in the biomass supply and value chains.

Table 1: Sustainability matrix for the utilization of acacia bio-oil for power generation using HFO engines

Cumulative improvement	**Techno-economic aspects (around conversion and application)**				**Socio-economic aspects**		**Ecological aspects**
	Oil yield & quality	*Production cost as a function of energy input*	*Compatibility with HFO*	*Engine performance*	*Supply chain capacity & dynamics*	*Potential socio-economic impact*	*Ecological benefits*
Current best scenario	Low yield, high HHV	High costs of electrical energy	Proven (Kass, 2019a), up to 25% blends. Higher ratios are possible for bio-oil of high HHV & low MC.	Not possible to test or run with small amounts of bio-oil produced	No need for further consideration.	No need for further consideration.	No need for further consideration.
Sustainable?	**NS**	**NS**	**PS**	**NS**	**-**	**-**	**-**
Fast pyrolysis conditions + up-scaling	High yield, High HHV	High costs of electrical energy	Proven; up to 25% blends. Higher ratios are possible for bio-oil of high HHV & low MC.	The engines are made for such residual fuels with high MC, viscosity & solids	No need for further consideration.	No need for further consideration.	No need for further consideration.
Sustainable?	**S**	**NS**	**PS**	**PS**	-	-	-
Energy integrated OR self-sufficient system	High yield, High HHV	Lower costs of electrical energy Bio-oil price, $0.94 lower than HFO, $1.72	Proven; up to 25% blends. Higher ratios are possible for bio-oil of high HHV & low MC.	Engines made for such residual fuels with high MC, viscosity & solids	Need for a spatial study of feedstock to give detailed supply and logistics strategy.	Mini-grid for remote areas, utilization of char for solid fuel. No policy restrictions	Relieving the environment of waste; few emissions still released in burning char & gas
Sustainable?	**S**	**PS**	**PS**	**PS**	**S**	**S**	**PaS**
Solar parabolic process	High yield, High HHV	Zero electricity costs; high investment costs. Bio-oil price, $0.94 lower than HFO, $1.72	Proven; up to 25% blends. Higher ratios are possible for bio-oil of high HHV & low MC.	Engines made for such residual fuels with high MC, viscosity & solids	Need for a GIS study to give detailed supply & logistics strategy	Mini-grid for remote areas, utilization of char for solid fuel. No policy restrictions	Reduced or eliminated need for char & gas fuel. Little emissions.
Sustainable?	**S**	**S**	**PS**	**PS**	**S**	**S**	**S**

Key
S- sustainable; NS- not sustainable; PS- potentially sustainable; PaS- partially sustainable

Table 2: Sustainability matrix for the utilization of pine bio-oil for power generation using HFO engines

Cumulative improvement	**Techno-economic aspects (around conversion and application)**				**Socio-economic aspects**		**Ecological aspects**
	Oil yield & quality	*Production cost as a function of energy input*	*Compatibility with HFO*	*Engine performance*	*Supply chain capacity & dynamics*	*Potential socio-economic impact*	*Ecological benefits*
Current best scenario	Low yield, high HHV	High costs of electrical energy	Proven (Kass, 2019a), up to 25% blends. Higher ratios could be difficult to sustain.	Not possible to test or run with small amounts of bi-oil produced	No need for further consideration.	No need for further consideration.	No need for further consideration.
Sustainable?	**NS**	**NS**	**PS**	**NS**	**-**	-	-
Fast pyrolysis conditions + Upscaling	High yield, High HHV	High costs of electrical energy	Proven (Kass, 2019a), up to 25% blends. Higher ratios could be difficult to sustain.	The engines are made for such residual fuels with high MC, viscosity & solids	No need for further consideration.	No need for further consideration.	No need for further consideration.
Sustainable?	**S**	**NS**	**PS**	**PS**	**-**	-	-
Energy integrated OR self-sufficient system	High yield, High HHV	Lower costs of electrical energy Bio-oil price, $0.94 lower than HFO, $1.72	Proven (Kass, 2019a), up to 25% blends. Higher ratios could be difficult to sustain.	Engines made for such residual fuels with high MC, viscosity & solids	Need for a spatial study of feedstock to give detailed supply and logistics strategy.	Mini-grid for remote areas, utilization of char for solid fuel. No policy restrictions	Relieving the environment of waste; few emissions still released in burning char & gas
Sustainable?	**S**	**PS**	**PS**	**PS**	**S**	**S**	**PaS**
Solar parabolic process	High yield, High HHV	Zero electricity costs; high investment costs. Bio-oil price, $0.94 lower than HFO, $1.72	Proven (Kass, 2019a), up to 25% blends. Higher ratios could be difficult to sustain.	Engines made for such residual fuels with high MC, viscosity & solids	Need for a GIS study to give detailed supply & logistics strategy	Mini-grid for remote areas, utilization of char for solid fuel. No policy restrictions	Reduced or eliminated need for char & gas fuel. Little or no emissions
Sustainable?	**S**	**S**	**PS**	**PS**	**S**	**S**	**S**

4. Conclusion

Literature gave satisfactory models that were useful in improving the techno-economic outlook of the pyrolysis systems. Both the self-energized and concentrated solar pyrolysis systems were found to be largely sustainable due to their ability to efficiently use waste-to-energy and renewable energy forms in the process. This greatly reduces reliance on fossil-fuel-based electricity and the associated socio-economic and environmental impacts. There are no policy restrictions in both countries for the use of the waste forestry residues, therefore the only binding issues on sustainability were the supply chain issues. A geographical information systems (GIS) spatial study is recommended to ensure a good supply chain strategy. Generally speaking, the socio-economic and ecological sustainability for such bio-energy projects that utilize waste is positive, which is the case for the pyrolysis system due to the clean energy supply, improved aesthetics and environment, along with employment creation in the biomass supply and value chains. However, there would be a need for a more detailed environmental impact assessment, which can be done using various methods including LCA or early process development evaluations. The next step would be to demonstrate the conceptual model in a pilot or industrial system involving all the system components.

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