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Modelling to analyse the process and sustainability performance of forestry-based bioenergy systems

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Abstract

This study develops a novel mathematical modelling framework for biomass combined heat and power systems (CHP) linking physicochemical/thermodynamic characteristics and life cycle sustainability. A total of twenty-nine indicators for the process (4), economic (5), environmental (8) and social global (5) and local (7) aspects have been analysed for sustainability. These are biomass throughput, electricity and steam generations and CHP efficiency; internal rate of return, capital, operating and feedstock costs and cost of production; global warming, fossil, land and water use, acidification, urban smog, eutrophication and ecotoxicity potentials; labour rights & decent work, health & safety, human rights, governance and community infrastructure; total forest land, direct/indirect jobs, gender equality and energy-water-sanitation access for communities, from biomass characteristics (carbon and hydrogen contents), energy demands and economic parameters. The model is disseminated as an open-web-resource <https://tesarrec.web.app/sustainability/chp>. In a case study approach, from 12.47 kt/year forestry residue, 1 MWe is generated with an associated low-pressure steam generation of 50 kt/year, at a cost of production of \$0.023/kWh, making “affordable and clean energy” (the UN Sustainable Development Goals, SDG7) for marginalised/poor communities. Bioenergy can curb >90% greenhouse gas emissions and primary energy, 6 kt CO₂ eq and 74

TJ annually, 87-53% water consumption, acidification and eutrophication, and 29-18% urban smog and ecotoxicity, compared to fossil-based counterpart. All five social themes in the Central American cluster countries can be improved by bioenergy. In addition to SDG7, SDG6: "clean water and sanitation for all" can be delivered by forestry-based bioenergy system.

Keywords: waste-to-energy, life cycle assessment (LCA), techno-economic analysis, social life cycle assessment (SLCA), community social deprivation analysis, water-energy nexus.

Introduction

Energy poverty and environmental impacts are global problems affecting developing countries disproportionately. The energy-environmental nexus issues are complex, affecting the ecosystem, human health and economic performance of countries and corporations (Halog and Manik 2011). Bioenergy can provide a sustainable solution to these nexus challenges (Martinez-Hernandez and Samsatli 2017). The need for a quantitative modelling framework to analyse the sustainability of bioenergy systems to tackle nexus challenges is indisputable and has been tackled by two main approaches, optimisation-based (Ong et al. 2021) and simulation-based (Sadhukhan et al. 2021). The former approach involves the minimisation of objective functions such as economic, environmental and social costs, etc. under the various supply and demand constraints. By applying mathematical programming, independent design and operating variables are optimised for the best tradeoffs and outcomes within the constraints (Sadhukhan et al. 2014). A simulation-based approach allows integrated process conceptualisation based on interactive mass, energy and momentum transfer models of underlying phenomena at unit or flowsheet scale. Both the approaches analyse scenarios and test the sensitivity of independent variables on output results, which can be techno-economic, environmental or social performance (Sadhukhan et al., 2014).

Bioenergy is primarily provided by a combined heat and power system (CHP) utilising bio-based residues (Wan et al. 2016a). Forestry-based wood residues are receiving greater attention

in the literature (Fitzpatrick 2016). A CHP is flexible in nature in terms of the provision of energy vectors, which, however, usually take the form of electricity and heat, the ratio between energy vectors and energy efficiency depending on the demands of the surrounding system. CHP comprises a biomass boiler to turn boiler feed water into high pressure superheated steam generation that is expanded in steam turbines to generate electricity. Steam can be extracted at any pressure depending on the system demand. The CHP system can be best analysed by an Aspen Plus simulation model (Wan et al. 2016b) applied in Mexico's bioenergy context (Martinez-Hernandez et al. 2017). However, for accessibility, a generic model must be developed and transferred into a usable platform, in this case, which is an open web resource (Sen 2020). The modelling platform developed this way allows testing of input variables, such as energy currency of biomass fuel to CHP, on the sensitivity of output results. Output results encompass underlying technical, economic, environmental and social impacts that are deemed important for sustainability analysis of CHP. This study thus focuses on a type IV system, "sustainable technology", and group 3 sustainability analysis, "sustainability indicators", following the systematic categorisations of systems and sustainability metrics (Sikdar 2003). Here, we present a targeted literature review concerning the modelling of the CHP and sustainability analysis using data from the literature and forest-based cooperative.

Sahu and Prabu (2021) have simulated a CHP using Aspen Plus (Sahu and Prabu 2021). Their Aspen Plus simulation model comprises a combustor model using RGibbs and high, medium and low pressure steam turbine models. The thermodynamic property package is Peng-Robinson. The TRNSYS tool (Klein et al. 2017) has been applied to simulate biomass boiler and steam turbines (Żołądek et al. 2021). Aspen Plus simulation and optimisation models for biomass-based heat and power generations are noted through turbine cycles (Rezaei et al. 2021). In the context of bioethanol production process simulation using Aspen Plus, a utility boiler has been shown (Petersen et al. 2021). The use of computational fluid dynamics

packages using detailed geometry and meshes is also noted in the literature (Puig-Gamero et al. 2021), which may not be relevant to the present study due to the aim of flowsheet or whole system simulation. There is a handful of research literature on carbon capture and storage (CCS) associated with CHP. Notably, the investment cost of CCS can be up to \$1150/kW, which is 20% of the total capital investment of an integrated gasification combined cycle system (IGCC) comprising gasifier, sour gas removal, water gas shift reactors, CCS, gas turbine, steam turbine, heat recovery steam generator or boiler and steam network system and air separation unit (Ng et al. 2010). Heat integration is key to the reduction of the cost of electricity generation, which can be \$0.066/kWh from an integrated IGCC with CCS (Ng et al. 2010). Complete recovery of useful heat is possible by turning boiler feed water into high pressure steam generation through sequential heat recovery from the heat recovery steam generator of the exhaust gas from the gas turbine, low and high temperature water gas shift reactors and cooler of the gas from the gasifier (Ng et al. 2010). However, the system is too complex to operate on a community scale. This makes the design of bioenergy systems challenging, which needs to be simple for operation by the communities as well as efficient to guarantee a minimum price for energy affordability to poor marginalised communities that may even be lacking foundational energy-water-sanitation services (Sadhukhan et al. 2019a). Carbon dioxide capture and reuse in the production of high value products are other strands of research literature on carbon dioxide capture that have also been published (Ng et al. 2013). The other focus of recent CHP studies entails biomass integrated gasification combined cycle and biomass integrated gasification fuel cell systems, rigorous simulation and efficiency analyses of which have been published earlier (Sadhukhan et al. 2010). As can be seen, even though we have considered highly integrated advanced efficient bioenergy systems, these are not compatible systems for serving poor marginalised communities. Moreover, the literature notes that much of the study focus is on European regions (Wang et al. 2018). This leaves an

important gap in the literature that is to apprehend a system for “affordable and clean energy” and “clean water and sanitation” (the United Nations Sustainable Development Goals, SDG6-7) (UN SDG 2015) for poor marginalised communities in developing countries.

Sustainability assessment of bioenergy has been the main emphasis of the scientific research communities. Sustainability assessment needs consideration of underlying criteria, technical, economic, environmental and social (Sikder 2003). While participatory approaches are more common (Emmanuel-Yusuf et al. 2017), analytical approaches modelling intrinsic interactions are emerging for life cycle sustainability assessment of systems (LCSA) (Sadhukhan et al. 2021). There are also debates on the selection of the sustainability criteria and whether to present them as individual criteria or as a single score by assigning weights from stakeholders to the multi-criteria. The literature is very rich in multi-criteria decision analysis, for example, Wang et al. (2018). González-Cruz et al. (2021) have provided a comprehensive overview of the multi-criteria methods (González-Cruz et al. 2021). The methods are useful for decision making from a set of choices (Niekamp et al. 2015). Another strand of research encourages the presentation of all plausible underlying sustainability criteria to stakeholders so that they are best informed of possible consequences and tradeoffs. The sustainability analysis framework adopts life cycle thinking. LCSA analyses comprise (environmental) life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA) following the ISO14040-44 and ISO26000 standards. LCA of bioenergy considers global warming potential, fossil energy use and land use as the main criteria. Forty-four literature works have been identified concerning these important environmental consequences of bioenergy (Roos and Ahlgren 2018). Primary analysis on sustainable biomass and bioenergy availability using a geographic information system, reveals an annual useful energy generation potential of 670.3 and 30.72 PJ from available agricultural and forestry land in Mexico (Honorato-Salazar and Sadhukhan 2020). Highly integrated bioenergy systems comprising green diesel synthesis by

hydroprocessing and biodiesel synthesis by transesterification have been designed to offset these environmental impacts in Mexico (Martinez-Hernandez et al. 2014). Other deemed important atmospheric and aquatic impacts include acidification, urban smog, eutrophication and ecotoxicity potentials, etc. (Sadhukhan et al. 2014). The economic indicators are profit, operational performance and capital, processing, utility and waste costs (de Faria et al. 2021). The cost parts can be aligned with the process engineering cost calculations for techno-economic analysis, direct, indirect and working capital, and fixed (including labour), variable (including processing, utility and waste costs) and miscellaneous operating costs, which have long-standing standard methods of calculation (Sadhukhan and Martinez-Hernandez 2017). Furthermore, the cost of production applying the net present value analysis and all the cost components is a useful indicator that captures all intrinsic process and macro-scale systemic variables (Sadhukhan et al. 2004). Compared to LCA and LCC, SLCA is an emerging but important area of research that must be distinctly applied rather than amalgamated to LCA to sustainability analysis study (Clift 2014). The SLCA following the ISO26000 standard suggests five social themes and twenty-two sub-themes for the representation of the social performance of a system (Shemfe et al. 2018). These social themes are aligned with the framework applied for recent literature classification (de Faria et al. 2021). The social hotspot database (SHDB) by New Earth is the most popular global database assigning scores to the various social themes in individual product sectors in individual countries (Norris et al. 2014). LCA, LCC and SLCA methods have a sound mathematical grounding for quantitative analyses of systems (Sadhukhan et al. 2021). Countless publications exist in LCA, LCC, SLCA and LCSA approaches (Visentin et al. 2020). However, studies only scarcely attempt to link fundamental process modelling through to sustainability assessment, with some exceptions (e.g. Sadhukhan et al. 2019b). This study thus aims to link a fundamental novel process model and sustainability analysis of bioenergy as far as possible using analytical tools and available

data from the forest-based cooperative and literature. In addition, local community level indicators are analysed for the UN SDG (UN SDG 2015) benefits of bioenergy.

The paper is structured as follows. The materials and methods section discusses the mathematical models and modelling bases for technical, economic, LCA, SLCA and local community-level socio-economic performance analyses. A case study approach is then taken to demonstrate the benefits of a forest-based cooperative in the poorest most deprived parts of Mexico. This case study provides a useful context for waste-to-energy approaches and for exploring how the modernisation of energy supply in forest-based supply chains through CHP can support the UN SDGs as well as policy programmes.

Methodology

The methodological components and structure followed in this study are depicted in Figure 1. The first step is to characterise the case study in terms of location, communities and type of organisations involved, poverty or social deprivation indicators available, biomass resource and bioenergy technology, bioenergy products and end uses. Scenarios are built and modelled to evaluate their techno-economic and environmental outcomes from fundamental physicochemical characterisations of CHP, biomass resources and supply logistics. SLCA indicators are sourced from the proprietary SHDB (Norris et al. 2014). Some important socio-economic indicators apply to local conditions obtained from the organisation managing the forest. Other indicators apply at the country level making them more relevant for comparisons between the countries in The Central American Electrical Interconnection System (SIEPAC) (Ecchevarria et al. 2017).

The following scenarios are evaluated.

1. Present scenario with limited generation (LG). This corresponds to an existing bioenergy generation capacity. In this case, the bioenergy generated is only used to replace grid electricity and fossil fuel within the sawmill. The surrounding communities have access to

electricity from the grid but there is a small percentage of households without electricity access.

2. Generation Expansion (GE) scenario. This corresponds to leveraging the use of biomass readily available and the existing generation capacity at the sawmill facility. The surplus electricity is provided to the surrounding communities to improve electricity access.

A bottom-up approach, modelling the bioenergy processing and conversion is adopted, which allows the inclusion of different technology parameters and thus an exploration of resulting technical, economic and environmental impacts. Next, the scenarios are evaluated using the indicators that are deemed important in selecting bioenergy systems for sustainability while embedding a life cycle thinking philosophy. This allows for the identification of social hotspots with potential social issues or trade-offs between benefits and negative impacts. It is worth noting that other contextual factors such as regulations and policy constraints are embedded in the construction of scenarios; for example, the self-generation is capped to a certain capacity, and there are also constraints to exported electricity to the grid.

Figure 1. The structure used for sustainability evaluation of bioenergy.

Bioenergy process modelling

The simulation of bioenergy systems has been carried out using the TESARREC™ CHP module (Sen 2020) and validated using the IMP's (Instituto Mexicano del Petróleo) in-house software tool IMPBio2Energy® built upon the plant data (Martinez-Hernandez et al. 2021). This robust technical performance model of the system illustrated in Figure 2 comprises Equations 1-4 to estimate biomass throughput, steam generation by the system, and electricity and CHP generation efficiencies from the electricity rating of the CHP.

$$Biomass\ throughput\ (wet)\ \frac{kg}{hour} = \frac{(1560 \times Electricity\ generation\ \frac{GWh}{year} - 0.23)}{(C \times 0.375 + H \times 1.154)} \times \frac{1}{\epsilon_{Boiler}} \times \frac{1}{\epsilon_{ST1}} \times \frac{1}{\epsilon_{ST2}} \times \frac{100}{(C+H)} \times \frac{100}{(100-M)} \quad \text{Equation 1}$$

Carbon and hydrogen contents (dry basis) in wt%, C and H , constitute the fundamental basis of the equations. C and H signify the energy currency of biomass. They have a calorific value of 37.5 and 115.4 MJ/kg, respectively. The term $(C \times 0.375 + H \times 1.154)$ signifies energy content within carbon and hydrogen in biomass, which is higher than the energy content (or calorific value) of the biomass due to the presence of inert in the biomass. This electricity generation from the back pressure steam turbine (dependent variable) has been plotted against the term $(C \times 0.375 + H \times 1.154)$ (independent variable) using the results of simulation in Aspen Plus 8.8 to obtain the first term on the right side in Equation 1. Adjustments are needed due to the efficiencies, such as, of boiler and (isentropic and mechanical) of back pressure steam turbine, ϵ_{Boiler} , ϵ_{ST1} , and ϵ_{ST2} , respectively, and to consider the presence of moisture in the biomass, M .

Equation 2 estimates the production rate of low pressure superheated steam at and above 1 atmospheric pressure.

$$Steam\ generation\ \frac{kg}{hour} =$$

$$\frac{(1560 \times \text{Electricity generation} \frac{GWh}{year} - 0.23)}{(C \times 0.375 + H \times 1.154)} \times \frac{1}{\epsilon_{Boiler}} \times \frac{1}{\epsilon_{ST1}} \times \frac{1}{\epsilon_{ST2}} \times (0.2807 \times (C \times 0.375 + H \times 1.154) + 0.0463))$$

Equation 2

The effect of energy content within carbon and hydrogen in biomass is captured in the final term on the right-hand side of Equation 2. The final term on the right-hand side in Equation 2 is based on the amount of steam generation concerning energy content within carbon and hydrogen in biomass using the results of simulation derived from Aspen Plus 8.8.

Equations 3-4 calculate the electricity, and heat and electricity generation efficiencies based on target output electricity generation, low pressure superheated steam generation and low heating value (*LHV*) of biomass.

Electricity generation efficiency

$$= \frac{411 \times \text{Electricity generation} \frac{GWh}{year}}{\text{Biomass throughput (wet)} \frac{kg}{hour} \times \text{Biomass (wet)} LHV \frac{MJ}{kg}}$$

Equation 3

CHP generation efficiency

$$= \frac{(411 \times \text{Electricity generation} \frac{GWh}{year} + 2.77 \times \text{Steam generation} \frac{kg}{hour})}{\text{Biomass throughput (wet)} \frac{kg}{hour} \times \text{Biomass (wet)} LHV \frac{MJ}{kg}}$$

Equation 4

411 is the factor employed to convert *Electricity generation* $\frac{GWh}{year}$ into MJ/hour: $\frac{1000000 \times 3.6}{24 \times 365}$.

This conversion factor is needed as usually, the annual electricity demand is available in GWh. The low pressure superheated steam at and above 1 atmospheric pressure and at 105°C has an enthalpy of 2.77 MJ/kg.

Figure 2. CHP configuration.

Bioenergy economic analysis

Capital cost, operating cost, cost of production of CHP and the discounted cash flow analysis over the life cycle of the CHP are determined using Equations 5-12 and parameters (Sadhukhan et al. 2014). The capital cost is determined from Equation 5 by first estimating the delivered cost of each component in the CHP, i.e. boiler and steam turbine and steam system. An *Installation factor* is then applied to estimate the total capital cost.

$$Capital\ cost = \left(\sum_i DC_i \times \left(\frac{present\ amount_i}{base\ production\ rate_i} \right)^{scale\ factor_i} \right) \times Installation\ factor$$

Equation 5

DC_i is the delivered cost of each component i in the CHP, $i \in boiler, steam\ turbine\ and\ steam\ system$, for their reference or *base production rate* _{i} . Their *base production rate* _{i} and DC_i are as follows.

For the boiler, the base size is 0.62 kg/s of biomass and DC_i for its base size is \$0.4323 million (Wan et al. 2016a-b). For the steam turbine and steam system, the base size is 10.3 MW electricity output and DC_i for its base size is \$5.1 million (Sadhukhan et al. 2014). The term

$scale\ factor_i = 0.7$ captures the effect of the economy of scale such that the cost-effectiveness increases with the increasing size of the unit.

The Installation factor or the Lang factor is applied to take account of the capital costs due to i) installation, instrumentation & control, piping, electrical systems, buildings (including services), yard improvements and service facilities (other components of direct capital cost, in addition to the delivered cost of equipment); ii) engineering & supervision, construction expenses, legal expenses, contractors' fees and contingency (indirect capital cost); and iii) working capital, to make up for the total *Capital cost* (Sadhukhan et al. 2014).

Thereafter, the net present value (NPV_y) calculation in a given year y of the CHP operation is applied (Equation 6) to take into account the depreciation of the economic margin with time.

$$NPV_y = NPV_{y-1} + \frac{(Product\ value - Opex - Capex)}{(1+IRR)^y} \quad \text{Equation 6}$$

$$NPV_{y=0} = Capital\ cost$$

IRR is the internal rate of return expressed as a fraction. $Capex$ is an *Annual Capital Charge* (as a fraction) applied to the *Capital cost* (Equation 7). $Opex$ is the operating cost (sum of the *fixed operating cost dependent on indirect annual capital cost* and the *labour dependent fixed operating cost*, applied with a multiplier (Equation 8). The *fixed operating cost dependent on indirect annual capital cost* is dependent on the Capital cost (Equation 9). The *labour dependent fixed operating cost* is a function of *Biomass throughput (wet)* $\frac{kg}{hour}$ (Equation 10).

$$Capex = Annual\ Capital\ Charge \times Capital\ cost \quad \text{Equation 7}$$

$$Opex = a \times (fixed\ operating\ cost\ dependent\ on\ indirect\ annual\ capital\ cost + labour\ dependent\ fixed\ operating\ cost) \quad \text{Equation 8}$$

$$fixed\ operating\ cost\ dependent\ on\ indirect\ annual\ capital\ cost =$$

$$\frac{Capital\ cost}{Installation\ factor} \times Annual\ Capital\ Charge \times b \quad \text{Equation 9}$$

$$\text{labour dependent fixed operating cost} = c \times \text{Biomass throughput (wet)} \frac{\text{kg}}{\text{hour}}$$

Equation 10

a, b and c are multipliers of the respective cost components to account for a larger set of cost components (Sadhukhan et al. 2014). The value of a in Equation 8 is 1.3 to account for the other costs such as research and development costs, sales expenses and general overheads.

The indirect capital cost is 1.26 times the delivered cost of equipment for solid-fluid processing systems. Furthermore, the fixed operating cost dependent on the indirect capital cost is 0.15 times the indirect capital cost. The *fixed operating cost dependent on indirect annual capital cost* includes the following cost items: maintenance, capital charges, insurance, local taxes and royalties. Thus, the value of b in Equation 9 is $1.26 \times 0.15 = 0.19$.

The *labour dependent fixed operating cost* is 1.9 times the personnel cost. The fixed operating cost dependent on the personnel cost includes the following cost items: labour, laboratory, supervision and plant overheads. In TESARREC™, the personnel cost is \$52033 per t/h throughput. Thus, the value of c in Equation 10 is $1.9 \times 52033/1000000 = 0.1$.

Product value in Equation 6 is the multiplication between the price and rate of production of individual products (electricity and low pressure superheated steam) (Equation 11).

$$\text{Product value} = \text{Electricity price} \times \text{Electricity generation} + \text{Steam price} \times \text{Steam generation}$$

Equation 11

Appropriate conversion factors are applied to have the cost analysis in a consistent unit.

Equation 12 shows the cost of production of CHP.

Cost of CHP production

$$= \frac{(\text{Capex} + \text{Opex}) + \text{Biomass cost}}{\text{Electricity generation} \frac{\text{GWh}}{\text{year}} \times \frac{\text{CHP generation efficiency}}{\text{Electricity generation efficiency}}}$$

Equation 12

LCA of bioenergy

Biomass input and energy output are the key linkages between the process model and the LCA model. Biomass input and energy output evaluations obtained from the process model are used to analyse the LCA of bioenergy. By the ISO14040-44 International Standards for LCA, the selection of impact categories for the life cycle impact assessment (LCIA) should be appropriate to the system's environmental performance. Supply chain activities included within the system boundary for environmental impact characterisations are biomass chipping, diesel consumption in machinery, biomass harvesting, biomass forwarding, infrastructure including CHP and exhaust emissions from the CHP. Eight deemed impact categories are selected for the environmental impact characterisations of the present study as shown in Table 1. The LCIA methodologies to characterise inventories into impacts are shown alongside. The LCIA methodologies used for the characterisation factors are the IPCC global warming potential over 100 years, CML for the fossil resource depletion potential, ILCD for the photochemical ozone formation potential, TRACI for the acidification, eutrophication and ecotoxicity potentials, and ReCiPe for water consumption. Following the ISO14040-44, mix and match between LCIA methods is a good indication of a fundamental understanding of environmental drivers for a system. These life cycle impact categories are fundamental to LCA studies, hence, for their detailed characterisation methods, a fundamental text is recommended (Sadhukhan et al. 2014). Furthermore, the land impact for biomass residue availability for CHP is noted through primary data collection from the forest-based cooperative. These impact categories represent a wide coverage of impacts on the atmosphere, water and ecosystem. While the environmental impact categories generally considered to be of the highest interest for energy systems (including bioenergy) are global warming potential and fossil resource consumption (aka. abiotic depletion potential (fossil fuels)), a wider range of impact categories is recommended to present a more complete picture of the system, its potential environmental

impacts and potential trade-offs between impact categories (Sadhukhan et al. 2014). All non-primary, data used for modelling the forestry residue CHP and the displaced fuel oil CHP including respective supply chain logistics are sourced from Ecoinvent 3.0 life cycle inventory (LCI) database. The selected Ecoinvent 3.0 LCI databases are {MX: Mexico}:

Forestry residue CHP: Electricity, high voltage {MX}| heat and power co-generation, wood chips (allocation, cut-off by classification - system)

Fuel oil CHP: Electricity, high voltage {MX}| electricity production, oil (allocation, cut-off by classification - system)

Table 1. Environmental impact categories selected for the LCIA.

Impact category	LCIA methodology	Unit
Global warming potential (100 yrs)	IPCC	kg CO ₂ eq
Abiotic depletion potential (fossil fuels)	CML	MJ
Photochemical ozone formation potential	ILCD	kg NMVOC eq
Acidification potential	TRACI	kg SO ₂ eq
Water consumption	ReCiPe	m ³
Eutrophication potential	TRACI	kg N eq
Ecotoxicity potential	TRACI	CTUe
Land use or sustainable forestry residue availability per land	Primary data from the cooperative	kg/m ²

(NMVOC = non-methane volatile organic compound; CTU = cumulative toxicity unit)

SLCA of bioenergy

The SLCA assessment is based on the social impact themes recognised in the SHDB shown in Table 2. Several attempts have been made to develop indicator sets for SLCA, including those of the UNEP (United Nations Environmental Programme) and the SETAC (Society of Environmental Toxicology and Chemistry). They have proposed five social themes and twenty-two sub-themes to assign scores and estimate the overall social score using a weighted summation methodology. The SLCA themes are 1) labour rights and decent work, 2) health and safety, 3) human rights, 4) governance and 5) community infrastructure. These themes and their sub-themes are applicable at a local level. The life cycle thinking philosophy embedded in the SLCA methodology helps to interconnect local and global level social themes and sub-

themes and focus on targeted indicators for socio-economic sustainability. The common consideration of life cycle stages in the analyses makes SLCA more comprehensive for the sustainability evaluation of bioenergy (Sadhukhan et al. 2014).

Table 2. Social impact themes and sub-themes.

Social Impact Sub-Themes	Social Impact Themes				
	Labour rights	Health and safety	Human rights	Governance	Community infrastructure
	1. Child labour	1. Injuries	1. Indigenous rights	1. Legal systems	1. Medical facilities
	2. Forced labour	2. Toxics	2. Conflicts	2. Corruption	2. Drinking water
	3. Excessive working time	3. Hazards	3. Gender equality		3. Sanitation
	4. Wage assessment		4. Human health		4. Children education
	5. Poverty				
	6. Migrant labour				
	7. Freedom of association				
	8. Unemployment				
	9. Labour laws				

The supply chain interactions are considered in the computation of the total index of a theme for a given sector in a given country. In constructing the SHDB, we have combined the UN Comtrade Database on import-export of electricity between countries (Comtrade 2019) and the social theme scores for the energy sector in the countries using the SHDB (Norris et al. 2014). The unit used to express the social impact themes is the medium-risk hour (mrh) in terms of labour-hours for a given production rate.

In this case, the countries in The Central America Electrical Interconnection System (Ecchevarria et al. 2017) can be compared to show which flow direction of electricity between

two countries would benefit in terms of social theme score. The individual social theme scores are factored by the netted fractional imports considering the supply chain and these factored individual social theme scores are added to give a total social theme score for a given sector in a given country. Equation 13 shows the individual total social theme score calculation.

$$Index_{T,p} = \sum_c R_{T,p,c} \times Frac_{p,c} \quad \text{where: } \sum_c Frac_{p,c} = 1 \quad \text{Equation 13}$$

$Index_{T,p}$ is the individual total social theme score for a given product p in each country. $R_{T,p,c}$ is the risk of a theme in the country of origin as well the countries (c) exporting to the given country (the countries of origin approach) or in the entire supply chain influencing the exports to the given country (the life cycle approach), the product p . $Frac_{p,c}$ is the fraction of the product p produced in the country or imported from other countries considering their corresponding supply chains.

Results and discussion

Data from forest-based community

The methodology is applied to a case study on forestry-based energy services for poor marginal communities (Luján-Álvarez et al. 2015). Table 3 shows primary data on the characteristics of the forest-based cooperative run and managed by communities and communal forest landowners organised in what is known in Mexico as ‘Ejidos’. The primary data in Table 3 that also include biomass availability and land use are obtained from the forest-based cooperative. The communities provide forestry waste to a sawmill in Durango State, considered one of the main stakeholders. The sawmill then uses residues to generate bioenergy for self-sufficiency. The sawmill which generates the biomass is in the community of Santiago Papasquiari, Durango and belongs to the Sezaric cooperative registered as a Rural Association of Collective Interest. The forest trees are of the genera *Pinus* spp. The major products are plywood and pinewood boards. The company is certified by the Forest Stewardship Council. The area of influence of the cooperative is depicted in Figure 3 and spans 8 municipalities in Northeast

Durango State (Santiago Papasquiaro, Otáez, Canelas, Topia, Tepehuanes and some parts of Guanaceví, Tamazula and San Dimas). The map also shows the degrees of social deprivation of these municipalities according to the value of indicators for 2015 reported by the National Council for the Evaluation of Social Development Policy (CONEVAL 2010). Figure 3 shows that at least five of the municipalities have a medium degree of social deprivation while one municipality (Tamazula) classified as of high social deprivation and two as having low social deprivation (Santiago Papasquiaro and Tepehuanes). Social deprivation indicators reported by CONEVAL include poor access to a potable water and sewage network and poor access to electricity, among other indicators. These three indicators are used in the results section to analyse the potential positive impact from the CHP utilising wood residues on enabling access to electricity and water services (SDG6-7).

Figure 3. Degree of social deprivation in the areas of influence of the case study for bioenergy generation in a sawmill in Durango state, Mexico.

Table 3. Characteristics of the community-managed forest and the cooperative-run mill.

Characteristic	Value
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Number of Ejidos and partner communities	40
Number of landowners	4620
Total managed forests area	445676 ha
Wood production area	163452 ha
Annual lumber production	261000 m ³
Number of direct permanent jobs	550
Indirect jobs (estimated)	2000
Female workforce	40%

The elemental composition of the biomass and higher heating value used as inputs to Equations 1-12 for the evaluations of technical, economic and environmental performance indicators are shown in Table 4, which are average values for pinewood residues (Martinez-Hernandez et al 2021). The biomass is combusted in a boiler to extract the heat of combustion into a high pressure superheated steam generation at 50 atmospheres. The high pressure superheated steam is then expanded in a back pressure steam turbine to generate electricity. After expansion, low pressure steam at one atmosphere leaves the turbine to meet the steam demand by the sawmill process. A reference biomass price of 25 \$/ton and grid electricity price of 0.0858 \$/kWh is considered. It also considers that the investment is depreciated, over a plant lifetime of 15 years at an internal rate of return of 10%. The installation factor applied is 1.5. The annual operating time is 6395 h/year. The boiler dimensionless energy efficiency is 0.85. The isentropic and mechanical efficiencies of back pressure steam turbine are 0.85 and 0.9. The low pressure steam (between 100 - 115°C) demand by the site is 7831 kg/h for the plywood pre-drying and other plant processes. The electricity demand by the site is 3.1975 GWh/y.

Table 4. Average wet analysis values for the typical pine residues.

Ultimate analysis	Value	Unit
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Moisture	15.0	%
Ash	1.4	%
C	44.2	%
H	5.1	%
O	34.0	%
N	0.3	%
HHV (dry basis)	20.28	MJ/kg

The two scenarios, as discussed earlier, represent the present bioenergy generation capacity processing readily usable biomass (residues and wastes), and full capacity operation of the CHP using available biomass (generation expansion scenario). In the present scenario, not all local households are supported by the electricity and heat generated by the mill. In the generation expansion scenario, on-site as well as community demands are met.

Bioenergy process, economic, LCA and SLCA modelling results

Table 5 shows the techno-economic performance comparisons between the two scenarios. Using Equations 1, biomass required is estimated for the two scenarios, 3.5 and 6.5 GWh/year electricity demands, as shown in Table 5. 30% and 56% of the steam demands (7831 kg/h) are met by the CHP configuration in Figure 2 in the present and generation expansion scenario, respectively (using Equation 2). The balance of the steam can be met by an additional boiler capacity (at energy efficiency of 0.85). Considering biomass for the CHP configuration (Equation 1) and biomass for the boiler to meet the entire heat demand of the site, the total biomass throughput is ~10 and 12.5 kt/year, respectively (Table 5). From Table 5, it can be observed that the bioenergy system can export electricity to the communities and that the cost of production can be lower than the cost of consuming electricity via the grid at the domestic tariff in the generation expansion scenario. Thus, providing cheaper electricity to enhance

livelihoods in local communities can be affordable for the sawmill. This shows the added economic margins due to the economy of scale, albeit requiring a greater initial investment to create enhanced capacity.

Table 5. Techno-economic performance results.

Scenario	Present	Generation expansion
Capacity (kW)	500	1000
Electricity generation GWh/year	3.485	6.473
Biomass required to cover 100% heat demand and $\geq 100\%$ electricity demand (kt wet/year)	9.978	12.47
Sawmill process electricity demand (GWh/year)	3.1975	3.1975
Electricity surplus to export (GWh/year)	0.2875	3.275
Capital cost (million \$)	1	1.6
Operating cost w/o biomass cost (million \$/year)	0.1	0.2
Biomass cost (million \$/year)	0.15	0.3
Cost of production (\$/kWh)	0.029	0.023

Sawmill process electricity demands and surplus electricity exports in the two scenarios are established from primary data collection on the sawmill. The capital cost is estimated using Equation 5, from the reference data given: *boiler*: for 0.62 kg/s of biomass, DC_i is \$0.4323 million (Wan et al. 2016a-b), *steam turbine and steam system*: for 10.3 MW electricity output, DC_i is \$5.1 million (Sadhukhan et al. 2014). In this study, for the boiler capital cost estimations, the biomass flowrates are 0.18 and 0.33 kg/s in the two scenarios. For the steam turbine's and steam system's capital cost estimations, the electricity outputs are 0.5 and 1 MW in the two scenarios. Applying the *scale factor*_{*i*} = 0.7, thus, the delivered cost of the boiler

and the steam turbine and steam system, in million \$ is estimated to be 0.18 and 0.28; 0.52 and 0.8, in the two scenarios, respectively. Applying an installation factor of 1.5 on the total delivered cost of the boiler and the steam turbine and steam system, the capital cost obtained is 1 and 1.6 million \$, in the two scenarios, respectively (Table 5).

Amongst the annual operating, capital and biomass costs, the biomass cost is the cost hotspot. However, biomass cost is a source of income generation for local communities and ensuring this price of forestry biomass commodity is essential for socio-economic improvements of the forestry-based poor marginal communities.

The electricity and CHP generation efficiencies are estimated to be 11% and 62% using Equations 3 and 4. This relatively low level of electricity generation efficiency is due to the low pressure superheated steam extraction from the outlet of the back pressure steam turbine. For a scenario with condensate recovery from the back pressure steam turbine, the electricity generation efficiency is 28% (Wan et al. 2016a-b).

Figure 4 shows the life cycle environmental impact savings by forestry (wood residue) CHP displacing the present fuel oil CHP, in the case study. In comparison to fuel oil CHP, global warming and resource savings are the primary drivers of wood residue CHP. Savings in water, acidification and eutrophication are also considerable. Photochemical ozone formation (urban smog) and ecotoxicity potential savings are lower compared with the other categories. These various levels (high, medium and low) of savings are colour coded accordingly in Figure 4a. Furthermore, the dominance analysis on the wood residue CHP shows that the biomass resource is the primary hot spot in most of the life cycle impact categories. The balance of the impacts come from biomass logistics. Figure 4b shows the values of life cycle environmental impact savings on an annual basis. The global warming potential savings in the present and generation expansion scenarios are 3 and 6 kt CO₂ eq/y, respectively. The corresponding fossil resource savings are 40 and 74 TJ/y. The various life cycle impact characterisations per kWh

electricity generation from the wood residue CHP and the fuel oil CHP (both in Mexico) forming the basis of these results are shown in Table 6. From Table 3, it is also noted that 163452 ha have 12.47 kt/year forestry residues available for the CHP. This gives biomass to land ratio of 7.6 kg/m².

In Mexico, the greenhouse gas emissions factor per unit of electricity produced is estimated at 56 g CO₂ eq/kWh for the wood residue CHP system while the value for fuel oil CHP system is 959 g CO₂ eq/kWh. Here, the following important results observed from the LCA using the Ecoinvent 3.0 data sources for the Electricity, high voltage {MX}| heat and power co-generation, wood chips (allocation, cut-off by classification - system).

1. The greenhouse gas sequestration potential by forestry biomass is 1.8 kg CO₂ eq/kg.
2. The above greenhouse gas sequestration potential by forestry biomass translates to 1.47 kg CO₂ eq/kWh electricity generation.
3. The greenhouse gases are emitted by the flue gas from the CHP (98.6%), biomass chipping (0.5%), diesel consumption in machinery (0.34%), biomass harvesting (0.3%), biomass forwarding (0.13%) and infrastructure (0.07%). The greenhouse gas emitted from these life cycle stages is 1.526 kg CO₂ eq/kWh electricity generation. Subtracting the greenhouse gas sequestration by forestry biomass (1.47 kg CO₂ eq/kWh electricity generation) from the total greenhouse gas emitted from the various life cycle stages (1.526 kg CO₂ eq/kWh electricity generation), the net greenhouse gas emission from the cradle-to-grave CHP is 56 g CO₂ eq/kWh. The hotspot is the flue gas emission from the CHP (98.6%).

Table 6. Comparisons of life cycle impact characterisations between the wood residue CHP and the fuel oil CHP per kWh electricity generation in Mexico.

Impact category per kWh electricity generation	Unit	Wood residue CHP	Fuel oil CHP
Global warming	kg CO ₂ eq	0.056	0.959
Abiotic depletion (fossil fuels)	MJ	0.62	12.01

Photochemical ozone formation	kg NMVOC eq	0.002822	0.003996
Acidification	kg SO ₂ eq	0.002014	0.007644
Water consumption	m ³	0.000157	0.001175
Eutrophication	kg N eq	0.000235	0.000505
Ecotoxicity	CTUe	1.13	1.39

Figure 4. LCA results of a wood-residues CHP referenced to a fuel oil-based CHP system in a Mexican sawmill case study, showing a) percentages of impact savings and percentage of impact dominance by biomass, and b) annual impact savings in the two scenarios.

The SLCA results include a comparison of relative scores, in individual social impact themes as well as overall, between countries participating in SIEPAC, Colombia, Costa Rica, Guatemala, Mexico, Nicaragua and Panama. The basis of the SLCA results comes from the

SHDB, a proprietary resource (Norris et al. 2014). Because of the paid resource, only relative social impact theme evaluations between countries for the energy sector are shown here. Lower the score better the social impact theme performance is. Thus, which way flow between two countries would improve the social performance can be assessed using the SHDB. The SHDB does not offer any social scores for the two other countries, El Salvador and Honduras, participating in this programme. Figure 5 shows social impact theme scores, scaled between Guatemala (100) and Mexico (1), in overall and five themes (Table 2). The lower the score, the better are the social conditions. Electricity from Mexico can be imported into five countries potentially sharing electricity interconnection systems including Guatemala, Nicaragua, Panama, Colombia and Costa Rica, in decreasing order of overall social impact savings as well as impact savings in the labour rights and decent work themes. In health and safety, impact savings decrease in the following order of countries, Panama, Nicaragua, Guatemala, Colombia and Costa Rica. In human rights, this sequence is Guatemala, Nicaragua, Colombia and Panama. Costa Rica is better performing than Mexico in human rights and governance in the electricity sector. In governance, the decreasing order of impact savings relative to Mexico's can be seen for Nicaragua, Guatemala, Panama and Colombia. In community infrastructure, the highest to the lowest savings relative to Mexico, are obtained for Nicaragua, Panama, Guatemala, Colombia and Costa Rica. All these observations in Figure 5 suggest that exporting average grid electricity from Mexico into these other five SIEPAC countries is desirable for improving social conditions both in the individual countries and across all the countries collectively. The analysis indicates that increasing self-generation of electricity and heat from biomass in Mexico has the potential to not only serve local communities in Mexico (see next section) but by enhancing social conditions in neighbouring countries to Mexico through the transfer of exportable 'surplus' grid electricity from Mexico to these other SEIPAC countries.

Figure 5. In-country savings in the SLCA themes by electricity import from Mexico.

Discussion including community benefits of bioenergy

The local community level indicators relevant to the UN SDGs include total forest land managed, job creation and gender equality (Table 3) (SDG 15, SDG8 and SDG5). Furthermore, the SDG6-7 are analysed based on literature data. The analysis of the potential use of excess electricity in the generation expansion scenario to supply energy and water services to the communities local to the case study mill has been carried out to show the improvements in SDG6: clean water and sanitation for all and SDG7: affordable and clean energy. The percentage of households without access to electricity in the various municipalities involved in the forest-based value chain are Canelas: 6.2%, Guanacevi: 6.6%, Otaez: 4.8%, Tamazula: 12.3%, Tepehuanes: 3.8%, Topia: 7.5%, Santiago Papasquiario: 4.0%, San Dimas: 6.4% (CONEVAL 2010). Using the statistics on the total number of households at each municipality, those percentages translate into a total of 2202 households without access to electricity. A sociodemographic study revealed that a rural household in Mexico consumes about 1135 kWh/year of electricity (Franco et al. 2014), which translates into a total demand of 2.5 GWh/year for the aforementioned municipalities. This means that the expansion generation

scenario with 3.275 GWh/year of excess electricity could meet the total electricity demand by the rural population living in the aforementioned municipalities and currently lacking access to electricity, although this assumes that electricity access for the population is given priority. Any remaining excess electricity can then be supplied to municipalities for provisioning potable water or sewage water treatment.

In the same municipalities, there is a total of 872 households without access to a water network, and 5114 households without access to a sewage system. Electricity is required for water pumping during extraction and distribution, potabilization and sewage treatment systems. In some cases, capacity for these water services exists, but high operational costs (mainly due to the cost of electricity) prevents municipalities or water service agencies from operating at full capacity (Zurita et al. 2012). The average electricity consumption for municipal water services in Durango was 0.58 kWh/m³ and about 70% goes to supply potable water and 30% to sewage treatment (CONUEE 2018). Assuming an average water consumption of 190 L/person/day and an average of 4 persons per household, the energy required is 0.095 GWh/year for potable water and 0.235 GWh/year for sewage treatment to be provided to the respective number of households lacking these services; a total of 0.33 GWh/year. Furthermore, $(3.275 - 2.5 - 0.33) = 0.445$ GWh/year towards electricity are available for these households without access to clean water and sanitation in these municipalities. Thus, the electricity supply is $(2.5 + 0.445) = 2.945$ GWh/year. If water services are given priority over electricity supply to households, the expansion generation scenario can meet this total electricity demand by relevant municipalities for provisioning water services plus the total demand of local households currently lacking access to electricity. The potential co-benefits of wood residue CHP would then enable synergies in the energy-water nexus in the location of the study - this is significant given the link between water supply, sewerage and public health.

Overall, in this study, the techno-economic and environmental impact modelling and local municipality and neighbouring country social impact modelling show that a substantial improvement is possible in all technical, economic, environmental and social dimensions of sustainability. The results of twenty-nine sustainability indicators analysed for the expansion generation scenario are shown in Figure 6.

This positive environmental and socio-economic impact serves as important evidence in support of investment for deploying forestry and wood residue-based CHP systems in other community managed, forest-based value chains in Mexico. Nowadays, proposed amendments to the Electricity Industry Law are discussed in Mexico. This paper offers relevant technical information for stakeholders to support decisions for bioenergy projects. Together with a revision of government policy and support for bioenergy projects, this can then be translated into enhanced social wellbeing by decreasing social deprivation in energy and water services. Thus, this study presents a market and industry perspective emphasising that bioenergy projects need a transdisciplinary approach, environmentally compatible technology practices, and sustainable supply chains. Investment opportunities should consider fulfilling community demands for foundational services, following the SDG6: clean water and sanitation for all and SDG7: affordable and clean energy, in technology and policy.

Process	Economic	Environmental-LCA (avoidance or saving/year)	Social-LCSA (in-country improvements from import from Mexico)	Social-Community SDG
<ol style="list-style-type: none"> 1. Biomass throughput: 12.47 kt/year 2. Electricity generation: 1 MWe 3. Steam generation: 50 kt/year 4. Energy efficiency: 0.62 	<ol style="list-style-type: none"> 1. Capital cost: \$1.6million 2. Internal rate of return: 10% 3. Operating cost: \$0.2million/year 4. Feedstock cost: \$0.3million/year 5. Cost of production: \$0.023/kWh 	<ol style="list-style-type: none"> 1. Global warming potential (100 yrs): 6 kt CO₂ eq. 2. Abiotic depletion potential (fossil fuels): 74 TJ 3. Photochemical ozone formation potential: 8 t NMVOC eq. 4. Acidification potential: 37 t SO₂ eq. 5. Water use: 6620 m³ 6. Eutrophication potential: 1.755 t N eq. 7. Ecotoxicity potential: 1.664 × 10⁶ CTUe 8. Sustainable forestry residue availability per land: 7.6 kg/m² 	<ol style="list-style-type: none"> 1. Labour rights and decent work: Guatemala > Nicaragua > Panama > Colombia > Costa Rica 2. Health and safety: Panama > Nicaragua > Guatemala > Colombia > Costa Rica 3. Human rights: Guatemala > Nicaragua > Colombia > Panama 4. Governance: Nicaragua > Guatemala > Panama > Colombia 5. Community infrastructure: Nicaragua > Panama > Guatemala > Colombia > Costa Rica 	<ol style="list-style-type: none"> 1. Total forest area (SDG15): 445676 ha 2. Direct permanent jobs (SDG8): 550 3. Indirect jobs (SDG8): 2000 4. Gender equality (SDG5): 40% women 5. Energy access (SDG7): 2.945 GWh/year for electrical energy 6. Water access (SDG6): 0.095 GWh/year for potable water access 7. Sanitation access (SDG6): 0.235 GWh/year for access to sanitation

Figure 6. Summary of results of twenty-nine sustainability indicators analysed for the expansion generation scenario (1 MWe).

Conclusions

This research has critically analysed a wide range of sustainability indicators for bioenergy CHP using whole system life cycle sustainability assessment methodologies. Physicochemical and thermodynamic characteristics are captured in the technical modelling of the system and form the basis for economic and environmental impact analysis. Social impact assessment following the social life cycle assessment guidelines and local community level data are analysed to establish the potential of self-generation in Mexico in serving local communities and for implications for grid interconnection within the SIEPAC framework.

Two scenarios, present and generation expansion corresponding to 0.5 and 1 MW electricity outputs are evaluated. The generation expansion capacity can meet the power and heat demand of the mill as well as the energy demands of the population living in deprivation of access to electricity or the energy demand for supplying water services by the municipalities in the forest-based value chain in Durango state. The cost of electricity generation in the generation expansion scenario (1 MW_e) is \$0.023 per kWh, this cost is lower than the current average grid electricity price. Environmental impact savings of between 20 and 95% across seven impact categories are found when switching to using bioenergy CHP compared with the conventional fuel oil-based energy system. The social impact assessment showed that exporting electricity from Mexico into Guatemala, Nicaragua, Panama, Colombia and Costa Rica has the potential to enhance social conditions in these SIEPAC countries. The 3.275 GWh/year of excess electricity generation in the bioenergy generation expansion scenario also has the potential to provide important social benefits locally in Mexico. Apart from potential job generation, this additional electricity supply would be sufficient to meet the whole demand by local households currently lacking electrical supply and demand of municipal energy-water-sanitation services. These findings provide valuable evidence for policymakers, businesses and civil society when considering opportunities to achieve sustainable supplies of energy and water for both local

and wider as well as SDG6: clean water and sanitation for all and SDG7: affordable and clean energy benefits. The application of the modern web-based open software resource TESARREC™ Trademark: UK00003321198 <https://tesarrec.web.app/sustainability/chp> has been demonstrated on biomass strategies to meet the net zero greenhouse gas emissions target.

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