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

Elias Martinez-Hernandez¹ · Jhuma Sadhukhan² · Jorge Aburto¹ · Myriam A. Amezcua-Allieri¹ · Stephen Morse² · Richard Murphy²

Received: 12 July 2021 / Accepted: 19 January 2022 / Published online: 16 February 2022
© The Author(s) 2022

Abstract

This study develops a novel mathematical modelling framework for biomass combined heat and power systems (CHP) that links biomass and process characteristics to sustainability assessment of the life cycle. A total of twenty-nine indicators for the process (four-indicators), economic (five-indicators), environmental (eight-indicators) and social global (five-indicators) and local (seven-indicators) aspects have been analysed for sustainability. These are technological: biomass throughput, electricity and steam generations and CHP efficiency; economic: internal rate of return, capital, operating and feedstock costs and cost of production; environmental: global warming, fossil, land and water use, acidification, urban smog, eutrophication and ecotoxicity potentials; social (global): labour rights and decent work, health & safety, human rights, governance and community infrastructure; social (local): 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. This paper applies the developed methodology to a case study in Mexico. From 12.47 kt/year forestry residue, 1 MWe is generated with an associated low-pressure steam generation of 50 kt/year, at the cost of production of \$0.023/kWh. This makes the energy provision “affordable and clean” for marginalised/poor communities (the UN Sustainable Development Goals, SDG7). Bioenergy can curb > 90% of the greenhouse gas emissions and primary energy use, 6 kt CO₂ eq and 74 TJ annually. Bioenergy reduces other environmental impacts considerably, water consumption, acidification and eutrophication by 87–53%, and urban smog and ecotoxicity by 29–18%. Bioenergy can improve all five social themes in the Central American cluster countries. In addition to the SDG7, the forestry-based bioenergy system can also achieve the SDG6: “clean water and sanitation for all”.

✉ Jhuma Sadhukhan
jhumasadhukhan@gmail.com

Elias Martinez-Hernandez
emartinez@imp.mx

¹ Biomass Conversion Division, Instituto Mexicano del
Petróleo, Lázaro Cárdenas 152, 07730 Mexico City, Mexico

² Centre for Environment and Sustainability, University
of Surrey, Guildford GU2 7XH, UK

Graphical abstract

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, involving the ecosystem, human health and economic performance of governments 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. It has been addressed by two main approaches, optimisation-based (Ong et al. 2021) and simulation-based (Sadhukhan et al. 2021). The former approach minimises economic, environmental and social objectives, 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 methods analyse scenarios and test the sensitivity of independent variables on output results, techno-economic, environmental or social performance (Sadhukhan et al. 2014).

A combined heat and power system (CHP) utilises bio-based residues (Wan et al. 2016a), such as forestry-based wood residues receiving greater attention in the literature (Fitzpatrick 2016). A CHP is flexible in terms of the provision of energy vectors, which 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 has been analysed by an Aspen Plus simulation model (Wan et al. 2016b) applied in Mexico's bioenergy context (Martinez-Hernandez et al. 2017).

However, a robust modelling platform that allows testing of input variables, such as energy currency of biomass fuel to CHP, on the sensitivity of output results is very much in need. Output results encompass underlying technical, economic, environmental and social impacts that are deemed essential 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 analysis concerning the CHP and sustainability analysis modelling 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). A utility boiler has been shown in bioethanol production process simulation using Aspen Plus (Petersen et al. 2021). The Bio2Energy® models based on equations from the IAPWS has been demonstrated to simulate and evaluate the techno-economics of CHP generation from agave bagasse, coffee residues and orange peels in Mexican agroindustry (Martinez 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) (Ng et al. 2010). An IGCC system comprises 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 reducing 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. A community-scale bioenergy system must be simple for operation by the communities and 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 high-value products are other strands of research literature on carbon dioxide capture (Ng et al. 2013). Another CHP configuration includes IGCC and biomass integrated gasification fuel cell systems (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 focuses on European regions (Wang et al. 2018). Thus, there is an essential 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) 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 selecting 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. The methods are helpful for decision-making from a set of choices (Niekamp et al. 2015). Another strand of research encourages presenting all plausible underlying sustainability criteria to inform possible consequences and tradeoffs best (Sadhukhan 2022). 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 (Martinez et al. 2013). Forty-four literature works exist on these critical environmental consequences of bioenergy (Roos and Ahlgren 2018). Primary analysis on sustainable biomass and bioenergy availability using a geographic information system reveals an annual 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 hydroprocessing and transesterification to produce green diesel and biodiesel have been designed to offset these environmental impacts in Mexico (Martinez-Hernandez

et al. 2014). Other significant environmental 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). Following 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 can be calculated (Sadhukhan and Martinez-Hernandez 2017). Furthermore, the cost of production applying the net present value analysis and all the cost components is a valuable 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 essential 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 to represent 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). New Earth's social hotspot database (SHDB) 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 rarely link fundamental process modelling to sustainability assessment, with exceptions (e.g. Sadhukhan et al. 2019b). This study thus aims to

connect a novel process model and sustainability analysis of bioenergy 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 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 valuable context for waste-to-energy approaches. It explores how the modernisation of energy supply in forest-based supply chains through CHP can support the UN SDGs and policy programmes.

Methodology

Figure 1 shows the methodological components in this study. The four main stages of calculations are process modelling, economic analysis, LCA and social assessment discussed in the following sections. The social assessment is further organised into SLCA and community impact. Except for the community impact assessment, for which the case study level data on the access to the energy, water and sanitation services was collected, all other models are generic. The process modelling step applies thermodynamic modelling to calculate required biomass throughput, heat and power generation capacities and efficiencies, extents of the demands met energy surpluses and equipment capacities. The process

Fig. 1 The methodology

model inputs are biomass analysis (carbon, hydrogen and moisture contents and low heating value (LHV), energy demand including steam conditions, efficiencies of devices and policy legislative contexts. The software used for this stage is Aspen Plus™, the IMP's (Instituto Mexicano del Petróleo) in-house software tool IMPBio2Energy® (Martínez-Hernández et al. 2021) and TESARREC™ CHP module <https://tesarrec.web.app/sustainability/chp> (University of Surrey 2020). The economic analysis, LCA and social assessment use the process modelling results to give the feasibility results. IMPBio2Energy® and TESARREC™ have been used to perform the economic analysis in terms of capital, feedstock and operating costs and the cost of energy production. Ecoinvent 3.0 is the source of life cycle inventories across the life cycle stages, discussed in the LCA section. TESARREC™ calculates the life cycle impacts per functional unit and impact savings against fossil-based counterparts. The social assessment has two aspects, SLCA and community impact. The SLCA indicators are sourced from the proprietary SHDB in the international power trade context (Norris et al. 2014) to compare between the countries in The Central American Electrical Interconnection System (SIEPAC) (Ecchevarria et al. 2017) and calculate the in-country savings in the SLCA themes. Some substantial community-level impacts on electricity and water access are calibrated to local conditions obtained from the organisation managing the forest.

Bioenergy process modelling

The simulation of bioenergy systems has been carried out using the TESARREC™ CHP module (University of Surrey 2020) and the IMP's (Instituto Mexicano del Petróleo) in-house software tool IMPBio2Energy® (Martínez-Hernández

et al. 2021). Aspen Plus™ provides the thermodynamic modelling basis of these two platforms. The Aspen Plus™ simulation results were validated against the plant data. Moisture and ash contents of biomass are from the ASTM D5142-09 (2009), while the ultimate analysis followed the ASTM D5373-93 (1993) protocol.

The CHP system modelled is shown in Fig. 2. The system consists of a biomass boiler with flue gas energy recovery to produce full steam. The water and air enter at ambient temperature. The steam pressure is typically from 10 to 65 bar and the superheated temperature is 500 °C. The steam is expanded in a backpressure turbine which generates low-pressure steam to supply other production processes (for example, the plywood drying and other heat demanding processes in a sawmill) and electricity. Additional boiler capacity is needed if the steam cogenerated with electricity is insufficient to cover the demand. The operating variables are shown in the Case Study section. Aspen Plus™ is the source of steam properties. It is also used for the thermodynamic modelling of the CHP in Fig. 2. Further details of IMP Bio2Energy® modelling are provided elsewhere (Martínez-Hernández et al. 2021).

This robust technical model of the system in TESARREC™ comprises Eqs. 1–4 to estimate biomass throughput, steam generation by the system, and electricity and CHP generation efficiencies from the electricity rating of the CHP (University of Surrey 2020). Equations 1 and 2 are empirical. Their coefficients were determined by linear regression of Aspen Plus™ simulation results, electricity generation and steam generation outputs concerning carbon and hydrogen content in biomass inputs. Energy efficiency equations are the ratio between electricity or total energy output and energy input through the biomass.

Fig. 2 CHP configuration

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

$$\times \frac{1}{\epsilon_{ST1}} \times \frac{1}{\epsilon_{ST2}} \times \frac{100}{(C + H)} \times \frac{100}{(100 - M)}$$

Carbon and hydrogen contents (dry basis) in wt%, C and H , constitute the fundamental basis of the equations. Carbon and hydrogen 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. Higher the carbon and hydrogen contents in the biomass, the lower the biomass throughput is to meet the electricity or energy demand. The same is true for the various efficiencies, such as, of boiler and (isentropic and mechanical) of backpressure steam turbine, ϵ_{Boiler} , ϵ_{ST1} , and ϵ_{ST2} , respectively. Higher the moisture content (M), the higher the biomass throughput is. In Aspen Plus™ simulation, RGibbs reactor and expander unit operations were chosen to represent the biomass boiler and the backpressure steam turbine. In Aspen Plus™ simulation, carbon and hydrogen contents in biomass were varied (51.5–53.5% and 5.5–6.5%) to capture their impacts on the output electricity generation. The values of input variables and output results were used to derive the empirical Eq. 1, i.e. the coefficients on the numerator of Eq. 1. The coefficients were determined by linear regression of Aspen Plus™ simulation results, electricity generation output concerning carbon and hydrogen content in biomass inputs. Because of the small ranges of the input variable values, the R-squared value of the linear regression is 1.

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

$$\text{Steam generation} \frac{\text{kg}}{\text{hour}} = \frac{\left(1560 \times \text{Electricity generation} \frac{\text{GWh}}{\text{year}} - 0.23\right)}{(C \times 0.375 + H \times 1.154)} \times \frac{1}{\epsilon_{\text{Boiler}}} \times \frac{1}{\epsilon_{ST1}} \times \frac{1}{\epsilon_{ST2}} \times (0.2807 \times (C \times 0.375 + H \times 1.154) + 0.0463) \quad (2)$$

The Aspen Plus™ simulation results on steam generation are obtained by varying the carbon and hydrogen contents in biomass. These values are used to deduce the empirical Eq. 2. The effect of energy content within carbon and hydrogen in biomass on the amount of steam generation is captured in the final term on the right-hand side of

Eq. 2. The coefficients were determined by linear regression of Aspen Plus™ simulation results, steam generation output concerning carbon and hydrogen content in biomass inputs. Because of the small ranges of the input variable values, the R-squared value of the linear regression is 1.

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. Energy efficiency equations are the ratio between electricity or total energy output and energy input through the biomass.

Electricity generation efficiency

$$= \frac{411 \times \text{Electricity generation} \frac{\text{GWh}}{\text{year}}}{\text{Biomass throughput (wet)} \frac{\text{kg}}{\text{hour}} \times \text{Biomass (wet)} \text{LHV} \frac{\text{MJ}}{\text{kg}}} \quad (3)$$

CHP generation efficiency

$$= \frac{\left(411 \times \text{Electricity generation} \frac{\text{GWh}}{\text{year}} + 2.77 \times \text{Steam generation} \frac{\text{kg}}{\text{hour}}\right)}{\text{Biomass throughput (wet)} \frac{\text{kg}}{\text{hour}} \times \text{Biomass (wet)} \text{LHV} \frac{\text{MJ}}{\text{kg}}} \quad (4)$$

411 is the factor employed to convert Electricity generation $\frac{\text{GWh}}{\text{year}}$ 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.

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 Eqs. 5–12 and parameters (Sadhukhan et al. 2014). The capital cost is determined from

Eq. 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.

$$\text{Capital cost} = \left(\sum_i \text{DC}_i \times \left(\frac{\text{present amount}_i}{\text{base production rate}_i} \right)^{\text{scale factor}_i} \right) \times \text{Installation factor} \quad (5)$$

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 production rate is 0.62 kg/s of biomass and DC_i is \$0.4323 million for its base size (Wan et al. 2016a-b). For the steam turbine and steam system, the base production rate is 10.3 MW electricity output and DC_i is \$5.1 million for its base size (Sadhukhan et al. 2014). The term $\text{scale factor}_i = 0.7$ captures the effect of the economy of scale; 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 and 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 and 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; Sadhukhan and Sen 2021).

After that, the net present value (NPV_y) calculation in a given year y of the CHP operation is applied (Eq. 6) to consider the depreciation of the economic margin with time.

$$\text{NPV}_y = \text{NPV}_{y-1} + \frac{(\text{Product value} - \text{Opex} - \text{Capex})}{(1 + \text{IRR})^y} \quad (6)$$

$$\text{NPV}_{y=0} = \text{Capital cost}$$

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 (Eq. 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 (Eq. 8). The fixed operating cost dependent on indirect annual capital cost is dependent on the Capital cost (Eq. 9). The labour dependent fixed operating cost is a function of Biomass throughput (wet) $\frac{\text{kg}}{\text{hour}}$ (Eq. 10).

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

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

$$\begin{aligned} & \text{fixed operating cost} \\ & \text{dependent on indirect annual capital cost} \\ & = \frac{\text{Capital cost}}{\text{Installation factor}} \times \text{Annual Capital Charge} \times b \end{aligned} \quad (9)$$

$$\begin{aligned} & \text{labour dependent fixed operating cost} \\ & = c \times \text{Biomass throughput (wet)} \frac{\text{kg}}{\text{hour}} \end{aligned} \quad (10)$$

a , b and c are multipliers of the respective cost components to account for a larger set of cost components (Sadhukhan et al. 2014; Sadhukhan and Sen 2021). The value of a in Eq. 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 Eq. 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 TESAR-RECTM, the personnel cost is \$52,033 per t/h throughput. Thus, the value of c in Eq. 10 is $1.9 \times 52033/1000000 = 0.1$.

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

$$\begin{aligned} \text{Product value} = & \text{Electricity price} \times \text{Electricity generation} \\ & + \text{Steam price} \times \text{Steam generation} \end{aligned} \quad (11)$$

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

Equation 12 shows the cost of production of CHP.

$$\begin{aligned} & \text{Cost of CHP production} \\ & = \frac{(\text{Capex} + \text{Opex}) + \text{Biomass cost}}{\text{Electricity generation} \frac{\text{GWh}}{\text{year}} \times \frac{\text{CHP generation efficiency}}{\text{Electricity generation efficiency}}} \end{aligned} \quad (12)$$

LCA of bioenergy

Biomass input and energy output are the critical linkages between the process and LCA models. Biomass input and energy output evaluations obtained from the process model analyse the LCA of bioenergy. By the ISO14040-44 International Standards for LCA, selecting 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, fuel 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. Alongside, the LCIA methodologies to characterise inventories into impacts are also shown. 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, mixing and matching LCIA methods is a good indication of a fundamental understanding of environmental drivers for a system. These life cycle impact categories are essential to LCA studies, and hence, for their detailed characterisation methods, an introductory 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 comprehensive coverage of effects on the atmosphere, water and ecosystem. While the environmental impact categories are generally considered to be of the highest interest for energy systems (including bioenergy), global warming potential and

fossil resource consumption (aka. Abiotic depletion potential (fossil fuels)), a more comprehensive range of impact categories present a complete picture of the system, its potential environmental impacts and potential tradeoffs between impact categories. All non-primary data used to model the forestry residue CHP and the displaced fuel oil CHP, including respective supply chain logistics, are sourced from the 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).

The Ecoinvent 3.0 database for the forestry residue CHP has flue gas emissions, biomass chipping, diesel consumption in machinery, biomass harvesting, biomass forwarding and infrastructure inventory data. The Results section later shows their LCIA attributions.

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

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)

Table 2 Social impact themes and sub-themes

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

methodology helps interconnect local and global social themes and sub-themes and focuses on targeted indicators for socio-economic sustainability. The standard consideration of life cycle stages in the analyses makes SLCA more comprehensive for the sustainability evaluation of bioenergy (Sadhukhan et al. 2014).

The supply chain interactions are considered when scoring a theme for a given product or sector in a given country. 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 from 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 in the interactive supply chains. An individual total social theme score for a given product in a country is the product of the risk of a theme in the country of origin as well the countries 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) and the fraction of the product produced in the country or imported from other countries considering their corresponding supply chains (Sadhukhan et al. 2021). These factored individual social theme scores are added to give a total social theme score for a given sector in a given country.

Results and discussion

Case study

The case study is a sawmill located in Santiago Papasquiaro and belongs to Sezaric, a cooperative association registered

as a Rural Association of Collective Interest. Santiago Papasquiaro is situated in the state of Durango, Mexico. The sawmill is dedicated to manufacturing export wooden furniture. The major products are plywood and pinewood boards. Nowadays, the sawmill generates energy from forestry waste via a forest-based cooperative which uses forest biomass to supply its energy demands. Communal producers of wood and forest biomass provide biomass (mainly from *Pinus* spp) to a sawmill that uses wood residues to generate bioenergy for the self-sufficiency of the local community. Sezaric is considered one of the best examples of a social enterprise in the state of Durango in Mexico due to the large area of forest resources available, sustainable forestry, and promoting jobs and income for local communities. The company is certified by the Forest Stewardship Council.

Due to the biomass availability and installed power generation capacity, the bioenergy generation system can be operated to generate surplus electricity which can then be provided to the associated communities to create positive socio-economic impacts. In addition, Sezaric represents an excellent example of women's inclusion, due to a total of 462 employees, 21.4% are women.

The two scenarios are considered for the case study.

1. Present scenario with limited generation (LG). This scenario corresponds to an existing bioenergy generation capacity that is regulated. The current policy only allows generation for self-supply and no export. The total power is capped at 500 kW of electricity. 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 a small percentage of households are without electricity access.
2. Generation Expansion (GE) scenario. This scenario corresponds to leveraging the use of biomass readily available and the full existing generation capacity at the sawmill facility, which is for a 1 MW. This scenario requires a higher amount of biomass. The surplus elec-

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

Characteristic	Value
Number of Ejidos and partner communities	40
Number of landowners	4620
Total managed forests area	445,676 ha
Wood production area	163,452 ha
Annual lumber production	261,000 m ³
Number of direct permanent jobs	550
Indirect jobs (estimated)	2000
Female workforce	40%

tricity could improve the access for the surrounding communities.

Case study characterisation

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, including biomass availability and land use, are obtained from the forest-based cooperative.

The communities provide forestry waste to the sawmill in Durango State; therefore they are considered one of the main stakeholders. The area of influence of the cooperative is depicted in Fig. 3 and spans 8 municipalities in North-east 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) is 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, amongst 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).

The elemental composition of the biomass and higher heating value used as inputs to Eqs. 1–12 for the evaluations of technical, economic and environmental performance indicators are shown in Table 4, which are average values for pinewood residues (Martínez-Hernández et al 2021).

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

Ultimate analysis	Value	Unit
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

For the specific case study, high-pressure superheated steam is generated at 50 bar. The high-pressure superheated steam is then expanded in a backpressure 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. Table 5 shows the primary data used for techno-economic analysis. The equipment and operating data came from the existing bioenergy system installed in the sawmill plant. The simulation results were thus validated against plant data with an average 5% difference in values.

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.

Table 5 Data used for the case study analyses

Characteristic	Value	Unit	References
Reference biomass price	25	\$/ton	Based on sawdust cost (Tauro et al. 2018)
Grid electricity price	0.0858	\$/kWh	2020 national grid average
Depreciation of investment	15	year	Assumption
Internal rate of return	10	%	Assumption
Installation factor	1.5		Assumption
Annual operating time	6395	h/year	Sawmill data
Boiler dimensionless energy efficiency	0.85		Assumption
Boiler operating pressure	50	bar	Assumption
Flue gas outlet temperature	150	°C	Assumption
Air and boiler feedwater temperature	25	°C	Assumption
Superheated steam temperature	500	°C	Assumption
Isentropic efficiency of turbine	0.85		Assumption
Mechanical efficiency of turbine	0.90		Assumption
Low-pressure steam demand (at 100–115 °C)	7831	kg/h	Sawmill data
Electricity demand	3.2	GWh/year	Sawmill data

Table 6 Techno-economic performance results

Scenario	Present	Generation expansion
Capacity (kW)	500	1000
Steam turbine and steam system size (MW)	0.5	1
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
Boiler size (biomass flowrate) (kg/s)	0.18	0.33
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

Bioenergy process, economic, LCA and SLCA modelling results

Table 6 shows the techno-economic performance comparisons between the two scenarios. Using Eqs. 1, biomass required is estimated for the two scenarios, 3.5 and 6.5 GWh/year electricity demands, as shown in Table 6. 30% and 56% of the steam demands (7831 kg/h) are met by the CHP configuration in Fig. 2 in the present and generation expansion scenario, respectively (using Eq. 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 (Eq. 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 6). From Table 6, 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. The generation expansion shows the added economic margins due to the economy of scale, albeit requiring a greater initial investment to create enhanced capacity.

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 Eq. 5, from the reference data given: boiler : for 0.62 kg/s of biomass flowrate, 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 in Eq. 5, the delivered cost of the boiler and the steam turbine and steam system is estimated to be (in million \$) 0.18 and 0.28 in the present, and 0.52 and 0.8 in the generation expansion 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 6).

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. Ensuring this price of forestry biomass commodity is essential for socio-economic improvements of the forestry-based poor marginal communities. 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 (\$0.0858 per kWh, Table 5).

The electricity and CHP generation efficiencies are estimated to be 11% and 62% using Eqs. 3 and 4. This relatively low electricity generation efficiency is due to the low pressure superheated steam extraction from the backpressure steam turbine outlet. For a scenario with condensate recovery from the backpressure 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 compared to fuel oil CHP, a common practise in Mexico. Compared 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 than the other categories. These various levels (high, medium and low) of savings are colour coded accordingly in Fig. 4a. Furthermore, the dominance analysis (impacts by life cycle stages, Sadhukhan et al. (2014)) on the wood residue CHP shows that biomass is the primary hot spot in most life cycle impact categories. The balance of the impacts comes from biomass logistics. Figure 4b shows the values of life cycle environmental impact savings annually. The global warming potential savings in the present and generation expansion scenarios are 3 and 6 kt CO₂ eq/year, respectively. The corresponding fossil resource savings are 40 and 74 TJ/year. 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 7. From Table 3, it is also noted that 163,452 ha have 12.47 kt/year forestry residues available for the CHP. The generation expansion scenario 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. In comparison, the value for fuel oil CHP system is 959 g CO₂ eq/kWh. Here, the following essential results were 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

Fig. 4 LCA results of a wood-residues CHP referenced 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

Table 7 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

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%).

The SLCA results include comparing relative scores in individual social impact themes and 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 data source (Norris et al. 2014). Because of the paid service, only

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

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, decreasing overall social impact savings and impact savings in the labour rights and decent work themes. In health and safety, impact savings fall in the following order of countries, Panama, Nicaragua, Guatemala, Colombia and Costa Rica. This sequence is Guatemala, Nicaragua, Colombia, and Panama in human rights. 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. The highest to the lowest savings relative to Mexico are obtained for Nicaragua, Panama, Guatemala, Colombia, and Costa Rica in community infrastructure. All these observations in Fig. 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 serve not only local communities in Mexico (see next section) but

also enhance social conditions in neighbouring countries to Mexico through the transfer of exportable 'surplus' grid electricity from Mexico to these other SEIPAC countries.

Discussion including community benefits of bioenergy

The local community level indicators relevant to the UN SDGs include total forest land management, job creation and gender equality (Table 3) (SDG15, SDG8 and SDG5). Furthermore, the SDG6-7 is analysed based on literature data. 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 Papasquiaro: 4.0%, San Dimas: 6.4% (CONEVAL 2010). Using the statistics on the total number of households at each municipality, those percentages translate into 2202 households without access to electricity. A sociodemographic study revealed that a rural home in Mexico consumes about 1135 kWh/year of electricity (Franco and Velázquez 2016), which translates into a total demand of 2.5 GWh/year for the municipalities above. Thus, the expansion generation scenario with 3.275 GWh/year of excess electricity could meet the total electricity demand of the rural population living in the municipalities above that currently lack access to electricity. However, this assumes that electricity access for

the people is given priority. Any remaining excess electricity can then be supplied to municipalities for provisioning potable water or sewage water treatment.

There are 872 households without a water network in the same municipalities and 5114 homes without 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. Still, high operational costs (mainly due to electricity) prevent 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 homes 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 enable synergies in the energy-water nexus in the study location—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 Fig. 6.

This positive environmental and socio-economic impact is essential evidence supporting 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. With a revision of government policy and support for bioenergy projects, this can 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 practises, 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.

Bioenergy process modelling	Bioenergy economic analysis	LCA of Bioenergy (avoidance or saving/year)	SLCA (in-country improvements from import from Mexico)	Community impacts
<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 6. Economic margin: \$0.0628/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

Fig. 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. 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 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 and 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, \$0.0858 per kWh. 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 can enhance social conditions in these SIEPAC countries. In the bioenergy generation expansion scenario, the 3.275 GWh/year of excess electricity generation can also provide significant 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 energy and water supplies for both local and wider and 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.

Acknowledgements This work has been supported by The British Council's Newton Fund Impact Scheme Grant Number: 540821111. The authors gratefully acknowledge Sohum Sen <https://github.com/sohumsen/Tesarrec> developed the TESARREC™ platform on the web. His CHP module on the TESARREC™ platform: <https://tesarrec.web.app/sustainability/chp> has been applied to evaluate the case study. The authors gratefully acknowledge GRUPO SEZARIC ZEPEDIN AR DE

IC, Durango, Mexico Sezaric for data on the sawmill and bioenergy system operation for the case study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- ASTM D5142-09 (2009) Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures. ASTM International, West Conshohocken, PA, USA
- ASTM D5373-93 (1993) Standard Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal and Coke. ASTM International, West Conshohocken, PA, USA
- Clift R (2014) Social life cycle assessment: What are we trying to do. In Proceedings of Pre-Proceedings of the 4th International Seminar in Social LCA. Social LCA in Progress 19–21
- CONEVAL (2010) Methodology for Multidimensional Poverty Measurement in Mexico 2010
- CONUEE (2018) Informe nacional de monitoreo de la eficiencia energética de México
- de Faria DR, de Medeiros JL, Araújo OQ (2021) Sustainability assessment for the chemical industry: Onwards to integrated system analysis. *J Clean Prod* 278:123966
- Ecchevarría C, Jerusun-Clements N, Mercado J et al (2017) Integración eléctrica centroamericana: Génesis, beneficios y prospectiva del Proyecto SIEPAC. Sistema de Interconexión Eléctrica de los Países de América Central Publications
- Emmanuel-Yusuf D, Morse S, Leach M (2017) Resilience and livelihoods in supply chains (RELISC): An analytical framework for the development and resilience of the UK wood fuel sector. *Sustain* 9(4):660
- Fitzpatrick JJ (2016) Environmental sustainability assessment of using forest wood for heat energy in Ireland. *Ren Sustain Energy Rev* 57:1287–1295
- Franco A, Velázquez M (2016) Una aproximación sociodemográfica al consumo de energía en los hogares mexicanos, 2014. In: Márquez Villeda M Ed. La situación demográfica México
- González-Cruz LA, Morales-Mendoza LF, Aguilar-Lasserre AA et al (2021) Optimal ecodesign selection for biodiesel production in biorefineries through multicriteria decision making. *Clean Technol Environ Policy*. <https://doi.org/10.1007/s10098-021-02141-9>
- Halog A, Manik Y (2011) Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustain* 3(2):469–499
- Honorato-Salazar JA, Sadhukhan J (2020) Annual biomass variation of agriculture crops and forestry residues, and seasonality of crop residues for energy production in Mexico. *Food Bioprod Process* 119:1–19
- Klein SA (2017) TRNSYS-A transient system simulation program. University of Wisconsin-Madison, Solar Energy Laboratory

- Luján-Álvarez C, Miguel Olivas-García J, Guadalupe González-Hernández H et al (2015) Community forestry in Mexico: strategic model for the empowerment and competitiveness in globalization. *Econ Soc y Territ* 15:665–696
- Martínez-Hernández E, Amezcua-Allieri MA, Aburto J (2021) Assessing the cost of biomass and bioenergy production in agroindustrial processes. *Energies* 14:4181
- Martínez-Hernández E, Ibrahim MH, Leach M et al (2013) Environmental sustainability analysis of UK whole-wheat bioethanol and CHP systems. *Biomass Bioenergy* 50:52–64
- Martínez-Hernández E, Martínez-Herrera J, Campbell GM et al (2014) Process integration, energy and GHG emission analyses of *Jatropha*-based biorefinery systems. *Biomass Conv Bioref* 4(2):105–124
- Martínez-Hernández E, Samsatli S (2017) Biorefineries and the food, energy, water nexus—towards a whole systems approach to design and planning. *Curr Opin Chem Eng* 18:16–22
- Ng KS, Lopez Y, Campbell GM et al (2010) Heat integration and analysis of decarbonised IGCC sites. *Chem Eng Res Des* 88(2):170–188
- Ng KS, Zhang N, Sadhukhan J (2013) Techno-economic analysis of polygeneration systems with carbon capture and storage and CO₂ reuse. *Chem Eng J* 219:96–108
- Niekamp S, Bharadwaj UR, Sadhukhan J et al (2015) A multi-criteria decision support framework for sustainable asset management and challenges in its application. *J Ind Prod Eng* 32(1):23–36
- Norris C, Norris G, Aulisio D (2014) Efficient assessment of social hotspots in the supply chains of 100 product categories using the social hotspots database. *Sustain* 6:6973–6984
- Ong SH, Tan RR, Andiappan V (2021) Optimisation of biochar-based supply chains for negative emissions and resource savings in carbon management networks. *Clean Technol Environ Policy* 23(2):621–638
- Petersen AM, Okoro OV, Chireshe F et al (2021) Systematic cost evaluations of biological and thermochemical processes for ethanol production from biomass residues and industrial off-gases. *Energy Conv Manage* 243:114398
- Puig-Gamero M, Pio DT, Tarelho LAC et al (2021) Simulation of biomass gasification in bubbling fluidized bed reactor using aspen plus®. *Energy Conv Manage* 235:113981
- Rezaei M, Sameti M, Nasiri F (2021) Biomass-fuelled combined heat and power: integration in district heating and thermal-energy storage. *Clean Energy* 5(1):44–56
- Roos A, Ahlgren S (2018) Consequential life cycle assessment of bio-energy systems—a literature review. *J Clean Prod* 189:358–373
- Sadhukhan J (2022) Net zero electricity systems in global economies by life cycle assessment (LCA) considering ecosystem, health, monetization, and soil CO₂ sequestration impacts. *Renew Energy* 184:960–974
- Sadhukhan J, Gadkari S, Martínez-Hernández E et al (2019a) Novel macroalgae (seaweed) biorefinery systems for integrated chemical, protein, salt, nutrient and mineral extractions and environmental protection by green synthesis and life cycle sustainability assessments. *Green Chem* 21(10):2635–2655
- Sadhukhan J, Martínez-Hernández E (2017) Material flow and sustainability analyses of biorefining of municipal solid waste. *Bioresour Technol* 243:135–146
- Sadhukhan J, Martínez-Hernández E, Amezcua-Allieri MA et al (2019) Economic and environmental impact evaluation of various biomass feedstock for bioethanol production and correlations to lignocellulosic composition. *Bioresour Technol Rep* 7:100230
- Sadhukhan J, Ng KS, Martínez-Hernández E (2014) Biorefineries and Chemical Processes: Design. Wiley, Integration and Sustainability Analysis
- Sadhukhan J, Sen S (2021) A novel mathematical modelling platform for evaluation of a novel biorefinery design with Green hydrogen recovery to produce renewable aviation fuel. *Chem Eng Res Des* 175:358–379
- Sadhukhan J, Sen S, Gadkari S (2021) The mathematics of life cycle sustainability assessment. *J Clean Prod* 309:127457
- Sadhukhan J, Zhang N, Zhu XX (2004) Analytical optimisation of industrial systems and applications to refineries, petrochemicals. *Chem Eng Sci* 59(20):4169–4192
- Sadhukhan J, Zhao Y, Shah N et al (2010) Performance analysis of integrated biomass gasification fuel cell (BGFC) and biomass gasification combined cycle (BGCC) systems. *Chem Eng Sci* 65(6):1942–1954
- Sahu P, Prabu V (2021) Techno-economic analysis of co-combustion of Indian coals with municipal solid waste in subcritical and supercritical based steam turbine power generating carbon-negative systems. *Energy*. <https://doi.org/10.1016/j.energy.2021.121053>
- Shemfe MB, Gadkari S, Sadhukhan J (2018) Social hotspot analysis and trade policy implications of the use of bioelectrochemical systems for resource recovery from wastewater. *Sustainability* 10(9):3193. Comtrade. <https://comtrade.un.org/data/>
- Sikdar SK (2003) Sustainable development and sustainability metrics. *AIChE J* 49(8):1928–1932
- Tauro R, García CA, Skutsch M, Masera O (2018) The potential for sustainable biomass pellets in Mexico: an analysis of energy potential, logistic costs and market demand. *Renew Sustain Energy Rev* 82:380–389
- University of Surrey (2020) TESARREC™ Trademark: UK00003321198
- Visentin C, da Silva Trentin AW, Braun AB et al (2020) Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies. *J Clean Prod* 270:122509
- Wan YK, Sadhukhan J, Ng DK (2016a) Techno-economic evaluations for feasibility of sago-based biorefinery, part 2: integrated bioethanol production and energy systems. *Chem Eng Res Des* 107:102–116
- Wan YK, Sadhukhan J, Ng KS et al (2016b) Techno-economic evaluations for feasibility of sago-based biorefinery, part 1: alternative energy systems. *Chem Eng Res Des* 107:263–279
- Wang J, Yang Y, Bentley Y et al (2018) Sustainability assessment of bioenergy from a global perspective: a review. *Sustain* 10(8):2739
- Żołądek M, Figaj R, Sornek K (2021) Energy analysis of a micro-scale biomass cogeneration system. *Energy Conv Manage* 236:114079
- Zurita F, Roy ED, White JR (2012) Municipal wastewater treatment in Mexico: current status and opportunities for employing ecological treatment systems. *Environ Technol* 33:1151–1158

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.