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Prospects of Sustainable Biomass-Based Power Generation in a Small Island Country

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ABSTRACT

Biomass resources are abundantly present in the Pacific Island Countries (PICs) but are mostly used for cooking and crop drying. Only three countries viz. Papua New Guinea, Fiji, and Samoa use biomass for power generation. This paper aims to (i) quantify the forest logging residue generated in Fiji, (ii) carry out a techno-economic and environmental assessment of a potential 10 MW biomass power plant (BPP) in Fiji and study the impact of feedstock cost (FC) on the electricity production cost (EPC) in relation to the financial viability, and (iii) discuss possible strategies to overcome challenges PICs face in developing biomass energy projects. It is found that a 10 MW BPP would require approximately 60,000 tonnes of biomass feedstock, which can be supplied by forest residue from logging in the western division of Viti Levu in Fiji. If the FC is taken as USD68.6/tonne and electricity export tariff to national grid is taken as USD0.1621/kWh, then the net present value is USD16.1 million, simple payback period is 5.6 years, and the benefit-to-cost ratio is 2.5. A sensitivity analysis reveals that electricity export tariff, availability of power plant, and feedstock costs are critical parameters affecting the NPV of the project. Various strategies such as utilising forest residues, planting short-rotation plantations in unused land, enabling policies, early stakeholder engagement, attractive electricity export tariff, and using appropriate harvesting and transportation technologies can help develop the biomass-based power sector in Fiji.

1. Introduction

Access to reliable energy is a primary requirement for the development of any nation because different sources of energy are used for electricity production, transport, and industry. Countries around the globe are concerned about their energy security coupled with climate change impacts and are looking for cleaner, greener, affordable alternate energy sources. One such alternative is bioenergy used as solid biomass for electricity generation and biofuels for electricity generation and transport fuels. According to (REN21, 2020), globally, 6.9% of Total Final Energy Consumption (TFEC) is from traditional biomass usage, while modern bioenergy provides around 2–3% of TFEC. In contrast, 79.9% of TFEC is from fossil fuels. There is a considerable opportunity for renewables to cater to this large share of energy consumption currently being met by fossil fuels. IRENA REmap 2030 envisages modern bioenergy to have the potential to become the most crucial source of growth in renewable energy use (IRENA, 2017).

Extensive research activity is underway to identify the potential of biomass waste to energy conversion in various countries (Chang et al., 2019; Di Fraia et al., 2020; Hiloidhari et al., 2019), the logistics of supplying biomass feedstock, and analysing the costs involved in harvesting, storage and transporting feedstock (Agar et al., 2020; Briones-Hidrovo et al., 2021). The advantage of biomass (especially waste from agriculture and forests) power generation relative to intermittent solar and wind resources is that it is one of the best forms of energy for providing baseload power if the feedstock supply chain is adequately addressed. Electricity can be generated all year long when supplied with a quality, sufficient and sustainable feedstock (Mana et al., 2021; Shabani and Sowlati, 2016). Biomass is also an attractive economic and environmentally friendlier option for power generation. After carrying out a techno-economic of an 11 MW biomass gasification power plant connected to the grid in Portugal (Cardoso et al., 2019), report that the net present value (NPV) of the project is strongly dependent on the electricity sales price and electricity production. For off-grid biomass power plants, it is cost effective to pair BPP with solar PV (Chambon et al., 2020). Majority of these studies are being done in European and Asian countries, but there is limited literature for the Pacific Island Counties (PICs).

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Most PICs have ambitious targets to reduce their carbon emissions although while facing financial, institutional, technical, and geographical challenges. They target 100% renewable energy based electricity generation by 2020–2030 (ADB, 2019). Biomass energy can play a pivotal role in achieving these targets. It diversifies renewable energy supply options beyond solar as recommended by (Cole and Banks, 2017). Biomass use in the PICs is mostly in the form of traditional biomass for cooking and crop drying (IRENA, 2013) with few biomass power plants for electricity production. Only Papua New Guinea, Fiji, and Samoa use biomass for power production (GlobeNewswire, 2019; IRENA, 2013; UN, 2020). Other PICs with available land, good soil quality, and enabling policies have plans to develop biomass power plants. However, there is a lack of published literature on biomass resource assessment and bioenergy potential in smaller PICs. For Vanuatu (Fischer and Pigneri, 2011), studied the possibility of 10 kW and 30 kW biomass gasifiers for possible installation in a rural area with a levelised cost of electricity of $1.60/kWh or less. More recently (Joseph and Prasad, 2020), analysed the electricity generation potential from municipal solid waste in eight different PICs and found mass incineration to have the highest electricity generation potential when compared to landfill gas to energy, anaerobic digestion, and refuse-derived fuel incineration.

Fiji has a diverse biomass resource, agricultural residues from crops (such as sugarcane, rice, coconut, root crops, etc.), livestock manure (poultry, pig, cattle, sheep, and goat), municipal solid waste, sewerage sludge, forest logging residue, and sawmill residue. In addition, perennial grass such as vetiver can also be used as biomass feedstock. This grass has been used in sugarcane farms for more than 50 years (Vanoh and Truong, 2020) for preventing soil erosion and improving soil quality but according to (Truong and Gawander, nodate) there is less uptake of vetiver by farmers, and some have even pulled it (Rosillo-Calle and Woods, 2003) report biomass resource data in 6 PICs using late 90's and early 2000 data. They did a preliminary assessment based on the limited available data, and their report showed forestry residues and agricultural waste having the highest potential for energy production for each of the six countries. (Woods et al., 2006) used biomass energy flow chart to show that forestry, agriculture, and livestock are the key biomass resources in Fiji, Vanuatu and Tuvalu, while (Chandra and Hemstock, 2015) inferred that sugarcane residues and forestry residues have the highest biomass energy potential in Fiji. However, sugarcane residue is already used by sugar mills for electricity generation and in recent years, there has been a decline in sugarcane production. Also, Fiji's agriculture sector is scattered all over the Fiji group and collection of feedstocks to a central site would prove to be costly and challenging. Sugar and copra were the most attractive agriculture-based industries in Fiji until the late 1990s but there has been a decline in productivity of sugarcane and copra (Prasad and Raturi, 2018), while the forestry sector has maintained its productivity over the past years (Vakatawabai, 2020). As will be seen in section 4 of this paper, pine log production is highest compared to mahogany and native log production in Fiji. Furthermore (FDoE and UNDP, 2014a), confirm that bagasse, logging, and forestry residues have the highest theoretical potential for electricity generation, but a techno-economic assessment was not done in their study. To sum up, there are no existing studies on techno-economic assessment of forest residue use in biomass power plants in Fiji. This study attempts to fill this gap in the literature serving as a benchmark for other studies in the Pacific. The results can also be used by government agencies and other key stakeholders in the energy sector for their future planning.

This paper aims to (i) quantify the forest logging residue generated in Fiji, (ii) carry out a techno-economic and environmental assessment of a potential 10 MW biomass power plant (BPP) and study the impact of feedstock cost (FC) on the electricity production cost (EPC) in relation to the financial viability of the 10 MW BPP, and (iii) discuss strategies to overcome challenges island countries face in developing biomass energy projects.

2. Setting the scene for Fiji

Fiji is a small island developing state with relatively negligible contribution to global emissions but is at the frontline of experiencing adverse climate change impacts. Despite various challenges, Fiji has made strong commitments to climate change mitigation.

2.1. Demography and economy

Fiji, Fig. 1, had a population close to 884,887 in 2017, growing at an average rate of 0.6% per annum. It has over 300 islands, out of which one-third are inhabited. The largest island is Viti Levu, where 81% of the population resides, followed by Vanua Levu that has 15% of the population. The real gross domestic product was USD5.243 billion in 2018 with an annual growth rate of 2.6% (FBoS, 2018). Tourism is the biggest sector that brings in most foreign exchange into the country (on average 18% of the real GDP) and is the main driver of economic growth. However, due to the COVID-19 pandemic, tourism activity has almost ceased. As a result, 2020 tourism earnings have decreased significantly from around USD150-200 million per quarter to just USD1.5-2 million per quarter (FBoS, 2018, 2020). With the substantial decrease in tourism earnings and job losses in the tourism sector, it is imperative to boost other sectors' activity. Hence, this study is well placed because it analyses forestry and energy sectors that can encourage growth in these sectors and help build the livelihoods of communities affected by the pandemic.

2.2. Grid power capacity and generation

Energy Fiji Limited, EFL, is the sole power utility in Fiji responsible for planning, generating, transmitting, and distributing grid electricity to four islands in Fiji: Viti Levu, Vanua Levu, Levuka, and Taveuni. In 2019, 1061 GWh of electricity was generated and supplied to the EFL grid. As seen from Fig. 2, the electricity generation share from biomass resources is significantly low compared to hydro and thermal power generation. Independent Power Producers (IPPs) produce electricity from biomass resources, while EFL generates all the other forms of grid electricity. These IPPs are Fiji Sugar Corporation (FSC), Tropik Woods Industries Limited (TWIL), and Nabou Green Energy Limited (NGEL).

FSC and TWIL have combined heat and power (CHP) plants where the heat is used for the mills' drying process. FSC sells power to the grid from its mills in Lautoka, Ba, and Labasa. Lautoka, Labasa, and Ba mills have cogeneration plants of 5 MW, 24 MW, and 9 MW respectively. These IPPs sell electricity to EFL only during the sugarcane crushing season from June to November (EFL, 2019). FSC first uses its electricity internally and then sells any excess energy to the grid. TWIL is a sawmill that produces electricity from its 9 MW power plant using pine residue and sells surplus electricity to the grid. NGEL, commissioned in 2017, uses woodchips to power its 12 MW biomass power plant. The project cost of NGEL was USD45 million (Lal, 2016).

2.3. Challenges faced by biomass power plants

2.3.1. Continuous supply of feedstock

The existing biomass power plants in Fiji procure their feedstock from (i) short-rotation plantation, (ii) forestry and factory wood residues, (iii) logging African Tulip, which is an invasive species in Fiji, and (iv) bagasse from sugar mills. However, with these resources, some BPPs are not able to utilise their full capacity. For example, a recently commissioned 12 MW biomass plant generated 16 GWh in 2018, while in 2019, it had generated only up to 4 GWh by November. It is reported that the same BPP owed landowners a significant amount of money (Elbourne and Ravuwai, 2020). This just confirms that there might not be enough revenue coming into the power plant due to a lack of sufficient electricity generation. However (MoF, 2021), has confirmed that the power plant now operates optimally with feedstock supplied by a

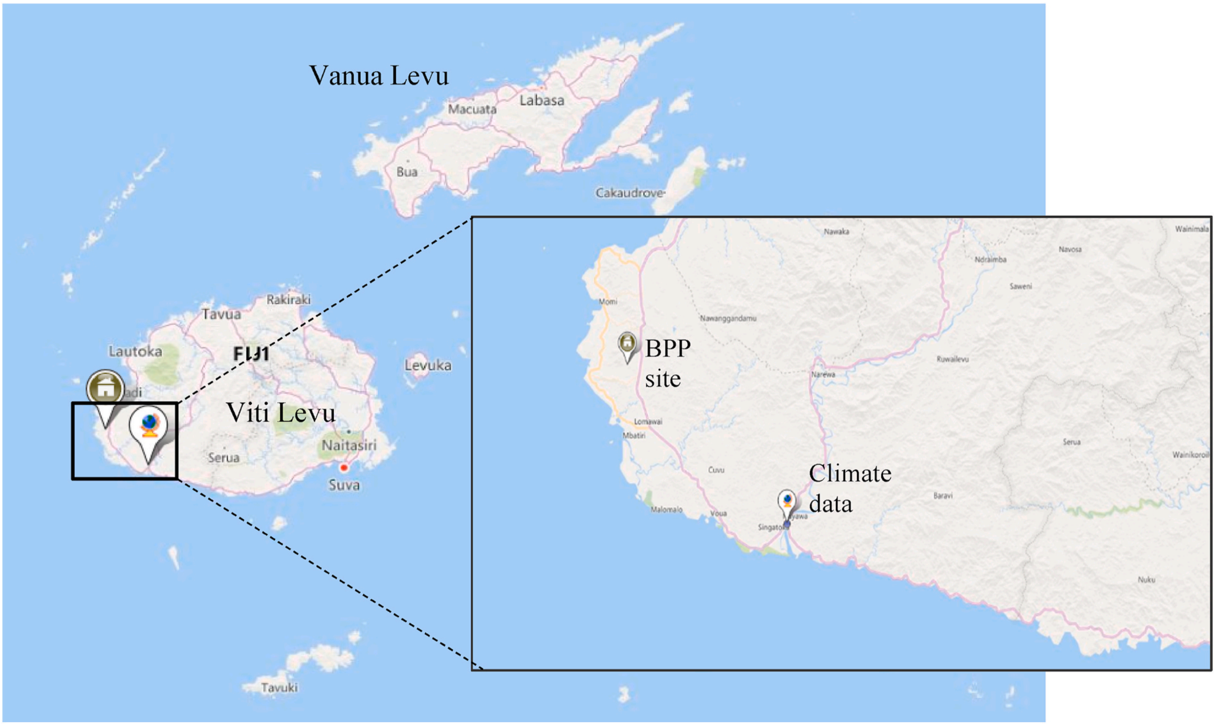

Fig. 1. Site location for proposed site location in the western division of Viti Levu.

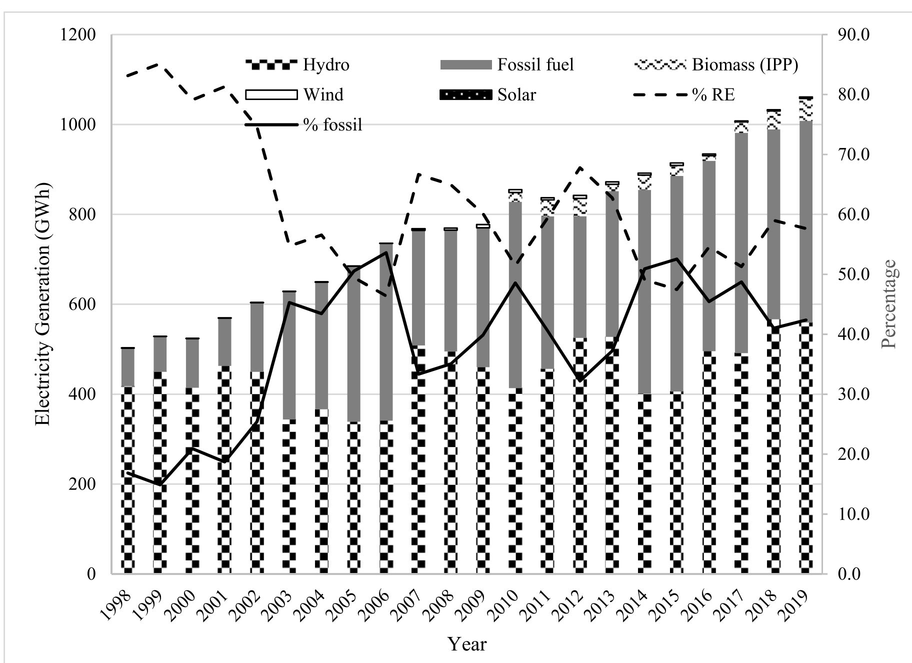

Fig. 2. Electricity generation for EFL grid over the past two decades. Data Source: (EFL, 2019).

sawmill in Vanua Levu and other feedstock.

2.3.2. Biomass inventory not available on public domain

A significant challenge for potential investors in BPP is ascertaining whether an adequate feedstock supply will be available in the future. There is no publicly available database in Fiji or the Pacific to determine suitable biomass resources. (Malico et al., 2016) highlight the lack of knowledge of biomass resource potential in developing countries as a major challenge to bioenergy exploitation.

2.3.3. Lack of standards, regulations, and policies to support biomass power generation

Fiji does not have a diverse feed-in-tariff structure that considers different generation technologies, locations, and generation costs. As per the Fijian Competition and Consumer Commission (FCCC), there exists an approved independent power producer (IPP) tariff rate of a minimum USD0.1621 per unit (FCCC, 2014). A high tariff can be given to IPPs based on the cost of generation and location of the power plant subject to an agreement by EFL. In addition, Fiji does not have sufficient enabling policies for biomass power generation such as standards on imported equipment and installing procedures, incentives for farmers to grow short-rotation woody crops or using forest residues for power generation.

2.3.4. Weather patterns

Another challenge is climate change impacts such as cyclones, flooding, and changing rainfall patterns. Lack of rain during planting seedlings can reduce the seedlings' survival rate (Chowdhury, 2019). Cyclones destroy crops, farms, and forests with cyclones becoming more severe now. The category 5 tropical cyclone Winston that hit Fiji in February 2016 damaged the forestry sector with an estimated loss of USD13.82 million (GoF, 2016a).

2.3.5. Setting fire to forest plantations

There are cases of forest fires in Fiji that impact the feedstock supply, cause loss of biodiversity, and increase greenhouse gas emissions. In 2017, Fiji Pine lost 2,500 ha of plantations because of fires (Tuilevuka, 2018). This loss was approximately 10% of Fiji Pine's production area. (King, 2001) reports that forest fires are a common occurrence from May to October in the western division of Fiji. According to (GlobalForestWatch, 2021) from February 2020 to February 2021, there were 22 visible infrared imaging radiometer suite (VIIRS) fire alerts for Fiji. Hence, there should be more fire management systems in Fiji and awareness creation in communities and landowners on forest fires. The Ministry of Forestry (MoF), Secretariat of Pacific Community, and other partners are developing a national strategy for managing forest fires (SPC, 2017) which will help in alleviating forest fires.

2.3.6. Salty air

The salty and moist air on the islands can cause rusting of metal structures in buildings. During the installation of one of the biomass power plants in Fiji, the effect of salty air on the equipment was not considered leading to cases of rusting equipment at the power plant.

2.3.7. Importation of equipment

Nearly all the equipment for a biomass power plant in Fiji are imported. As a result, prolonged disruptions in electricity generation can occur if crucial equipment or component is to be replaced.

3. Method

This study is divided into three parts. The first part deals with the determination of forest residue from different divisions in Fiji. The second is the techno-economic feasibility study of a 10 MW biomass power plant project. Finally, the last part discusses strategies to overcome the challenges faced by Fiji and other island countries in developing BPPs.

3.1. Forest residue potential

The annual log production data was sourced from Fiji Department of Forestry (FDoF) for Fiji's forest residue potential determination. In Fiji, mostly three types of trees are logged: pine, mahogany, and native. Pine trees are harvested when they reach 16–20 years of age, mahogany trees are harvested at 30–40 years depending on their harvestable diameter, and native trees are logged once the trees mature and permission is granted by the MoF.

Not all native trees are logged due to forest conservation and management plans and hence, Equation (1) estimates the volume of logged forest residue, and Equation (2) calculates the mass of forest residue generated.

$$V_{WL} = \frac{V_L \times r}{1 - r} \tag{1}$$

where V_{WL} is the volume of waste from logging (m^3), V_L is the volume of log production (m^3), and r is the waste ratio (0–1).

Equation (2) was used to calculate the mass of waste generated from forest logging, $M_{residue}$.

$$M_{residue} = V_{WL} \times \frac{\text{density of wood}}{1000} \tag{2}$$

According to (Koopmans and Koppejan, 1997), log to forest ratio is 50:50, that is, for every 1 m^3 of log produced there is 1 m^3 of forest residue. (GOI, 1990) reports that 40% residue is left after logging where 12% is stemwood above the first branch, 13.4% is branchwood, 9.4% natural defects, 1.8% stemwood below the first branch, 1.3% falling damage, 1.6% stumpwood, and 0.5% leaves. Hence, this study takes an average value of 35% for forest residue to calculate the volume of waste. The density of pine, mahogany and native trees were taken as 465, 490 and 500 kg m^{-3} respectively.

3.2. Technical and financial analysis of a proposed 10 MW BPP

RETScreen is a clean energy management software used by the public and private sector that helps professionals assess the technical and financial viability of multiple renewable energy, energy efficiency, and cogeneration projects (RETScreen, 2020). (Malico et al., 2016) have used RETScreen to assess the financial viability of a biomass heating system, while (Blair and Mabee, 2020) have used RETScreen to obtain climate data for a forest-based community in Ontario and analysed different technologies for heating an energy system fuelled by forest residue. This study uses RETScreen to carry out technical and financial analysis of a proposed 10 MW biomass power plant in Fiji.

For this feasibility study, a biomass power plant running on Rankine cycle is proposed. (Madadian et al., 2021) describe in detail the operation of a steam turbine running on the Rankine cycle. A typical biomass power plant in Fiji would obtain wood from forest or sawmill residues or short-rotation trees. Burned wooden material that is left over in the forest can be used in the biomass power plant but it is not considered in this paper as the FDoF is striving to take appropriate measures to prevent forest/plantation forest fires under the Forest Bill 2016 (GoF, 2016b). The feedstock considered in this work would be chipped at the power plant site and moved to the storage building for later use in the boiler. The feedstock would be combusted to provide heat to the boiler that produces high-pressure and high-temperature steam. The high-pressure steam would then drive the turbine connected to the generator to generate electricity, Fig. 3. The condensed steam would be pumped back into the boiler. The ash generated from burning woodchips can be collected and transported to the plantations for use as fertilizer.

The proposed BPP site is Sigatoka, located on the western side of Viti Levu Island, Fig. 1, which receives 5.48 kWh/m^2/day of solar energy and has an annual precipitation of 1,975 mm, Fig. 4. The biomass feedstock was taken to be wood chips with an energy content of 19.8

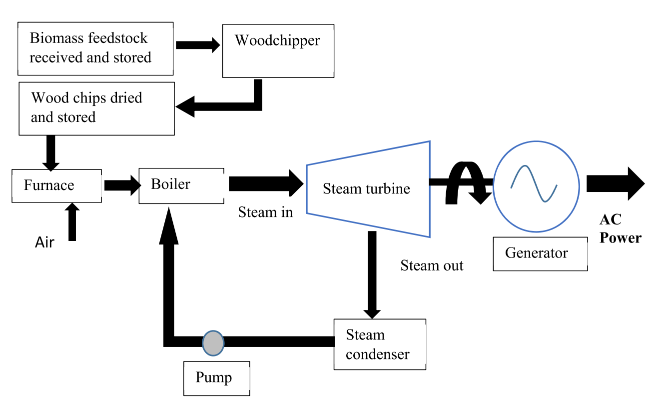

Fig. 3. Block diagram for typical biomass power plant.

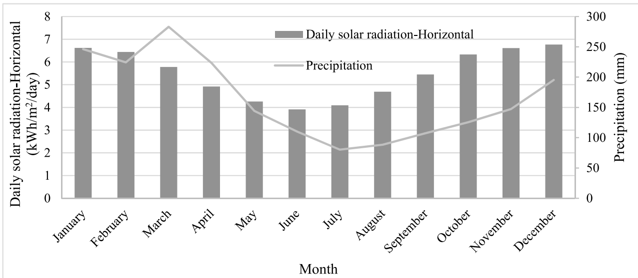

Fig. 4. Climatic conditions for the proposed site. Data source: (RETScreen, 2020).

MJ/kg. A backpressure steam turbine was considered for modelling, and Table 1 summarises the technical details for the steam turbine. The technical details in Table 1 is sourced from virtual analyser in RETScreen using a 5-star benchmark database (RETScreen, 2020) for a steam turbine power plant with biomass as the feedstock.

For financial viability analysis, the discount rate was taken as 10% (Prasad and Bansal, 2011), project lifetime as 25 years, and the project investment cost as USD3,675/kW based on the figures for the 12 MW biomass power plant installed in Fiji (Dean, 2014). According to FCCC, an independent power producer supplying electricity to the national grid on 24/7 basis would get a minimum IPP rate of USD0.1621/kWh (FCCC, 2014). Fiji has exported pine woodchips to China at approximately USD68.6/tonne (Chambers, 2020). Hence, electricity export rate of USD0.1621/kWh and FC of USD68.6/tonne were considered for determining the financials of the 10 MW BPP project. The inflation rate pre-COVID-19 pandemic was 1.77% in Fiji in 2019 and the 10-year average was 3.2% (Macrotrends, 2021). However, during COVID-19 outbreak, inflation is forecasted to be 1% by end of 2020 and 1.4% by end of 2021 (RBF, 2020). Hence, a 3.2% inflation rate and 2% fuel cost escalation rate are assumed.

A sensitivity analysis was also carried out to study the effect on EPC and NPV by changing the FC and electricity export tariff variables. To study the effect of electricity export rate on the projects financials, the electricity export rate was varied while keeping FC constant. This was done because there are instances in Fiji when the utility pays less than USD0.1621/kWh to IPPs. In addition, to see the effect of variability of feedstock price on the EPC, sensitivity analysis was done by varying the feedstock cost while keeping the electricity export tariff constant. Further, sensitivity analysis was also carried out to determine the most critical factor affecting the net present value, simple payback period and EPC of the proposed 10 MW BPP project, similar to a study by (Naqvi et al., 2017).

Table 1
Technical details of steam turbine considered in modelling.

Parameter	Unit	Quantity
Steam turbine		
Steam flow	kg/h	40,000
Operating pressure	kPa	3,600
Saturation temperature	°C	244
Superheated temperature	°C	420
Enthalpy	kJ/kg	3,276
Entropy	kJ/kg/K	6.9
Back Pressure		
Back pressure	kPa	7
Temperature	°C	39
Mixture quality		0.82
Enthalpy	kJ/kg	2,146
Theoretical steam rate (TSR)	kg/kWh	3.2
Steam turbine efficiency	%	80
Actual steam rate (ASR)	kg/kWh	4
Summary		
Power capacity	kW	10,048
Availability	%	85
Seasonal efficiency	%	80
Return temperature	°C	39
Fuel required	GJ/h	156
Initial costs	USD/kW	3,675
Operation and maintenance costs (O&M)	USD/kW/year	154
Electricity exported to grid	MWh	74,816

4. Results

4.1. Potential of forestry residue availability

According to (DoF, 2015), Fiji has a total of 1.2 million hectares of forest area, of which 82.1% is native forest, 7.3% pine plantations, 5.6% mahogany plantations and 5% mangroves. Northern division has the largest forest area covering 40.2% of the total, followed by central-eastern division with 31.0% and western division with 28.8%, Fig. 5. Native forests are most extensive because they are protected under the laws. Pine and mahogany forests are heavily logged while a small number of native species are logged, Fig. 6. The high production of pine logs is because it contributes to commercial and export activity in Fiji.

Considering log production data by different divisions from 2009 to 2015 in Fig. 7, the western division has the highest log production. The average annual log production for western, central, and northern is 259,417 m^3, 130,749 m^3 and 97,135 m^3 respectively. Out of the total log production in western division, 97% are pine logs while 2% are native and 1% mahogany, Fig. 7. This is because western is the dryer side and weather conditions are suitable for pine tree growth. In the central division 46% are pine logs while 48% are mahogany and the remaining are native logs. On average, there is 46% of native log production in the northern division while 48% is pine logs and 6% mahogany logs.

Using Equation (2), the average annual forest residue generated using 2009–2019 data is estimated as 112,000 tonnes, half the amount required by a 10 MW plant. However, these residues are spread all over the country in central, western, and northern division.

At the time of analysis, the log production data available to authors for analysis from different Fiji divisions dated from 2009 to 2015. Based on this data, the estimated forest residue generated annually from central, western, and northern divisions is 34,000, 65,000, and 25,000 tonnes respectively.

4.2. Case-study of technical and financial analysis

Simulations show that a feedstock input rate of 156 GJ/h, equivalent to 8 tonnes per hour and approximately 60,000 tonnes/annum, is needed by a 10 MW BPP. This input would yield 74.8 GWh of electricity per annum when the annual system availability is 85%. This can increase the renewable share in Fiji's electricity generation and make the energy sources used by EFL more diverse. In their analysis (Malek et al., 2017) have also found 80 GWh of annual energy generation from a 10

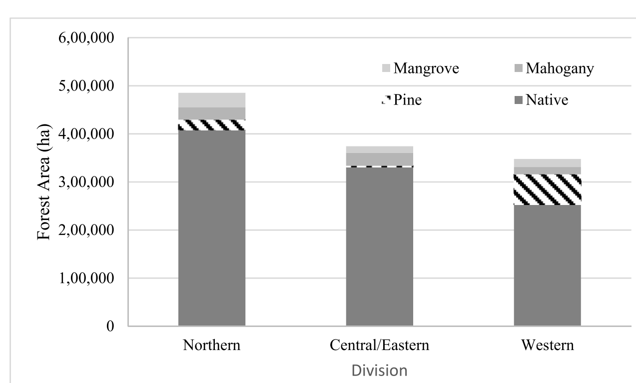

Fig. 5. Forest areas in different divisions in Fiji. Data Source: (DoF, 2015).

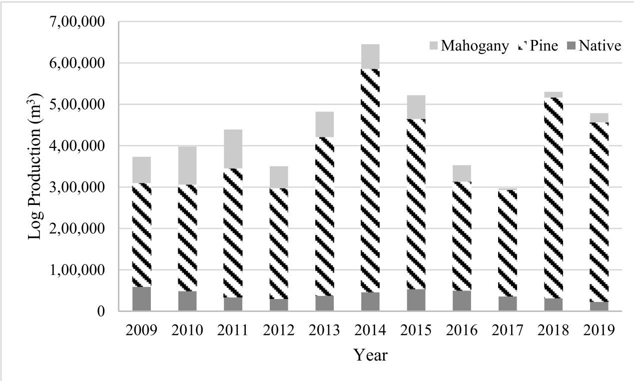

Fig. 6. Log production in Fiji over the past 11 years. Data Source: (DoF, 2015; Vakatawabai, 2020).

MW biomass power plant.

Running the financial viability of a 10 MW biomass power plant in Fiji yields interesting results as shown in Table 2. If the electricity export tariff is taken as USD0.1621/kWh and FC as USD68.6/tonne, then the NPV is USD 16.1 million, EPC is USD0.14/kWh, internal rate of return (IRR) is 28.9% (against a discount rate of 10%) with a simple payback period of 5.6 years and benefit to cost ratio of 2.5. This scenario should be financially attractive for a potential BPP investor, given a reliable feedstock supply chain. (Abdelhady et al., 2018) calculated the cost of power generation from rice straw as USD0.06–0.10/kWh, while (Mana et al., 2021) analysed the cost of production as USD0.113/kWh from agricultural biomass waste and (Masum et al., 2020) found the cost of power generation from pine chips as USD0.113/kWh. The results of these studies are comparable with the analysis done in this paper.

A sensitivity analysis was carried out with FC and electricity export tariff as variables to see their effect on EPC and NPV (Table 2). When the FC is kept constant at USD68.6/tonne, and the electricity export tariff is decreased, it is seen that the BPP project would lose its financial attractiveness if the electricity export tariff is less than USD0.14/kWh. On the other hand, electricity tariff more than or equal to USD0.14/kWh yields positive financial returns for BPP investors. This raises the question: to make BPP financially attractive at low electricity export tariff, what should be the feedstock price?

To answer this question, the electricity export tariff was kept constant at USD0.1621/kWh and the FC was varied to study changes in EPC, Table 2. This would inform the stakeholders about the maximum FC to keep the project as financially viable. One of the challenges of biomass-based power generation in Fiji is the electricity export tariff given by

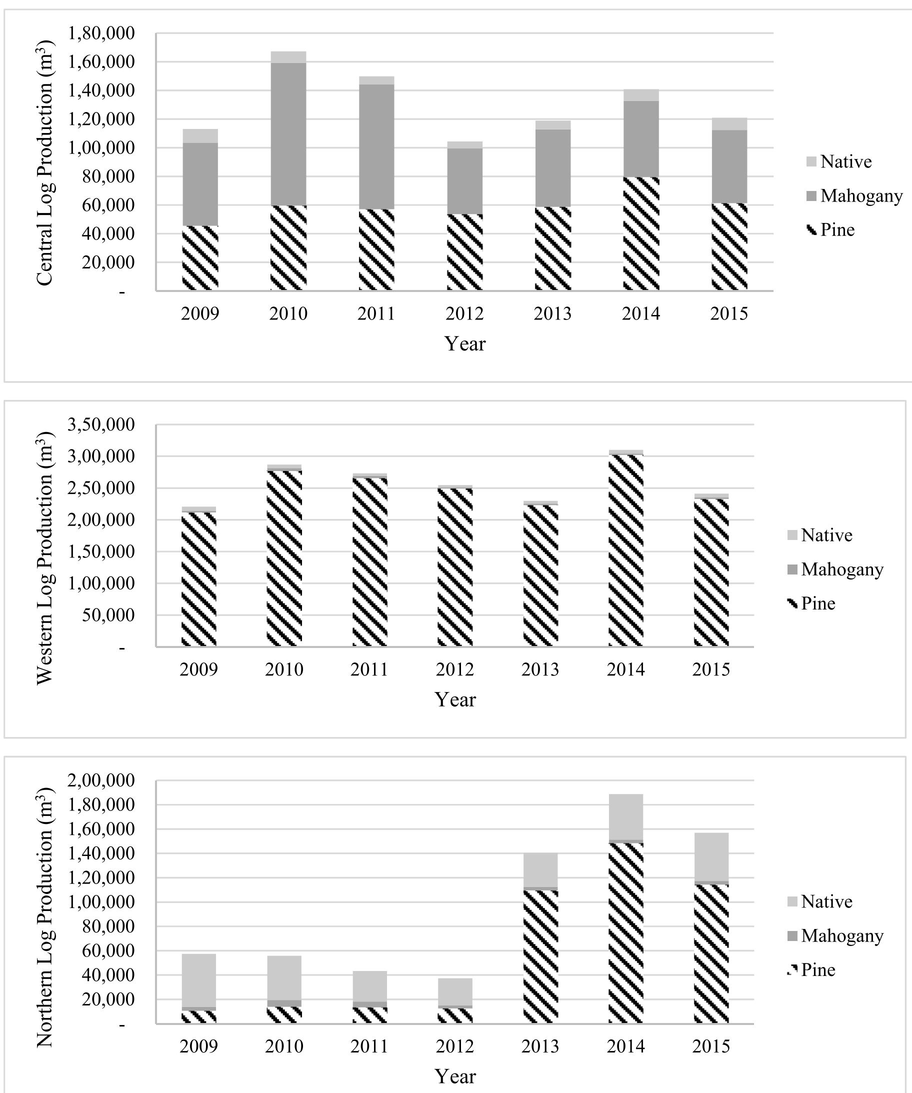

Fig. 7. Annual log production by different divisions in Fiji. Data Source: (Cakautabu, 2016).

Table 2
Analysing financial viability when feedstock price varies and when tariff varies.

Parameters	Unit								
Fuel cost escalation rate	%	2%							
Inflation rate	%	3.2%							
Discount rate	%	10%							
Project life	Years	25							
Capital cost	USD/kW	3,675							
FC – USD68.6/tonne									
Electricity export tariff	USD/kWh	0.1621	0.147	0.139	0.1225				
Pre-tax IRR – equity	%	28.9	17.2	10.4	negative				
Simple payback	Year	5.6	6.8	7.6	10.3				
Equity payback	Year	3.2	5	7.7	> project lifetime				
NPV	USD	16.1 M	5.77 M	0.29 M	−11 M				
Annual life cycle saving	USD/yr	1.77 M	0.64 M	0.03 M	−1.2 M				
Benefit-cost ratio (BCR)		2.5	1.5	1	0.006				
GHG reduction cost	USD/tCO_2	−81.3	−29.11	−1.46	55.59				
EPC	USD/kWh	0.14	0.14	0.14	0.14				
Keeping electricity export tariff	*USD/kWh*	*0.1621*							
FC	USD/tonne	29.4	39.2	49	58.8	68.6	78.4	88.2	98
Pre-tax IRR - equity	%	52.4	46.7	41.2	35	28.9	22.4	15.1	5.4
Simple payback	Year	4.2	4.5	4.8	5.2	5.6	6.2	6.8	7.6
Equity payback	Year	1.9	2.1	2.4	2.7	3.2	3.9	5.2	16
NPV	USD	41.0 M	34.8 M	29.55 M	22.3 M	16.1 M	9.9 M	3.7 M	−2.55 M
Annual life cycle saving	USD/yr	4.5 M	3.8 M	3.25 M	2.5 M	1.8 M	1.1 M	0.4 M	−0.287 M
Benefit-cost ratio (BCR)		4.7	4.2	3.7	3	2.5	1.9	1.3	0.77
GHG reduction cost	USD/tCO_2	−207	−175	−149	−113	−81.3	−49.93	−18.54	12.85
EPC	USD/kWh	0.103	0.112	0.1186	0.131	0.14	0.149	0.158	0.167

utilities to IPPs. Table 2 shows the price parity of electricity export tariff to feedstock cost. If the electricity export tariff is USD0.1621/kWh, then to have a positive net present value, feedstock price must be less than USD98/tonne. Higher than this value would make the project's financials unattractive by increasing the EPC. Potential investors can use the EPC to negotiate the electricity export tariff with the regulatory bodies and provide an explanation to stakeholders.

Fig. 8 shows the relationship between EPC and FC, and Equation (3) models how electricity production cost is dependent on feedstock cost.

From linear regression in Fig. 8, it was found that:

$$EPC = 0.0009\ FC + 0.075 \text{ with an } R^2\text{-value of } 1. \tag{3}$$

Where EPC is in USD/kWh and FC is the feedstock cost in USD/tonne.

In making biomass power generation projects successful, FC must be calculated with as much accuracy as possible because it has a significant bearing on EPC as seen in this study as well as in (Abdelhady et al., 2018; Mana et al., 2021). In Fiji, the actual biomass feedstock cost is unknown, and this sensitivity analysis shows how varying feedstock costs affect EPC. The stakeholders can use this relationship to negotiate their electricity export/import tariff.

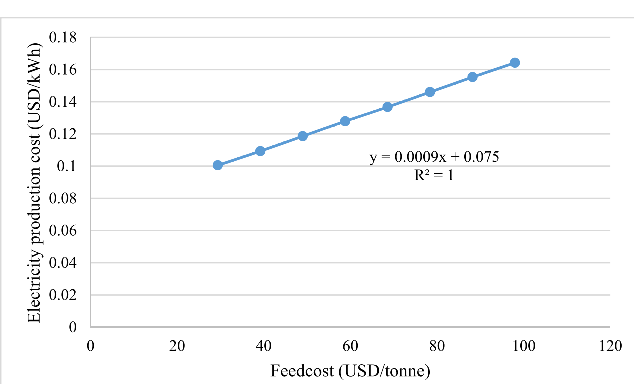

Fig. 8. Correlation of feedstock cost and biomass energy production cost.

4.3. Sensitivity analyses

4.3.1. Effect on NPV

A further sensitivity analysis was run on NPV of about 16.1 million USD as a base case selected at (i) capital cost USD3,675/kW, (ii) O&M costs of USD154/kW-yr, (iii) discount rate of 10%, (iv) inflation rate of 3.2%, (v) FC of USD68.6/tonne, (vi) electricity export tariff of USD0.1621/kWh and (vii) availability of power plant of 85%. As shown in Fig. 9 the most critical parameter is electricity export tariff followed by availability of the power plant and then the FC. This is also confirmed by (Cardoso et al., 2019) who reported that NPV is greatly affected by the electricity sale price. Our analysis shows that a 10% decrease in electricity export tariff will result in a 69% decrease in NPV, indicating the importance of negotiating a suitable and long-term electricity export tariff rate.

If the electricity export tariff decreases lower than 15% (less than approximately USD0.14/kWh), the NPV becomes negative, indicating

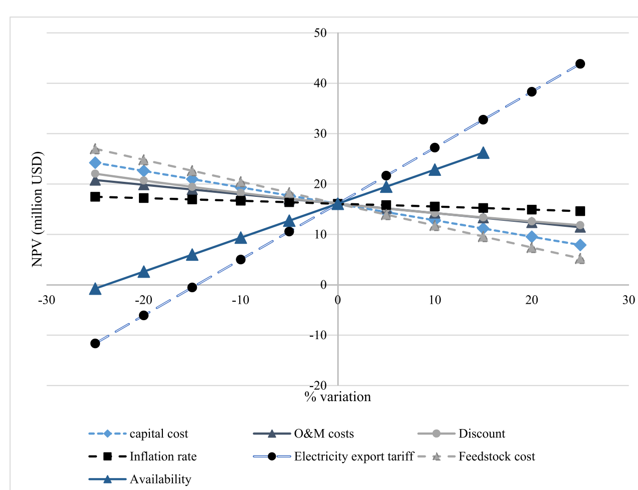

Fig. 9. Sensitivity diagram of net present value.

the project is not financially feasible. For biomass-based power plants, availability of power plants depends on the downtime for maintenance of the plant and the downtime due to shortage in the feedstock. Analysis shows an 84% decrease in NPV when availability of power plant decreases by 20%, that is, the availability of the power plant is 68% (5,957 h per year). FC is the third critical parameter for the project's financial viability. FC will depend on forest residue or energy crops harvesting techniques, transportation costs, feedstock processing, and storage costs. If the FC increases by 20%, then the NPV decreases by 54%.

About 51% variation in NPV is observed when the capital cost varies by ±25%. Further, O&M costs and discount rate changes have approximately 20–30% variation in NPV when these parameters vary by 20%. Inflation rate is relatively least effective on NPV as it shows only 9% variation in NPV when the inflation rate varies by 25%.

4.3.2. Effect on simple payback period

The most critical parameters affecting the simple payback period are electricity export tariff, power plant availability, capital cost, and FC as shown in Fig. 10. The simple payback period is inversely related to electricity export tariff and availability of the power plant, while it is directly related to capital cost, O&M cost, and FC. The discount rate and inflation rate do not affect the simple payback period because simple payback period does not consider the time value of money. If the electricity export tariff decreases by 25% from its base value of USD0.1621/kWh, the simple payback period increases by 87.5% from its base value of 5.6 years. Similarly, if the power plant availability decreases (due to maintenance) by 25% from its base value of 85%, then the simple payback period increases by 44%. In contrast, capital cost affects the simple payback period linearly. That is, when the capital cost increases by 25% from its base value of USD3,675/kW, the simple payback period increases by 25%. Likewise, if the FC increases by 25% from its base value of USD68.6/tonnes, the simple payback period increases by approximately 20%.

4.3.3. Effect on EPC

Sensitivity analysis was carried out to analyse the impact of the various parameters on electricity production cost. The most critical factors affecting the EPC are again seen to be power plant availability, FC followed by capital cost, and then O&M cost as seen in Fig. 11. If the availability of the power plant reduces by 25%, then the EPC increases by 18%. FC has a positive linear relationship with EPC. If the FC increases by 20%, the EPC increases by approximately 9%. A 25% variation in capital cost and O&M cost, varies the EPC by 8.6% and 5% respectively. Discount rate and inflation rate least affect the EPC, as a 25% variation in these parameters only makes a 1–2% variation in EPC.

While the financial and technical feasibility of the proposed BPP looks promising from the preceding analysis, it is imperative to study the biomass supply chain to make the project feasible. Factors such as locations of the biomass power plants, feedstock types, land availability, and sustainable forestry are discussed below.

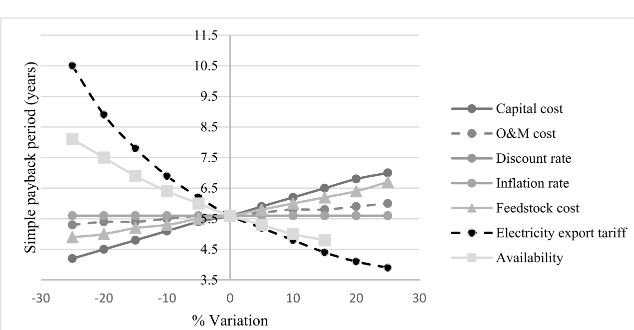

Fig. 10. Sensitivity diagram on simple payback period.

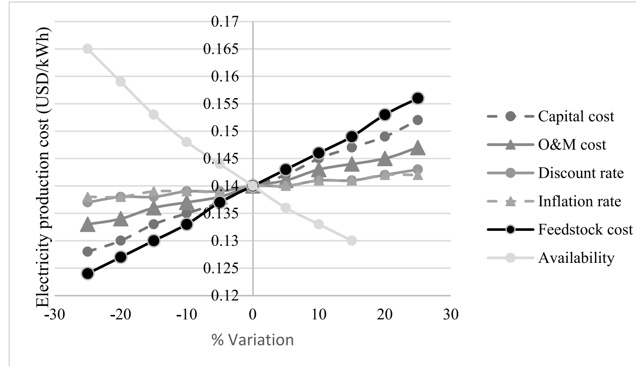

Fig. 11. Sensitivity diagram on electricity production cost.

5. Discussion

5.1. Electricity production from biomass resource versus biomass resource for carbon sequestration

Before any further discussion on strategies to promote BPP in Fiji, it is imperative to discuss the implications of Fiji being the 10th country in the world (and the first small island developing state) to sign a USD12.5 million Emission Reduction Payment Agreement (ERPA) with the Forest Carbon Partnership Facility (FCPF). As a part of this agreement, Fiji will reduce its carbon emissions through native forest management, integrated land use planning, sustainable pine and mahogany plantations, community-driven afforestation, climate-smart agroforestry, and alternative livelihoods initiative (WB, 2021). Local communities and other stakeholders were consulted on their role in ERPA to have fair recognition and reward for all stakeholders. Even though this initiative supports afforestation, it also encourages sustainable pine and mahogany plantations and climate-smart agroforestry. The development of short-rotation woody crops can also be part of this initiative. Sustainably growing them can reduce emissions by capturing carbon while providing feedstock to biomass power plants to support Fiji meet its international commitments as well as national development goals. (Favero et al., 2020; Lin and Ge, 2020) also highlight in their studies that developing forestry sector bring in economic income and act as carbon sinks. (Lin and Ge, 2020) highlight that countries, especially developing countries, need to balance bioenergy production that reduce carbon emissions and forests that sequester carbon. For Fiji, there can be dedicated areas for carbon sequestration and dedicated areas for planting forests to provide biomass feedstock to BPPs.

5.2. Strategies to promote sustainable biomass power plant

The main requirement of any BPP is the availability of quality feedstock at the lowest possible price continuously throughout the year. The availability of feedstock depends on feedstock costs, which is affected by access and use of land, transportation, processing, and storage costs. Therefore, it is critical to site the BPP in such a way so that feedstock supply costs are minimised. Apart from forest residues, short rotation woody crops (that have coppicing ability and can be harvested 5–8 years of age, perennial grasses or chicken manure can be considered as feedstocks. Diverse feedstock supply options are vital for BPPs availability. The electricity export tariff offered to IPPs can positively affect the investors who can pay for feedstock and procure and plant more feedstock for the BPP. The capital and O&M costs also affect the BPP's sustainability as low values of these ensure more saving and less time to recover the initial investments. These strategies are summarised in Fig. 12 and are discussed below for a BPP's optimal and sustainable operation.

5.2.1. Enabling policy and regulatory environment for BPP

Lack of institutional arrangement and enabling policy are the major drawbacks in developing and implementing biomass power projects (Carlos and Khang, 2008), and so (ADB, 2009) recommends that successful development and deployment of biomass power generation require targeted and end-use specific policy prescriptions. Currently, Fiji is providing 5-year tax holidays to developers undertaking renewable energy projects, and charges zero duty for importing renewable energy goods (FRCS, 2018). It has an Import Substitution & Export Finance Facility that offers concessional loans for new renewable energy investments and sustainable public transport. However, to promote sustainable BPP, Fiji must also provide (i) incentives for farmers for planting short-rotation woody crops (ii) incentives to communities for collecting and/or transporting forest residues, (iii) incentives to landowners for using or providing their land for growing energy crops, (iv) incentives, concessions or subsidies to transporters supplying feedstock to power plants, (v) financing mechanisms or risk-reducing mechanisms for investors to invest in biomass power generation and (vi) attractive feed-in tariff to IPPs.

5.2.2. Early stakeholder engagement

(Rajala et al., 2021) stated that projects gained broader support and manifested in tangible outcomes in the longer term when genuine and early stakeholder engagement was done while (Andersen et al., 2006; Waris et al., 2019) provided insights into critical factors of stakeholder engagement that lead to the success of renewable energy projects and project completion on time and at cost. Hence, early engagement of local communities or villages, landowners, loggers, and truckers is a must for biomass power plants' successful operation for any BPP project. The key stakeholders need to be consulted so that they have active participation in the electricity generation processes. From the power plants' planning stage to the actual operation, these key stakeholders must know and understand the crucial part they would play in the power plant's success. In Fiji, an informal community consultation session ("talanoa") must be held with villagers, village headman and transporters to discuss their contribution as landowners and forest farmers. Also, women must be included in the discussion for their assistance in forest residue collection and related income generation activities. Manual collection of forest residue (branches and stems) in developing countries can create job opportunities for locals and maintain nutrient in the forest area by leaving the twigs and leaves (Eker et al., 2017). This is applicable to Fiji as many people have moved back to their villages during COVID-19 and so engagement in the forestry sector can prove to be an income generation activity.

5.2.3. Land tenure, contract agreements and lease agreements

Around 90% of Fiji's land is owned communally (known as *mataqali*), while the remaining is state-owned or private (freehold). For forests, 90% of the native forests belong to communities, and planted forests are on leased land where the land belongs to *mataqali* but trees are owned by companies that rent land (SPC, 2015). The Fiji Pine Limited and Fiji Hardwood Corporation Limited are the central bodies that oversee the logging of planted forests. Usually, a 99-year lease is given to farmers.

MoF is trying to develop lease agreements and contracts to make land available to biomass plant investors to plant energy crops. For these agreements, the MoF is working with the Ministry of iTaukei, sugarcane farmers, and government administrators for different districts that are stakeholders for this vital task (MoF, 2019). However, Fiji can learn from past experience of biomass power plants in the U.S. (Wiltsee, 2000) that long term contracts are a liability because landowners feel that they have lost control of their land and hence (Roise, 2016), suggests short-term contracts (5–7 years).

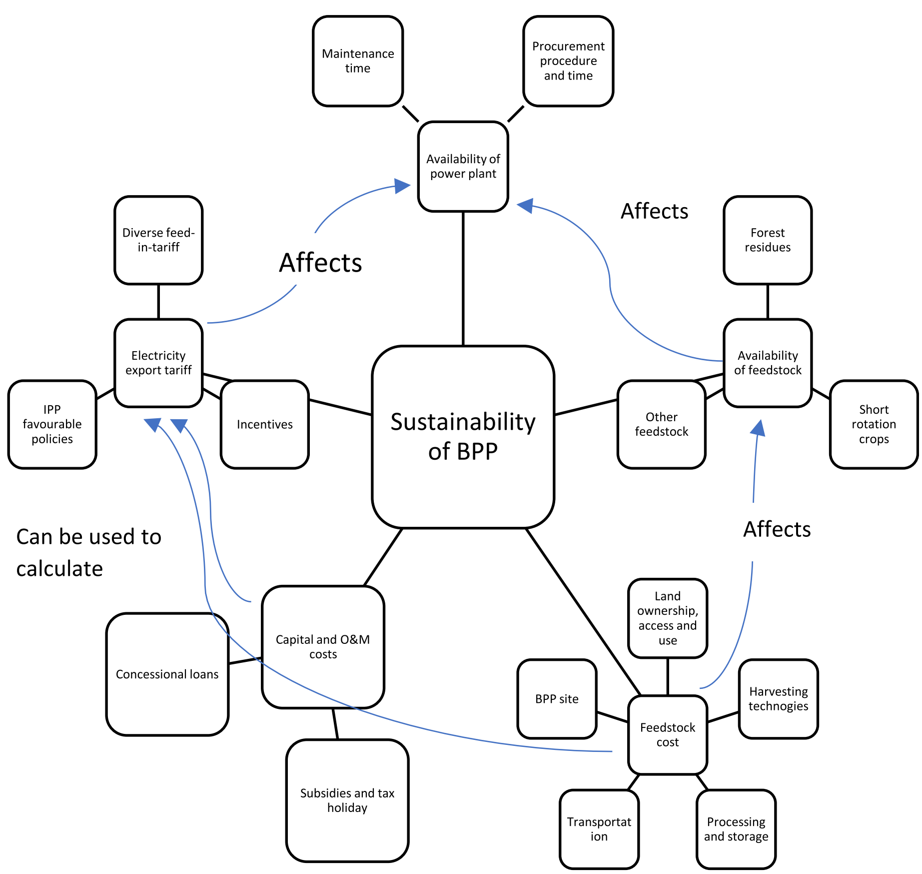

Fig. 12. Concept map of sustainability of biomass power plant.

5.2.4. Dedicated land for short-rotation woody crops (SRWC)

Based on the RETScreen tool analysis, a 10 MW power plant needs approximately 60,000 tonnes of feedstock per annum when the feedstock's energy content is taken as 19.8 MJ/kg. Due to seasonal variability, if forest residue is not available, one option for meeting feedstock demand is planting short-rotation woody crops. However, there must be access to land and long-term commitment of growers and landowners to do this. (Christersson and Verma, 2006) report that short-rotation plantations are trees grown either as single stems or as coppice systems, with a rotation period of fewer than 30 years and with an annual woody production of at least 10 tonnes of dry matter or 25 m^3 per hectare. So, considering wood production of 10 tonnes/annum output from short-rotation plantations, 6,000 ha of land is needed.

One option for land could be the sugarcane farms that are no longer used for farming due to farmers' lease not being renewed or farmers not willing to do sugarcane farming because they have migrated to towns or cities for other more lucrative job or are too old and their children turning to "white collar" jobs after getting tertiary education. (Kumari and Nakano, 2016) confirm that sugar production has declined from 1998 mainly due to decrease in harvested area, from 66,000 ha in 1999 to 49,000 ha in 2009. Hence, people interested in farming short-rotation plantations or energy crops used in BPPs can apply for agricultural lease or forestry land lease from iTaukei Land Trust Board.

Degraded land could also be another option for growing short-rotation woody crops (Koutika and Richardson, 2019). In Fiji, land degradation drivers are deforestation, intensive sloping, flat farming, and reclamation of mangrove swamps (FAO, 2018). Stakeholders can work with the MoF to identify degraded land areas where short-rotation woody crops can be grown and other food crops (FAO, 2018).

5.2.5. Planting short-rotation woody crops (SRWC)

The government, ministries, communities, and landowners must begin planting short-rotation trees to diversify energy supply options for electricity generation. Subsidies and other incentives must be given to boost planting. Currently, FDoF promotes planting 30 million trees in 15 years (30MT15Y) to protect the environment. The sustainable growth of short-rotation plantations can contribute towards this goal while also providing fuel for BPP.

SRWC, also called woody energy crops, are mainly hardwood trees harvested within five to eight years of planting, grown on various soil types, require few inputs, and little or no pesticide or fertilizer. As a result, they are an ideal feedstock for biomass supply chains (Jackson, 2019) because of their high biomass productivity and ability to grow quickly even after severe damage from hurricanes (Schroth and da Mota, 2014).

The land requirement for SRWC can lead to a food versus fuel debate, especially for small island states. However, one solution is to do integrated farming, that is, agroforestry. Pacific region has been doing agroforestry for decades (Vergara and Nair, 1985) but its utilisation in Fiji is not on a great scale. Hence, SRWC planting can be combined with the farming of crops or livestock on the same land. This solves the fuel vs. food debate, restores nutrient cycling and sequesters carbon (Koutika and Richardson, 2019).

In Fiji, the MoF is acquiring land and planting SRWC such as Gliricidia sepium, Acacia mangium, Acacia auriculiformis and Eucalyptus camaldulensis. These plants prefer a sunny tropical climate and can grow in low-medium fertility soil.

5.2.6. Utilising waste generated during logging

Utilising forest residue for commercial purposes has a positive social and economic impact on people living near forest areas. In addition (Smyth et al., 2017), conclude that using harvest residue for bioenergy production reduces GHG emissions in populated regions and (Rijal et al., 2020) state that forest residue is an attractive source for bioenergy production because of its abundance and renewability. For the proposed 10 MW BPP, 60,000 tonnes of feedstock are needed annually. This can easily be supplied by forest residue generation from western division in Fiji as seen from results in section 4.2, which shows 65,000 tonnes of annual forest residue generated in western division. However, the feedstock transporting cost, storage space, handling cost, drying cost, and losses along these process lines must all be considered.

5.2.7. Planning logistics of planting, harvesting and transporting

With the enabling policy instruments, farmers will be able to plan, preferably a year before planting. The process involved during planting SRWC, extracting forest residue or short-rotation wood crops from the plantations, storage, handling, and delivery to power stations needs to be well understood. The main aim during harvesting and transporting is to adhere to safety procedures while minimising biomass losses and costs. A model was built that can be used to identify wood biomass availability and cost characteristics for any region or country given the area's specific characteristics (Simon et al., 2021). In addition, several researchers discuss that biomass transport costs can take majority of the total FC and is an influencing factor in determining the cost-benefit analysis (Ko and Lautala, 2018; Li et al., 2021; Mohaghegh et al., 2021). In terms of siting of biomass power plant, (Li et al., 2021) analysis shows that if the transporting radius is less than 40 km, then economic costs are low, which (Schnorf et al., 2021) concurs and further find that for some cases, breakeven point is even reached as further as 400 km.

Hence, a BPP needs to be strategically sited, and route of transport carefully planned to decrease FC. In addition, (Sahoo et al., 2019) found that the lowest cost is when forest residues are transported in log trucks and chipped at the power plant while (Zhao and Li, 2016) have analysed a model where biomass feedstock is collected from site and transported to primary site for processing and storage, then third party logistics companies come in to transport the stored feedstock to the BPP. So, there can be different types of biomass feedstock storage considered. To have an efficient operation, reduce costs, and reduce transport emissions for biomass feedstock coming from long distances, feedstocks can be processed and stored at a facility from where bulk transporting can then be done to the BPP site.

Hence, for Fiji's case, it is imperative to build a supply-chain network where the costs at each stage (forests, storage, powerplant) are well known and adequately incentivised to keep all actors working together. In terms of feedstock price paid to farmers; sugarcane farmers in Fiji are getting USD41.65/tonne of sugarcane sold to FSC mills (Boyle, 2020), so a feedstock price of more than USD41.65/tonne and less than USD98/tonne can be given to potential planters interested in selling to BPP. In addition, Fiji's western division has a small railway infrastructure used during the sugarcane crushing season June to November. This same infrastructure could be used to transport feedstock to BPP if the plant is suitably located.

5.2.8. Utilising waste generated from sawmills

There are two types of sawmill present in Fiji: portable and static. In 2015, there were 30 static mills, 63 portable mills and 12 operational kilns (DoF, 2015). To estimate the sawmill residue generation, difference between the input and output volume of sawmill is calculated. (DoF, 2015) reported the material balance from sawmills in 2015 for different divisions.

The input and output volume difference was calculated as 31,180 m^3, 21,256 m^3 and 17,163 m^3 from northern, central, and western divisions respectively for 2015. This difference is around 50% of the input volume. The residue volume in 2015 was 69,599 m^3 while in 2014, it was 69,247 m^3 using the data provided by (Wainiqolo, 2014). Using 2014 data, it was found that 51% of the waste generated are from mahogany, 33% from pine and the rest from native species. Sawmill material balance for 2015 did not appear as a category in the list of different species of wood. So, assuming 2014 species distribution for various divisions in 2015, 13,596 tonnes, 9,269 tonnes and 7,484 tonnes of waste are generated from northern, central, and western divisions respectively. It is seen that the northern division has the highest sawmill residue generation. Hence, there is scope for BPP in the northern division as well.

5.2.9. Utilising other feedstock for the power plant and cofiring

In case of declining timber production in the future, it is advisable to consider alternative feedstock. However, the operating procedure for a power plant may change when different feedstock is used. Fiji has some significantly sized poultry farms. Thirty-two tonnes of poultry manure are generated in central division per day while 323 tonnes of poultry manure are generated per day in the western division and 17 tonnes per day in the northern division (FDoE and UNDP, 2014b). This manure can be made into briquettes and co-fired with wood chips at BPP. It reduces the feedstock supply risk for power producers and eliminates waste that the poultry industry is trying to dispose of. (Billen et al., 2015) show that chicken manure's electricity production is possible with added benefit of reduced emissions, and ash production from combustion could be recovered as phosphorous potassium (PK) fertilizer. However, care must be taken to improve the materials where ash is deposited. Due to high PK content, there will be agglomeration on the boards where ash is collected and the boiler tubes can be fouled (Billen et al., 2015).

Perennial grass such as vetiver can also be used to cofire BPP. (Masum et al., 2020) have studied economics and environmental effects of cofiring coal power plants with 9 different biomass feedstocks. One of the feedstocks they considered was perennial grasses and the cost of biopower from perennial grasses ranged from 120 to 130 USD/MWh compared to USD113/MWh for pine chips. Hence, perennial grass can be grown on the same land as SRWC and can be used as feedstock in BPP.

5.2.10. Increasing collaborative research and development

Forestry, agriculture, and energy sectors should enhance research and development collaboration between them. Some potential study areas can be cost of harvesting SRWC and or forest residues, the productivity of woodchipper when different species are chipped, and intensive study on the availability of woody biomass feedstock for BPP. The potential of perennial grass can also be explored in future studies to determine its feasibility for use in BPP. More collaboration between the MoF and academic institutions is needed to collect and analyse relevant data for bioenergy production and potential for carbon sequestration. In addition, business models need to be developed on increasing the radius of getting feedstock into the BPP. The planting costs, harvesting costs, transport costs, and feedstock cost must be studied so that all actors involved benefit from engaging.

It is recommended that the soil properties in different divisions in Fiji are studied for planning SRWC and also the type of land tenure. GIS study can be done to visualise the areas where planting can be done and determine plots where BPP could be installed given its proximity to continuous feedstock supply. In addition, monthly or weekly log production data need to be analysed to see how it varies within a year. FSC and TWIL currently use biomass in their CHP plants, so cogeneration is another possibility for using biomass resources and should be further investigated in any future study.

5.3. Environmental impact of biomass-based power plants

Fiji is trying to diversify its electricity generation portfolio for grid electricity. On average, Fiji has 54% of grid electricity generated from renewables (mainly hydro, as seen in Fig. 2), while the rest is from burning industrial diesel oil and heavy fuel oil. With an emission factor of Fiji's grid as 0.551 tCO_{2e}/MWh (UNFCCC, 2018), a 10 MW BPP can reduce the carbon emissions equivalent to 39,108 tCO_{2e}/year. This is the same as 16.8 million litres of gasoline not consumed or 3,597 ha of forest absorbing carbon. Hence, over its lifetime, 10 MW BPP can save 0.98 $MtCO_{2e}$ emissions. A 10 MW wind farm installed in Fiji in 2007 (EFL, 2019) has saved 37,225 tonnes of carbon emissions since its operation. The considerable difference can be attributed to the low capacity factor of the installed wind farm. Grid-connected solar PV generation in Fiji is mainly from commercial companies that have installed mostly roof-top solar PV to meet their demand and selling any excess to the grid. In total, approximately 4 MW of grid-connected solar PV is installed, and there are additional plans to bring more IPPs in solar power generation. A potential 10 MW solar PV can save 8,232 tCO_{2e}/year as calculated from a quick RETScreen analysis. One of the existing BPPs in Fiji of 12 MW capacity, is currently listed under UNFCCC as a clean development mechanism (CDM) project with 31,485 tCO_{2e} GHG reduction potential annually (UNFCCC, 2018).

Fiji Department of Environment has an environmental impact assessment unit to avoid irreversible changes and severe damage to the land, flora, and fauna, and enhance social aspects of development proposals. Implementation of any BPP has to undergo an EIA to study its effect on the environment and establish strategies to minimise the project's impact on the environment.

6. Conclusion

Island nations are striving to satisfy their international climate change related commitments while ensuring national development and energy security. For biomass power plants in Fiji and elsewhere, the technical aspects are not much of a problem. The real issue is the adequate and sustainable supply of quality feedstock. BPP can be sustainable if enabling policies, early stakeholder engagement, electricity export tariff, land tenure and lease agreements, and incentives for BPP stakeholders are available.

A proposed 10 MW BPP can generate 74.8 GWh of electricity annually with a GHG reduction potential of 39,108 tCO_{2e}/year. If the electricity export tariff is USD0.1621/kWh, then to have a positive NPV, the feedstock price must be less than USD98/tonne. Also, if the feedstock price is taken as USD41.65/tonne (the same rate that sugarcane farmers are paid), or USD68.6/tonne (same price for woodchip export), then the financials for a 10 MW BPP is still positive. Sensitivity analysis has shown that electricity export tariff followed by availability of power plant and the feedstock costs are the most critical parameters that impact the net present value of a BPP. In addition, 60,000 tonnes per annum of feedstock is needed for a 10 MW biomass power plant. To meet this demand, forest logging residue can be used. Calculations showed that estimated forest residue generated annually from central, western, and northern divisions in Fiji are 34,000, 65,000 and 25,000 tonnes respectively.

To supplement this feedstock, SRWC is proposed to be planted on empty, unused agricultural land, or degraded land or SWRC with food crops are grown in integrated farming. To invest into the planting of SRWC, it is recommended that awareness and training are needed. This study can be replicated for other developing countries to guide their policymakers.

CRediT authorship contribution statement

Ravita D. Prasad: Methodology, Writing – original draft, simulation, results and analysis and revising the original draft. **Atul Raturi:** Conceptualization, Methodology, Supervision, reviewing and revising the original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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